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Forests and water

A synthesis of the contemporary science and its relevance for community forestry in the Asia–Pacific region

RECOFTC
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"Much folklore and many myths remain about the role of land use and its relation to hydrology, and these hinder rational decision making. This is particularly true in relation to forestry, agroforestry and hydrology: claims by enthusiastic agroforesters and foresters are often not supportable. The perception that forests are always necessarily 'good' for the environment and water resources has, however, become so deeply ingrained in our collective psyches that it is usually accepted unthinkingly. The view is routinely reinforced by the media and is all-pervasive..."

Professor Ian Calder, *The Blue Revolution: Land Use and Integrated Water Resources Management,* Earthscan Press, 2005, p. 29

Contents

Preface

This paper was intended as a framework for internal discussions within RECOFTC on forest–water issues. The terms of reference required it be limited to 20 pages. Hence, it is not a complete or thorough analysis of all the issues; rather, it summarizes the key aspects of the scientific consensus that are particularly relevant for community forestry and points the way to relevant literature for anyone wanting to follow up on specific topics. Due to these limitations, agroforestry was excluded from the paper's discussions.

The results of previous scientific reviews of forest–water issues spanning three decades were drawn upon to inform many of the outlined positions. These were supplemented by reference to contemporary scientific literature wherever possible. A total of 101 references are cited in the document, covering many of the milestones in the science of forest hydrology over the past century. Included are major reviews of forest–water interactions. Effort was made to keep jargon and technical hydrological language to a minimum so that the document could be understood easily by a range of readers. For example, the terms "infiltration-excess overland flow", "saturation overland flow" and "saturation excess overland flow" were conflated into the single term "overland flow" throughout the text.

It was recognized at the outset that many aspects of the scientific consensus on forest–water issues will run counter to some of the views that constitute the popular narrative on the topic. This will challenge many long-held beliefs of some readers. Meeting such challenges is part of the process of professional renewal to which we should all aspire.

The paper benefited greatly from comments by David Cassells, Tony Costantini and Andrew Ingles, who kindly reviewed an early draft, as well as from feedback by RECOFTC staff and critiques from several external reviewers.

Don Gilmour

Executive summary

Concerns about the hydrological impact of forest management go back more than a century and continue to the present day. These concerns have tended to focus on the effects of forests and forest management on various streamflow parameters (particularly total water yield, low flows and flood flows), soil erosion, stream sedimentation, water quality, landslides and the water use of different vegetation types and species. There is now a solid body of scientific information for understanding and interpreting the relationships between forests and water in both temperate and tropical regions. However, there is also a parallel and deeply entrenched "popular narrative" that often runs counter to the consensus views of the forest hydrology scientific community.

The purpose of this report is threefold: (i) summarize the scientific consensus on the hydrological impacts of forest management in relation to the popular narrative; (ii) propose recommendations to community forestry policy-makers and practitioners to plan for and manage hydrological aspects of community forestry and (iii) propose recommendations to the Center for People and Forests (RECOFTC) on the incorporation of contemporary scientific knowledge on hydrological aspects of community forestry into the RECOFTC strategies and programme.

Scientific consensus on forest–water relations
The following summarizes the scientific consensus about forest–water relations, in juxtaposition with the popular narrative.

Forests and rainfall

Popular narrative: *Forests increase rainfall (and conversely, the removal of forests decreases rainfall).*

Key finding: The clearing of forests is highly unlikely to reduce total rainfall, and conversely, there is no evidence that reforestation increases rainfall. Caveat: In the few locations where "occult precipitation"[1] occurs, the clearing of cloud forests can cause a reduction in net precipitation.

Forests and water yield

Popular narrative: *Forests increase water yield (and conversely, the removal of forests decreases water yield).*

Water use of forests versus water use of other forms of vegetation

Key findings: For annual rainfall regimes greater than about 500 mm, forests use more water than shorter forms of vegetation because deeper root systems, higher Leaf Area Indices and greater rainfall interception lead to higher evapotranspiration. Taller forms of vegetation are also associated with greater surface roughness than shorter forms, which induces greater turbulence, leading to higher transpiration. Hence humid forested catchments yield lower total volumes of water (for wells, springs and streams) than humid catchments covered by shorter forms of vegetation.

Tree harvesting and water yield

Key findings: (1) In general, harvesting trees from forested catchments results in an increase in total water yield, with the greatest proportional increase occurring in low flow periods, such as the dry season. The increase in water yield declines over time if the forest is allowed to regrow.
(2) Forest management practices, such as planting density, stand structure, and size of area harvested can have a significant effect on water use, and potentially on water yield, particularly at the local level.

Water use of different tree species

Key finding: Trees produce biomass by using water for growth processes. By and large, trees that grow fast on a particular site, and produce much biomass, use a lot of water. Eucalyptus species have not been found to use more water than other tree species for equivalent biomass production.

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[1] "Occult precipitation" is precipitation in liquid (fog drip) and solid (rime) forms that are induced when clouds or fog encounter trees or other vegetation.

Forests and floods

Popular narrative: *Forests reduce floods (and conversely, the removal of forests increases floods).*

Key findings: (1) Increases in peak (flood) flows as a result of cutting trees are observable for small to medium-sized rainfall events in relatively small catchments – less than about 10 km².
(2) The major determinants of large scale flooding at all catchment scales are: rainfall amount and intensity, antecedent rainfall and catchment geomorphology – not vegetation type.

Forests and low flows

Popular narrative: *Forests increase baseflows (and conversely, the removal of forests decreases baseflows).*

Key findings: (1) A heavy reduction in forest cover or deforestation generally results in an increase in dry-season (base) flows, but the longevity of the increase will depend on the future condition of the catchment, particularly the infiltration capacity of the surface soil.
(2) Reforestation generally results in a decrease in base (low) flows that may last for several decades. The impacts are likely to be most noticeable in small catchments.
(3) The reforestation of catchments with heavily compacted soils can have variable effects on low flows, depending on the trade-off between the increase in rainwater infiltrated into the soil as site amelioration progresses and the increase in evapotranspiration from the expanding tree cover.
(4) There is some uncertainty about the extent to which these generalizations are universally applicable.

Forests and flow regulation

Popular narrative: *Forests regulate streamflows, in that they reduce high flows and increase baseflows (and conversely, the removal of forests results in less well regulated streamflows).*

Key findings: (1) In small catchments and for small rainfall events, forests have a limited capacity to regulate streamflows (to reduce flood flows), compared with other well-managed vegetation types, but there is no demonstrated capacity to increase baseflows.
2) For large catchments and particularly for large rainfall events, forests have no demonstrated capacity to regulate streamflows, compared with other well-managed vegetation types.
(3) Deforested catchments that have become severely degraded with heavily compacted soils can exhibit poorly regulated streamflows. A high percentage of rainfall, particularly from heavy rainfall events, can be converted to overland flow (rather than infiltrated into the soil surface) that can contribute to high flood peaks, with a large proportion of the rainfall reappearing rapidly as streamflow. Urbanized catchments with a lot of sealed surfaces are extreme examples of this.

Forests, erosion and water quality

Popular narrative: *Forests reduce erosion (and conversely, the removal of forests increases erosion).*

Key findings: (1) Generally speaking, well-managed forests, free of grazing and other disturbances, provide good catchment cover that minimizes hillslope erosion and produces high-quality water that is free of sediment.
(2) Trees *per se* do not prevent erosion and, under some conditions, significant surface erosion can occur under undisturbed forests. The condition of the soil surface and, particularly, the retention of understory vegetation, grasses and litter are the primary determinants of surface erosion on hillslopes.
(3) The removal of trees does not, in itself, cause erosion, but poorly planned and executed timber harvesting operations that create substantial disturbance to the soil surface can result in substantial erosion, leading to stream sedimentation and a reduction in water quality.
(4) Stream banks are often the major source of sediment across a catchment, and the retention or development of riparian vegetation, particularly with a complex structure of grasses, shrubs and trees, can play a significant role in minimizing stream bank erosion and stream sedimentation and improving water quality.

Forests and landslides

Popular narrative: *Forests prevent or mitigate landslides (and conversely, the removal of forests increases landslides).*

Key findings: (1) The presence of deep root systems in forests can reduce the probability of shallow landslides (less than 3 m) in inherently unstable sites because of the cohesive strength of the roots.
(2) The removal of forests increases the risk of shallow landslides (less than 3 m) in inherently unstable sites.
(3) The occurrence of large-scale landslides (more than 3 m) is determined more by geologic, topographic and climatic factors than by the presence or absence of forests.

There have been very few studies focused specifically on community forests,[2] either plantation or natural. The following summarizes the studies that have relevance to forest-water relationships.

Key findings from hydrological studies focused on community forestry

Simply planting trees on community land where the soils has been compacted is not sufficient to restore the hydrological functions of the site. Attention needs to be given to ongoing management of the reforested areas to balance product use with hydrological functioning. Of specific importance are: (i) balancing use (particularly the removal of leaf litter and understory vegetation) and cattle grazing with the retention of organic matter and its incorporation into the surface soil and (ii) limiting activities such as animal grazing that can lead to the compaction of the soil surface. This represents an added dimension to the already complex process of community forest management and will present considerable challenges to both forest-dependent communities and governments.

Recommendations to community forestry policy-makers and practitioners

- Recognize the limited ability of community forestry to affect the hydrological functioning of large catchments. The impacts of forest management on most aspects of the hydrological cycle will be felt more at the local level than in larger catchments. Local impacts are diluted as the size of the catchment increases.
- Recognize the need for trade-offs between biomass harvesting and water values. For example, if dry-season water flow is of critical local importance, then silvicultural systems may be needed to manage the forest to increase dry-season flows.
- Recognize the need for trade-offs between managing community forests to maximize carbon capture and storage and managing for a range of other values, including water values.

Conclusions

The science of forest–water relationships is now well understood, and there is scientific consensus of the major processes involved and the general direction of management impacts. Although some policy uncertainty remains, there is sufficient knowledge to make "best bet" policy and practical decisions on most matters that relate to forest–water interactions. It is important that RECOFTC as an organization and its staff present a consistent position on matters related to forest–water interactions and one that is based on sound science – reflected by the contemporary scientific consensus.

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[2] "Community forestry" is a broad term used to describe models of forest management that place local people at the centre of decision-making. There is no particular reason why the hydrological functioning of community forests should differ from that of non-community forests. However, the TOR for this paper required a specific focus on community forests.

1. Introduction

1.1 Background to the review

Concerns about the hydrological impact of forest management go back more than a century (Ice and Stednick, 2004). These concerns have tended to focus on the effects of forests and forest management on various streamflow parameters (particularly total water yield, low flows and flood flows), soil erosion, stream sedimentation, water quality and landslides. Other aspects that have been of concern from time to time include the link between forests and rainfall and the water use of different vegetation types and species. Andeasssian (2004) gives a detailed account of the evolution of the debate surrounding forest–water interactions, beginning with Pliny the Elder in the first century A.D.

The long history of scientific research into forest hydrology starts with the famous Wagon Wheel Gap experiments in the United States that commenced in 1909 (Bates and Henry, 1928), although there were earlier efforts in Switzerland to measure streamflow from two catchments with different levels of forest cover (Ice and Stednick, 2004). Most forest hydrology research until the 1970s was carried out in humid temperate forest regions, particularly the United States, and the understanding that came from that work was perceived to apply equally to the tropics and subtropics. Since the 1970s, however, there has been an increasing amount of research carried out in tropical and subtropical regions, which has led to a more nuanced understanding of basic hydrological processes that apply in these regions. Cassells et al. 1985a and 1985b) provide a discussion of the key hydrological differences between humid temperate and tropical regions (a brief summary appears later in this paper).

The classic research approach developed in the early to middle twentieth century to study forest–water relations used paired catchments.[3] In this approach, after a period of calibration (generally over several years, during which time the hydrological performance of the selected catchments – in particular, their rainfall–runoff relationships – is compared), one catchment of the pair is retained as a control while a treatment, such as forest harvesting or complete clearing, is applied to the other catchment and the results are then measured. (Much of this original groundbreaking work was reviewed in a classic paper by Bosch and Hewlett (1982); a more recent paper by Brown et al. (2005) updated the paired-catchment experiments with a focus on changes in water yield from alterations to vegetation cover.)

Although the initial research tended to be somewhat empirical, over time there has been a substantial refinement in our ability to investigate, understand and interpret the basic processes that underpin forest–water relationships (Bonell and Bruijnzeel, 2005). This increasingly sophisticated and nuanced understanding has resulted in widespread acceptance within the scientific community of the basic hydrological impacts of most forest management practices. It also has contributed to the development and adoption by many forest management authorities around the world, particularly in the industrialized world, of best management practices to minimize adverse hydrological impacts (Cassells and Bruijnzeel, 2005).

A considerable amount of research into forest hydrology has been carried out at the scale of small plots. Such studies are very useful in gaining insights into hydrological processes and making comparisons between, for example, the response of different soil or vegetation types to rainfall. However, there are limitations when trying to extrapolate findings from small plots to a catchment scale. Extrapolation of processes, such as infiltration, overland flow, sediment transport and subsurface water flow from hill side plots to a catchment scale, (even to small catchments), is notoriously problematic. The heterogeneity of most catchments adds to the difficulties (see Bissonnais et al., 1998; Cammeraat, 2002; Sivapalan and Kalma, 1995 for discussions of this topic of extrapolation). Thus, where possible, catchment scale studies were selected to illustrate key issues in this paper, although supported by process studies where possible. The incorporation of plot-scale process studies into controlled catchment experiments is the ideal situation to maximize insights, but this is rarely achieved, particularly in tropical regions.

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[3] Two catchments were generally selected based on their physiographic similarity, on the assumption that their hydrological performance would also be similar. While this approach is intrinsically appealing, in practice there are many difficulties in making comparisons. However, more recent developments in carrying out studies of the underlying hydrological processes that influence rainfall runoff relationships have led to greater understanding of what is going on inside the "black box" of the catchments below the soil surface.

1.2 Disconnect between scientific consensus and the popular narrative of forest–water interactions

As noted, the extensive research carried out over the past half century has led to a solid body of scientific information for understanding and interpreting the nature and dynamics of hydrological processes as they apply in forested catchments. However, these processes are complex and require the application of expert knowledge of climatic, geological, soil, biological and human systems and their interactions in the real world. There is also a parallel set of deeply entrenched "popular" beliefs that often run counter to the consensus views of the forest hydrology scientific community. These beliefs, taken together, have contributed to the development of a "popular narrative" that is based on "folklore, myth, or misunderstanding of research" (Hamilton, 1985, p. 680). These beliefs run counter to virtually all scientific reviews and analyses that have taken place over the past 30 years. Andreassian (2004, p. 18) noted, "The long historical debate on Water and Forests has shown how popular myths and misconceptions may prevent the emergence of sound scientific reasoning."

The primary elements of this popular narrative (adapted from Calder, 2000; Calder, 2005; FAO, 2002 and Hamilton, 1985) relevant to this paper are as follows:

1. Forests increase rainfall (and conversely, the removal of forests decreases rainfall).
2. Forests increase water yield (and conversely, the removal of forests decreases water yield).
3. Forests reduce floods (and conversely, the removal of forests increases floods).
4. Forests increase baseflows (and conversely, the removal of forests decreases baseflows).
5. Forests regulate streamflows – they reduce high flows and increase baseflows (and conversely, the removal of forests results in less well regulated streamflows).
6. Forests reduce erosion (and conversely, the removal of forests increases erosion).
7. Forests prevent or mitigate landslides (and conversely, the removal of forests increases landslides).

Fisher (1990) noted that some of the popular and widespread beliefs frequently become so pervasive that they assume the dimension of a myth – in the anthropological sense that it is a "charter for action". Table 1 gives some examples of this.

Table 1: Examples of the popular narrative (based on unscientific perceptions) leading to a charter for action

Popular narrative (popularly held beliefs not supported by scientific evidence)	Charter for action based on popular narrative
Forests produce rainfall.	Contemporary "scientific" opinion convinced the European colonial powers to establish tropical forest reserves with the explicit goal of maintaining rainfall, starting in the British West Indies in 1763 (Chomitz and Kumari, 1996).
The "Theory of Himalayan Environmental Degradation" (a phrase coined by Ives and Messerli, 1989, see also Ives, 2005) purported (among other things) to link deforestation in the foothills of the Himalayas with widespread and disastrous flooding and sedimentation in the Ganges floodplain, particularly in Bangladesh.	The widespread acceptance of the simplistic links of this theory by governments and aid agencies acted as a justification for the expenditure of vast sums of money on reforestation schemes in the Himalayan foothills, particularly in Nepal, during the 1980s, partly in the hope that this would reduce flooding and sedimentation in the lower Ganges (Gilmour and Fisher, 1991).
Large-scale reforestation will regulate streamflows and reduce erosion in large catchments.	Large-scale reforestation with pines was carried out in Sri Lanka's Mahaweli catchment in the 1990s, mainly on degraded tea plantations. It is now realized that pine afforestation has reduced both annual and seasonal flows, so the project had the opposite effect to that intended. In addition, on-site erosion virtually ceased when the tea plantations were colonized naturally by grass (Calder, 2005).

Logging of forests in mountainous terrain will cause or exacerbate large-scale floods and cause landslides. (FAO, 2001 explains the rationale for this belief.)	• Logging bans were imposed in Thailand in 1989 following disastrous floods and landslides in the south of the country in 1988. This was done in response to media reports and popular opinion that linked commercial timber harvesting with flooding and landslides (FAO, 2001). • A logging ban was imposed in natural forests in 13 provinces in the Yangtze River valley in China in 1998, following severe flooding in the region. The ban remains in place (*People's Daily*, 2001; FAO, 2001).
Eucalyptus species are "water guzzlers" compared with native tree species and will dry out soils and cause wells to dry up. (Casson, 1997 and Calder, 2005 provide examples of this belief.)	• Eucalypts have been removed from certain areas in Kenya on the order of the government (WRM, 2009). • Planting eucalypts was (and still is) very controversial in much of Thailand (Pousajja, 1996) and in the mid-late 1980s the Government adopted an implicit policy of not promoting eucalypt planting, largely because of pressure from environmental NGOs. • A large government-sponsored programme in South Africa was established in 1995 to clear alien invasive species, including eucalypts, partly on the basis that they used more water than native species (UNEP, undated).
Deforestation will lead to a drastic reduction in water yield and major increases in erosion and stream sedimentation. (The widely held belief in this causal link among politicians and the media in Thailand is described by Enters, 1992, who also notes that shifting cultivators were perceived as the perpetrators of deforestation and, hence, as the culprits in reducing water yield and causing erosion.)	Substantial investment was made in catchment management projects in the highlands of northern Thailand in the 1980s and 1990s (Sombatpanit, 1992, quoted in Enters, 1992). Activities centred on changing the attitude and behaviour of hill farmers and, in some situations, moving them out of catchments (McKinnon and Vienne, 1989, quoted in Enters, 1992).
Extensive tree planting will decrease large-scale flooding. (The rationale for this belief is outlined in FAO, 2005.)	Following severe flooding in Thailand in 2012, a draft national strategy was prepared to restore forests in headwater areas and prevent deforestation in an endeavour to reduce large-scale flooding. Calls have also been made to remove two million people from the country's mountain zones (*The Nation*, 2012).

The views associated with the popular narrative are routinely reinforced by the media and have even become embedded in some influential environmental policy documents (Calder, 2000). Calder noted (2000, p. 19), "These simplistic views, particularly as they imply the inevitable link between the absence of forests and 'degradation' of water resources, have created a mindset which not only links 'degradation' with 'less forest' but rehabilitation and conservation with 'more forest'. This mindset has caused, and continues to cause, governments, development agencies and UN organizations to commit funds to afforestation or reforestation programmes in the mistaken belief that this is necessarily the best or only way to improve water resources. Clearly there are many valid reasons for afforestation or reforestation programmes, but where the objectives are to improve water resources they are unlikely to be achieved."

1.3 Reasons for the persistence of the popular narrative

One might question why the popular narrative, with its myths and misunderstandings, continues to persist in the face of scientific consensus on key aspects of forest–water relationships. There are many reasons for this (see Hamilton, 1985; Calder, 2000; Calder 2005; and FAO, 2005 for detailed discussions). Calder (2000) postulated that there are seven main reasons for the persistence of the popular narrative:

- Researchers have not made their results available to a broad community of people operating in disciplines related to environmental research and decision-making and to the general public.
- Research grant-making bodies tend to promote single disciplinary research where impacts are not linked to policy and decision-making in the real world.
- Managers and decision-makers do not take the trouble to make themselves aware of contemporary scientific developments.
- The media are generally content to repeat conventional wisdom and pseudoscience rather than check authenticity.
- The scientific community has a vested interest in assuring that no questions are finally answered so that research funding can continue.
- Structural inadequacies within and among large organizations hinder information flows.
- Inappropriate systems of economic incentives, penalties and regulations governing land management and production practices persist.

Even though the science of forest hydrology in temperate regions is no longer young, it is only since the late 1980s that sufficient research has been carried out in humid tropical regions to enable a science-based explanation of forest–water interactions to be formulated that is applicable to these regions. Cassells et al. (1987) noted that the evolving knowledge of tropical forest hydrology was not always applied in forest management and forest policy development. Indeed, where it was applied, it was often against strong resistance from forest bureaucracies and the forest industry. Many of the ideas that prevailed prior to the 1980s still persist and have influenced university teaching in some countries as well as popular attitudes.

In addition to the seven reasons previously cited for sustaining the popular narrative, part of the rationale is undoubtedly a desire by many people and groups, including the popular media, for simple and easily understood cause–effect relationships. Thus, they tend to generalize and oversimplify the complex and overlapping processes involved. This is exacerbated by the well-intentioned desire of many foresters and agroforesters to promote the use of forests as being good for the environment in all situations.

1.4 Purpose of this paper and approach taken

The purpose of this paper is threefold: (i) summarize the scientific consensus on the hydrological impacts of forest management; (ii) propose recommendations to community forestry policy-makers and practitioners to plan for and manage hydrological aspects of community forestry and (iii) propose recommendations to RECOFTC – The Center for People and Forests on the incorporation of contemporary scientific knowledge on hydrological aspects of community forestry into its strategies and programme.

As noted, interest by policy-makers and forest managers in forest–water interactions has been high for many decades, if not centuries. Partly because of this general interest but particularly driven by the disconnect between the popular narrative and science-based understandings, numerous attempts have been made over the past 30 years to review comprehensively the results of forest hydrology research around the world and summarize the state of knowledge. The most important of these reviews are listed in table 2.

Table 2: Selection of important reviews of forest–water relations since 1983

Year of review	Title of review (in chronological order)	Geographic focus of review	Number of references cited
1983	L.S. Hamilton, with P.N. King. *Tropical forest watersheds: hydrological and soils response to major uses or conversions.* Boulder, Colorado: Westview Press.	Tropical	203

Year of review	Title of review (in chronological order)	Geographic focus of review	Number of references cited
1985	L.S. Hamilton. Overcoming myths about soil and water impacts of tropical forest land uses. In: S.A. El-Swaify, W.C. Moldenhauer and A. Lo, eds. *Soil erosion and conservation.* Ankeny, IA: Soil Conservation Society of America. pp.680-690.	Tropical	34
1987	D.S. Cassells, M. Bonell, L.S. Hamilton and D.A. Gilmour. The protective role of tropical forests: A state of knowledge review. In N.T. Vergara and N.D. Brianes, eds. *Agroforestry in the humid tropics.* Honolulu: Environment and Policy Institute, East-West Center. pp.31-58.	Tropical	73
1989	L.A. Bruijnzeel, with C.N. Bremmer. *Highland-lowland interactions in the Ganges Brahmaputra River Basin: a review of published literature.* Occasional Paper No. 11. Kathmandu: International Centre for Integrated Mountain Development.	Ganges/ Brahmaputra River Basins	278
1990	L.A. Bruijnzeel. *Hydrology of moist tropical forests and effects of conversion: a state of knowledge review.* Paris and Amsterdam: UNESCO and Free University Amsterdam.	Humid tropics	659
1993	L.M. Reid. *Research and cumulative watershed effects.* Pacific Southwest Research Station, General Technical Report PSW-GTR-141. Washington, DC: US Department of Agriculture, Forest Service.	US	918
2002	FAO. Land-water linkages in rural watersheds. *FAO Land and Water Bulletin 9.* Rome: Food and Agriculture Organization of the United Nations.	Global	
2002	Forestry Agency of Japan. *International expert meeting on forests and water,* Shiga, Japan, 20–22 Nov. 2002. Tokyo: Ministry of Agriculture, Forestry and Fisheries.	Global	
2004	L.A. Bruijnzeel. Hydrological functions of tropical forests: not seeing the soil for the trees. *Agriculture, Ecosystems and Environment,* 104. pp.185-228.	Tropical	332
2004	V. Andreassian. Waters and forests: from historical controversy to scientific debate. *Journal of Hydrology,* 291. pp.1-27.	Global	88
2005	M. Bonell and L.A. Bruijnzeel, eds. *Forests, water and people in the humid tropics: past, present and future hydrological research for integrated land and water management.* International Hydrology Series. Paris and Cambridge: UNESCO and Cambridge University Press.	Humid tropics	
2005	I.R. Calder. *Blue revolution: integrated land and water resources management.* Oxford: Earthscan.	Global	243
2005	FAO. *Forests and floods: drowning in fiction or thriving on facts?* RAP Publication 2005/03. Bangkok: Food and Agriculture Organization of the United Nations.	Global	51

Year of review	Title of review (in chronological order)	Geographic focus of review	Number of references cited
2005	A.E. Brown, A.E., L. Zhang, T.A. McMahon, A.W. Western and R.A. Vertessy. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology*, 310. pp. 28-61.	Global	106
2007	I.R. Calder, T. Hofer, S. Vermont and D. Warren. Towards a new understanding of forests and water. *Unasylva*, No. 229, 58(4). Rome: Food and Agriculture Organization of the United Nations. pp.3-10.	Global	15
2008	FAO. *Forests and water.* FAO Forestry Paper 155, Rome: Food and Agriculture Organization of the United Nations.	Global	151

The book edited by Bonell and Bruijnzeel (2005) is worthy of special mention. It is a 925-page volume that is a state-of-the-art overview of current knowledge on the hydrological functioning of tropical forests, the environmental impacts of forest disturbance and conversion and the best ways to minimize the adverse impacts.

This paper draws heavily on the results of the reviews listed in table 2, supplemented by additional studies and reports. Where possible, original research papers were perused, particularly those that have had an important influence on the scientific views of contentious issues. While there is a large body of literature on forest–water interactions in general, very little of it relates specifically to community forestry.

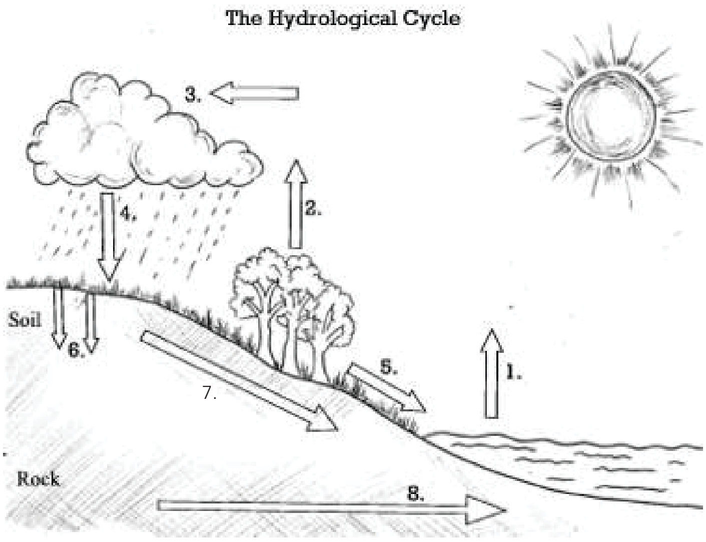
2. Hydrological processes in forested catchments – Basic concepts

An understanding of the hydrological cycle is necessary for any informed discussion of forest–water interactions. Before moving into the summary of the hydrological impacts of forest management, the following describes the basic hydrological processes that operate in forested catchments.

The hydrological cycle

Water moves in a continuous cycle from the atmosphere to the earth by precipitation and eventually back to the atmosphere by evaporation, with the process driven by energy from the sun. This is referred to as the "hydrological cycle" (figure 1). The amount and type of streamflow coming from a catchment (the water yield) is a measure of the interaction among many factors, including rainfall, geology, geomorphology, soil and vegetation.

Figure 1: The hydrological cycle



Components of the hydrological cycle

1. **Evaporation** from open water surfaces, soil and vegetation
2. **Transpiration** from vegetation (evaporation and transpiration are collectively referred to as **evapotranspiration**)
3. **Movement of atmospheric moisture and cloud formation**
4. **Precipitation**
5. **Saturation overland flow** of rainfall excess
6. **Infiltration** of rainwater into the soil surface, and **percolation** into subsoil zones and underground aquifers
7. **Lateral subsurface flow**
8. **Storage of groundwater** in underground aquifers and discharge into streams

The concept of "water balance" is useful for studying the quantum of water throughout the hydrological cycle. The water balance underpins our understanding of catchment hydrology because it accounts for all the water within the cycle. Simply stated, this is:

$$\mathbf{P = Et + Q + \Delta G +/- \Delta S,}^{4}$$ where:

P = **precipitation** on the catchment
Et = **evapotranspiration** (water use from vegetation plus evaporation from vegetation, soil and water surfaces)
Q = **streamflow** from the catchment (water yield)
ΔG = **change in groundwater storage**
ΔS = **change in soil water storage**

Table 3 reflects the annual water balance (averaged over a four-year period) for an undisturbed tropical rainforest catchment in a heavy rainfall region of northern Australia.

Table 3: Average annual water balance (1969–1973) of an undisturbed tropical rainforest catchment in northern Australia

Component		Water (depth in mm)
P	Precipitation	3,899
Et	Evapotranspiration	1,502 (39% of rainfall)
Q	Streamflow (surface water yield)	2,374 (61% of rainfall)
∆G	Recharge to groundwater	22
∆S	Change in soil water storage between measurement periods	1

Source: Gilmour, 1975.

Understanding the water balance helps us to assess the hydrological implications of different land management options, and improves the basis for informed management decision- making. For example, it is quite common for evapotranspiration from forests in humid regions to account for more than 50 percent of the annual rainfall. Yet, in more arid environments, forests can consume virtually all of the precipitation, leaving little or nothing for streamflow or groundwater recharge (Malagnoux et al., 2007).

From the time precipitation reaches the earth's surface until it returns to the atmosphere through transpiration and evaporation, it can be influenced to some extent by human activities. The components of the hydrological cycle that are most susceptible to modification by land use management are those associated with: (i) the use of water by vegetation (evapotranspiration) and (ii) the differential flow pathways for water moving over the soil surface and into and through the soil mantle.

Against this understanding, the following section discusses forest–water relationships in more detail.

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[4] Modified from Gregory and Walling, 1973.

3. Literature review of hydrological impacts of forest management

Forest land use policies in many countries are influenced to some extent by the perceived effect of forests on the hydrological functioning of catchments, soil erosion control and sediment-reduction benefits. It is extremely important that policies are informed by the best science available. This section summarizes the scientific consensus of key aspects of forest–water relationships that are likely to be of concern to policy-makers and field practitioners. The popular narrative is used as an organizing framework for the discussion.

One important point to keep in mind is that while it is possible to make scientifically sound generalizations about particular forest–water interactions, these often need to be qualified because of site-specific conditions. Some of these qualifications are discussed throughout this section.

3.1 Forests and rainfall

Popular narrative: *Forests increase rainfall (and conversely, the removal of forests decreases rainfall).*

There has been an interest in the link between forests and rainfall for many centuries. Chomitz and Kumari (1996) described some of the scientific and policy aspects of a running debate, ongoing since the eighteenth century. The location of forests in heavy rainfall areas has led many to assume a causation function for forests rather than a dependent association. Scientists rejected that relationship as they began to understand the basic processes involved in rainfall generation and its spatial distribution. For example, orographic precipitation is a phenomenon that occurs when moisture-laden winds ascend mountains; as the air expands in response to a drop in atmospheric pressure, it also cools, and the moisture it holds condenses and finally falls as rain. This produces moisture regimes suitable for the growth of forests.

Many conservationists in the 1980s argued that cutting forests, particularly tropical rainforests, would create droughts and result in desertification. Campaigns to “save the rainforests” revolved around this argument (Hamilton, 1985). There is also folklore in many countries that links the removal of trees with reduced rainfall. However, the bulk of scientific evidence shows little or no relationship between the presence or absence of trees and rainfall (Bruijnzeel et al., 2005).

Despite this general conclusion, there is one well-documented exception. It relates to cloud forests, which occur in particular physiographic locations where there is a high incidence of fog or wind-driven low clouds. These are typically associated with coastal fog belts or high elevation areas where montane cloud forests occur. In such situations, forests can capture and condense atmospheric moisture (they effectively sieve water out of the fog and cloud) and increase the local precipitation, which is referred to as “occult” precipitation. Loss of trees in such sites results in a loss of moisture from the overall water budget of the area, although this could be offset partially by reduced transpiration (see Hamilton et al., 1993; and Bruijnzeel et al., 2010 for a thorough discussion of cloud forests).

There are only a relatively few areas where occult precipitation occurs. Bruijzneel et al. (2011) estimated that tropical montane cloud forests constitute about 6.6 percent of all tropical montane forests.

A second qualification to the general conclusion comes from recent modelling work of meteorological systems that operate on a continental scale, such as occur in the Amazon and Congo basins. The modelling conclusions suggest that in these vast areas, the forest may generate some of its rain through the re-precipitation of forest evapotranspiration, although the amount is likely to be small (Bruijnzeel et al., 2005). This issue has received more recent attention with the publication of a controversial paper (Makarieva et al., 2013) that argued, on the basis of theoretical atmospheric physics, that forests act as biotic pumps and are the driving force behind precipitation over land masses. That paper and its theory have been subjected to considerable criticism from the mainstream scientific community, including the publishing journal’s own peer reviewers. In addition, some of the assertions in the paper – such as the suggestion that lack of rainfall in the seasonally wet, semi-arid tropics and subtropics of Western Australia are due to deforestation – are clearly wrong. The aridity of these environments predates human settlement and is known to be a result of the northern geological movement of the Australasian continental plate over hundreds of millions of years.

In contrast to the argument made by Makarieva et al., Angelini et al. (2011) found that "…rain in Amazonia comes primarily from large-scale weather systems coupling interior regions to the ocean and is not directly driven by local evaporation". And that: "This analysis reaffirms the view that changes in precipitation over continental reaches are a product of complex processes only partly influenced but not controlled by local water sources or vegetation." (p. 243).

Overall, there is little empirical evidence to support either this modelling work or the theoretical analysis. Rather, the opposite is true. The Asian monsoon, for example, is demonstrably driven by seasonal shifts in continental temperature gradients (Callaghan and Bonell, 2005) and has certainly survived both historical and recent anthropogenic deforestation in the region.

Key finding

The clearing of forests is highly unlikely to reduce total rainfall, and conversely, there is no evidence that reforestation increases rainfall. ***Caveat:*** In the few locations where occult precipitation occurs, the clearing of cloud forests can cause a reduction in net precipitation.

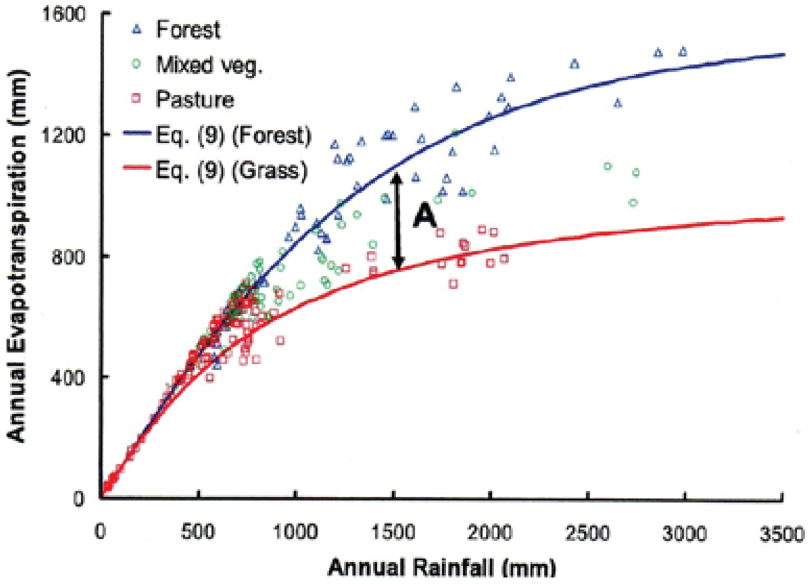
3.2 Forests and water yield

Popular narrative: Forests increase water yield (and conversely, the removal of forests decreases water yield).

Water yield of forests and other vegetation types

In spite of the complexity of the soil–vegetation–atmosphere system, the most important factors controlling mean annual evapotranspiration (water use) are annual rainfall and vegetation type (Zhang, 2001). Because of the deep-rooted nature of most forests, compared with the shallow rooting depth of most other vegetation types (such as grasses) plus their high Leaf Area Index, forests tend to consume more water (and intercept more rainfall, which is evaporated back into the atmosphere) than other vegetation types. Figure 2, which draws on more than 250 catchment studies across 29 countries, illustrates this by relating water use (expressed as annual evapotranspiration) to the prevailing rainfall (Zhang et al., 2001).

Figure 2: Relationship between annual evapotranspiration and rainfall, by vegetation type



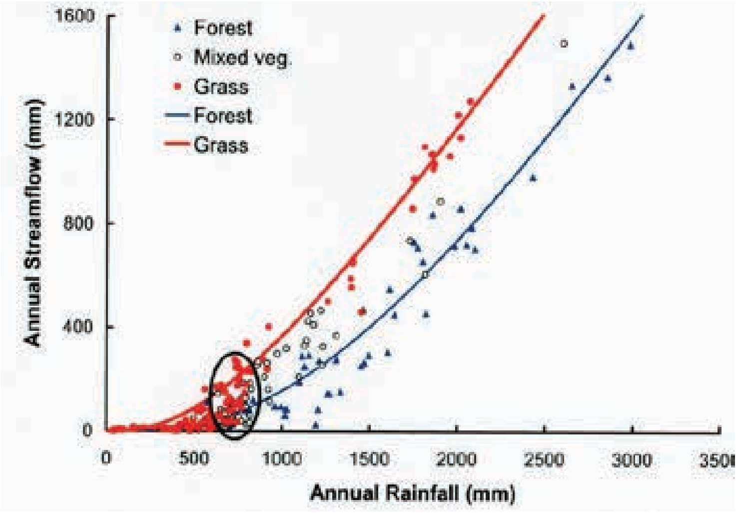
Source: Zhang et al., 2001.

The data in figure 2 indicates that for annual rainfall less than about 500 mm, there is little difference in water use between forests and pasture; but at more than that amount, the gap in water use between forests and pasture widens with increasing rainfall. The annual evapotranspiration of mixed vegetation types, such as mixtures of trees, agricultural crops and pastures, falls between the forest and pasture values.

This work leads to the general conclusion that in humid temperate and tropical regions, high water use by forests will translate into lower total water yield from forested catchments, compared with pasture and mixed-vegetation catchments. Figure 3 indicates the mean annual streamflow for different vegetation types, calculated from the data set used in figure 2 (Zhang, 2005).

The conclusion that forested catchments have greater evapotranspiration than catchments with lower forms of vegetation and hence yield less water is supported by a large body of research over many years (see Bosch and Hewlett, 1982 and Bruijnzeel et al., 2005 for summaries). This conclusion has been demonstrated at the large landscape scale by the extensive development of dry-land salinity in Australia. As Engineers Australia (2012) reported, large-scale forest clearing for agriculture and grazing over the past century resulted in more soil water being available to percolate to groundwater (rather than being transpired by forests), causing a gradual rise of water tables through saline soil profiles. When the saline groundwater reached the surface, evaporation allows salt to accumulate in the upper soil horizons; saline areas have appeared and expanded, killing the vegetation. More than 17 million ha were adversely impacted, resulting in a massive loss of production.

Figure 3: Mean annual streamflow calculated from the data in figure 2



Source: Zhang, 2005.

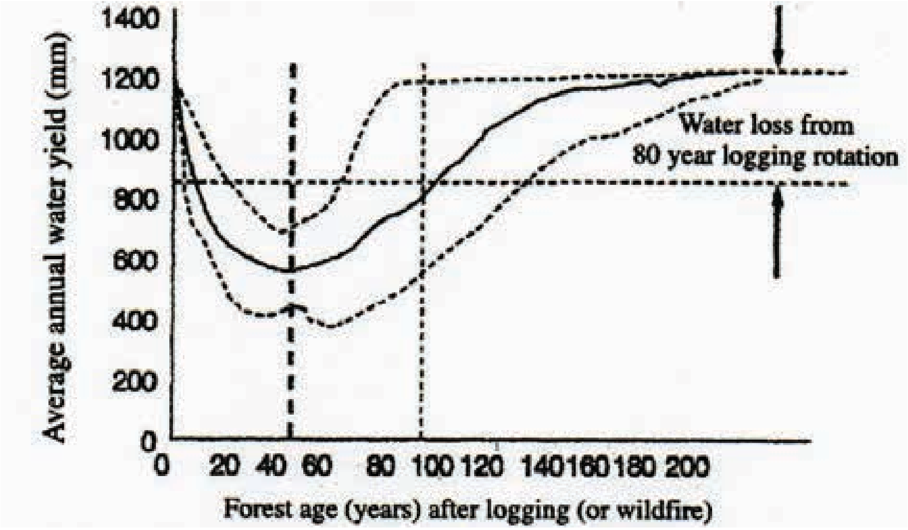
Huang and Zhang (2004) and Zhang et al. (2007) both reported on significant reductions in total water yield from catchments in China's Loess Plateau as a result of large-scale afforestation since the late 1950s. Huang and Zhang (2004) calculated that mean annual water yield (both surface runoff and baseflow) of a 1,100-km² catchment decreased by 32 percent from 1967 to 1989; they attributed this mostly to the establishment of tree plantations during that time. By 1989, the plantations covered 26 percent of the catchment, which is in a relatively low rainfall zone (422 mm per year). Seasonal runoff and baseflow also decreased during that same time period, with the greatest reduction occurring in summer and the smallest reduction in winter.

Zhang et al. (2007) also reviewed work by Lane et al. (2003), who examined changes to streamflow persistence in ten catchments with various levels of afforestation. Their analysis showed that different catchments respond to afforestation in different ways; in some, the high flows were more affected, while in others, the impact was greater on low flows. However, flows of all magnitudes were clearly reduced by afforestation.

It is worth emphasizing that the water use of forests can change over time as they grow and mature. In particular, their Leaf Area Index changes and hence their ability to both intercept rainfall and extract water from the soil. Detailed and long-running research in southern Australia on the water use of eucalypt forests demonstrates that fast-growing regrowth stands of ash-type eucalypts, that typically occur following clear-cut logging or wildfires, consume substantially more water than old-growth stands of the same species (Peel et al., 2000; Vertessy et al., 1996). This translates into decreased water yield from catchments with young regrowth stands (compared with old growth stands), and the effect persists for several decades. Figure 4 illustrates the relationship between forest age and annual water yield from catchments with different-aged natural forests of *Eucalyptus regnans*.

The relationships described here for the ash-type eucalypts have been well documented in many studies. However, recent analysis of a range of controlled catchment studies in mixed-species eucalypt forests suggests that there is no evidence of age-related decline in water yield for mixed-species eucalypts (Bren, 2013). Rather, it is attributed to the different ecological response of ash-type eucalypts to disturbances, such as fire or harvesting. Ash-type eucalypts typically respond to severe disturbance with dense even-age regeneration. Mixed-species eucalypt forests are much more heterogeneous and are not managed as even-aged stands.

Figure 4: Relationship between forest age and annual water yield for *Eucalyptus regnans* forests (dashed lines denote 95 percent confidence limits)



Source: Kuczera, 1985.

Key findings

For annual rainfall regimes greater than about 500 mm, forests use more water than shorter forms of vegetation because deeper-root systems, higher Leaf Area Indices and greater rainfall interception lead to higher evapotranspiration. Taller forms of vegetation are also associated with greater surface roughness than shorter forms, which induces greater turbulence, leading to higher transpiration. Hence, humid forested catchments yield lower total volumes of water (for wells, springs and streams) than humid catchments covered by shorter forms of vegetation.

Tree harvesting and water yield

One of the most widespread beliefs about forest–water relations is that harvesting timber from forested catchments and clearing forests causes wells, springs and streams to cease flowing, and that, conversely, reforesting bare hillsides will cause water to reappear in wells, springs and streams (Hamilton, 1985). As described by Hamilton, this belief is based on an analogy of forests as “sponges” that soak up water during wet periods and release it slowly and evenly in the dry season. Put simply, this implies that forested watersheds absorb virtually all the incipient rainfall and release it slowly into streams during the year – little or none runs off over the soil surface during most rainfall events.

However, the consensus of extensive research in controlled catchment studies is that harvesting trees causes an increase in total water yield, with the greatest proportional increase occurring in low flow periods (Bosch and Hewlett, 1982; Andreassian, 2005). The following box summarizes some of the results of the famous Bosch and Hewlett analysis of 78 controlled catchment experiments and 16 trend line experiments, covering a wide range of environments with mean annual precipitation ranging from 265 mm to 3,300 mm, along with a more recent analysis by Andreassian (2004) of 137 paired catchment studies.

Box 1
Results from catchment experiments of the effect of vegetation changes on water yield

1. Bosch and Hewlett's (1982, p. 3) review of 94 catchment experiments

"The direction of change in water yield following forest operations can be predicted with fair accuracy since no experiments, with the exception of perhaps one, have resulted in reductions in water yield with reductions in cover, or increases in yield with increases in cover. The approximate magnitude of changes can also be estimated. Pine and eucalypt forest types cause on average 40 mm change in water yield per 10 percent change in cover and deciduous hardwood and scrub ~25 and 10 mm, respectively."

Most of the studies in this analysis were from temperate areas, but studies from tropical and subtropical areas were also included.

2. Andreassian's (2004, p. 17) review of 137 paired-catchment studies

"Forests undoubtedly have an impact on the water balance at the basin scale: forest water consumption is generally higher than that of other vegetation types. Deforestation therefore results in an increase of water yield and reforestation in a decrease."

The studies in Andreassian's analysis covered the spectrum from temperate to tropical, although the majority were from temperate areas.

Detailed studies of the underlying hydrological processes indicate that harvesting trees or clearing forests causes an immediate reduction in evapotranspiration and, consequently, more water is available to generate streamflow. In general, the greater the biomass of vegetation removed, the greater the increase in total water yield (Bosch and Hewlett, 1982; Bruijnzeel et al., 2005; Calder, 2005). The increase in water yield declines over time if the forest is able to regrow and the Leaf Area Index increases. However, in many tropical situations, deforestation is frequently followed by site degradation of various sorts, particularly compaction of the surface soil. This can lead to a reduction in infiltration capacity and an increase in surface runoff. If degradation is widespread and severe, the expected steady return to pre-clearing hydrological conditions may not eventuate.

Key findings

(1) In general, harvesting trees from forested catchments results in an increase in total water yield, with the greatest proportional increase occurring in low flow periods, such as the dry season. The increase in water yield, however, declines over time if the forest is allowed to regrow.

(2) Forest management practices, such as planting density, stand structure and size of area harvested, can significantly affect water use and potentially water yield, particularly at the local level.

Comparative water use of different tree species

Plantation forestry generally makes use of fast-growing trees, particularly species of *Eucalyptus, Acacia* and *Pinus.* These genera also have been widely used in many social and community forestry programmes, particularly in Asia. By the late 1990s, more than four million ha of *Eucalyptus* plantations had been established in India, Thailand, Viet Nam and other parts of Asia (Casson, 1997). Calder (2005) noted that about half of all plantation forests in the tropics and subtropics consist of *Eucalyptus* species. These are popular because of their high growth rates and their ability to grow in a wide range of site conditions.

However, criticisms are often made that fast-growing trees, particularly exotics, use more water than native trees and lead to the drying out of soils and the drying up of wells and streams. This criticism is levelled particularly at *Eucalyptus* species (Casson, 1997; Calder, 2005). In some countries, this has prompted the banning of eucalypts from use in certain areas (WRM, 2009), while in other countries to strong, and occasionally violent, social protests against the planting of eucalypts (Casson, 1997; Calder, 2005).

Extensive research has been carried out in southern India (in a dry zone with about 800 mm of annual rainfall) in an attempt to resolve the issues related to water use of eucalypts, compared with that of other tree species and agricultural crops (Calder et al., 1997).

A summary of these research results indicated that:

- The water use of young *Eucalyptus* plantations on a medium-depth soil (approximately 3 m) was no greater than that of the indigenous, semi-degraded, dry deciduous forest.
- The annual water use of *Eucalyptus* and the indigenous, semi-degraded, dry deciduous forest approximated the annual rainfall of 800 mm.
- At all sites, the water use of forest was about twice that of finger millet *(Eleusine coracana),* a commonly grown annual agricultural crop.

Calder (2005) also reported on plot scale research evidence that pointed to eucalypts having high water use efficiency, as they produced more biomass per unit of water used than other tree species. Other research has also demonstrated that eucalypts are not inherently more profligate water users than pines when soil water is not limiting (Myers et al. 1996).

Key findings

Trees produce biomass by using water for growth processes. By and large, trees that are fast growing on a particular site, and produce much biomass, use a lot of water. *Eucalyptus* species have not been found to use more water than any other tree species for equivalent biomass production.

3.3 Forests and floods

Popular narrative: Forests reduce floods (and conversely, the removal of forests increases floods).

There is a widespread belief that shifting cultivation, logging and clearing of upland catchments is a major cause of downstream flooding, with the argument revolving round the loss of the "sponge effect" of the forest (Hamilton, with King, 1983; Enters, 1992; *The Nation*, 2012). Certainly, if heavy rain occurs following a lengthy period of dry weather, then some of the rain will go towards satisfying the soil water deficit that has built up.

As previously pointed out, forests are heavy users of water, compared with most other vegetation types; so there may be a greater soil water deficit built up under forests than under other vegetation types, at least on deep soils. When this occurs, the amount of water available to flow into streams in forested catchments will be less than that in non-forested catchments during the first rains of the wet season. For example, catchment water-balance studies in a heavy rainfall environment in northern Australia indicated that, at the end of the dry season, a forested catchment required 291 mm of rain to satisfy the soil water deficit, whereas an adjacent recently cleared catchment required only 94 mm – a difference of 197 mm (Gilmour, 1975). In that situation, the first 197 mm of rain at the beginning of the wet season would have gone into bringing the forested catchment to the same soil water status as the cleared catchment. However, once soils (under all vegetation types) are saturated, there is no further capacity to absorb water. Additional rain will quickly find its way into stream channels. This is particularly relevant in humid tropical regions, such as those affected by the Asian monsoon, which are subject to extended heavy wet seasons.

It is also perceived that flooding can be reduced or eliminated by large-scale reforestation. Bruijnzeel (2004) provided numerous examples of the articulation of this belief from South and Southeast Asia. Bruijnzeel made the important point that when considering the relationship of forests to floods, it is necessary to take into account not just the effect of vegetation but also the characteristics of the soil, particularly infiltration capacity and the capacity of the soil to store water. He presented evidence to indicate that peak flows can increase markedly when deforestation is followed by widespread soil degradation. Soil depth is also an important criterion.

In discussing this topic, it is necessary to distinguish between flood flows generated by small to medium-sized rainfall events and those generated by large rainfall events. The size of the catchment is also of importance. The clear indications from a range of studies are that substantial increases in peak (flood) flow as a result of cutting forests are observable for small to medium-sized rainfall events and for relatively small catchments – less than about 10 km.^{2} There is little or no measurable impact of forest cutting on flood flows generated by large rainfall events at any catchment scale, small or large (Bruijnzeel et al., 2005). Once soils become saturated during a large rainfall event, they are unable to absorb additional rainfall, irrespective of the type of vegetation cover. In large catchments, the effects of flooding tend to be averaged out across different sub-catchments (FAO, 2007). The major determinants of large-scale flooding are: rainfall amount and intensity, antecedent rainfall[5] and catchment geomorphology[6] – not vegetation type (Bruijnzeel 2004; Bruijnzeel with Bremmer, 1989; Calder, 2005).

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[5] "Antecedent rainfall" refers to the amount of rainfall in the period leading up to the flood-inducing rainfall.

Key findings

(1) Increases in peak (flood) flows as a result of cutting trees are observable for small to medium-sized rainfall events in relatively small catchments – less than about 10 km².

(2) The major determinants of large-scale flooding at all catchment scales are: rainfall amount and intensity, antecedent rainfall and catchment geomorphology – not vegetation type.

3.4 Forests and low flows

Popular narrative: Forests increase baseflows (and conversely, the removal of forests decreases baseflows).

Low flows are important because they occur when water is least available and frequently in greatest demand. This is particularly the case in areas that experience seasonal rainfall patterns. In his text on *Forest Hydrology*, Lee (1980) concluded that the attractive notion that forested catchments (compared with non-forested catchments) can prolong flow during low flow periods is clearly false.

Brown et al. (2005) emphasized that while the effect of vegetation change on a mean annual basis is well understood, the research on seasonal water yield reported in the literature is limited and primarily of a descriptive or graphical nature, rendering quantitative generalizations difficult to make. They also noted that in tropical catchments, two types of responses were observed, with either a uniform proportional change in water yield in all seasons or a greater proportional change in dry-season flow.

Most experimental evidence suggests that afforestation will significantly reduce dry-season flow or even cause streams to dry up completely (Zhang et al., 2007). Zhang et al. (2007, p. 27) concluded, "This is because trees can sustain relatively high transpiration rates throughout the dry season and hence create large soil water deficits. Proportionally, the reduction in dry-season flow due to afforestation is generally greater than the reduction in storm-flow; although the latter has a greater impact on total annual runoff volume."

Although there is a lack of information to enable quantitative estimates to be made of the impact of forest changes on low flows, there are some well-documented studies that support the general direction of change, as noted previously by Zhang et al. (2007). FAO (2008) reported on the large-scale planting of pines on dry zone grasslands in Fiji and the resultant dry-season streamflow reductions of 65 percent. The same publication presented research evidence from South Africa on reductions in water yield, including dry-season flows, following afforestation of native grasslands.

Bruijnzeel et al. (2005) concluded from their comprehensive review that reforestation results in a decrease in low flows in the short term (about 30 years). They also concluded that deforestation generally increases water yield during low flow periods. However, they warned that dry season flows can be reduced if the capacity of the soil to absorb water is seriously impaired, as can occur when surface soils become severely compacted.

Despite these generalized conclusions, there is some uncertainty. Calder (2005) considered that competing processes may result in either increased or decreased dry season flows as a result of changes to forest cover, and he considered that the impacts are very site-specific. For example, when considering the reforestation of degraded sites, there is a trade-off between the increase in rainwater infiltrated into the soil as site amelioration progresses and the increase in evapotranspiration from the expanding tree cover. Hence, it is probably prudent to be cautious in applying the generalized conclusions.

Key findings

(1) Heavy reduction in forest cover or deforestation generally results in an increase in dry season (base) flows, but the longevity of the increase will depend on the future condition of the catchment, particularly the infiltration capacity of the surface soil.

(2) Reforestation generally results in a decrease in base (low) flows that may last for several decades. The impacts are likely to be most noticeable in small catchments.

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[6] "Geomorphology" refers to the configuration of landforms.

(3) Reforestation of catchments with heavily compacted soils can have variable effects on low flows, depending on the trade-off between the increase in rainwater infiltrated into the soil as site amelioration progresses and the increase in evapotranspiration from the expanding tree cover.

(4) There is some uncertainty about the extent to which the generalizations expressed here are universally applicable.

3.5 Forests and flow regulation

Popular narrative: Forests regulate streamflows, in that they reduce high flows and increase baseflows (and conversely, the removal of forests results in less well regulated streamflows).

It is commonly believed that a major role of forests is to regulate streamflow; to some extent, this is true (FAO, 2007). However, the ability of forests to perform this function has often been exaggerated (Calder et al., 2007). The basis for this belief in regulation is the concept that forests act as sponges, soaking up water during wet periods and slowly releasing it into streams during dry periods, thus keeping forested streams flowing longer into the dry season.

In small catchments and for small rainfall events, forests may decrease peak flows, but they also tend to reduce base (low) flows – as discussed in the previous two sections. At the local level, regulation of streamflows depends largely on soil depth, soil structure and the degree of previous saturation. For example, shallow soils have a lower capacity to absorb rainfall than deep soils and as a result, they tend to produce flash floods (FAO, 2007). However, once forests become degraded, particularly if the surface soil becomes compacted, as frequently occurs in tropical regions following disturbance, overland flow can become a progressively more dominant stormflow pathway (Krishnaswamy et al., 2012). Under these circumstances, degraded catchments are likely to have markedly less well regulated streamflow regime than undisturbed or well-managed forested catchments.

Although the relationships discussed in the previous sections are generally applicable, research has shown that there is often considerable variability in catchment response at a local scale (Talsma and Hallam, 1982). In modelling the response of catchments to rainfall, Moore et al. (1988) emphasized the variability of runoff response in different parts of forested catchments. The response depended on a range of soil, topographic and other attributes. These influenced water flow processes, particularly the balance between surface and subsurface flow. Burch et al. (1987) noted that continuous macropore pathways in forested catchments contributed to rapid rises and falls in forest water tables, but the pathways appeared to be absent under grassland. Bonell (2005) provided a comprehensive discussion of runoff generation processes in tropical forests and also emphasized the variable nature of runoff generation at the hillslope scale in such environments.

Despite the local-scale spatial variability just described, it is widely acknowledged that forests have little capacity to regulate streamflows in large catchments and for large rainfall events, compared with alternate vegetation covers (Bruijnzeel et al., 2005). In extremely wet environments, forest clearing in even small catchments has little or no impact on flood flows because even undisturbed forested catchments generate large volumes of flood flow, which tend to override the relatively small changes to the flow regime caused by vegetation alteration (Gilmour and Bonell, 1977).

Key findings

(1) In small catchments and for small rainfall events, forests have a limited capacity to regulate streamflows – to reduce flood flows, compared with other well-managed vegetation types, but no demonstrated capacity to increase baseflows.

(2) For large catchments and particularly for large rainfall events, forests have no demonstrated capacity to regulate streamflows, compared with other well-managed vegetation types.

(3) Deforested catchments that have become severely degraded with heavily compacted soils can exhibit poorly regulated streamflows. A high percentage of the rainfall, particularly from heavy rainfall events, can be converted to overland flow (rather than infiltrated into the soil surface), which can contribute to high flood peaks, with a large proportion of the rainfall reappearing rapidly as streamflow. Urbanized catchments with a lot of sealed surfaces are extreme examples of this.

3.6 Forests, erosion and water quality

Popular narrative: Forests reduce erosion (and conversely, the removal of forests increases erosion).

It is useful to distinguish between erosion on hillslopes and that associated with stream banks because somewhat different processes are at play, with the result that the impact of trees and forests are different in the different situations.

Hillslope erosion

It is widely perceived that the presence of forests can control erosion and improve water quality. Wiersum (1984) makes the important distinction between the effects of trees per se and the effects of forests as integrated ecosystems. By and large, well-managed forests do tend to provide good protection against erosion on hillslopes but so too does well-managed grassland. However, the forest canopy itself does not prevent erosion; rather, what is critical are the conditions at the soil surface (FAO, 2007; FAO, 2008). Continuous vegetative cover of the soil surface reduces the terminal velocity of raindrops, thus reducing their erosive power. Incorporation of vegetative matter into the soil surface also tends to increase its infiltration capacity, thus reducing the amount of water that flows over the surface (Gilmour, 1977).

Gardner and Gerrard (2002) make the point that ground cover beneath the trees, especially leaf litter, is more effective in reducing runoff than the amount of canopy cover. Water dripping from tree canopies can coalesce into large-sized drops, which reach terminal velocities similar to that of rainfall in the open. These can cause substantial raindrop erosion on bare soil (Calder, 2005; FAO, 2007). In addition, surface vegetative matter protects the soil from the erosive force of running water. Hence, forests with limited protective soil cover, such as some dense forests of teak and eucalypt plantations, can be subject to high levels of surface soil erosion and even gullying.

Some community forests – with management that allows the removal of understory material and leaf litter – can be at increased risk of surface erosion (FAO, 2007). This is exacerbated in situations in which overland flow[7] is a common occurrence because of the erosive energy of water flowing over the soil surface rather than percolating into the soil mantle (Bruijnzeel et al., 2005). Many vegetation types can provide conditions that will minimize hillslope erosion, from continuous grass swards to forests.

Harvesting trees per se does not result in an increase in erosion. However, a distinction needs to be drawn between the cutting of trees and the overall logging and extraction processes. It is the latter that, if not properly planned and executed, can result in the removal of surface vegetation cover and disturbance of the soil surface with its dense mat of roots and can dramatically increase the potential for hillslope erosion (Gilmour, 1977). Accelerated erosion resulting from poorly executed harvesting is exacerbated in naturally dispersive soil types and can occasionally reach spectacular proportions (Gilmour, 1977). Reduced-impact logging systems have been developed and promoted to minimize the negative impacts frequently associated with unconstrained commercial harvesting (FAO, 2004).

A survey of more than 60 catchment sediment yield studies in South-East Asia demonstrated the deleterious effect (in terms of on-site erosion and stream sedimentation) of common forms of forest disturbance, such as selective logging, clearing for agriculture or plantations and particularly for mining, roading and urbanization (Bruijnzeel, 2004). Conversely, it has been shown that agroforestry practices in South-East Asia that incorporate cover crops with trees reduce surface erosion on hillslopes by more than an order of magnitude compared with monoculture plantations with no ground cover (Sidle et al., 2006).

Hillslope erosion results in the loss of nutrients and friable topsoil, with the result that on-site productivity may be reduced. Perhaps an equally important consequence is the movement of eroded material into streams, with a resultant increase in sedimentation and nutrient pollution and loss of water quality. Clearly, the management of ground cover is of critical importance in reducing on-site erosion and stream sedimentation. However, it is important to recognize that not all soil eroded from a site necessarily finds its way into streams. Much may be

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[7] "Overland flow" refers to rainfall that is unable to infiltrate into the soil and runs over the surface. It has the potential to find its way quickly into streams and cause rapid stream rises (Gilmour and Bonell, 1979; Bonell et al., 1983; Bruijnzeel et al., 2005).

re-deposited down slope and can add to the fertility of other sites (Enters, 1992; Stocking, 1996, quoted in Calder, 2005). This is another example where the assumption of simple cause–effect relationships is fraught with difficulties.

Stream bank erosion

Streamflow has the potential to initiate erosion in the beds and banks of water courses, particularly during flood flows. Olley et al. (2012) estimated that 2.7 million m^3 of soil was eroded from just 57 km of stream banks of the upper Brisbane River in northeastern Australia during a major flood in 2011. They also concluded that stream bank erosion was the dominant source of sediment pollution into southeast Queensland's water storages, estuaries and the adjacent Moreton Bay.

It is widely recognized that the presence of riparian vegetation (vegetation along the banks of streams), which includes trees with deep rooting systems, minimizes stream bank erosion. Riparian vegetation is most effective where it consists of a complex structure of grasses, shrubs and trees with deep, well-developed root systems (Olley et al., 2010). This works in two main ways: (i) by physically protecting the soil surface from the erosive effects of surface runoff – the root mat holds the soil together, making it less susceptible to erosion and (ii) by reducing the velocity of the running water as a result of added friction caused when water flows through dense vegetation (decreasing surface shear stress) and thus reducing the erosive power of the water. Olley et al. (in press 2013) calculated that the sediment load in a stream with a 30 percent riparian vegetation cover that incorporated trees would be about one third that of a stream with no riparian vegetation.

The important role of vegetation in minimizing stream bank erosion and improving water quality is recognized by many forest management authorities who require the retention of buffer zones adjacent to streams for special management (Hamilton with King, 1983; Cassells et al., 1987). This generally involves maintaining the integrity of the riparian vegetation and avoiding such activities as machine operations that will disturb the soil surface within the buffer zone.

Many "river improvement trusts" were established in Australia during the mid-twentieth century with the aim of, among other things, mitigating floods. Paradoxically, a critical part of their approach was to remove riparian and floodplain vegetation in an attempt to encourage floodwater to move from floodplains and river beds as quickly as possible (Fryirs et al., 2007). This approach still has currency in parts of the country, which contributes to another manifestation of the popular narrative, one that postulates that "the presence of trees causes floods and erosion" and conversely that "the removal of trees mitigates floods".

The negative impacts associated with decades of work by river improvement trusts in removing trees from riparian areas and floodplains have reached alarming proportions in some situations (Olley et al., 2012). Nonetheless, this mythology persists despite scientific evidence that the removal of riparian vegetation results in greatly increased water velocity, with a resultant increase in stream bank erosion and stream sedimentation and a loss of water quality.

Key findings

(1) Generally speaking, well-managed forests, free of grazing and other disturbances, provide good catchment cover that minimizes hillslope erosion and produces high-quality water that is free of sediment.

(2) Trees *per se* do not prevent erosion and, under some conditions, significant surface erosion can occur in undisturbed forests. The condition of the soil surface and particularly the retention of understory vegetation, grasses and litter are the primary determinants of surface erosion on hillslopes.

(3) Removal of trees does not, in itself, cause erosion, but poorly planned and executed timber-harvesting operations that create substantial disturbance to the soil surface can result in considerable erosion, leading to stream sedimentation and a reduction in water quality.

(4) Stream banks are often the major source of sediment across a catchment, and the retention or development of riparian vegetation, particularly with a complex structure of grasses, shrubs and trees (with their deep root systems), can play a significant role in minimizing stream bank erosion and stream sedimentation and improving water quality.

3.7 Forests and landslides

Popular narrative: Forests prevent or mitigate landslides (and conversely, the removal of forests increases landslides).

It is popularly believed that forests can prevent or mitigate landslides because of their deep rooting system. In assessing the relevance of this belief, it is important to consider the effects of both site-specific conditions and scale. Some sites, even steep ones, are inherently more stable than others if the soil resistance to shear is high. There are numerous examples of steep deforested and grassed slopes that have been stable for centuries. In general, small-scale landslides and slips tend to be episodic events triggered by prolonged rainfall and the accumulation of water in the soil mantle, generally on steep, inherently unstable hillslopes.

Numerous studies have demonstrated that the enhanced soil shear strength provided by deep-rooted trees and shrubs is important for slope stability, and the presence of trees can reduce the probability of shallow landslides of less than about 3 m, particularly where the stability is finely balanced (FAO, 2007; O'Loughlin, 1974; Sidle et al., 2006). In such situations, clearing the forest or harvesting trees can trigger landslides (O'Loughlin. 1974). Techniques have been developed for predicting and mapping the susceptibility of hillslopes to landslides (Trustrum et al., 1990).

The occurrence of deep-seated landslides (more than 3 m) is determined more by geologic, topographic and climatic factors than by the presence or absence of forests (Bruijnzeel and Bremmer, 1989 and 2004; Bruijnzeel et al., 2005). Without doubt, in geologically dynamic zones, such as the Himalayas, the large-scale mass wastage that is such a common feature of the landscape is not a result of deforestation and thus cannot be prevented by reforestation (Bruijnzeel and Bremmer, 1989; Ives and Messerli, 1989; Ramsay, 1987).

Key findings

(1) The presence of deep-root systems in forests can reduce the probability of shallow landslides (less than 3 m) in inherently unstable sites because of the cohesive strength of the roots.

(2) The removal of forests increases the risk of shallow landslides (less than 3 m) in inherently unstable sites.

(3) The occurrence of large-scale landslides (more than 3 m) is determined more by geologic, topographic and climatic factors than by the presence or absence of forests.

3.8 Forest–water research specifically focused on community forestry

Although much of the general research on the forest–water relationships summarized in the previous sections has relevance for community forestry, there have been few such studies focused specifically on community forests and even fewer that consider the impact of community forestry management regimes, such as the restoration of degraded forests. Perhaps because community forestry has a relatively long history in Nepal and because hydrological considerations had a considerable part in the formulation of what became known as the "Theory of Himalayan Environmental Degradation" (Ives and Messerli, 1989), most reported studies come from Nepal.

Gilmour et al. (1987) carried out a series of soil hydraulic studies in different-aged community forest plantations in the mid hills of Nepal to investigate the local and potential downstream hydrological consequences of reforesting degraded landscapes by local community groups. It was widely believed that the compaction caused by deforestation and subsequent heavy vegetation use and animal grazing would lead to a decline in infiltration, an increase in surface runoff and hence potential downstream flooding.

The results of the research demonstrated that the surface 10 cm of soil in a heavily grazed unplanted area was heavily compacted (compared with soils in nearby natural forest); but even so, only 17 percent of the monsoon rain days included rainfall events for which the short term (five-minute[8]) rainfall intensity exceeded the

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[8] This refers to five-minute periods during which rainfall intensity exceeds the infiltration rate of the surface soil and can generate overland flow.

surface infiltration rate. Five- and 12-year-old plantations on similar sites exhibited much higher infiltration rates, reflecting amelioration of the soil following plantation establishment and protection from grazing.

The general conclusion was that infiltration of most of the monsoon season rains would not be impeded in the plantations and very little overland flow could be expected, except for short periods during the heaviest of the monsoon season rainfall events. Surface runoff on even the degraded sites was still relatively rare and was not considered to be a significant influence on downstream floods. However, it was thought that the localized surface flow could have an influence on localized soil erosion and that, in turn, this could have implications for maintaining site productivity.

Ghimire et al. (2013) reported on a follow-up study on the same sites in Nepal 25 years after the original measurements were made, when the oldest of the plantations were about 37 years. The results indicated that there was little change to the permeability of the heavily grazed and unplanted site, suggesting that it had reached a plateau. However, the infiltration of the surface soil in the plantations had declined significantly, possibly because regular harvesting of grass, understory vegetation and litter by community members resulted in less organic material being available for incorporation into the soil surface to continue the process of amelioration evident in the initial years following plantation establishment.

Notwithstanding the measured reduction in surface infiltration, there were still very few occasions when short-term (five-minute) monsoon season rainfall events would exceed the infiltration capacity and initiate surface runoff. Because of the short periods of time when surface runoff can occur, it is unlikely to have any important effect on flood flows, particularly given the diverse land use patterns and other heterogeneous aspects of catchments in the area.

A plot-scale study of surface runoff in a severely degraded Shorea robusta forest site (though not a community forest) was carried out by Gardner and Gerrard (2002) in the mid hills of Nepal. The study findings indicated that surface runoff can be initiated on such sites even when rainfall intensities are lower than the measured infiltration capacity. Gardner and Gerrard inferred that, for a variety of reasons, the actual infiltration capacity during storms may be lower than the measured capacity. They recorded very high rates of surface runoff in degraded sites with little or no surface vegetation cover but much lower rates of surface runoff from plots with high levels of surface vegetation, particularly a mix of grass and litter.

Similar findings were reported by Tiwari et al. (2009), who also used plot-scale studies in the mid hills of Nepal. They recorded high rates of surface runoff from both community-managed and open-access degraded Shorea robusta forests. Their results reinforced the findings of Gardner and Gerrard (2002) about the importance of a good ground cover of grasses and litter in minimizing surface runoff and soil loss. However, comparisons between the two forest management regimes (community-managed and open-access) used in their study were problematic because of the very different characteristics of the two sites.

An important point needs to be made about the studies described in this section: they are all plot-scale studies. As noted in the paper's introduction, such studies are very useful in gaining insights into hydrological processes and making comparisons between different sites, but there are limitations when trying to extrapolate the findings to a catchment scale.

Key finding

Simply planting trees on community land where the soils have been compacted is not sufficient to restore the hydrological functions of a site. Attention needs to be given to the ongoing management of the reforested areas to balance product use with hydrological functioning. Of specific importance are: (i) balancing use (particularly the removal of leaf litter and understory vegetation) and cattle grazing with the retention of organic matter and its incorporation into the surface soil and (ii) limiting activities such as animal grazing that can lead to the compaction of the soil surface. This represents an added dimension to the already complex process of community forest management and will present considerable challenge to both local communities and governments.

4. Differences between temperate and tropical forest hydrology, with particular reference to Asia

A major finding that derived from many of the paired-catchment and other experiments in the temperate regions of north America during the middle decades of the twentieth century was that, because of the highly permeable soils that generally occurs in well-managed forested watersheds, overland flow is a rare phenomenon over most of the catchment area (Cassells et al., 1985b).

This is undoubtedly true but primarily because the rainfall intensities normally experienced in temperate regions are lower than the infiltration capacity of the soils; so most of the rain infiltrates into the soil, leaving little to run off over the surface (as overland flow). Where overland flow does occur, it tends to be confined to a small part of the basin around the channel (Kunkle, 1974). This finding has influenced much of the policy and popular beliefs about forests and water that have persisted to the present time.

While the underlying hydrological processes that operate within catchments tend to be universal across all regions, differences in catchment response manifest themselves as a result of: (i) differences in rainfall regimes and (ii) differential flow pathways for water, once it reaches the soil surface.

Humid tropical and subtropical rainfall regimes tend to be characterized by both long-duration high rainfall totals and high-intensity rainfall. The regularity of high-intensity rainfall events is probably the most important difference between the two regions, and it impacts on many hydrological processes. In the humid tropics, high-intensity rainfall is the norm and the infiltration capacity of even highly permeable soils is frequently exceeded by the rainfall intensity. This gives rise to overland flow on a regular basis. This is a rare phenomenon in humid temperate environments. This difference is critical, because it means that any disturbance of the catchment has to accommodate regular periods of overland flow, with its potential to initiate soil erosion and contribute to stream sedimentation.

5. Forest–water relations and community forestry – Relevance for policy and practice

The management objectives for community forestry tend to be articulated at two levels: (i) at the government policy level, and (ii) at the community level. At the government policy level, objectives for community forestry are set in the context of an overall regulatory framework. This may or may not include mention of water resources or the hydrological functioning of community forests. Similarly, at the community level where more detailed and explicit management objectives are set for each individual community forest, water may or may not receive specific mention. This will depend to some degree on the extent to which water or catchment functions are locally perceived as being important.

It is evident from the earlier discussions in this paper that there are gaps between the popular narrative pertaining to forest–water interactions and the scientific consensus. In the past, some aspects of the popular narrative directly influenced policy-making at both the government and community levels. In the search for a more rational approach to policy-making at both levels, it is important to narrow the gap between the scientific consensus and the popular narrative to avoid adverse influence on policy-making. As a contribution to this end, several scenarios with forest–water implications are presented below. These cover some of the situations likely to be encountered in community forestry in the Asia–Pacific region. They are discussed in terms of the likely hydrological impacts, using the hydrological cycle and water budget as key concepts. While these scenarios can be viewed as generally applicable in most situations, there can be exceptions due to the unique nature of local conditions.

5.1 Forest–water scenarios relevant to community forestry

Scenario 1: Reforestation and restoration of degraded forests

Some community forestry groups in the Asia–Pacific region commence their community management with degraded forests with compacted soils. What could we expect the hydrological impacts to be as their restoration proceeds?

- As plant biomass increases, it would be expected that water use by the vegetation (evapotranspiration) would increase and less water would be available to flow into streams or make its way via deep seepage into groundwater storage. This could have impacts at the local level, with a steady decrease in total water yield as the new forests age. This could be noted by reduced streamflows, particularly during the dry season, and/or by lower water levels in wells.
- If the soil surface of hillslopes is managed to retain a cover of low vegetation and leaf litter, it would be expected that there would be a reduction in surface erosion, with an associated improvement in the sediment level of the stream water.
- If riparian vegetation cover is enhanced, particularly with the addition of trees, stream bank erosion would decrease, leading to a substantial reduction in stream sedimentation and an improvement in water quality.
- Once the forest is restored to a near natural condition, a slight reduction in peak (flood) flows would be expected at the local level for small rainfall events. However, this effect would not translate far downstream because it would be diluted by many other factors.
- In situations where severe site degradation, including soil compaction, has taken place to the extent that soil infiltration capacity has been severely compromised, it would be expected that restoration could slowly improve the infiltration capacity of the surface soils. This could reduce the incidence of overland flow, which in turn could reduce the potential for surface erosion and increase the amount of water infiltrating into the soil surface. Whether this translates into changes in the water yield would depend on the trade-off between the increase in infiltrated water and losses from evapotranspiration as the forest grows.

Scenario 2: Provision of water for downstream use

To what extent can we manage established community forests to increase water yield for local or downstream use?

There are some limited options to manage community forests to increase total water yield, but there are also invariably some trade-offs involved.

- Assuming the forest is fully stocked, silvicultural treatments could be applied that aim at reducing the standing biomass to decrease evapotranspiration and increase percolation of rainfall excess into streamflow or groundwater storage. Suitable treatments could consist of heavy thinning or clearing patches of trees and replacing them with grasses.
- The impact of such treatments would be greatest in small catchments at the local level and would decrease over time if the harvested trees were allowed to regrow. The effect would also decrease downstream because of dilution of on-site effects with their translation into larger catchments.

Scenario 3: Situations in which dry season (base) flows are critical for domestic water supply (local or downstream), irrigation or power generation

To what extent can community forests be managed to increase dry-season (base) flows to benefit local or downstream domestic water supply, irrigation or power generation?

In general, silvicultural practices of the type normally associated with the sustainable management of community forests have limited ability to increase dry season flows, but there are some possibilities.

- Establishing community forests with seedlings widely spaced (perhaps 500 stems ha^{-1} rather than the more normal 1,600 stems ha^{-1}) would have the effect of producing an open forest that would yield more water than a densely stocked forest, with much of the additional water occurring during low flow periods. However, the effect is unlikely to be translated far downstream. In addition, it is only likely to persist until the trees fully occupy the site (i.e. until annual biomass production is similar for the two stocking rates). This is particularly relevant in drier regions, where soil water is limiting.
- A variation on the option above would be to plant densely and then thin, early and heavily before canopy closure. The harvested material could be used for firewood or poles. As with the previous option, the effect is unlikely to be translated far downstream.
- Removal of a large percentage of trees in mature community forests could increase dry-season (base) flows at the local level, but the effect is unlikely to be translated far downstream into large catchments.
- Removal of a large percentage of trees to increase dry-season flows would need to be traded off against the reduction in biomass production and the possibility of increasing surface erosion (by exposing the soil surface to direct raindrop impact). There is also the possibility of reducing surface infiltration capacity of the soil if heavy grazing is allowed or most of the low-growing vegetation and leaf litter is removed for local use. This could lead to increasing overland flow, with consequences for soil erosion, stream sedimentation and locally increased peak (flood) flows.

Scenario 4: Prevention of landslides

To what extent can community forests be expected to reduce the probability of landslides?

- Retention of trees on landslide-prone areas can be expected to limit the occurrence of shallow landslides (less than about 3 m).
- Planting trees on landslide-prone areas can be expected to limit the occurrence of shallow landslides (less than about 3 m) after the root system is well established, except around the gully heads, where engineering measures may be needed.
- Retaining or planting trees in landslide-prone areas cannot be expected to mitigate the occurrence of large-scale deep landslides (more than about 3 m).

Scenario 5: Community forests within a larger catchment

It is not uncommon for community forests to be located within catchments where catchment management authorities have set objectives aimed at improving the overall catchment functioning. To what extent can the management of community forests be expected to contribute to wider catchment management objectives?

- Community forests normally occur in a landscape mosaic of agricultural, grazing and forest land of different tenure – not all of it community managed. Management of community forests can contribute to the broader objectives, but the hydrological impacts of individual treatment at local levels will be diluted as the catchment size increases.

Scenario 6: Community forestry, water and carbon

During the past decade, there has been considerable debate about the possibilities of local communities obtaining direct financial benefit from managing their forests to maximize carbon capture and storage by participating in schemes such as REDD+. To participate in such schemes, communities have to demonstrate "additionality" – i.e. that their management will result in "additional" carbon being stored compared with their "normal" management.

Specifically, additionality refers to the need for countries to show that achieved rates of reduction of deforestation and degradation or conservation, sustainable management or enhancement of forest carbon stocks would have not occurred in the absence of REDD+ activities (IUCN, 2013).

There is no intention here of going into all the ramifications associated with REDD and similar schemes or discussing whether the expectations of genuine community benefit are realistic. However, it is worth exploring the implications of such approaches in terms of potential impacts on the hydrological regime.

If communities are to modify their management objectives to include something along the lines of "maximizing carbon capture and storage", this could certainly impact on the production of other goods, such as water.[9] Achieving a carbon objective would mean that total plant biomass (and hence carbon) would have to be maintained at levels as high as possible (in fact, higher than "normal" management in order to conform to the "additionality" requirement). In silvicultural terms, this translates into a management regime that would maintain dense stands of trees and limit thinning and final crop harvesting.[10] (Maximum standing biomass is generally achieved in unthinned forests even though the annual increment of individual trees can be greater in regularly thinned forests.) The most likely hydrological impacts of such a regime in situations where soil water is not limiting for much of the year (such as many humid tropical regions) would be an increase in water use by the vegetation (associated with dense stocking, high Leaf Area Index and heavy rainfall interception), leading to a reduction in total water yield, particularly during low flow periods. The impact would be felt more at a local scale than at a large catchment scale.

5.2 Brief statement to policy-makers about hydrological impacts of community forest management

The key messages for each of the major issues associated with forest–water relations are given in the boxes in the previous sections and the scenarios outlined in this section. However, it would be useful to package them into one brief statement that might be of interest to policy-makers. This could be:

While the hydrological impact of vegetation changes in a catchment can be context specific, there are generalizations that are valid across a wide spectrum of situations. In general terms, the hydrological benefits of community forest management are less than popularly believed. However, well-managed community forests can produce hydrological benefits, but most of them are likely to be locally specific – felt mainly on-site or nearby rather than far downstream. In situations in which community forestry is effective in restoring degraded forests where there is substantial bare soil, there generally will be a reduction in hillslope and stream bank erosion, with a local and downstream improvement in water quality.

5.3 Recommendations to community forestry policy-makers and practitioners

The following recommendations are based on the scientific consensus on forest-water relations as they relate to community forestry.

- Recognize the limited ability of community forestry to affect the hydrological functioning of large catchments. The impacts of forest management on most aspects of the hydrological cycle will be felt more at the local level than in larger catchments. Local impacts are diluted as the size of the catchment increases.
- Recognize the need for trade-offs between biomass harvesting and water values. For example, if dry- season water flow is of critical local importance, then silvicultural systems may be needed to manage the forest to increase dry-season flows.

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[9] In addition, managing forests for timber production may be incompatible with managing them to maximize carbon capture and storage.

[10] In this scenario, a question arises in terms of the length of time it is possible to maintain forests at a high stocking level (with high carbon storage).

- Recognize the need for trade-offs between managing community forests to maximize carbon capture and storage and managing for a range of other values, including water values.

5.4 Gaps in knowledge among community forestry practitioners

The science of forest–water relationships is well understood, compared with the situation half a century ago and there is scientific consensus on the major processes involved and the general direction of most management impacts. There is certainly sufficient knowledge to make “best bet” policy and practical decisions on matters that relate to forest–water interactions associated with community forestry as long as there is a reasonable understanding of the underlying hydrological processes. Nonetheless, there are areas in which additional information is needed to apply that knowledge to contemporary community forestry. Perhaps one of the major scientific gaps in knowledge relates to runoff relations associated with the restoration of degraded forests.

The following highlights some of the gaps in current knowledge needed by community forestry practitioners and that fall within the ambit of RECOFTC’s current programme:

- Information on demand-driven catchment services, such as high-quality water or carbon capture and storage, and mechanisms to link them to specific and measurable attributes of community forestry management.
- Approaches to integrate the management of forest and water resources at the local level to achieve improved social and environmental outcomes.
- Likely impact of climate change on forest–water interactions in typical situations in the Asia–Pacific region.

6.Conclusions

In the frontispiece to this report, a quote from Professor Ian Calder (2005) warned that simplistic views and misunderstandings of the nature of forest influences on water resources could lead to the misallocation of human and financial resources and produce perverse outcomes. We should keep in mind that the costs that arise from such misunderstanding or the deliberate or inadvertent perpetuation of myths and misinterpretations about the direction, magnitude and nature of forest influences are likely to fall differentially on the rural poor and marginalized communities who live in and near forest areas.

As a conclusion to this review, it is pertinent to bear in mind a warning made 30 years ago by Hamilton, with King (1983, p. 131), which is as relevant today as it was then. “Perhaps foresters have been guilty of acquiescing by silence to the use of some misinterpretations and misunderstandings, because the arguments or rhetoric being used were aimed at protecting forest resources or at establishing new forests – surely actions worthy of nations and statesmen. But, if we close the watershed forests to human use and reservoirs still silt up, and when we have totally reclothed the basin in planted forest and we still have floods, and if on top of that the streams dry up, or dry up even more … then there may be a well-deserved backlash and the credibility of foresters and other watershed professionals may be called into serious question … Let us not condone the use of unsupportable or questionable hydrologic and erosional relationships in this important policy scenario.”

The final cautionary thought in this report is attributed to Cassells (2002), who suggested that forest hydrologists and forest land use managers would do well to adopt a famous prayer to guide their work:

God, grant me the serenity to accept the things I cannot change,
The courage to change the things I can,
And wisdom to know the difference.

With apologies to the *Serenity Prayer*, attributed to Reinhold Niebuhr (1943) American theologian (Wikipedia).

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Asia–Pacific focus

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