ISSN 0258-6150

FAO FORESTRY PAPER

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Forests and water

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Cover photograph:
Kiutaköngäs rapids, Oulanka National Park, Finland (FAO/FO-6885/P. Ceci)

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A thematic study prepared in the framework of the
Global Forest Resources Assessment 2005

L.S. Hamilton

with contributions from:
N. Dudley
G. Greminger
N. Hassan
D. Lamb
S. Stolton
S. Tognetti

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2008

ISBN 978-92-5-106090-2

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Foreword

The availability and quality of clean water in many regions of the world is increasingly threatened by overuse, misuse and pollution. In this context, the relationship between forests and water is a critical issue that must be accorded high priority.

Forested catchments supply a high proportion of the water for domestic, agricultural, industrial and ecological needs in both upstream and downstream areas. A key challenge faced by land, forest and water managers is to maximize this wide range of multi-sectoral forest benefits without detriment to water resources and ecosystem function. To address this challenge, there is an urgent need for better understanding of the interface between forests/trees and water, for awareness raising and capacity building in forest hydrology, and for embedding this knowledge and research findings in policies. There is also need to develop institutional mechanisms to enhance synergies in dealing with forests and water issues and to implement and enforce action programmes at the national and regional levels.

Until a few years ago, forests and water policies were based on the assumption that under any hydrological and ecological circumstances, forest is the best land cover for maximizing water yield, regulating seasonal flows and ensuring high water quality. According to this assumption, conserving (or extending) forest cover in upstream watersheds was the most effective measure for enhancing water availability for agriculture, industrial and domestic uses, as well as for preventing floods in downstream areas. However, forest hydrology research conducted during the 1980s and 1990s suggests a different picture. Although the important role of upstream forest cover in ensuring the delivery of quality water has been confirmed, generalizations about the impact of such cover on downstream annual and seasonal flows are fallacious and misleading. Instead, studies have shown that, especially in arid or semi-arid ecosystems, forests are not the best land cover for increasing downstream water yields. Moreover, there is solid evidence that the protective effects of upstream forest cover against seasonal downstream floods have often been overestimated. This is especially true regarding major events affecting large-scale watersheds or river basins.

The International Year of Freshwater (IYF 2003) and the Third World Water Forum (Kyoto, Japan, 2003) advanced the incorporation of this new understanding of biophysical interactions between forests and water into policies. In particular, the International Expert Meeting on Forest and Water, held in Shiga, Japan in November 2002 in preparation for IYF and the Third Water Forum (International Forestry Cooperation Office, 2002), highlighted the need for a more holistic approach to capture interactions among water, forest, other land uses and socio-economic factors in complex watershed ecosystems. Since then, the Shiga

Declaration has become a key reference for the development of a new generation of forests and water policies.

In the work of the FAO Forestry Department, the relationship between forests and water has been receiving increased attention over recent years. The chapter entitled “Sustainable use and management of freshwater resources: the role of forests” in the *State of the World’s Forests 2003* (FAO, 2003) was a milestone in establishing the Forestry Department’s forest and water programme entity. The relationship between forests and water was a major component in the FAO-led global review of watershed management programmes and projects (FAO, 2006b).

This thematic study on forests and water was developed in the context of the Global Forest Resources Assessment programme. It is directed to a broad range of technical experts, scientists and decision-makers, particularly national authorities, and presents recommendations on giving more attention to the role of forests and trees in water protection and management at the national level. It also calls for stronger collaboration between the water and forest communities.

Jose Antonio Prado
Director
Forest Management Division
FAO Forestry Department

Acknowledgements

The Global Forest Resources Assessment 2005 (FRA 2005) represents a major effort of FAO's Forestry Department, FAO member countries, donors, partners and individual experts. It involved more than 800 people, with national correspondents and their teams providing detailed country reports. In addition to the main report (FAO, 2006a), several thematic studies have been prepared. *Forests and water* is the report of a thematic study carried out in response to the increasing worldwide attention to this topic.

The main author of this publication is L.S. Hamilton, a world-renowned expert in forest hydrology. As well as writing the bulk of the material, Professor Hamilton coordinated a small team of authors who contributed specific sections of the study: N. Hassan (swamp forests), D. Lamb (forests on saline susceptible soils), N. Dudley and S. Stolton (municipal water supply forests), P. Greminger (avalanche protection forests) and S. Tognetti (payment for environmental services).

The study was prepared under the overall supervision of T. Hofer, the officer in charge of the programme entity on forests and water in the FAO Forestry Department. M. Achouri, M. Wilkie, P. Warren, D. McGuire and P. Ceci provided technical advice and support. W. Fleming, P.-C. Zingari, A. Whiteman and T. Facon submitted valuable review comments. L. Ball edited the report and A. Perlis, officer in charge of publications in the Forestry Department, oversaw the finalization of the book.

Acronyms

CIFOR	Center for International Forestry Research
FEMAT	Forest Ecosystem Management Assessment Team (United States)
FONAFIFO	Fondo Nacional de Financiamiento Forestal (Costa Rica)
FRA	Global Forest Resources Assessment
FRIM	Forest Research Institute of Malaysia
GDP	gross domestic product
GEF	Global Environment Facility
ICL	International Consortium on Landslides
IIED	International Institute for Environment and Development
IUCN	International Union for the Conservation of Nature
IYF	International Year of Freshwater
NGO	non-governmental organization
NWFP	non-wood forest product
PES	payment for environmental services
SFRA	streamflow reduction activity
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USGS	United States Geological Survey
WCMC	World Conservation Monitoring Centre (UNEP)
WWF	World Wide Fund for Nature

Executive summary

Overall, current forest hydrology research suggests that the assumption that more trees equals more water (which has inspired most forests and water policy) is based on incorrect understanding of the hydrological cycle in forest ecosystems. The forest ecosystem is in fact a major user of water. Tree canopies reduce groundwater and streamflow, through interception of precipitation, and evaporation and transpiration from foliage. As both natural and human-established forests use more water than most replacement land cover (including agriculture and grazing), there is no question that even partial forest removal increases downstream water yields. The removal of water-demanding forest cover has therefore sometimes been suggested as a means of preventing or mitigating droughts, especially in semi-arid areas. However, such a policy should be weighed against the consequent loss of the many other services and goods that forests supply. These include erosion control, improved water quality, carbon fixation, reduced salinization, recreation and aesthetic appeal, timber, fuelwood, other forest products, and biodiversity.

It is well established that partial or complete removal of the tree cover accelerates water discharge, increasing the risk of flood during the rainy season and drought in the dry season. Forest cover's importance in regulating hydrological flows has often been overestimated, however; the impacts of forest cover removal are evident only at the micro-level and in association with short-duration and low-intensity rainfall events (which tend to be the most frequent). As rainfall duration or intensity increases and the distance down the watershed and river basin becomes greater, other factors start to override or dwarf the effects experienced close to the deforested area.

At the macro-scale, natural processes – rather than land management in the upper watershed – are responsible for flooding. Hence, although there are many good reasons for reforesting watersheds (e.g. reducing soil loss, keeping sediments out of streams, maintaining agricultural production, wildlife habitat), reducing flood risk control is certainly not one of them. Reforestation to prevent or reduce floods is effective at only a local scale of a few hundred hectares.

Forests' most significant contribution to the hydrological balance of watershed ecosystems is in maintaining high-quality water. This is achieved through minimizing soil erosion on site, reducing sediment in water bodies (wetlands, ponds and lakes, streams and rivers) and trapping/filtering other water pollutants in the forest litter and underwood. Good forest cover is the most effective land cover for keeping water as sediment-free as possible. Forest is certainly the best cover for drinking-water supply watersheds, because forestry activities involve no use of fertilizer, pesticide and fossil fuel, or outfalls from domestic sewage or industrial processes.

A number of special forest situations are very important for water resources and their management:

- Cloud forests should be maintained as forest because they are important for water production, erosion control and biodiversity, and generally unsuitable for other sustainable uses. They need to be identified in local, regional and national inventories. Loss of cloud forests is irreversible because of the complex relationships among their flora, fauna and soil. The conservation of cloud forests and their designation as protected areas should be a national priority.
- Swamp forests have a unique role in local water balance and the global ecology. They should be designated as environmentally sensitive areas where the maintenance of hydrological integrity is a management priority. They should be given legal protection, and the potential long-term and immediate effects of any planned large-scale conversion to other land use should be subject to environmental impact assessment.
- Salinization is a widespread problem, particularly in regions with an extended dry season. Recent reports suggest that worldwide, 77 million ha of land is affected by salinization induced by human activities, mainly changes in vegetative cover and excessive irrigation. Deforestation should be avoided in forested areas with saline subsoils or groundwater. Any change to the hydrological cycle in such landscapes may mobilize stored salts.
- Because of their undergrowth, leaf litter, debris and uncompacted soils, forests are almost certainly the best and safest land cover for minimizing all kinds of surface erosion. Areas prone to slippage, which is probably the most serious form of erosion, need to be kept in forest cover, woodland or agroforestry/sylvopastoral systems with fairly dense tree cover.
- Vegetated strips along stream/riverbanks and lake/pond shores have important water-protective functions. Forested buffer zones perform these particularly well because of deep, strong root systems. Forest riparian buffers can stabilize the banks of flowing water bodies, minimizing erosion and thus reducing the sediment entering the water. The forest floor and soil can also trap sediment as it moves towards flowing water from upslope areas outside the buffer. Forested riparian buffer zones that shield perennial watercourses and other water bodies from quality impairment should be identified and officially designated for special treatment in land use.
- Lack of clean drinking-water and adequate sanitation reduces the quality of life for an estimated 1 billion city dwellers around the world, along with many people living in rural areas, principally in Africa, Asia and Latin America. Tight budgets are forcing many municipalities to explore innovative approaches to maintaining supplies of pure drinking-water. Increasingly, this includes examining the potential for forested catchments to supply urban drinking-water. Although forests are already viewed as water suppliers, much remains to be learned and applied in order to maximize these benefits.

- Avalanche protection is an existential challenge for the inhabitants of high mountain regions around the world, whose lives and activities also face many other considerable risks. Forests play a significant role in avalanche reduction. Mountain hazard mapping should make specific reference to protective forests and designate them for special treatment.

On small mountainous islands, forests' classic influences on water quantity and quality prevail. The relative shortness of the streams leads to close upstream-downstream linkages; what happens in the uplands usually alters the quantity and quality of water, including through flooding, low flows, sedimentation and water-borne pollutants. Freshwater resources on small islands are very often scarce and therefore precious. Forest management decision-makers must therefore be especially cautious about alterations or removals that impair water resources.

The degradation of watersheds has led to greater recognition of the numerous ways they support human well-being through ecosystem services, and consequently to greater value being placed on them. Watershed services may include provision of freshwater, regulation of both water and sediment flows and maintenance of natural flow regimes, which support entire ecosystems and ways of life. However, the complexity and natural variability of watershed processes, which are dominated by randomly timed and extreme events, make it difficult, if not impossible, unequivocally to link all causes and effects. Payments for watershed services will not solve all watershed degradation problems, but can be an important component of a broader management strategy.

1. Introduction

> *Lack of access to water for meeting basic needs such as health, hygiene and food security undermines development and inflicts enormous hardship on more than a billion members of the human family. And its quality reveals everything, right or wrong, that we do in safeguarding the global environment.*
>
> Former United Nations Secretary-General Kofi Annan (UNESCO, 2003)

At the United Nations Millennium Summit in 2000, 147 world leaders adopted the target of halving, by 2015, the proportion of people who are unable to reach or afford safe drinking-water. Although most of the earth's surface is water, there seems to be insufficient freshwater to meet the needs and wants of its burgeoning human population or its plants and animals, both domesticated and wild. The United Nations International Year of Freshwater (IYF) in 2003 highlighted the critical need to have water available – in the right place, in adequate amounts, of sufficient quality and at the right time. Forests play a key role in this availability, but the Economic Commission for Europe (2004) warns:

> The current attention given to freshwater issues does not put enough emphasis on the role of water-related ecosystems in providing solutions, possibly due to lack of awareness. Promoting awareness, for instance through information campaigns and other specific activities, about the role of wetlands and forests as water suppliers among the different stakeholders in the whole watershed (national authorities, the public and the private sector) is essential. The benefit to upstream and downstream populations should be publicized.

It is therefore very appropriate that "Forests and water" was selected as one of the thematic studies implemented for FAO's Global Forest Resources Assessment 2005 (FRA 2005) (see Box 1).

This study deals with the extent to which forests cover land surface and with their importance to the hydrological cycle (Figure 1). It provides information for much-needed efforts to maintain and restore water-related ecosystems – identified by the United Nations Commission for Europe as a global priority. By intercepting precipitation, evaporating moisture from vegetative surfaces, transpiring soil moisture, capturing fog water and maintaining soil infiltration, forests influence the amount of water available from groundwater, surface watercourses and water bodies. By maintaining or improving soil infiltration and soil water storage capacity, they influence the timing of water delivery. By minimizing erosion, they minimize impairment of water quality due to sedimentation. Forests can also protect water bodies and watercourses by trapping sediments and pollutants from other upslope land uses and activities. Along streams, forests provide shade, thus reducing water temperature. As watershed land cover, protected or well-managed

BOX 1

Forests with a protective function

Early assessments of forest resources focused on forests' productive functions, particularly wood supply, which policy-makers identified as the main issue. In many countries there is now increased awareness of forests' importance in providing environmental services through their protective functions. FRA 2005 therefore included a first assessment of the area of forest with a protective function. Information on the following two variables was collected.

Area of forest designated for protective purposes

This variable indicates the extent of forest areas set aside for protective purposes, either by legal prescription or by decision of the landowner or manager.

The world's forests have many protective functions, some local and some global. These include influence on climate, protection from wind erosion, coastal protection, protection from avalanches, air-pollution filtering and protection of water resources.

Forest designation is reported as "primary function" and "total area with function". Forest areas whose designated protection function is considered significantly more important than its other functions are reported as having protection as their primary function. All forest areas with a designated protective function (not necessarily primary) are reported under total area with function.

Area of protective forest plantations

Protective forest plantations are forests of introduced and, sometimes, native species established through planting or seeding, with few species, even spacing and/or even-aged stands. They are predominantly for providing services such as soil and water protection, rehabilitation of degraded lands and combating desertification.

In FRA 2005, not all countries were able to provide quantitative information for these variables, but an initial evaluation was made of the importance of the protective functions of forests worldwide.

Key findings

In 2005, the extent of forest with protection as its designated primary function was estimated to be 348 million ha, or 9 percent of the global forest area. Some 1 190 million ha of forest – or 65 percent of the total – was identified as having a designated protective function (not necessarily as its primary function).

The findings of FRA 2005 suggest that there is a trend towards identifying and designating increasing areas for forest protection. Worldwide, the percentage of forest with protection as its primary function grew from 8 percent in 1990 to 9 percent in 2005 – representing an increase of more than 50 million ha. The proportion of the world's forests designated with a protective function also expanded, from 61 percent in 1990 to 65 percent in 2005 – an increase of nearly 60 million ha.

It seems likely that the trend for classifying a growing proportion of the world's forests as having a primary function of protection will continue, and that FRA 2010 will show more than 9 percent in this category.

The total protective forest plantation area was estimated to be 30 million ha in 2005, or 0.8 percent of global forest area. This area increased by 405 000 ha per year from 1990 to 2000 and by 330 000 ha per year from 2000 to 2005, but regions and subregions reported markedly varying changes.

The many protective functions of forests, and their growing importance make it increasingly necessary for countries to gather, analyse and present information on the extent and condition of protective forests.

FRA 2005 was a first attempt to evaluate the importance of forests' protective functions at the global level and was based on a limited number of quantitative variables. Nevertheless, these variables all show a positive trend, indicating increased recognition of these important functions – including those related to the conservation of water resources.

Source: FAO, 2006a.

FIGURE 1
The hydrologic cycle

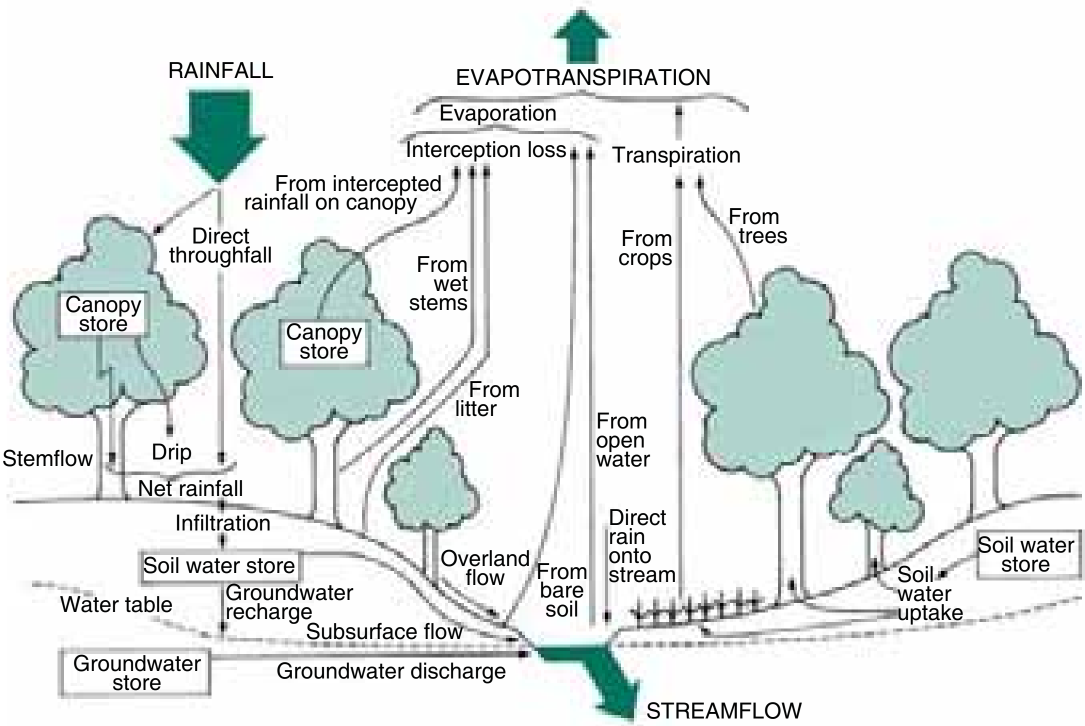


TABLE 1
Impact of change in land use on water parameters, by basin size

Parameter	Basin size (km²)						
	0.1	1	10	100	1 000	10 000	100 000
Average flow	x	x	x	x	o	o	o
Peak flow	x	x	x	x	o	o	o
Base flow	x	x	x	x	o	o	o
Groundwater recharge	x	x	x	x	o	o	o
Sediment load	x	x	x	x	o	o	o
Nutrients	x	x	x	x	x	o	o
Organic matter	x	x	x	x	o	o	o
Pathogens	x	x	x	o	o	o	o
Salinity	x	x	x	x	x	x	x
Pesticides	x	x	x	x	x	x	x
Heavy metals	x	x	x	x	x	x	x
Thermal regime	**x**	**x**	**o**	**o**	**o**	**o**	**o**

x = observable impact; o = no observable impact.
Source: FAO, 2001.

forests are without equal in increasing hydrological and erosion safety and water quality: water may well be forests' most useful and important product. The following chapters take a closer look at some of these issues.

As well as protecting water resources, forests also conserve biodiversity. National commitments to the United Nations Convention on Biological Diversity are being fulfilled through measures to safeguard water and establish "protected" and "protective" forests, as well as many kinds of forests certified for sustainability. Forests also provide carbon fixation and several other environmental services.

Climate change will have a significant impact on hydrology and water resources (Bergkamp, Orlando and Burton, 2003). This may be manifested in increased catastrophes such as floods, droughts and landslides – all of which may be influenced by forest cover. Situations affecting the most vulnerable groups within societies require particular attention. Restoration of damaged/degraded forest ecosystems can help forests to "cushion" the effects of climate change.

A brief discussion of forests' role regarding water quantity (Chapter 2) and quality (Chapter 3) is followed by descriptions of special forest types or situations where the relationship between forests and water is especially significant (Chapter 4). These can be considered "red flag" warning situations, where protective values are very high. The special case of mountainous small islands is discussed in Chapter 5. Chapter 6 analyses the rationale and examples of payment for environmental services (PES) programmes. These chapters explain and amplify the information presented in Table 1, which shows the impact of change in land use, for example among forest, agriculture and managed grassland, on various water parameters, at different scales. Guidelines are offered at the end of each section, and the study concludes with a brief set of recommendations in Chapter 7.

2. Forests and water quantity

The conversion of precipitation to groundwater and streamflow is reduced by the interception of forests and by evaporation from the tree canopy (see Figure 1). It is reduced further through transpiration of soil moisture from foliage. These can be described as losses to the useful water system, but it is through this water use and photosynthesis that trees produce wood, leaves, flowers, fruit and seeds. With its flora and fauna, the forest ecosystem is a major user of water, but also provides enormous benefits for humanity: from birds to boards to bears, from fuelwood to medicines, from carbon fixation to orchids and chestnuts, there is a treasury of products from forest biodiversity. Recreation and landscape aesthetics can be added to these, as well as a high degree of soil erosion control, and – in the right circumstances – avalanche hazard reduction.

Human society is concerned about the beneficial and deleterious impacts of forests on water quantity, because sometimes there is too much water (flooding) and sometimes not enough. This concern involves many myths and misunderstandings and much misinterpretation and misinformation – the "four Ms" (Hamilton, 1985). It has been claimed, for instance, that logging and land clearing in the Nepalese Himalayas have been responsible for devastating flooding of the lower Ganges in India, and that restoring forests can cause dry rivers to flow again, relieving drought (*World Water*, 1981). Such misinterpretations of hydrological science persist.

TOO MUCH WATER?

It is confirmed that partial or complete removal of the tree cover increases the total amount of water in streams flowing from the catchment area. This is largely because of decreased evapotranspiration by trees, which act as deep-rooted "water pumps" (Hamilton and King, 1983; Bruijnzeel, 1990). Higher water yields continue throughout the year, with the greatest percentage increase (often a doubling of pre-removal flow) occurring in the dry season. Light, selective harvesting or removal of non-wood forest products (NWFPs) has little or no impact on streamflow, but the effect increases with the amount of trees removed, up to clear-cutting (Bruijnzeel, 1990). Yield increase seems desirable during streamflow shortages in the dry season, but can present a problem during the wet season, when increased flows make flooding a hazard. Effects on flow occur close to the forest area being cut, but only for short-duration/low-intensity rainfall events (which are usually also the most frequent).

As rainfall duration or intensity increase and the distance down the watershed and river basin becomes greater, other factors override or dwarf the effects experienced close to the treated area. These factors include the size and morphometry of the basin, what happens in other tributary streams, the direction of the storm path and the intensity and duration of the storm. Ives and Messerli (1989) described this phenomenon in terms of microscale watersheds (< 50 km^2), mesoscale watersheds (50 to 20 000 km^2) and macroscale basins (> 20 000 km^2). At the microscale, land-use practices may influence streamflow and sediment discharge, depending on soil depth and precipitation variability. At the mesoscale, downstream effects of forest operations and other land uses are probably obliterated by the high intensity and high variability of natural events and discharges from other watersheds. At the macroscale, natural processes – rather than human interventions in the upper watershed – are responsible for flooding and high sedimentation rates. Hewlett (1982) reviewed the evidence from watershed research worldwide and reported that no cause and effect was demonstrated between forest cutting in the headwaters and floods in the lower basin. No conflicting information has been published since, more than 20 years later.

Even on the local scale, much depends on the depth of the soil and the character of the precipitation event. Deep soils can store more water before they become saturated, and deep-rooted trees make the soil mantle more receptive for storing water from a new event. Antecedent rainfall and soil water storage have a great influence on the generation of runoff. Thus, for frequently occurring rainfall events of short duration or low intensity, forested soils may reduce or prevent flash floods locally. For the rarer prolonged or high-intensity storms, however, once the soil layer becomes saturated, water will run off, even where there is full, undisturbed forest cover. On shallow soils, especially steep ones, storage is much less and the watershed is more prone to flash floods; trees or other vegetation or land use can do little to stem the fast subsurface and overland flows.

The four Ms persist, however. The disastrous floods of November 1988 in southern Thailand were mistakenly blamed on logging, and the government issued a nationwide ban on logging (Rao, 1988). The same year, a flood disaster in Bangladesh was erroneously attributed to deforestation in the Indian and Nepalese mountains, where the mighty Ganges and Brahmaputra rivers have their headwaters. This was international scapegoating to avoid tough decisions about floodplain occupancy and river management in the lower basin (Hamilton, 1988). Many more examples could be cited of this popular misinformation. A recent major publication related to hydrological processes in large river basins (Hofer and Messerli, 2006) presents strong scientific evidence for abandoning the myth that deforestation in the Himalayas creates major floods in the lowlands of the Ganges and Brahmaputra. A publication by FAO and the Center for International Forestry Research (FAO and CIFOR, 2005) has this to say:

> Although forests can play a certain role in delaying and reducing peak floodwater flows at local levels, scientific evidence clearly indicates that forests cannot stop catastrophic large-scale floods, commonly caused by severe meteorological events …. This in no way diminishes the need for proper management and conservation of upland forests. But it does point toward the critical need for integrated approaches in river-basin management that look beyond simplistic forest-based "solutions".

However, flooding and flood damage are often greatly aggravated by sediment and debris arriving in stream channels from the landslips and landslides that frequently accompany flood-producing rainfall events. Scatena, Planos-Gutiérrez and Schellekens (2005) suggest that intense, short-duration events create shallow slips and debris flows, while long-duration, low-intensity events produce larger, deeper debris avalanches and slumps. Research has shown that tree roots impart substantial strength to soils, giving a higher safety margin against shallow landslipping and debris flows (O'Loughlin, 1974). Thus, although forest cover may not appreciably reduce the amount of water moving into watercourses from a large storm event, it can influence the severity of flooding and flood damage.

The misperception persists that reforesting watersheds is effective in reducing or preventing floods. Again, there is no evidence for this, except at the very local scale of a few hundred hectares. There are many very good reasons for rehabilitating watersheds, including reducing soil loss, keeping sediment out of streams, maintaining agricultural production and increasing forest wildlife habitat, but achieving substantial flood reduction is not one of them (Hamilton and Pearce, 1987).

Box 2 presents a summary of the usual effects that land uses involving forests have on stormflow response and flooding at the local level.

NOT ENOUGH WATER?

There is no question that forest removal, even partial, increases overall water yield. Both natural and planted forests use more water than most replacement land cover, including agriculture and grazing. Reported first-year increases in water yield following forest clearance in the humid tropics, for instance, range from 110 to 825 mm, depending on local rainfall (Box 3). Evaporation/transpiration losses are greater from evergreen than from deciduous forest, and the drier and less windy the climate, the less the evaporation loss, because leaves in dry climates are generally narrower and smaller (Nisbet and McKay, 2002).

A dated, but still valid review of almost 100 paired catchment experiments throughout the world (Bosch and Hewlett, 1982) indicated that all of those involving removal of forest cover resulted in higher streamflow totals. More recent reviews (e.g. Grip, Fritsch and Bruijnzeel, 2005) have not altered this information. However, this does not hold true when montane cloud forests are cut or removed (see Chapter 4). In conifer forests, where much water arrives as snow, closed- or only slightly open-canopied forest can delay snow-melt, allowing more time for discharge from lower, open lands to clear out of channels. This may have an ameliorating effect on floods and increase the period during which snow-melt provides water for downstream uses. Light cutting can increase the snowfall reaching the ground by reducing that held in the crowns and evaporated.

Does this mean that trees or forests should be removed because of their heavy use of water? This has sometimes been suggested during droughts, but it would impair or eliminate the many values that forests supply, including forest wildlife and flora, erosion minimization, improved water quality (Chapter 3), carbon

BOX 2

Stormflow and flooding from land-use activities

Land-use activities affect stormflow response and flooding at the local level in the following ways:

- Removal of vegetation or conversion from plants with high to those with low annual transpiration and interception losses can increase stormflow volumes and the magnitude of peak flows. Such practices can also expand the source areas of flow. After a precipitation event, soil moisture and water tables tend to be higher, so less storage is available to hold precipitation from the next event, and source areas are expanded.
- Activities that reduce soils' infiltration capacity, such as intensive grazing, road construction and logging, can increase surface runoff. As the proportion of precipitation converted to surface runoff increases, streamflow responds more quickly to precipitation events, resulting in higher peak discharges. Activities that promote infiltration can be expected to have the opposite effect.
- Development of roads, drainage ditches and skidding trails and alterations of the stream channel can change the overall conveyance system in a watershed. The effect is usually an increase in peak discharge caused by the shorter time it takes the flow to reach the watershed outlet.
- Increased erosion and sedimentation can reduce the capacity of stream channels at both upstream and downstream locations. Flows that would previously have remained within the streambanks may now flood.

For precipitation events that are not extreme in amount and duration, these impacts can have a noticeable effect on stormflow volume and on peak magnitude and timing. As the amount and duration of precipitation increase, the influence of the soil-plant system on stormflow diminishes. The influence of vegetative cover is therefore minimal for the extremely large precipitation events that are usually associated with major floods.

Source: Brooks *et al*., 1991.

fixation, forest recreation and aesthetic appeal, and a continued flow of forest products. In saline-prone areas, it would bring salts closer to the soil surface (third section of Chapter 4). In cloud forest, it would reduce water input into the catchment (first section of Chapter 4). A major dilemma is that although water quantity can be increased by forest removal, the land uses replacing forest are more intensive in human and/or animal activity.

Grassland is a good watershed cover for water yield, but has two major weaknesses: on slip-prone lands, there are no tree roots to provide greater slope stability; and there is a tendency to allow overgrazing of grassland, resulting in compaction and possible soil erosion, which increase peak flows, may cause sediment discharge into watercourses and can even reduce infiltration so severely that base flows decline (Hamilton and King, 1983). Tree harvesting through partial cutting or forest regeneration retains the site in tree cover (rather than converting it) and temporarily increases water yields throughout the year, but the use of skid trails, haul roads, winching channels and landings for the removal of wood tends to impair water quality, owing to accelerated erosion until recovery is complete. The greatest yield increases will occur on the deeper soils, where deep root systems exploit more soil moisture. Thang and Chappell (2005) present up-to-date guidelines for minimizing the hydrological impact of forest harvesting in Malaysia.

The effects of reforestation or afforestation on water yields are usually the reverse of those for forest removal (Hamilton and Pearce, 1987). They vary depending on whether the land is still in reasonable hydrological health or has been severely degraded from long-term, non-conservative use. Locally, for frequent short, low-intensity storm events, flash flooding should be reduced where soils are deep. On the other hand, low flows are usually diminished as well, especially where fast-growing, heavy water-using species are employed (Case study 1). For instance, the Fiji Pine Commission's planting of Caribbean *Pinus* in their dry zone grasslands resulted in dry-season streamflow reductions of 65 percent (Kammer

BOX 3

Effects of forest manipulation on water yield

- Carefully executed light, selective harvesting will have little if any effect on streamflow, which increases with the amount of timber removed.
- The data set for the humid tropics supports the general finding of Bosch and Hewlett (1982) that removal of natural forest cover may result in a considerable initial increase in water yield (up to 800 mm per year); possibly more in high-rainfall regions, depending mainly on the amount of rain received after treatment.
- Depending on rainfall patterns, there is a rather irregular decline in streamflow gain, with time, associated with the establishment of the new cover. No data have been published regarding the number of years needed for a return to pre-cut streamflow totals in the case of natural regrowth, but it may take more than eight years.
- Water yield after maturation of the new vegetation may: remain above original streamflow totals in the case of conversion to annual cropping, grassland or tea plantations; return to original levels (*Pinus* plantation after full canopy closure); or remain below previous values (reforestation of grassland with *Pinus* or *Eucalyptus*). Coppicing of *Eucalyptus* after ten years caused even stronger reductions for two years.

Source: Extracted from Bruijnzeel, 1990.

CASE STUDY 1

Forest plantations in semi-arid South Africa

South Africa is a water-scarce country with average annual rainfall, unevenly distributed, of about 500 mm. With an estimated 1 400 m^3 of water per person per year, it ranks among the countries with the lowest water availability. Although only slightly more than 1 percent of South Africa is covered by closed-canopy forests (primarily exotic species timber plantations of *Pinus*, *Eucalyptus* and *Acacia* species), these lie in the upper reaches of catchments that supply 60 percent of its freshwater. Nearly all the country's plantations are on previously native grasslands. In some cases, water reductions are experienced as soon as two years after planting. Maximum streamflow decreases occur relatively early in these fast-growing stands, and then diminish. Concerns about water use by forest plantations are not unique to South Africa, but it is the first country to impose charges on plantations for using water.

The National Water Act of 1998 classifies forest plantation as a streamflow reduction activity (SFRA), the only land use so classified. One reason that other dryland crops (maize, wheat, sorghum and sugar cane) are not classified as SFRAs is that less is known about their water use. The licensing of timber plantations began in 1999. Prices are based on the catchment's budget, which include the costs for water monitoring and management, improving water availability, operating water schemes and funding water conservation activities. Each catchment budget is divided according to the volumes used by each economic sector. The volume for forestry was based on average rainfall in the catchment by species, using rainfall of 60 mm per year. In 2002, forest charges ranged from 2 to 6 South African rand per hectare per year. Volume uses in various sectors are being refined. One problem with the programme is that there is no compensatory payment or reduction in charges for the benefits that trees provide to water quality. Trees intercept rainfall nutrients and recycle them; by reducing surface erosion, trees also lower the amounts of water-impairing sediment.

Source: Jacobsen, 2003.

and Raj, 1979). There are many stories of flow reductions following *Eucalyptus* plantation, encouraging FAO to publish *The eucalypt dilemma* (FAO, 1988b). Scott, Bruijnzeel and Mackensen (2005) reviewed the experience and research in this topic. The special case of reforestation in mountains where persistent wind-driven fog or cloud occurs should result in more water in dry-season streamflows, but there is not yet any scientific evidence to corroborate this (see Chapter 4).

GROUNDWATER LEVELS

Forest cover influences groundwater levels, wells and springs, as well as safeguarding water quality. As noted by Foster and Chilton, (1993):

> Groundwater should be regarded as a valuable, but potentially fragile resource in the humid tropics, which, in some cases, is highly vulnerable to pollution from the uncontrolled disposal of urban and industrial liquid effluents and solid wastes, as well as from intensive agricultural cultivation, and saline intrusion in coastal areas due to local overexploitation.

This statement is true for more than the humid tropics. The safest protection for groundwater is forest cover on its sources. Harvesting or removing the forest raises groundwater levels (Working Group on the Influence of Man on the Hydrologic Cycle, 1972). Any salts present in the upper soil layers could be moved into the rooting zone of plants, with deleterious effects (e.g. the Australian experience described in the section on Forests on saline-susceptible soils in Chapter 4). Conversely, planting forests on open land where the water table is close to the surface will lower groundwater levels, improving drainage.

GUIDELINES

Forest removal, either partial or total, results in increased streamflows and higher groundwater levels. These effects occur mainly at the local, small watershed level and cannot be extrapolated to large river basins where flooding or insufficient dry-season flows are problems. Even at the local level, these effects may be desirable or undesirable. It is the soil that stores water, not the trees, and tree roots are more like pumps than sponges. Soil depth and precipitation characteristics cause great variations in the general pattern. Prolonged or high-intensity storm events usually override the influence that forests and forest manipulation have on water yields, with the exception of those very close to the area being treated. Manipulations to improve water yield must take into account the possible impairment of water quality (see Chapter 3) and other values, such as landslip and avalanche protection, wildlife habitat and biodiversity maintenance.

Reforestation or afforestation of open land generally has the opposite effects on water quantity to those of forest removal. Sediment discharge may be significantly reduced, which may result in less severe flooding.

3. Forests and water quality

Forests' most significant contribution to water for all living things is in maintaining high water quality. They achieve this through minimizing soil erosion on site, thus reducing sediment in water bodies (wetlands, ponds and lakes, streams and rivers), and through trapping or filtering other water pollutants.

EROSION AND SEDIMENT

Transported and deposited erosion is called sediment. This section describes how forests – and forest alteration – influence sediment from transport and deposition by minimizing erosion. Although one of the most serious consequences of erosion is loss of soil productivity, this section is concerned mostly with the effect on water resources. Erosion decreases soil's water storage capacity, and usually causes reduced infiltration on eroded sites, thus speeding both subsurface and overland flow.

Sediment deposition can be beneficial if it occurs in the right place, but there are usually a host of unwanted effects from transported and deposited sediment. Sediment can reduce reservoir capacity; impair water for drinking and domestic or industrial uses; obstruct navigation channels; raise river beds, which reduces the capacity to handle water safely; adversely alter aquatic habitat in streams; fill the spawning grounds of fish; wear down turbine blades in power installations; and cause landslides, which damage people and their structures and block channels, resulting in floods.

In riparian zones and along the shores of water bodies where wave action is a factor, the roots of shrubs in the tree and forest understorey stabilize banks against erosion. This occurs in coastal mangroves, streambanks and large ponds and lakes. For meandering rivers, forest cover may only delay the inexorable natural erosion that contributes much sediment to watercourses, but delay is often important to land users on the outcurves of such watercourses. Streambank stabilization with tree plantings (often with willow cuttings and fibre mats) can slow the process, but if done on one small stretch alone, may simply shift the problem elsewhere.

On sloping land, soil moves downhill owing to gravity and displacement by the splash action of raindrops. Forest cover provides the most effective barrier to natural erosion, and loss of forest cover, resulting from other land uses, always increases human-accelerated erosion, unless soil conservation is carried out.

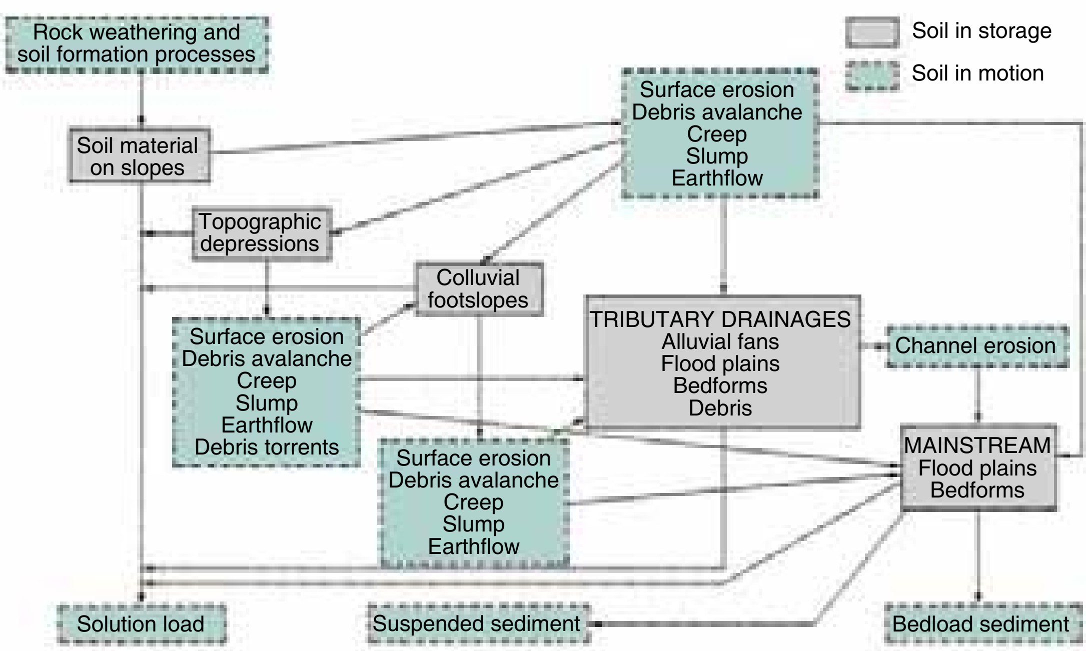
Erosion spans a range of phenomena from surface erosion (sheetwash and rills) through gullies (advanced surface erosion) to mass soil movement (landslips, slumps, debris avalanches and landslides). These are all natural processes and can occur on land under forest. Mass soil movements are usually caused by earth tremors or high-intensity or prolonged storms that saturate soils and result in high pore pressure and buoyancy. Erosion and sedimentation processes on watershed sloping lands are shown in Figure 2, which illustrates soil in storage and in motion.

The most effective land use for keeping water as sediment-free as possible is good forest cover, with its understorey, surface litter, debris and organically enriched soil. For instance, in the Ethiopian highlands, soil loss under forest averaged 1 tonne per hectare, the lowest of seven categories of land use (Hurni, 1988). It is not the tall tree canopy that protects soil against raindrop impact, but rather the leaves between the ground surface and 10 m in height and the litter on the soil surface that reduce this splash erosion force (Wiersum, 1984). Together with the surface tree roots, these also reduce surface sheet erosion and rill formation.

Timber or wood harvesting that bares the soil surface or channels water – as a result of extractive activities such as skid roads, haul roads and landings – increases the risk of erosion (Hamilton and King, 1983). In water supply areas, all harvesting must follow best conservation logging practices to maintain quality water. Good basic guidelines for minimizing the adverse soil erosion and sediment consequences of logging are provided in Megahan and Schweithelm (1983) and Gilmour (1977). Since these were produced, country and local guidelines have been developed for local situations, and many countries have established regulations for acceptable management practices that prevent sedimentation of watercourses.

Forests are also the safest cover for preventing mass soil movements. Deep tree roots that penetrate through different soil layers provide some protection against shallow landslips by increasing shear strength (O'Loughlin, 1974). Forest removal (clearing) removes this root shear strength, leading to eventual disaster

FIGURE 2
Erosion and sedimentation processes in a watershed



Source: Megahan, 1981.

in landslip-prone sites, while forest harvesting (logging) reduces it, depending on the heaviness of the cut and the rate at which the regenerating forest re-establishes deep root systems (discussed further in Chapter 4).

Erosion material arriving from upslope as sheetwash or rills can be filtered and trapped by adequate streamside forest buffer zones. Gullies and mass erosion can be stopped by only exceptionally wide riparian buffers (also discussed in Chapter 4).

Forest restoration is one of the best ways of restoring productivity and reducing sedimentation in degraded areas of cleared land experiencing any kind of accelerated erosion. Forest restoration may be used in conjunction with other conservation land uses or physical structures, and is a separate topic. It usually requires an integrated and multifaceted rehabilitation programme, in which reforestation is a major component. For instance, the Green Hills watershed programme instituted in the degraded Chitagong Hill tracts of Bangladesh includes tree planting, development of self-help community organizations for water supply, fire control, health and improved agricultural practices (Moung Thowai Ching, personal communication, 2003). Case study 2 describes how a watershed restoration project in Taiwan Province of China helped to reduce reservoir sedimentation by 45 percent.

OTHER WATER POLLUTANTS

Soil is not the only material that can impair water quality. Depending on the type of land use, various levels of other pollutants can also drain into the watercourse. Forest cover in the watershed above the site of concern (e.g. a drinking-water supply reservoir) is the best option for limiting this. Most forest uses involve no fertilizer, pesticides, fossil fuel runoff or outfalls from domestic sewage or industrial processes. Where logging occurs, care should be taken with machinery fuels and lubricants, as the accumulation of small spills during routine handling, or larger, accidental spills, can seriously contaminate soils and drainage water. All oils, particularly diesel, migrate quickly through soil, and even small quantities can taint drinking-water supplies and disrupt water treatment processes (Nisbet and McKay, 2002). Other types of land use that use machine fuels and lubricants, such as agriculture and transportation routes, are even more risky owing to the frequency of spills and intensity of use compared with forest harvesting.

Forests in water supply catchments are the best solution for reducing pollution risks. If they are logged using mechanical equipment and roads, good conservation logging regimes must be used. Many drinking-water catchments – for example part of the Melbourne, Australia water supply area – have been carefully logged for decades with no apparent water quality problems (Dudley and Stolton, 2003), although about half the watershed's lands are in unharvested national parks.

The impact of changed land uses when forest areas become suburban is well illustrated by a New York City water catchment, the Croton system. Here, a partly protected and partly "working" forest landscape is gradually shifting from forest management to rural residence – single home ownerships with large backyards of 0.5 to 2 ha. This is resulting in increased nutrient loading from septic systems,

CASE STUDY 2

Reservoir sediment reduction in Taiwan Province of China

The 20 480-ha Wuseh watershed in the Central Mountain Range of Taiwan drains into the Wushah Reservoir (completed in 1958). The terrain is steep, with an average slope of 57 percent. Average annual rainfall is 2 235 mm, mostly from May to October, with a dry period from October to January. Two-thirds of the watershed was covered in natural forest (14 099 ha); there were 4 205 ha of grasslands; 856 ha of cultivated land; 1 046 ha of denuded land resulting from unsustainable slash–and-burn cultivation; 276 ha of other uses. The aboriginal population numbered 1 900.

A programme of land-use changes and education was instituted. By 1988, with an average annual expenditure of US$200 000, the following was accomplished:

- 2 660 ha of reforestation;
- 490 ha of soil conservation on cultivated lands;
- three fire lookout towers and a suppression network;
- 33 km of new forest road and bank protection on 38 km of a major highway (the latter due to typhoon damage in 1982);
- eight check dams and gully control work;
- introduction of fruit trees and agroforestry, conservation farming, new crop varieties and marketing;
- training courses in tree planting, fire protection, soil conservation, home economics and hand crafts for women.

From 1957, reservoir sedimentation data were collected and a base rate established. From 1965 until 1985, attributed to the rehabilitation programme, sedimentation was reduced by 55 percent of the base rate. The unit cost of reducing 1 cubic metre was US$0.20.

Source: Extracted from Sheng, 1986.

lawn fertilizers, animal wastes (often horses) and road salts; nutrient transport is accelerated by the growing areas of impervious surfaces (Heisig, 2000). The chemicals studied include ammonia, total phosphorous and orthophosphates, but nitrogen and others may also increase.

Any non-point source pollution can be greatly reduced, or even eliminated, by adequate forest buffer zones along watercourses (see Chapter 4 for more detail). Such zones do not prevent groundwater contamination, however, which needs to be addressed by modified on-site practices.

The following are the only cases in which forests are not the most effective watershed cover for delivering the highest-quality water:

- in some dense, planted monocultures with little or no understorey and ground cover, which experience increased surface erosion rates (see earlier discussion);

- where atmospheric pollutants are "captured" by trees more than by other vegetation (owing to the trees' height and aerodynamic resistance) and added to the soil and water. This occurs prevalently in mountain forests of the industrialized Northern Hemisphere (Hamilton, Gilmour and Cassells, 1997).

GUIDELINES

When water quality is a high priority, forests are the best cover or land use (Case Study 3). Undisturbed forest cover provides the greatest protection against erosion, sedimentation and impairment by other contaminants. The best use is designated forests with management regimes, such as core zones of national parks or watershed protected reserves. The values foregone in commercial harvests may be more than offset as quality water becomes more scarce and more valuable. Many municipalities throughout the world, such as Caracas, Freetown, Harare, New York City, Quito and Singapore, have sought to establish water supply areas in protected forests (see Chapter 4), which are not intensively used by humans, domestic animals or machines.

Where forest extraction is carried out, sediment production and chemical pollution should be minimized. Roads, log landings, skid trails and soil compaction need to be addressed as the chief sources of sediment. Landslip-prone areas can

CASE STUDY 3

The Panama Canal and water quality

Sedimentation and growth of water weeds create problems for shipping in the Panama Canal, and require expensive dredging. An adequate, regulated supply of freshwater is also needed. Forests' role in both these issues is recognized by the Smithsonian Tropical Research Institute in Panama, which has recommended reforestation of denuded parts of the watershed. This would reduce not only sedimentation, but also the flow into the canal of nutrients that stimulate aquatic vegetation growth. Reforestation would decrease total water inflow, but the regulated effect of reducing peak flows would result in more useful water, requiring less water storage. It has been proposed that companies dependent on the canal buy bonds to pay for the reforestation.

In the meantime, a US$10 million debt-for-nature swap over 14 years through The Nature Conservancy (which is pledging US$1.6 million) is strengthening the protection of existing forest watershed land. This involves 129 000 ha in Chagres National Park, with its rich biodiversity. The watershed also provides drinking-water for Colón and Panama City.

Source: Adapted from *Plant Talk,* 2003.

be major contributors to sedimentation and flooding. They need identification and special care and should be harvested only lightly by non-mechanized means. Recreational infrastructure must also be carefully sited and managed. Riparian buffer zones of forest or dense vegetation and adequate width are extremely important.

4. "Red flag" forest situations

MOUNTAIN CLOUD OR FOG FORESTS

Of all forest situations, cloud or fog forests have the closest interrelationship with freshwater. These forests occur on mountains or upland areas that are bathed in frequent or persistent fog, particularly where wind-driven cloud intersects directly with the surface. Occurring particularly in the tropics, cloud forests are common on large mountains in the interior, at elevations of 2 000 to 3 000 m. On coastal ranges, they can occur at about 1 200 m, and on small oceanic islands may occur even at 500 m (Hamilton, Juvik and Scatena, 1994). In addition to normal vertical precipitation, these forests have another source of water: the interception and water-stripping of horizontally moving fog, which can add hundreds of millimetres of water per year to the ecosystem and its watershed (Bruijnzeel and Hamilton, 2000).

Recent estimates of the extent of cloud forests in the tropics vary considerably. The official estimate of the World Conservation Monitoring Centre (WCMC) of the United Nations Environment Programme (UNEP) is based on forest cover and altitudinal range and gives potential global area. In 2004 this estimate was 380 000 km^2, less than 2.5 percent of all tropical forests (Bubb *et al.*, 2004). An

Cloud forests are important for water production, erosion control and biodiversity (Malaysia)

K. SHONO

estimate based on cloud-affected forest modelling gives a much larger figure of 2.2 million km^2 (14.2 percent of all tropical forests) (Mulligan and Burke, 2005). This variation reflects the difficulty in defining and locating these ecosystems. A database at UNEP-WCMC locates more than 560 points known to be cloud forests (Aldrich *et al.*, 1997).

Cloud forest trees are usually shorter in stature than those in lower montane forests, much more mossy and more heavily laden with bromeliads, orchids, ferns, lichens and liverworts (epiphytes). Tree stems become increasingly crooked and gnarled with elevation, tree ferns and bamboo are common, and mosses cover the rocks and fallen stems. In a few situations, however, fine, straight, taller trees can develop, as in the *Podocarpus* cloud forests in the Andes and the *Quercus* forests in Costa Rica's Talamanca Cordillera. All the epiphytic vegetative surfaces, together with the tree foliage, twigs, branches, stems and shrubs provide a "net" for capturing horizontal precipitation from fog or cloud and adding it as fog drip or stem flow to the watershed budget. Transpiration is relatively low in fog-shrouded forests with small leaves and often wet and waterlogged soils, so this loss is minimized.

The amount of "extra" water obtained by cloud forests varies markedly according to rainfall patterns, topographic position, frequency or persistence of cloud and extent to which clouds are wind-driven (Table 2). The increase may be 15 to 20 percent of rainfall for rainfalls of 2 000 to 3 000 mm per year, and up to 50 to 60 percent for exposed ridge-top locations and lower precipitation

TABLE 2
Examples of amounts of horizontal precipitation in tropical montane cloud forests as determined by fog catchers

Location	Elevation in metres	Horizontal precipitation as % of rainfall	Period
Colombia, Serrania de Maquira	865	63	dry season
Costa Rica, Cerro Buenavista	3 500	18	annual
Costa Rica, Balalaica	1 300	33	annual
Costa Rica, Balalaica	1 300	15	wet season
Hawaii, Mauna Loa	1 580	30	annual
Hawaii, Mauna Loa	2 530	68	annual
Malaysia, Gunung Silam	884	9	annual
Mexico, Sierra Madre	1 330	15	wet season
Mexico, Sierra Madre	1 330	85	dry season
Puerto Rico, Pico del Oeste	1 050	7	annual
Venezuela, Cerro Santa Ana	815	32	annual
Venezuela, Cerro Santa Ana	815	66	dry season
Venezuela, Cerro Copey	987	11	annual
Venezuela, Cerro Copey	987	9	dry season
Venezuela, Zumbador	3 100	4	annual
Venezuela, Zumbador	3 100	19	dry season

Source: Nik, 1996.

BOX 4

Examples of cloud forests and water supply

Millions of people depend on high-quality freshwater flowing from mountain cloud and similar forests. The cloud forests in La Tigra National Park in Honduras sustain a well-regulated, quality water flow throughout the year, providing more than 40 percent of the water supply of the 850 000 people in the capital city, Tegucigalpa. The 2.5 million people in the Tanzanian city of Dar es Salaam rely on drinking-water from the Uluguru Mountains and hydroelectric power from the cloud forests of the Udzungwa Mountains, which are now the focus of modest conservation actions. Other city populations supplied by cloud forest water include the 1.3 million people in Quito and the 20 million in Mexico City.

Celaque Mountain in the north of Honduras is called "Box of Water" in the Lencan language and has been worshipped by the Lenca for millennia as a god mountain that supplies life-giving water to the land and people. With dense cloud forest cover, Celaque Mountain generates nine major rivers and countless streams, which feed clean water to nearby cities and communities. In Guatemala, the Sierra de las Minas Biosphere Reserve contains 60 percent of the country's remaining cloud forest habitat. More than 60 permanent rivers drain the reserve, making it the country's biggest single water resource. This is especially significant for the Motagua Valley to the southeast of the sierra, which is a rain-shadow desert heavily dependent on irrigation. In arid and semi-arid areas, patches of cloud forest are even more crucial for water supply to surrounding communities, especially during the dry season, for example on Mount Kenya.

Without the River Chagres, construction of the Panama Canal would have been nearly impossible. Its source is high up on the upper watershed in a series of mountains blanketed by tropical cloud forest. This ecosystem ensures the water supply for Lake Madden and Lake Gatun, which provide the necessary draft for transiting ships.

Source: IUCN and WWF, 2000.

(Bruijnzeel and Hamilton, 2000). Water catch in fog/cloud situations in areas of lower and seasonal rainfall can be 100 percent or more higher than that in lower forests. In areas of low rainfall, but frequent, wind-driven fog, even single trees can become important water collectors for wildlife, domestic stock or people. A famous examples was found on El Hierro, one of the Canary Islands, where one of several "fountain trees" (a laurel) was used for centuries as the main source of water for people and their animals until it was uprooted by a storm (Gioda *et al.*, 1992). The tree was so important that it is depicted on the island's municipal coat of arms. A replacement tree was established in 1945, and continues to capture valuable amounts of fog water to this day.

Trees can be planted in strategic fog locations to capture horizontal precipitation for use. Where tree planting is difficult because of lack of rainfall, as in the coastal hills of Chile and Peru, mesh barriers have been erected, creating an artificial fog forest that provides potable water for water-scarce communities.

If cloud forests are removed, much of this extra water capture is lost. Although reductions following clearing have not been adequately quantified through research, the precautionary principle should prevail (Bruijnzeel, 2005). It is recommended that cloud/fog forest areas be identified, mapped and protected for the water services they render. Payments to landowners for retaining cloud forest have been instituted in Costa Rica and elsewhere (Chapter 6). Giving them legal status as watershed protection forests, national parks or nature reserves is another desirable response. Cloud forests have extremely high biodiversity value, as endemism in these forest belts on mountains is outstanding. They are home to such animals as the African mountain gorilla, Andean spectacled bear, mountain tapir, resplendent quetzal and several at-risk amphibians (Bruijnzeel and Hamilton, 2000). Studies by BirdLife International have shown the importance of tropical montane cloud forests to restricted-range and threatened bird species worldwide (Long, 1994).

As mentioned, it is estimated that these forests potentially cover less than 2.5 percent of the world's tropical moist forest (Bubb *et al.*, 2004). This is a generous estimate, based on excluding lower-elevation mountain forests from maps, but including 605 known sites of actual cloud forest. It does not include

Swamp forests have a unique role in water balance; they are sensitive environments where the maintenance of hydrological integrity is a management priority (Poland)

P. CECI

subtropical montane cloud forest. It is of interest that potential cloud forest in Asia is estimated to be 14.6 percent of the continent's tropical mountain forests, a higher proportion than in other continents.

Although cloud forest sites are often unsuitable for conversion to other sustainable uses – because of soil limitations, climate and accessibility problems – vegetable production, opium or coca growing, grazing, coffee growing and even golf courses and resorts are threats. Overcutting for charcoal production or fuelwood is also a danger in these cool montane locations (Case study 4). Global warming appears to be raising the cloud deck in some places, with potentially serious adverse impacts on both water supply and biodiversity.

Guidelines

In view of their importance for water production, erosion control and biodiversity, and their general unsuitability for other sustainable uses, cloud forests should be maintained as forest. They need to be identified in local, regional and national inventories. Their loss is irreversible owing to the complex relationships among their flora, fauna and soils (Hamilton, 1995). The conservation of cloud forests and their designation as protected areas should be national priorities.

SWAMP FORESTS

Swamp forests are a major forest type with a unique role in local water balance and the global ecology. A swamp forest is any wetland with woody vegetation – irrespective of the size of the plants, which can range from 1 m, such as the mangrove plant *Rhizophora mangle*, to the 50-m tall cypress *Taxodium distichum* (Lugo, Brinson and Brown, 1990). Freshwater swamp forests are an important source of fish and other aquatic foods and of timber and fuelwood. They interact with biogeochemical cycles and the food chain, have a fundamental role in the dynamics of local water quantity and quality (Maltby, 1997; Maltby and Proctor, 1996) and provide distinctive habitats for biodiversity. Inland swamp forests protect watersheds, while coastal swamps protect coasts against tides, rising sea water levels and natural hazards.

In any climatic zone, hydrology is the most important determinant for the establishment and maintenance of specific types of swamp (Lugo, Brinson and Brown, 1990; Mitsch and Gosselink, 1993). It is also a key determinant in species distribution, wetland productivity (biomass produced per unit of time) and nutrient cycling and availability. The hydrology of basin wetlands (i.e. those in topographic depressions) is different from that of riverine or fringe wetlands. Local topography also affects water flow. A large basin wetland may include a mixture of wetland types of varying behaviour (basin or riverine), according to the location and season. The level of nutrients flowing in or out of a swamp is also important in determining its nature.

A better model of potential swamp forest structure and function is obtained when hydrology is considered together with nutrient content and flow (eutrophic versus oligotrophic or minerotrophic versus ombrotrophic) (Brown, 1981; Odum,

CASE STUDY 4

Fragmentation threats to cloud forest in Xalapa, Veracruz, Mexico

The destruction of tropical montane cloud forest in the western region of Xalapa, Veracruz has accelerated considerably in the last few decades. To determine the degree and pattern of cloud forest fragmentation in this region, 33 aerial photographs (scale 1:20 000) were digitized and photo-interpreted to generate maps of vegetation and land use. Additional information on slope, slope aspect and human settlements was incorporated into a geographic information system. In the study area of 12 843 ha, 19 fragments of undisturbed forest remain, occupying just 10 percent of the region. The dominant land uses are pasture (37 percent), urban areas (1 percent), secondary vegetation (17 percent) and disturbed forest (17 percent).

The few flat areas available in the region (3.2 percent) are occupied by urban zones and pasture, while undisturbed forest is found mostly on steep slopes, with a northern exposure and located far from human activity. Fragments of forests are surrounded by pasture, disturbed forests and secondary vegetation, which may produce strong edge effects and reduce the overall undisturbed forest cover by another 15 to 54 percent, depending on the size of the forest fragment. Results indicate that 90 percent of the forest in the region has already been destroyed, and the remainder is in danger of disappearing. There is need for a regional development plan that considers the importance of cloud forests as biodiversity reservoirs and providers of key environmental services, protects surviving fragments of undisturbed forest, and promotes ecological restoration of disturbed forest and establishment of corridors connecting forest remnants.

Source: Abstracted from Williams-Linera, Manson and Isunza Vera, 2000.

1984, both cited in Lugo, Brinson and Brown, 1990). These last authors stress the need to consider the chemical aspects of forested wetlands more holistically. They also allude to the confused state of the nomenclature used to identify forested wetlands, resulting from the emphasis on species composition and vegetation types, which vary geographically, rather than on hydrology and geomorphology, for which geographic variation is much less. For example, Swain and Kearsley (2001) identified 11 distinct classes of temperate swamp forests based on predominant tree species (conifer, hardwood and shrub vegetation).

Forested swamps develop more structure and are more productive under riverine conditions (Lugo, Brinson and Brown, 1990). Alteration of swamp vegetative cover, such as through timber harvesting, alters water quality and quantity (Immirzi, Maltby and Vijanrnsorn, 1996; Ensign and Mallin, 2001). Hydrological alterations affecting water quality or quantity in swamp forests affect community structure and component species. Nutrient enrichment from surrounding land use also affects community structure by allowing less tolerant species to displace low-nutrient specialists (Swain and Kearsley, 2001; van Andel, 2003). For example, water at a post-clear-cut coastal swamp forest displays significantly more suspended solids, total nitrogen, total phosphorus, total Kjeldahl nitrogen and fecal coliform bacteria, and significantly less dissolved oxygen. Longer-term deleterious effects include recurrent nuisance algal blooms. Even a 10-m uncut buffer zone is inadequate to prevent these impacts on water quality (Ensign and Mallin, 2001).

The hydrology of peat swamps is highly complex and is key to the functioning of peat swamp ecosystems (Case study 5). Some peat swamps lie on top of an impermeable layer of rock or soil, preventing the passage of water between the aquifer and the swamp. Other swamps owe their existence to groundwater that has come to the surface as springs, while still others form on permeable soils overlying aquifers, allowing water to recharge the aquifer directly. Because of their large extent, these peat swamps are very important in maintaining hydrological balance at the landscape scale. The central areas of these swamps can be permanently saturated with water, while marginal areas have variable water regimes and may be influenced by river flooding, especially during wet seasons (Rieley, Ahmad-Shah and Brady, 1996).

Water is stored in the inert or inactive layer (catotelm) of peat swamps, in volumes found to remain relatively constant for long periods if the swamp is undisturbed. Most changes in water storage occur with changes in the water table level. These storage changes account for no more than 3 to 10 percent of the storage volume (Ingram, 1983). Water drains freely in the upper, active layer (acrotelm). Water storage in the acrotelm is critical to the water balance in swamps and surrounding areas, and the effects of deforestation, drainage or peat extraction (and the ensuing oxidation and degradation of drained areas of swamps) have strong implications for local hydrology.

Peatlands form more than half the world's wetland areas (Maltby and Immirzi, 1996). In the tropics, peat swamp forests can develop over areas that were once covered by mangroves. As organic matter accumulates under anaerobic, waterlogged conditions, and levees develop that reduce salt-water intrusion, inland species begin to replace mangroves. The soil is so anaerobic that bacteria cannot convert fallen vegetative matter into humus. This vegetative litter is then converted into peat, which continues to build up over time. As peat accumulates, the water table changes and different forest species gain dominance. In one site in Sarawak, Malaysia, a peat dome stretching across 20 km of swamp was found to include six different forest types, located in concentric rings. Soil core samples from the oldest forest in the centre of the dome indicated that the six types succeeded one another. The inner type was stunted open forest, while the outer forest comprised 50 m-high commercial species. Peat swamp forest is thus a successional stage of a freshwater swamp forest characterized by soils with a very low pH, few minerals and very low natural decomposition of litter (Jacobs, 1988).

Natural peat swamp forests function as aquifers because they absorb and store water during wet periods, releasing it slowly during periods of low rainfall. They

CASE STUDY 5

Conservation and sustainable use of the Southeast Pahang peat swamp forest

Peat swamp forest cover in Malaysia is now restricted to small areas in northern and southeastern Selangor, Tasek Bera (southern Pahang), a large complex in southeastern Pahang, the Klias Peninsula in Sabah, the inland reaches of the Baram River and the periphery of Loagan Bunut in Sarawak. The Southeast Pahang peat swamp forest is believed to be the largest, least disturbed peat swamp forest in mainland Asia remaining as a single, nearly contiguous forest complex.

As one of the most threatened wetland habitat types in the world, this forest is the focus of global conservation interest. It harbours a unique assemblage of lowland tropical forest biodiversity, provides important benefits and services and supports the livelihoods of numerous local communities. At the national level, it has been designated as a highly threatened, environmentally sensitive areas under the draft national plan recently prepared by the Federal Town and Country Planning Department. BirdLife International has designated the area an important bird area, and it is the site of the five-year Conservation and Sustainable Use of Tropical Peat Swamp Forests and Associated Wetland Ecosystems, a joint project of the Forest Research Institute of Malaysia (FRIM), the United Nations Development Programme (UNDP) and the Global Environment Facility (GEF).

The spectrum of habitats found in the Southeast Pahang peat swamp forest range from shallow aquatic ones near the coast to the rich mosaic of wet- and dryland habitats found further inland. Forest types in this complex belong to climatic climax formations (e.g. lowland dipterocarp forest) and edaphic climax formations such as mangrove forest, peat swamp forest, beach forest, freshwater swamp forest, heath forest, riparian fringe forest and unstable forest formations (e.g. padang vegetation).

Major river channels in the forest complex include the Bebar and Merchong Rivers, both flowing westward from the eastern hills. They are blackwater rivers, draining the peat swamp area, and have very low pH and dissolved oxygen levels. There is also an extensive network of channels where the swamp had been drained for timber extraction and agricultural development. Tidal influence on the rivers is very marked, especially when there is low river discharge, and extends a considerable distance up the low gradient, with backflow occurring at high tides. Saline penetration up river channels causes a characteristic zonation of riverine vegetation along the rivers' lower reaches.

Macrophyte beds are limited, the commonest being *Utricularia aurea*, which occurs in the slower flowing parts of the river and in some of the human-made canals. A significant find in the Bebar River is the *Cryptocoryne cordata* bed along parts of its upper reaches. These are important areas for spawning, feeding and nurseries for young fish. Euryhaline and freshwater fish and shrimps migrate up and down the rivers, usually daily with the tides for feeding and seasonally for spawning.

Of the 238 peat swamp forest flora taxa recorded for peninsular Malaysia, at least 221 have been recorded in the Southeast Pahang forest. The most significant include: *Gonostylus bancanus* (ramin), an important timber species with restricted distribution in Malaysia and elsewhere; *Durio carinatus*, a source of food for hornbills and other wildlife; *Tetra glabra*, an important commercial species; *Astonia angustiloba,* a preferred nesting site for the lesser adjutant stork, *Leptoptilus javanicus*; and *Nageia motlei*, a relatively rare gymnosperm. Also found are 17 tree species endemic to peninsular Malaysia, 62 species of mammals (three endangered, five vulnerable and nine near threatened) (IUCN, 2002), 233 species of birds (eight endemic to Sundaland), eight species of turtles, 17 species of amphibians and 56 species of fish. Of the fish species considered to be stenotopic (tolerant of only a narrow range of environmental factors) to blackwater rivers in peninsular Malaysia, 70 percent have been recorded in this forest; two of the 17 amphibian species (*Pseudobufo subasper* and *Rana baramica*) appear to be exclusively peat swamp species.

The Jakuns, the main indigenous population in the Southeast Pahang forest, depend on the natural resources of the complex for the bulk of their basic needs – food, shelter and medicines. Fish from the peat swamp forest is an important dietary source of protein for the communities living on its fringes and along the waterways. Houses are constructed entirely of swamp forest products. Rattan is used for tools, household utensils and fish traps, while the leaves of *Pandanus* spp. are used in crafts.

The forest compartments of this forest were still intact in 2000, although surrounding areas have been logged or converted to agriculture, which threatens ecological integrity. Drainage of the swamp forests for conversion to agricultural use alters the local hydrology through the creation of dams, weirs and tidal gates for irrigation. The use of fire to clear land close to the forest also threatens the ecological integrity of the complex. Drainage can lead to drying out of the surface peat layer, making fire a serious hazard. Peat fires are difficult to extinguish and burn for extended periods.

Peat swamp management should adopt an integrated ecosystem approach, which takes into consideration the economic, social and ecosystem benefits that can be derived from the swamp forest. Such an approach manages resource use adaptively to meet the twin objectives of sustainability and maintenance of the complex’s productive potential. This is the overall objective of the FRIM-UNDP/GEF project.

Source: Abstracted from FRIM, UNDP and GEF, 2004.

thus contribute to a more even river flow between the dry and wet seasons (Rieley, Ahmad-Shah and Brady, 1996; Urapeepatananpong and Pitayakajornwute, 1996). They can therefore be a source of irrigation water – for example, the North Selangor peat swamp forest provides irrigation for paddies during the dry season (Prentice and Parish, 1992). In Sarawak, peat swamps are a source of potable water (Lee and Chai, 1996). Peat swamps along coasts act as buffers between the marine and freshwater systems, maintaining a balance between them and preventing saline intrusion into coastal lands, while protecting off-shore fisheries from land-based sources of pollution (FAO, 1988a; Rieley, Ahmad-Shah and Brady, 1996).

Several water discharge processes other than evapotranspiration operate in peat swamps. These include seepage (the mass transport of liquid through porous media), pipe flow from subsurface erosion, overland flow and open channel flow (through rills, streams or rivers). These processes are strongly affected by activities that lower peat swamp water levels, such as the construction of drainage schemes for conversion to agricultural use, canalization for timber extraction, groundwater abstraction and the building of major roads. These lead to degradation of the ecosystem, reflected in the irregular discharge of variable river water flows, peat surface subsidence and increased flooding frequency.

The North Selangor peat swamp forest is an example of conflicting land-use options in a wetland ecosystem (Yusop, Krogh and Kasran, 1999). Here, there was extensive excavation of peat during construction of canals to facilitate log extraction. There has also been clear competition for water resources; water in the area is needed both for irrigation and for the forest to sustain its ecological functions. Flow from the Bernam River, which once provided the major recharge to the ecosystem, especially in the northwestern part of the forest, has been diverted to augment water supply for irrigation. It has been calculated that the peat swamp contributes 11 percent of the water for the 20 000 ha Tanjung Karang Irrigation Scheme. There are already signs of ecological degradation, with water pH in the extraction canals remaining between pH 3.7 and 3.8, compared with averages of between 6.0 and 5.9 in the main irrigation canals.

In Southeast Asia, in addition to brackish peat swamp forests along the coasts, there are also periodically flooded freshwater swamp forests. One of the largest seasonal swamp forests in mainland Southeast Asia borders Tonle Sap Lake in central Cambodia. During the monsoon season (May through October), a slight incline in the central Cambodian Depression forces the Mekong River to reverse its flow up the 80 km-long Tonle Sap channel, pushing water into the forests surrounding the lake, which is Southeast Asia's biggest freshwater lake. The lake level rises by 10 to 15 m during the rainy season, covering a 20 to 25 km ring of surrounding forests, or some 1 500 square miles (about 579 km^2) of land area. More than 200 species of fish migrate into the flooded forest to spawn during the rainy season, feeding off plants and insects that live on submerged trees.

Guidelines

Swamp forests should be designated as environmentally sensitive areas where maintenance of hydrological integrity is a management priority. They should be given legal protection, and the potential long- and immediate-term effects of any planned large-scale conversion to other land use should be subject to careful environmental impact assessment. Ecosystem composition and function should be maintained as far as possible, and activities that conserve the integrity and beauty of swamp forests should be favoured. Management must take into account the interrelationships between swamp forests and adjacent ecosystems and the social and economic setting in which the swamps exist. Swamp forest management should be based on:

- an appreciation of the precautionary principle, which requires decision-makers to take care that proposed forest interventions will not incur unexpected, high future costs;
- an understanding of the forests' carrying capacity and sustainable use;
- the maintenance of environmental goods and services from the forests;
- avoidance of unexpected irreversible damage and loss of ecosystem resilience;
- awareness of the likelihood of unexpected off-site effects.

FORESTS ON SALINE-SUSCEPTIBLE SOILS

Salinization is a widespread problem, particularly in drier landscapes or regions with an extended dry season. Recent reports suggest that worldwide 77 million ha of land is affected by salinization induced by human activities. This is referred to as secondary salinization to distinguish it from naturally occurring or primary salinization. A high proportion of secondary salinization (41 percent) is caused by changes in vegetative cover, with the remainder resulting from excessive irrigation. In both situations, salinization is induced by alterations to the hydrological cycle that mobilize salt stored in the soil (Ghassemi, Jakeman and Nix, 1995).

There are two key sources of salt in soils: salt brought by rain, which in coastal

Coastal forests maintain a balance between marine and freshwater systems, and prevent saline intrusion into coastal lands (Bangladesh)

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areas tends to have higher salt loads than in inland ones; and weathering of the former marine sediments that underlie many soils. Salt may be flushed from the soil profile if rainfall is plentiful and the soil has a sandy texture, but can accumulate in soils if rainfall is less or the soils are heavier-textured and less easily flushed.

Changes to vegetative cover, such as deforestation, alter the hydrological cycle by reducing rainfall interception and plant transpiration. This allows more water to reach the groundwater layer, and the water table rises, bringing with it any salt present in the soil profile. Once the water table arrives within 1 or 2 m of the soil surface, evaporation leads to a concentration of salt in the root zone. This can eventually reach concentrations that affect plant growth (O'Loughlin and Sandanandan Nambiar, 2001).

Under normal conditions, a variety of plant communities, including forests, can develop on soils containing substantial amounts of stored salt. This is usually because most of the salt is contained in the lower strata of the soil profile, and evapotranspiration by plants ensures that groundwater recharge is slow and water tables remain relatively far below the soil surface. In some situations, however, surface soils may have higher salt content, and forest communities will contain species adapted to these stronger concentrations.

Consequences of logging or forest clearing

Any form of forest disturbance will affect the rate of transpiration and hence the hydrological cycle. The question is, how much disturbance can occur before salts stored in the soil profile are mobilized? The following are three possible scenarios.

Selective logging: Field evidence suggests that when a forest is selectively logged (polycyclic logging) and allowed to regenerate immediately, the impact on the hydrological cycle will be short-lived. In selective logging, only a few trees per hectare are generally removed. Smaller-size classes normally remain in the sub-canopy layer, and grow to fill the canopy gap, utilizing the soil resources that have become available (including water).

Clear felling: The impact of clear felling (monocyclic logging) is less certain, as it depends on the extent of the canopy gap created. Small felling areas of only 1 or 2 ha that are quickly filled by newly regenerated and fast-growing young trees are unlikely to cause any stored salt to be mobilized. In fact, the larger overall leaf area may make the evapotranspiration rate greater in these patches of young regrowth than in the original, undisturbed forest. Larger felling areas may be more problematic, although rapid regrowth is still likely to minimize any potential salinity problems.

Forest clearing and replacement by other vegetative cover: When extensive, this type of disturbance creates longer-lasting impacts on hydrological cycles and is a common cause of dryland salinity. Where forests are cleared and replaced by crops or pastures, there is usually a change from deep-rooted to shallow-rooted plants. In the case of crops there may also be changes in the duration of plant growth at the site and the amount of rainfall intercepted by plant leaves. This reduces the rate of evapotranspiration and increases the amount of water percolating down through the soil profile and recharging the groundwater. Examples of this process in a temperate and a tropical region are given in Case studies 6 and 7.

Consequences of changed hydrological cycle

These changes in the hydrological cycle cause groundwater levels to rise. In some cases, the saline groundwater reaches the surface, directly increasing the salinity of streams. This usually occurs in lower slope positions and may be some distance from where the forest was cleared. Increased water percolation can also increase

CASE STUDY 6

Deforestation and salinity in Western Australia

The southwestern part of Western Australia has a Mediterranean climate, with wet winters and long dry summers. Away from the coast, much of this region has annual rainfall of less than 800 mm. Large areas of the southwest have become affected by salinization following forest clearing and replacement by agriculture. Most of this salt originated in rainfall. Prior to clearing, evapotranspiration used much of the precipitation, but deforestation has allowed groundwater recharge to increase and water tables to rise. Deforestation has been extensive and little forest remains in many of the most productive agricultural areas. The problem first attracted attention in the 1920s, but land clearing continued until the 1980s before it became too large to ignore.

Apart from the proportion of the catchment that is deforested, factors affecting the degree of salinization are annual rainfall, amount of salt storage in the soil profile, groundwater hydrology, and clearing history. Current forecasts are that salinity will eventually affect more than 7 percent of the region's agricultural area. In addition, as much as 50 percent of the divertable water resources are no longer potable or are of marginal quality. Responses to this problem are being tested, including reforestation with various woody plants, and engineering solutions such as groundwater pumping and drainage to remove saline groundwater. Reforestation options include growing *Eucalyptus globulus* on short rotations to increase evapotranspiration. The timber can be used for pulpwood, thereby returning cash to landowners. This approach is not suitable in all cases (e.g. in lower-rainfall areas), and a variety of approaches are usually needed. In the meantime, groundwater levels in still-forested catchments are currently declining during an extended period of below-average rainfall.

Source: Ghassemi, Jakeman and Nix, 1995.

CASE STUDY 7

Deforestation and salinity in northeastern Thailand

Northeastern Thailand has rainfall of more than 1 400 mm, but there is a long dry season between October and April. Salinity is a major problem, affecting more than 2.9 million ha, or 17 percent of the total area. Much of this originates from the rock salt that underlies the region; a high proportion of wells in the plains yield salty water. Salinity is not a new problem, but it has been accentuated in recent years by rapid forest clearing. The region's forest cover declined from 42 percent in 1961 to only 13 percent in 1985. Most of the cleared land has been used for cropping shallow-rooted plants, and there is no doubt that the replacement of forests by crops has caused increases in the recharge of aquifers and in saline seepages on lower slopes and valley floors. The water table has risen by 3 to 8 m in some places; salt has also originated from the weathering of underlying sediments and been transported through shallow interflow to low-lying areas.

Current treatment programmes include reforestation in recharge areas to lower the water table and reduce pressure in the artesian aquifers. Reforestation is also being tried in the discharge areas lower in the valleys, but it can be difficult to render reforestation acceptable to poor farmers with limited areas of land for farming. Extensive reforestation may be possible only where there are large areas of vacant public land. Some form of agroforestry will be needed in other areas.

Source: Ghassemi, Jakeman and Nix, 1995.

the pressure in confined or unconfined aquifers, causing upward leakage of saline water from these. The saline water eventually reaches the soil surface and affects land salinization (Ghassemi, Jakeman and Nix, 1995).

The rate at which these changes occur depends on circumstances. Evidence from small experimental catchment studies in Western Australia shows that groundwater usually begins to rise within a year or so of forest clearing. However, it may be longer before the negative impacts of extensive forest clearing are evident at the larger landscape level. This depends on the depth of the original water table and the extent of clearing.

These changes render soils less suited to new (non-forest) land uses, such as crop production, and reduce the quality of the water draining from the watersheds to downstream users. In both cases, the impacts of deforestation may be evident at some distance (downslope or downstream) from the deforested area.

Reforestation to overcome salinization

There is considerable scope for reducing the spread of salinity and increasing the productivity of salt-affected soils through some form of reforestation or agroforestry to restore the hydrological cycle and increase evapotranspiration.

However, several issues must be resolved before this can occur. First it is necessary to identify where in the watershed any reforestation should take place (Farrington and Salama, 1996; Stirzaker, Cook and Knight, 1999). Experience suggests that it is often better to reforest non-saline recharge areas where rainfall enters the soil, and to increase evapotranspiration there, rather than attempting to reforest highly saline areas in valley floors. These often need more tolerant species and special treatments, such as mounding to favour establishment.

Another issue is which species to plant. The best species will have high water usage, be tolerant to the site conditions (e.g. amount of rainfall) and have sufficient commercial value that landowners can afford to plant it. Ghassemi, Jakeman and Nix (1995) list species that have been used in various locations around the world. A third issue is how much reforestation will be needed in a salinized watershed to restore enough of the hydrological cycle to solve the problem. Current evidence suggests that recharge limitation and lowered groundwater levels are most quickly achieved by planting large blocks of trees (covering more than 50 percent of the watershed), rather than establishing scattered isolated trees or planting narrow belts (Ghassemi, Jakeman and Nix, 1995). In agroforestry systems, the tree component therefore needs to be substantial to be effective. There appears to be a strong linear relationship between tree leaf cover (forest cover multiplied by crown density) and dropping water tables.

One reason why reforestation is less widely adopted than might be expected is that many landowners find its opportunity cost too high. Resolving the problem requires landowners to reforest (i.e. cease agricultural production) on part of their apparently non-saline land in order to address salinity in another part, or even on some other owner's land. In the short term, it may seem more rational for landowners not to reforest, especially when the beneficiaries of reforestation are distant and contribute nothing to the costs.

Guidelines

Deforestation should be avoided in forested areas with saline subsoils or groundwater. Any change to the hydrological cycle in such landscapes may mobilize stored salts. For salinized areas, reforestation with fast-growing trees can help reduce groundwater levels and thus reduce salinization. This should be done in groundwater recharge areas (usually in upper slope positions), although tree planting of salt-tolerant species in lower parts of the landscape may also be possible when salinization is not too severe.

FORESTS ON SITES WITH HIGH LANDSLIP RISK

With their undergrowth, leaf litter, forest debris and uncompacted soils, forests are almost without question the best and safest land cover for minimizing surface erosion of all kinds (Wiersum, 1985; Kellman, 1969). On sloping lands within any climatic regime, the earlier FAO land suitability classes for lands that might safely be cleared and used for crops or grazing were predicated on this function of minimizing erosion under various uses (FAO, 1976). With their stronger, deeper

Forest cover stabilizes fragile slopes disturbed by an earthquake in the Hindu Kush Himalayan region (Pakistan)

root systems, forests are also the best land cover for minimizing the hazard of shallow landslips (Rapp, 1997; O'Loughlin, 1974; Ziemer, 1981). Such landslips are often catastrophic, and this section presents the case for keeping slip-prone lands in forest cover. Short-duration, intense storm events generally create shallow landslips, while prolonged, low-intensity events produce the deeper, larger landslides for which forests may be ineffectual – witness the estimated 20 000 landslips and landslides that occurred in a single day in the Sikkim-Darjeeling area in a 1968 event (Ives, 1970).

What was possibly, in terms of human life, the Western Hemisphere's worst natural disaster in 500 years occurred on 16 and 17 December 1999. (The December 2004 tsunami disaster in South and Southeast Asia dwarfs this.) Hundreds of landslips and landslides killed 50 000 of the 500 000 people living on the coastal slopes and at the base of Venezuela's Cordillera de la Costa range (Myers, 2000); 40 000 homes were destroyed, and most roads. The previous year, Hurricane Mitch had triggered thousands of landslips and landslides in Central America – the worst natural disaster to strike the region in 200 years. Shallow landslips, deep landslides and flooding affected 6.4 million people, killing 9 976 and leaving 11 140 unaccounted for, 13 143 injured and 500 000 homeless (International Federation of the Red Cross, 2000).

A large number of internationally noteworthy mass erosion events occurred at the end of the 1980s: southern Thailand in 1988 after torrential rainfall; Cyclone Bola in New Zealand in the same year; Puerto Rico during Hurricane Hugo in 1989; and the Philippines in 1990. Most damage was due to slope failures in hundreds or thousands of shallow landslips, with some large landslides. It is interesting to note that devastation in southern Thailand and the Philippines was blamed on logging, although most of the failures were on land cleared for crops (Rao, 1988; Hamilton, 1992). It was the same in the 1999 Venezuelan catastrophe – almost all the landslips were on cleared land. Slope failures and high damage occur periodically, generating much discussion and research on the role of forest cover in reducing the incidence or severity of these mass movements. Case study 8 gives a post-disaster analysis of the true causes of southern Thailand's floods in 1988.

It is difficult to distinguish human-caused slope failures from natural ones (Bruijnzeel and Bremmer, 1989). There is a common lay misperception that slope failures do not occur in undisturbed forest lands, and popular confusion about the types of mass movements that can be influenced by vegetation. The following classification was developed from studies in the United Republic of Tanzania and seems to be applicable in many locations (Rapp, Berry and Temple, 1972):

- Class 1: numerous, small, 1 to 2 m-deep, 5 to 20 m-wide earthslides and mudflows, triggered by heavy rainstorms, occurring at intervals of about ten to 20 years.
- Class 2: occasional, large earthslides, cutting many metres in depth into the weathered bedrock, below the anchoring effect of tree roots, and occurring at much longer intervals.

Much scientific attention has focused on the role of forest cover in reducing the incidence and severity of shallow landslips (Class 1). It is accepted that these can both be reduced or even eliminated by good forest cover. Large, deep-seated mass movements (Class 2) seem to be beyond the control of vegetation, but most research has been done in temperate countries, especially Japan (protection forests), New Zealand (pastureland and logging), Taiwan Province of China (protection forests) and the western United States (associated with logging).

In a study of land degradation in the Uluguru Mountains of the United Republic of Tanzania, Rapp (1997) examined numerous, small (1 to 2 m-deep, 5 to 20 m-wide) earthslides and mudflows in a 75 km^2 area, which occurred after more than 100 mm of rain had fallen in less than three hours, He found that of 840 landslides only three started on slopes under forest cover – the remainder were in cultivated or grazed areas on similarly steep slopes. The importance of tree roots in providing shear resistance in slip-prone soils has been demonstrated in studies by O'Loughlin (1974) and Ziemer (1981). This work and its subsequent confirmation provide the basis for guidelines in this area.

All very steep lands benefit from being in forest cover, especially those in seismically active areas; pressure to clear land occurs where slopes are intermediate but still slip-prone – and this is where the red flag needs to be raised. Prudent land use could avoid many of the catastrophic results that were seen in Thailand in the 1988 storm, when former forest land that had been cleared to establish rubber plantations failed in thousands of landslips. The subsequent ban on logging did

CASE STUDY 8

Floods and landslips in southern Thailand

In November 1988, following an unprecedented downpour and flash floods, mud slides descended from the hills surrounding Nakhon Si Thammarat province in southern Thailand. Hundreds of landslides littered the hill slopes almost overnight, killing 200 people, burying 300 houses under sand and knocking down hundreds of fruit trees.

Floods uprooted trees along the path of their flow, and debris caused blockages and dammed up water in some locations. As the rainfall continued, these blockades broke up and the released waters coalesced and surged forward, carrying sand, uprooted trees and other debris. This unprecedented flow scoured the streambanks, flooded houses and fields and changed the course of rivers. The people affected included small farmers cultivating rubber, fruit growers and the landless.

This area was originally covered by a typical tropical, moist forest with a complex of vegetation consisting of the predominant trees, the dominant canopy, other layers of trees, shrubs, climbers and undergrowth. Some areas were logged until some years ago, when they were cleared and converted into rubber plantations, which were established even on steep slopes. In most cases, there was no cover crop and very little vegetation to protect the ground – just the rubber trees, many of which were only recently planted.

Several news reports attributed the flood damage to logging operations. The outcry resulted in a government decree banning logging. A less sensational but more realistic explanation for the flood damage is the combination of several factors that together proved to be disastrous:

- The slopes where the slides occurred were steep, often with angles of more than 25º.
- The basic geological underpinning for the topsoil was deeply weathered and extremely fractured granite formations, which are easily eroded.
- The soil blanket was not sufficiently anchored by the young rubber trees’ roots – the most common vegetation in the area of the slides.
- The vegetation was sparse, with no vegetative cover between the rows of rubber trees.
- Records show that from 20 to 23 November 1988, hill areas of the province received 1 022 mm of rainfall, which saturated the soil.
- The intense rainfall could not be absorbed, particularly on the steep upper reaches, and the resulting sheet of water flowed downwards.
- Runoff and slope failures created landslides on the generally steep hill slopes.

The numerous scars and deep gullies that today mark the landscape of Nakhon Si Thammarat province present an unrivalled opportunity to demonstrate how landslips can be recovered and brought into productive use. In response to the Government of Thailand’s request, FAO has approved a Technical Cooperation Programme project that will work with foresters and agronomists in Thailand to attempt rehabilitation of some landslips.

Source: Adapted from Rao, 1988.

not apply to land clearing (Hamilton, 1991). In several regions of New Zealand that were largely cleared of native forest for grazing in the 1870s, slip-prone land has experienced serious erosion from major storm events. The erosion rate measured in the Wairarapa region was 2.8 percent per decade in the period 1938 to 1977, and resulted in 56 percent eroded land in hill-slope scars in 1984 (Trustrum, Thomas and Douglas, 1984). This material appears as excessive sedimentation in watercourses.

In September 2004, Hurricane Jeanne passed over the Dominican Republic, Puerto Rico and Haiti, resulting in landslips and flooding. Aide and Grau (2005) report that although these countries received similar levels of precipitation, there were seven flood-related deaths in Puerto Rico, 24 in the Dominican Republic, and more than 3 000 in Haiti. There are complicating factors, but these authors attribute the diverse landslip and flood damage to differences in vegetative cover, with forested areas and abandoned, reverting shrublands being less damaged by erosive agents.

The challenge is to identify these red flag areas in advance and to maintain them in forest or woodland. The general factors that influence mass wasting are known; presence of water, type of rock or mineral and state of weathering, number and density of natural fracture planes, and structure and inclination of slope. Practical field guides are needed for identifying slip-prone areas where forest retention is desirable. Megahan and King's 1985 guidelines are particularly good for this. They point out that in highly erosion-prone areas, the major hazards are found on slopes greater than 45 to 55 percent, with maximum frequency of about 70 percent; concave slopes, which concentrate water; and soils that are low in cohesion. Shallow soils over bedrock or with pronounced discontinuity of texture or structure may become saturated, buoyant and slip-prone. Megahan and King discuss rainfall erosivity, and the difficulty of obtaining good data in the tropics.

Based on reported research worldwide, Blaschke, Trustrum and Hicks (2000) produced a map showing the approximate extent of areas where mass-movement erosion affects land productivity, as well as a table showing land use, rainfall, land form, area affected, duration of event and soil loss rate, by country or region. Good data are few and scattered. Studies such as Humphreys and Brookfield (1991) in Papua New Guinea report that shallow slope failures are by far the most common erosion forms in cultivated steep lands. The result is not only reduced productivity, but also sediment loads in watercourses, which impair water quality, have an impact on aquatic life and promote flooding.

Well-managed agroforestry or sylvopastoral systems with high percentages of deep-rooted trees would give more safety than crop or pasture alone, because of root shear strength. No research indicates the necessary tree density on slip-prone sites, but the more the trees, the greater the safety margin.

Roads associated with logging or other uses are often a triggering agent, because the cut and fill on side slopes further destabilizes these troublesome sites.

In summary, trees are the safest land cover where high-intensity or prolonged rainfall is characteristic of slopes of about 70 percent – but also as low as 45 percent

– and that have spoon-shaped concavity or shallow, planar surfaces. When there are no tree roots, there is high risk of slope failures. Clearing is inadvisable and should only be sanctioned if there is the certainty of:

- quick re-establishment of tree crops such as rubber or tree plantations (although there is a long vulnerable period until new tree roots become effective);
- immediate terracing for crop production plus trees in an agroforesty system, assurance of adequate terrace maintenance and the ability to repair minor landslip damage quickly; or
- a sylvopastoral system with abundant deep-rooted trees and conservative grazing management.

Forest harvesting reduces the stabilizing ability of roots when cut trees die, and there is a vulnerable period of several years before new roots are effective. If a serious storm event occurs during this period, landslips may ensue. Logging roads represent a further destabilizing force on these unstable sites.

Established in 2002 with its headquarters in Kyoto, Japan, the International Consortium on Landslides (ICL) promotes landslide research for the benefit of society and the environment. The interface between forests and water and the role of forests in mitigating landslide risks and hazards are important components in ICL's activities.

Guidelines

Slip-prone areas are probably the most serious form of erosion that can be minimized by sound land-use policies and management. Tree roots impart a margin of safety by improving soil shear resistance. To reduce the occurrence and severity of shallow landslips, slip-prone areas need to be kept in forest cover, woodland or agroforestry/sylvopastoral systems with fairly dense tree cover. Such areas can be identified in advance of land-use decisions, based on erosivity, slope, slope shape, and soil shallowness and cohesiveness. Roads are a particular problem.

RIPARIAN BUFFER ZONES

Vegetated strips along stream/riverbanks and lake/pond shores have important water-protection functions. Forested buffer zones fulfil these functions particularly well because of their deep, strong root systems. Unlogged, undisturbed forests are best, but logging with good conservation management does not seem to impair these natural water-quality protection services. Riparian buffer zones form the vital link between watershed land uses and the stream system or standing water body.

Forest riparian buffers can stabilize the banks of flowing water bodies, minimizing erosion and thus reducing the sediment entering the water. The forest floor and soil can also trap sediment moving towards the flowing water from upslope areas outside the buffer. Forests with good understorey structure and density, along smaller streambanks and during high flows may disperse flood crests, reduce water velocity and thus reduce erosion. Harmful nutrients

Forest riparian buffers stabilize river banks, reduce erosion and filter lateral inflow from sediments and pollutants (Sierra Leone)

moving downslope in surface runoff or subsurface flow, such as those from excessive fertilizer application or pesticides, can be trapped, thus preventing this type of water pollution, which is often harmful to both people and aquatic life (O'Laughlin and Belt, 1995). This trapping function is also performed by lake and pond buffer zones. It is thought that tree and other plant uptake, microbial activity and soil immobilization play roles in this process of reducing pollutants. Tree mycorrhizal fungi absorb nutrients (especially nitrogen and phosphates) and keep them out of adjacent water. Streams with forested banks have greater populations of aquatic insects, which process more organic matter, nitrogen and phosphorus than they do in streams with denuded banks, resulting in higher water quality (Margolis, 2004).

Tree or branch fall in forested riparian belts provides large woody debris that increases stream habitat variety for fish and other aquatic organisms. A host of other benefits accrue, such as shade to influence water temperature, leaf and fruit debris for the fishery food chain, habitats for avian and terrestrial wildlife (cover with access to water and corridors for movement) and general biodiversity conservation.

These benefits and their function in conserving water quality mean that these zones should have legally protected or protective status (Hamilton, 1997). Many countries already have either guidelines or legislation on buffer zones of varying widths, where no or only restricted use of land or forests is permitted. Gregory *et al.* (1991) reviewed recent thinking on the ecosystem services provided. Most official forest harvesting guidelines include the maintenance of no-logging strips of at least 20 m from each bank of the stream (greater as the slope increases), such as those for Malaysia (Mok, 1986) or tropical Queensland, Australia (Cassells and Bonell, 1986). For national forests in the United States, the Forest Ecosystem Management Assessment Team (FEMAT) considered that sediment-bearing overland flow from logging roads could be handled by 65-m buffers (FEMAT, 1993). Many states in the United States have regulatory controls to reduce non-point source pollution (mainly sediment) through best management practices that focus on uncut riparian buffer zones. In 1996, the United States Natural Resources Conservation Service established the National Conservation Buffer Initiative, which now involves more than 100 conservation agencies, agribusinesses and agricultural and environmental organizations and promotes the use of conservation buffers (Randolph, 2004).

Box 5 provides an example of a logging code of practice from Papua New Guinea.

BOX 5

Papua New Guinea Logging Code[a]

This code requires that buffer zones be identified, demarcated and observed by stakeholders, particularly the timber industry, to ensure that forest harvesting is conducted in ways that conserve water resources:

- For lakes, lagoons, coastal shoreline and swamps, the minimum buffer zone is 100 m, extending from the water body, high tide mark or edge of mangroves.
- The buffer zone for large, permanent rivers, considered Class 1, is 50 m on each side of the watercourse.
- The buffer zone for small, permanent creeks or streams, considered Class 2, is 10 m on each side of the watercourse.
- The buffer zone for a stream (permanent or non-permanent) of any width used by the community is 50 m on each side of the watercourse. Buffer zones for culturally significant water sources require careful consideration, including the exclusion of logging to protect the catchment area of the water source.
- Log ponds and wharves do not require buffer zones, but maximum shoreline clearance is 100 m.

All buffer zones are marked in the field before logging activities are granted approval. The buffer and water crossing points for logging roads are also shown on the plans approved in the field by forestry officers.

[a] 97 percent of Papua New Guinea's land is traditionally owned. Sustainable forest harvesting requires forest management agreements between the owners and the State. Under these agreements, which include riparian buffer-zone guidelines, forest areas with slopes of more than 30 percent are considered water catchment areas and are not logged.

Source: Kaip, 2002.

How wide should a forest buffer be? In part, this depends on the goals of the landowner or regulator. The recommended width for riparian buffer strips is constantly being re-evaluated scientifically, and is generally increasing as more is learned about their influence on water quality: from 20 to 30 m (Bosch and Hewlett, 1982), through a minimum of 25 m (Megahan and Schweithelm, 1983) and up to 50 m (O'Laughlin and Belt, 1995). Width must also take the slope and proposed use into account, as indicated in the Papua New Guinea code and the FEMAT report. Given the many other values of riparian buffers, it is prudent to err on the side of excess width, despite some short-term economic loss from foregoing forest products (but not usually NWFPs).

For the other wooded land category, including most agroforestry systems, it is reported that a 25 m-wide buffer of tree, shrub, herb and grass vegetation can remove 80 to 90 percent of the nitrogen, 85 to 95 percent of the sediment and more than 90 percent of the herbicides running off crop fields (Schultz, 1996). Trees are especially important in this mix, because their rhizosphere usually supports an abundance of microorganisms that can degrade herbicides, insecticides and some other toxic compounds (Haselwander and Bowen, 1996). For naturally meandering rivers and streams, the buffer needs to follow the channel. Buffers will not constrain major meanders, so the initial buffer width on such watercourses may need to be substantially wider than that indicated. Recent studies in Canada have shown that phosphorus and potassium from fertilizer applied as far as 2 to 4 km away can have an impact on wetlands that are not adequately buffered (Houlahan and Findlay, 2004), leading to recommendations for much wider buffer zones in non-forested landscapes.

Guidelines

Establishing vegetation (a combination of trees, shrubs and grasses) along river courses is one of the least expensive and most effective methods for protecting water quality, particularly from sediment and nutrient influx. Forested riparian buffer zones that shield perennial watercourses and other water bodies from quality impairment should be identified and officially designated for special treatment in land use. The policy should be to maintain as much of the zone as possible intact, so that it may fulfil its sediment- and pollution-minimizing roles. This will often entail a total ban on clearing and wood harvesting. NWFPs may usually be removed safely. The buffer should be at least 30 m wide, and wider for steep slopes prone to surface erosion or landslips, or where agricultural use predominates. Buffer zones also serve many other purposes, involving good aquatic and terrestrial wildlife habitats, biodiversity, aesthetic values and recreation. For the best water quality, it is advisable to restore degraded or missing riparian buffers to forest.

MUNICIPAL WATER SUPPLY FORESTS

Lack of clean drinking-water and adequate sanitation reduces the quality of life for an estimated 1 billion city dwellers around the world, along with many people


C. CARLINO

Around 85 percent of San Francisco's drinking-water comes from the Hetch Hetchy watershed in Yosemite National Park (United States of America)

living in rural areas, principally in Africa, Asia and Latin America. Every year, 2.2 million deaths – 4 percent of all global fatalities – are attributed to diseases contracted as a result of the lack of pure drinking-water (United Nations Human Settlements Programme, 2003). Supplying clean water consistently is one of the most urgent aims in development and poverty-reduction strategies. Water purification systems are capital-intensive and expensive to maintain, however, making potable water a high-value product beyond the reach of many local authorities and individual consumers. The rich buy bottled water and the poor get sick.

The need to provide clean water on a tight budget is forcing many municipalities to explore innovative approaches to maintaining supplies of pure drinking-water. Increasingly, this includes examining the potential role of forested catchments in supplying urban drinking-water.

How forests can help

The relationship between forests and water is complex and subject to myth and misinterpretation. Contrary to much popular opinion, most forests do not increase water flow in catchments. In fact the reverse is true, as a vigorous young forest usually returns more water to the atmosphere via evapotranspiration than grassland or scrub does, thus reducing the flow reaching streams and rivers (Calder, 2000). Reducing the canopy closure through careful harvesting can yield more water, but some reduction in water quality may result (Hamilton and

King, 1983; Bruijnzeel, 1990) (see Chapter 2). An important exception is tropical montane cloud forest, where trees and their epiphytes can "harvest" horizontally moving fog, which is an addition to vertical precipitation (Hamilton, Juvik and Scatena, 1994).

There is also little evidence that forests can prevent catastrophic flooding, although they do cause some beneficial reduction in peak flow and delayed peaks at the local level (Hamilton and King, 1983). In spite of this, several governments have introduced logging bans after extreme flooding events on the main stems of large river systems.

Although most forests provide less total quantity of water, they almost always increase water *quality*, compared with most other land uses (Chapter 3). The water draining from natural forests is often exceptionally pure, thus radically reducing the costs of purification for domestic use. To a large extent, this is because many of the activities that create pollution are absent from natural forests. Leaf litter, ground vegetation, shrub layers and forest floor debris keep surface erosion (and therefore sediment) to a minimum, and the dense humus layer in forests may also play some role in filtering water.

The positive relationship between forests and water quality is already being exploited to help supply clean drinking-water to millions of people around the world. A survey of the world's 105 largest cities, carried out for the World Wide Fund for Nature (WWF) and the World Bank in 2003, found that one-third draw a substantial amount of their drinking-water from protected forest catchments (Dudley and Stolton, 2003). Countless other smaller towns and cities do the same, and industries that need clean water are often deliberately located in the catchment areas of natural forests.

What kind of protected forests?

Many of the forests supplying drinking-water to the cities in the WWF/World Bank research are legally established protected areas recognized by the International Union for the Conservation of Nature (IUCN) and the Convention on Biological Diversity: national parks, wildlife reserves and wilderness areas. IUCN divides protected areas into six categories, depending on management objectives and ranging from strictly protected reserves, where visitation is tightly controlled, to cultural landscapes, where protection takes place alongside settled communities. In many cases, legal protection was originally given for aesthetic reasons or to conserve natural features or biodiversity, and the water supply benefits were incidental or recognized only later. Other forests are managed under multiple-use plans or for timber, but with emphasis on protecting their water services. Some forests remain in existence largely by accident, or because of official or unofficial payments by water users.

Some examples

The following examples show a variety of ways in which forests are (or are not) protecting municipal water supplies.

Quito, Ecuador: Some 80 percent of the 1.5 million population receives drinking-water from the Antisana (120 000 ha) and Cayambe-Coca (403 103 ha) ecological reserves. Local water companies help pay for management of these reserves in return for clean water. The municipal government and a local non-governmental organization (NGO) are developing management plans to protect the watersheds, including stricter protection of the upper watershed, erosion prevention, and bank and slope stabilization (Echeverría, 2001).

São Paulo, Brazil: Drinking-water for the city's 18 million inhabitants comes from forests in six protected areas. The most important of these is Cantareira State Park (IUCN Category II, 7 900 ha), which supplies half the metropolitan area's water and is located in the remnants of the highly endangered Atlantic forest (Dudley and Stolton, 2003).

Singapore: Half the island's water comes from Bukit Timah National Park (which is the remaining 3 percent of the original forest cover) and the central catchment areas, which have been restored as natural forest (both IUCN Category IV, totalling 2 796 ha). The forests were originally protected to maintain water, but are now also recognized as extremely important repositories of biodiversity (Bugna, 2002).

Tokyo, Japan: The city draws almost all its water from two landscape protected areas: Nikko National Park (IUCN Category V, 140 698 ha) and Chichibu-Tama National Park (Titibu-Tama) (Category V, 121 600 ha). In these areas, conservation and recreation are balanced in the forest management carried out by the Bureau of Waterworks of the Tokyo Metropolitan Government, which has the specific aim of maintaining water quality (Dudley and Stolton, 2003).

Nairobi, Kenya: Much of the city's water comes from rivers originating in the Aberdares (including Aberdares National Park, IUCN Category II, 76 619 ha) and the Mount Kenya National Park water catchment (Category II, 71 759 ha). Unfortunately, despite nominal protection, illegal encroachment and logging are continuing to degrade the area, with a detrimental impact on the city's water supply. It is estimated that all forests of the Mount Kenya protected area have been logged at least once (Nakagawa *et al.*, 1994).

New York City, United States (Case study 12 in Chapter 6): Rather than funding construction of a new water purification plant through taxes, New Yorkers voted to subsidize forest protection as a cheaper and more acceptable option for maintaining clean water supplies. Management applies a mosaic of different approaches, including complete protection, easements for landowners and low-impact, selective logging on some lands. Catskill State Park (IUCN Category V, 99 788 ha) protects much of the Catskill/Delaware and Croton watersheds, the city's main sources (Perrot-Maître and Davis, 2001).

Stockholm, Sweden: Lake Mälaren and Lake Bornsjön supply Stockholm's drinking-water. The water company, Stockholm Vatten, controls most of the 5 543-ha watershed of Lake Bornsjön, of which 2 323 ha, or about 40 percent, is productive forest certified by the Forest Stewardship Council. Although timber is extracted and sold, management focuses primarily on protecting water quality, and areas are designated for conservation and restoration (Soil Association, 1998).

Potential for economic benefits

In all the cases outlined, forests are serving multiple functions. Soil and water protection also generally delivers biodiversity conservation, and vice versa. In cases such as New York and Stockholm (and the situation is similar in Beijing), a mosaic of different uses supplies good-quality drinking-water while supporting commercial activities in protected areas, including tourism. Clearly, the added value that clean water provides can help support land management activities that would otherwise be uneconomic, including those in many protected areas.

A team of researchers from Argentina, the Netherlands and the United States has put an average price tag of US$33 trillion a year on fundamental ecosystem services, nearly twice the value of the global gross domestic product (GDP) of US$18 trillion, with water regulation and supply estimated to be worth US$2.3 trillion (Costanza *et al.*, 1997). Experience with payment for environmental services (PES) schemes has been increasing as in the case of Quito, mentioned earlier. PES refers to any system for ensuring that those who benefit from environmental services, such as clean water and carbon sequestration, pay those who make economic or social sacrifices to maintain natural ecosystems. PES works best where there are a few recipients (for instance, a water company, a factory or a municipal authority) and a clearly identified group of providers (such as land right holders who maintain high-quality forest) (Pagiola, Bishop and Landell-Mills, 2002). Many Latin American countries have developed systems. For instance, small-scale hydropower users in Costa Rica are paying landowners to maintain forests in their catchments. This topic is developed in Chapter 6.

Lack of awareness of the benefits of forests

A few successful case studies do not add up to the general recognition that protected or carefully managed forests can help pay for themselves by supplying clean water. PES schemes have a mixed history and are not always successful. The WWF/World Bank study found that many water companies and city authorities have little understanding of the pros and cons of using forests to protect water. Some water providers have completely unrealistic ideas about the scale of benefits that accrue from healthy forests, while others do not even recognize that there would be benefits. Decisions are often based on hearsay or partial information. Nevertheless, there are exceptions, where forest management strategies have been drawn up using the best available information. These include the water companies of New York City and Melbourne, Australia.

Guidelines

Although forests are now increasingly viewed as water suppliers, much remains to be learned and applied if these benefits are to be maximized. Various interest groups, including water companies, forest owners, protected area managers and anyone involved in PES schemes, need technical guidance that explains the issues and ensures the best possible land-use choices. This should be accompanied by good educational and outreach materials on the benefits, highlighting the links among forest protection, good management and drinking-water. Well-thought-out financial and policy incentives are needed (and, where necessary, perverse incentives should be removed) to encourage good management for good water.

VERNAL POOLS

There is increasing recognition of the importance of vernal pools in forested areas for their role in restoring and conserving amphibian biodiversity. A forest or woodland vernal pool is a relatively small, shallow depression containing an isolated body of water that collects annually in a wooded area. The hydroperiod lasts at least through the spring season before drying up (Thompson and Sorenson, 2000). The pool has no inlet or outlet that would permit the entry of fish. These ephemeral wetlands are generally less than 0.2 ha in size and less than 1 m in depth. These attributes prevent fish life, and thus fish predation on amphibians' eggs and larvae – the two stages at which amphibians are most vulnerable.

The amphibian life found in vernal pool habitats consists of salamanders, frogs and toads. Many amphibians are in threatened or endangered status, and globally there numbers have declined in the last decade. This process of decline is characterizing amphibian populations everywhere, and not just in vernal pool. Of the 5 743 known species, 1 856 (nearly one-third) are in danger of extinction (Stolzenburg, 2005). Suggested causes include habitat loss, pesticides and other water pollutants, acid rain and other air pollutants, increased ultraviolet radiation, global warming, fungal and other pathogens, and combinations of several of these. For example, global warming seems to be implicated in the disappearance of several frog and toad species, including the endemic golden toad, from Costa Rica's forests (Pounds, Fogden and Campbell, 1999). Amphibians are believed to be one of the most sensitive indicators of ecosystem and even human health, as canaries once were in mines.

Vernal pools have received relatively little study and regulation because of their ephemeral character. In addition, their small size makes them difficult to detect in aerial photos, even when taken at the peak of the wet season.

Most concern about vernal pool conservation originates in industrialized, developed countries, but even here there appear to be few nationwide regulations for their protection, unless a species is on the official endangered list. Some larger vernal pools may be classified as official wetlands and may have regulatory protection. Massachusetts in the United States has a provision for designating and

The importance of vernal pools in forested areas is increasingly recognized, especially for their role in restoring and conserving amphibian biodiversity (United States of America)

certifying vernal pools, which protects them from alteration and includes a forest buffer strip (Westing, 2003). As forests worldwide are managed increasingly for multiple goods and services, those related to water resources and biodiversity will become more important. It would therefore be appropriate for governments and forest managers to turn their attention to vernal pools.

The main management measures needed are avoidance of the pools' destruction or impairment and provision of a two-tiered buffer zone. These ephemeral pools may be difficult to identify after water levels have receded, but the cup-shaped basin, general lack of vegetation and thicker organic layer can reveal their locations. These areas need to be identified, marked and mapped in the spring. Global positioning systems are useful in mapping. Vernal pools occur more frequently and have greater carrying capacity for amphibians in deciduous broadleaved forests than in conifer forests (Westing, 2003). Based on 16 field studies compiled by Westing, a core buffer zone consisting of the flooded area plus 15 m is recommended for protecting approximately the 0.5 ha of the largest pools. Within this area there should be no cutting, skidding or road construction. Trees in the buffer provide shade and wind screen to inhibit the pool's drying out. Although a treeless vernal pool may seem ideal for the yarding of logs during dry periods, this too must be avoided. It is also desirable to have a secondary buffer of forest about 15 m wide that is only lightly harvested or modified and that protects against drying and extends the foraging habitat.

Guidelines

Best and acceptable management practices and forest certification systems should recognize these important ephemeral wetland components of forest land and should establish criteria for effective buffer zone protection.

AVALANCHE PROTECTION FORESTS

Avalanche protection represents an existential challenge for the inhabitants of high mountain regions around the world (Box 6). It is one of the many and considerable risks of living and carrying out activities in these areas. During the period 1953 to 1988, three leading newspapers (the *New York Times*, the *Toronto Globe and Mail* and *The Times* of London) reported 18 major avalanches, each of which resulted in at least ten deaths, 50 injuries, and more than US$1 million of damage and emergency assistance from outside the damage zone (Hewitt, 1997). The avalanches were widely distributed: seven in Central and South America six in Europe, two in East Asia, two in Southwest and South Asia, and one in Southeast Asia. Many other occurrences of great local impact, which were not covered by these newspapers, involved small villages, a few skiers or climbers and rural mountain roads or railways. In spite of this, avalanches received little attention in the International Decade for Natural Disaster Reduction (1990 to 2000), and forests' significant role in providing some defence against them was largely ignored. Mountain hazard mapping should therefore include mass snow movements, which are site-specific, and any protective forests designated for special treatment.

A forest belt protects a hydropower plant and transalpine railway from potential avalanches (Switzerland)

T. HOFER

BOX 6

International experiences: the avalanche winter of 1999 in the European Alpine region

The winter of 1999 claimed a total of 70 lives in Austria, France, Italy and Switzerland, mainly in residential areas and to a lesser extent on roads. The mountain village of Evolène in the Swiss canton of Valais was particularly badly hit, with the loss of 12 lives; there were another 12 victims in Chamonix in the Savoy Alps of France, and a total of 38 lives were lost in the villages of Ischgl/Valzur and Galtür in the Paznau valley of the Austrian Tyrol. One life was lost in Morgex in Italy's Aosta valley. In Switzerland alone, approximately 1 000 destructive avalanches occurred (Nothiger and Elsasser, 2004).

Problems involving the clearing of snow and/or the risk of avalanche led to temporary closures of the international transit axes that cross the Alps, such as the Gotthard motorway and railway, the Tauern motorway and railway, the Arlberg road tunnel and the San Bernardino and Great St. Bernhard passes.

In the hundreds of areas within the Alpine region that were affected by avalanches, many locations and entire valleys were completely isolated for days. In some places, local residents and tourists had to be evacuated. This caused some tourists, who were not directly at risk from avalanches but were marooned in their holiday destinations, to perceive the mountain landscape – previously viewed as a leisure paradise – as life-threatening. Some tourists could not cope with the situation, which lasted for a considerable time. They wanted to be rescued and, in many cases, the few available helicopters represented their only hope of escape.

In addition to the lives lost, almost 1 billion Swiss francs of damage was caused to residential and industrial buildings, Alpine barns and stables, avalanche defence structures, energy cables, communications and transport infrastructure (including cable railways) and mountain forests. Indirect economic losses arising from the disruption of transport and supplies were estimated at 500 million Swiss francs – half the cost of the material damage.

The emergency was exacerbated by the presence of hundreds of thousands of tourists holidaying in the Alps in February. This led to spontaneous solidarity between marooned tourists and local residents, who became increasingly dependent on each other as the emergency progressed.

Source: Gremminger, 2005.

Formation of avalanches

A snow-covered slope is composed of layers of snow with recognizable boundaries. Depending on the properties of the boundary layers, creeping movements can occur. Sliding movements can also occur, depending on the properties of the soil surface and snow cover. In the event of overload, these can lead to sliding of the entire snow cover. Such movements depend on the following site factors:

- slope gradient;
- thickness of the snow;
- type of snow;
- properties of the boundary layers.

Slab avalanches are associated with:

- slopes of gradients in excess of 58 percent;
- weak layers and/or sliding areas;
- snow cover with homogeneous layers;
- bonded (cohesive) snow.

Loose-snow avalanches mainly arise on:

- slopes with gradients of 85 to 170 percent;
- weakly bonded snow.

Forest avalanches are those whose release zone is located in a forest. They occur where there are large gaps in the forest, the size of which is a crucial factor in determining the scale of snow movements. In sub-alpine and high montane zones in particular, large and small gaps in forest stands are a component of near-natural forest structure, which is essential for forest regeneration. It is therefore impossible to control completely the movement of snow in forests.

Integrated avalanche risk reduction

An avalanche protection scheme should be based on a combination of complementary measures:

- avoidance of areas at risk from avalanche, by taking natural hazards into account in spatial planning (hazard registers and hazard maps are essential decision aids in this);
- biological engineering measures to prevent avalanche release, such as reforestation or afforestation, and the maintenance of protective forests;
- technical and organizational measures for early warning of avalanche activity, including avalanche forecasts and early warning of the build-up of large volumes of snow as a basis for evacuation and the closure of transport routes;
- periodic checking, maintenance and repair of existing protective structures, including those for the protection of objects and avalanche release barriers.

The ski resort of Vail, in Colorado, the United States has a well planned avoidance strategy, which includes the identification and mapping of snow avalanche hazard zones and the development and enforcement of zoning land-use regulations (Oaks and Dexter, 1987).

Protective forest

Forest also influences the formation of snow cover, and thus avalanche formation, through interception, cooler stand climates and the roughness of the soil caused by standing trees and by stems and branches on the ground.

CASE STUDY 9

Forest avalanche protection in Switzerland

Human life and activity in the Alpine region of Switzerland would not be possible if the mountains were not covered with forests, which protect more than 7 000 ha of lower-lying residential and industrial zones and numerous transport routes against natural hazards. Approximately 130 000 buildings and several hundred kilometres of rail and road links benefit. Protective forests are particularly important on slopes at risk of avalanche, in the direct watershed areas of mountain torrents and on steep slopes vulnerable to soil erosion. Some 30 percent of the approximately 700 000 ha of mountain forest provide direct protection against avalanches and rock fall.

About one-third of the Swiss Alpine region is under forest cover. At high altitudes, up to the natural tree line 2 000 m above sea level, evergreen coniferous forest provides the greatest avalanche protection in terms of area. Over the past 120 years, many slopes at risk of avalanche have been reforested. Millions of newly planted trees are now rooted on steep slopes of between 28 and 45°, which would be potential avalanche release zones without these forests. A mountain forest with no large gaps between the trees prevents the development of an even slab of snow, thus stabilizing the snow pack. Mountain forests protect against avalanche release in several hundred square kilometres of this region.

Following the extreme avalanche winters of the early 1950s, the Alpine regions of Austria, France, Germany, Italy and Switzerland have engaged in intensive avalanche protection efforts, in which maintaining effective protective forests has played an important role. Similar protection strategies were already being pursued in Austria, Bavaria, Liechtenstein and Switzerland. The devastating winter of 1950/1951 claimed 98 avalanche victims in the Swiss Alpine region and destroyed nearly 1 500 buildings. Most of these people were taken by surprise and crushed to death when their houses were submerged by snow.

Owing to the boom in winter tourism and enormous growth in the transport of people and goods across the Alps, the potential hazard zone is now far more intensively used than it was in the 1950s. Thus, with a comparable level of avalanche frequency in 1998/1999, about five times as many people were located in mountain areas at particular risk than in the winter of 1950/1951. However, the loss of life and damage caused by avalanches in that year were significantly lower than in 1950/1951. The fact that this extreme avalanche winter did not claim more lives and cause more damage to property cannot be explained by luck alone; it can be assumed that the intensification of preventive measures since the 1950s provided excellent protection, which paid off.

Source: Gremminger, 2005.

Trees significantly reduce the likelihood of avalanche release (Case study 9). On forested slopes, release is expected only on gradients of at least 70 percent, compared with 58 percent on exposed slopes or slopes with larch stands. Fewer avalanches can be expected in areas with extensive forest stands than on open areas, but if an avalanche is released in such an area it will be greater than it would have been in an area without forest.

Trees at least twice as tall as the snow depth contribute to preventing snow avalanches. Short trees completely covered with snow (e.g. Swiss mountain pine and green alder) can actually promote avalanche formation through the elastic movement of the branches. Deciduous tree species, which are bare in winter, are only effective for low snowfall levels; their effect is limited for major snowfalls. Deciduous species are often planted along the boundaries of avalanche courses because evergreen tree species are swept away by avalanches, owing to their greater air resistance.

In snow depths of 1 to 2 m, which merely affect the tree trunks, a forest can slow an avalanche down. When flow depths are deeper and speeds higher, such as in loose-snow avalanches, the forest will be destroyed, but it can exert a braking effect in the avalanche release zone if the speed of the moving snow is not too high. This reduces the scope of the avalanche.

In many developed countries, the collection of wood in wind throw areas is no longer economically viable, so such wood is left on the ground. This practice is not recommended for several reasons, including the risk of bark-beetle infestation, but the wind throw often provides very efficient protection against snow movements. Dead wood, tree stumps, root masses and fallen stems create a surface structure that has a positive influence on snow deposits, effectively anchoring the snow cover to the soil. This wood offers good protection in typical avalanche release situations, i.e. on slope gradients of 58 to 84 percent. In very steep locations and when there are exceptionally large volumes of snow, the wood may not withstand the load, and the snow will move together with the wood. This risk increases gradually owing to biological decomposition of the wood, and should be taken into account in situations involving high risk of damage.

Guidelines

National hazard mapping in mountain environments is gradually becoming standard policy and procedure in many countries. Avalanche risk areas need to be part of this effort.

Forests at high elevations of more than 58 percent slope in areas where enough snow falls to trigger slab or loose-snow avalanches are potential avalanche protection forests. These are red flag zones, but protecting these forests is only part of the task. Establishing tree cover in open avalanche source areas above the tree line can also contribute to protection. With climate change, tree lines are shifting upwards naturally, making this increasingly feasible. Harvesting must be carried out with utmost care. The management of such forests is complex, and it is advisable to consult the expert literature and experienced people before undertaking any forest disturbance. Uninformed and inadequate forest utilization can increase risk in hazard-prone areas below the forest. Forests need to be regenerated as they age and become more prone to degradation and loss of function. Wildlife has an impact on regeneration because many forms of wildlife find part of their habitat requirements in avalanche chute areas. Monitoring and maintenance – of not only the forests but also the changing areas of concern (new avalanche-prone areas) – become even more urgent because of climate change.

An integrated avalanche protection programme should give priority to biological measures for protective function and technical options for early warning systems.

5. The special case of mountainous small islands

Chapters 2 and 3 described how forests' effects on water quantity and quality were manifest mainly at the local level. This chapter describes how small islands exemplify the "short pipeline" phenomenon, in which forests have a significant influence on hydrology and erosion.

Freshwater resources on small islands are often scarce and therefore precious. Forest management decision-makers must therefore be especially cautious about alterations or removals that impair water resources. Mountainous, small ocean islands may experience high rainfall in the uplands owing to orographic effects, along with rapid rainfall gradients, especially on the leeward side. Cloud forests may occur on the windward slopes and ridges even at relatively modest elevations of 300 to 400 m, adding their captured water (Hamilton, Juvik and Scatena, 1994). (The first section of Chapter 4 discusses cloud forests' important role in the hydrological cycle and as erosion minimization cover.) On steep slopes, if soils are thin (i.e. not deep volcanics), watersheds may respond quickly to rainfall events, and flash floods from even short-duration storms may be a problem. Hurricanes or intense storms can result in serious erosion, including mass soil movement in the form of shallow landslips and landslides. The resulting sediment may not only impair water quality and aggravate flooding on the island, but also deposit silt on coral reefs, which are a major asset for many tropical islands.

The watersheds of small mountainous islands are of the size and nature referred to in Chapter 2 as microscale (less than 50 km^2) or the lower end of mesoscale (50 to 20 000 km^2), with upland forest and land-use practices influencing streamflow and sediment discharge (Ives and Messerli, 1989) (Boxes 2 and 3 in Chapter 2).

Small islands' size and need for self-sufficiency mean that forests must be cleared for food production. Mountainous small islands are therefore well-suited to agroforestry systems, which provide some soil and water protection from trees. An appropriate scale that avoids larger-scale industrialized agriculture is more favourable to water quality, because it allows lower chemical inputs through integrated pest management (rather than reliance on pesticides). Any logging should observe the highest standards of soil and water conservation. In these short (and often steep) stream systems, adequate riparian buffer zones of forest or other dense vegetative cover are extremely important (section on Riparian buffer zones in Chapter 4) for keeping sediment out of the watercourse and off reef systems. Islands are subject to ocean storm surges and tsunamis; coastal forests such as mangrove should be assigned a conservation status in recognition of their protective role.

Small mountainous islands, especially those dominated by a single or a few peaks, lend themselves to a traditional, integrated watershed management system (Case study 10). The hydrological unit provides a good basis for land-use policy and management, because it integrates soil, water and human activities more effectively than other planning or management units can. These three linked elements are especially important in small islands. An interesting traditional system of land-use control in wedge-shaped watershed units (which are narrowest at the summit and widest at the coast), practised in Hawaii in what are called *ahupua`a*, is described in Case study 11 and illustrated in Figure 3.

CASE STUDY 10

Government/community watershed management on Pohnpei

In 1987, the state of Pohnpei in the Federated States of Micronesia enacted the Pohnpei Watershed Forest Reserve and Mangrove Protection Act. This designated 5 200 ha of the central upland forest area (containing cloud forest) and 5 525 ha of coastal mangrove forest as protected areas. Upland forest at between 450 and 780 m above sea level was protected by government decree. Traditional clans were invited to participate, and a community-based approach was developed.

The resulting management programme unites local community and traditional institutions with municipal and state governments. The Division of Forestry is the lead agency, with ultimate responsibility for developing and implementing the management programme and regulating use within the Watershed Forest Reserve. The Division of Forestry chief acts as chairperson of the Watershed Steering Committee, which serves as the advisory board to the division and its parent agency, the Department of Conservation and Resource Surveillance. Municipal watershed protection officers liaise with the Division of Forestry and the Watershed Steering Committee in watershed matters, particularly regarding infrastructure development. Each of about ten watershed management units has a local, autonomous watershed area management committee, consisting of the local village chiefs or their delegates, who co-manage the watershed with the Division of Forestry.

Following a community education programme in each unit, the Watershed Steering Committee works with the watershed area managment committees to develop and implement watershed unit plans, which cover the entire watershed unit from the cloud forest to the reef. Outside the legally designated areas, the plans can only recommend actions. Compliance is largely voluntary, but the involvement of communities and their leaders is expected to generate support.

Source: Adapted from Raynor, 1994.

CASE STUDY 11

Hawaiian *ahupua`a*

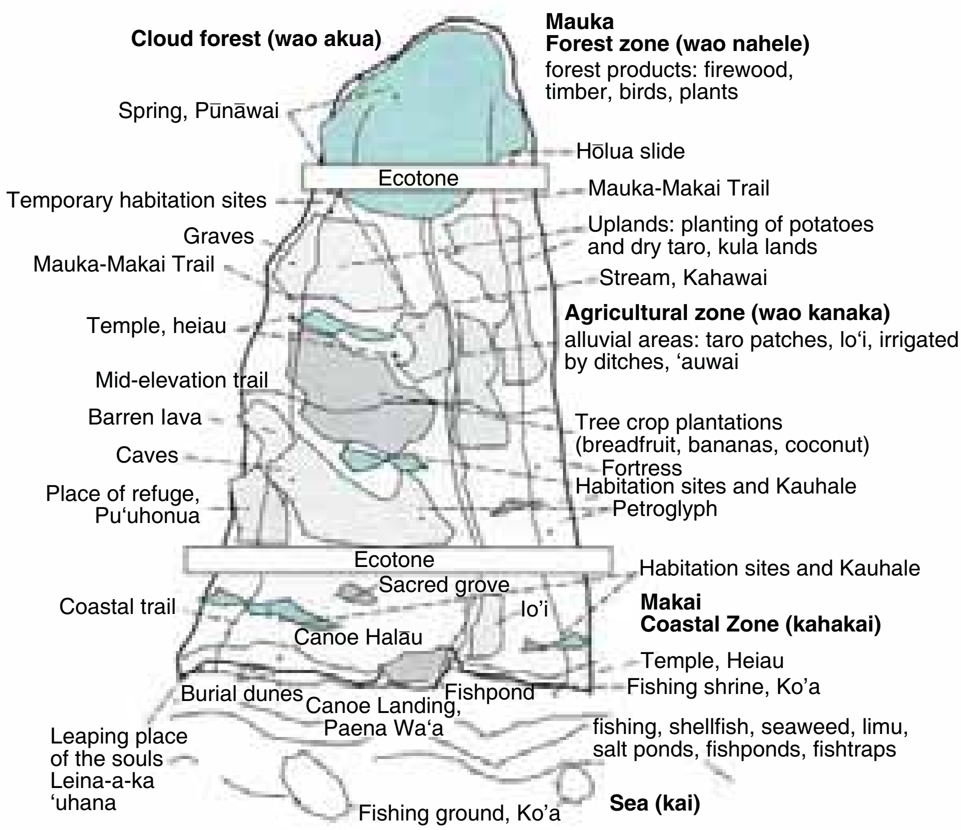
Where possible, the *ahupua`a* extended from the highest mountain peaks to the coast and beyond, usually to the outer edge of the offshore coral reef. Each was designed to be a self-contained economic and environmental unit, providing for the *ali`i* (the chiefs) and the *maka`āinana* (the people). The upper forests provided wood, bird feathers for capes, and various edible, medicinal and ceremonial plants. The moderate slopes produced upland crops, and the lowlands were planted in taro. Ocean products could be harvested from the shore and reef. Included within the *ahupua`a* were freshwater and marine fish ponds, irrigation systems and the communities' homes and ceremonial buildings.

The *ali`i*, assisted by a *konohiki* (land agent), maintained both political and economic control of the land and its resources. Political boundaries coincided with watershed boundaries, and the hydrological delineation provided a unit that sustained livelihoods by providing a variety of forest products and opportunities for agriculture and aquaculture.

Source: Adapted from Raynor, 1994.

FIGURE 3

Ahupua`a – typical land division in Hawaii



Source: Minerbi, 1999.

Guidelines

On mountainous small islands, the classic influences of forests on water quantity and quality prevail. The relative shortness of the streams leads to close upstream–downstream linkages; what happens in the uplands usually alters the quantity and quality of water, including through flooding, low flows, sedimentation and water-borne pollutants. For instance, cutting forests by more than 10 percent increases streamflow throughout the year, the effect increasing with the amount of trees removed. Forest clearing may increase flood peaks, shift them forward in time and increase stormflow volumes. It also increases dry-season yields. Cutting of cloud forests reduces water yield, because fog water capture is lost. Subsequent land uses that substantially increase the area of impervious soil surface (e.g. overgrazing, roads, buildings) will aggravate flooding and diminish dry-season flows. Water quality will almost inevitably suffer owing to increased erosion and sediment, and possibly the pollutants that more intensive use often involves. Adequate riparian buffer zones can help reduce impairment of water quality, which is important not only for human and livestock use, but also for coastal reefs, fishponds and shallow water fisheries.

On small islands, forests and water are more intimately related because everything is local. Forests are the safest upland cover and merit legal watershed protection status or very conservative use. Where food production is required in a less protective zone, agroforestry systems with significant tree components should be considered for slip-prone land. Forested or densely vegetated, ungrazed riparian buffer zones are the highest priority.

6. Payments for environmental services

Watershed degradation has led to greater recognition of the numerous ways watersheds support human well-being through ecosystem services and, consequently, to greater value being placed on them. These services may include provision of freshwater for various uses, regulation of both water and sediment flows, and maintenance of natural flow regimes that support entire ecosystems and ways of life.

Regulation of land-use practices alone has not ensured continued provision of services. It places a disproportionate share of the conservation costs on upstream land users without giving them corresponding access to benefits. For example, States often claim ownership of forested areas and protect watersheds through policies that exclude local populations from resources on which they have traditionally relied. This may lead local people to engage in what have suddenly become illegal practices, or to occupy more marginal land areas (Tomich, Thomas and van Noordwijk, 2004; Blaikie and Muldavin, 2004).

Market-based arrangements are a way for upstream land users to recover the costs of maintaining forest cover, and a way of funding other land-management practices to protect watershed services. They are also advocated for landscape approaches to conservation, which require the creation of incentives for conservation on privately held land.

Market-based approaches in which payments are contingent on achieving desired outcomes can lead to more efficient resource allocation and more cost-effective solutions. However, there are a number of scientific and institutional challenges to their implementation, the transaction costs of which may make these approaches impractical. Among the challenges is that of demonstrating and quantifying the actual benefits to those who are asked to pay for them. This requires an understanding of complex ecosystem processes, over time in specific places, the identification of effective management actions to maintain these, and reasonable assurance that buyers will have access to benefits in the future. Finding the most efficient and effective approaches also requires the capacity to learn and adjust to new information.

This chapter provides an overview of the range of services provided by watersheds and the diverse payment arrangements tried. It concludes with a discussion of implementation challenges and highlights key issues to consider in the design and further development of such initiatives.

ECOSYSTEM SERVICES PROVIDED BY WATERSHEDS

Watershed services are the products of ecosystem processes that provide various direct and indirect benefits, including:

- freshwater for diverse human uses;
- flow regulation and filtration, which control rates of surface runoff. At local scales, control of runoff can provide a buffer against peak or flood flows; help to maintain base or dry-season flow; allow the recharge of water stored in soil, groundwater, wetlands and floodplains; and control the level of groundwater tables. Control of water runoff also controls the flow of pollutants and sediment that affect water quality (FAO, 2002).

Watersheds also provide supporting services, including:

- maintenance of the natural flow and disturbance regimes that drive all ecosystem processes, thereby maintaining habitat diversity and ecosystem resilience. River channels, wetlands, riparian habitats, mangroves, estuaries and coastal zone processes all support livelihoods in numerous ways and all depend on the timing of water and sediment flows;
- conservation of cultural values, including aesthetic qualities that support tourism, recreation and traditional ways of living.

These services are interdependent; the provision of freshwater for direct uses depends on the maintenance of its regulatory and support services. For example, activities to increase the supply of freshwater and land use changes to increase the supply of food often come at the expense of maintaining the natural flow and disturbance regimes that ensure a regular supply of both. As these regulatory and support services decline, human well-being will increasingly depend on achieving an optimal balance between these trade-offs (Aylward *et al.*, 2006). Site-specific assessments are needed to identify the benefits provided in a specific social and economic context, and the scales and economic significance of these benefits. Such assessments can also help avoid common misperceptions and generalizations regarding forests' role in the hydrological cycle: for example, the belief that they increase dry season flows and prevent large-scale floods (Hamilton and King, 1983). Instead, forests should be regarded as one component of an integrated approach to watershed management that includes land-use and management practices (FAO and CIFOR, 2005) (Chapter 2).

TYPES OF PAYMENT INITIATIVES

A review of case studies conducted by the International Institute for Environment and Development (IIED) in 2002 identified 287 initiatives involving payment for forest ecosystem services, of which 61 were specifically related to watersheds. The main concerns addressed in these initiatives were maintenance of dry-season flows, protection of water quality and control of sedimentation (Landell-Mills and Porras, 2002). The findings were generally consistent with other case study reviews (Perrot-Maître and Davis, 2001; FAO, 2002; Rosa *et al.*, 2003; FAO, 2004; Tognetti, Aylward and Mendoza, 2005).

PES initiatives take various forms depending on the characteristics of the service, the scale of the ecosystem processes producing it, and the socio-economic and institutional context. They range from informal, community-based initiatives, through more formal, voluntary contractual arrangements between individual parties, to complex arrangements among multiple parties facilitated by intermediary organizations. In the last category, payments to landowners may take the form of transfers from government or intermediary organizations of funds that have been pooled from diverse users with a common interest rather than from specific user groups.

Other commonly used approaches are the acquisition of easements that restrict land use, and tradable development rights that allow developers to exchange rights in one location for permits to develop at a higher density in other locations. Marketable permits allow for trading between different sources of pollution, to lower the cost of complying with regulatory standards or total emissions caps, and can provide revenue for funding conservation practices. Certification that producers have adhered to specified management practices, which is indicated to consumers through labelling, may increase the market share of a product and/or result in a price premium. On a larger scale with more diverse conditions, such as that of the New York City watershed (Case study 12), or when multiple services are covered, as in Costa Rica's Fondo Nacional de Financiamiento Forestal (FONAFIFO) programme (Case study 13), initiatives often use a mix of complementary market-based, regulatory and policy incentives.

Sources of funds are user or licence fees, taxes and donations. In general, user and licence fees are more feasible when it is possible to limit services to those who pay for them, such as domestic and industrial water users. Taxes and donations are usually necessary to cover more generalized benefits, such as maintaining biodiversity, for which the beneficiaries are less identifiable or more widely dispersed. Taxes may also be more appropriate for meeting policy objectives that increase equity. In Colombia, for example, taxes on all hydropower facilities finance the protection of watersheds with no hydropower facility (Becerra and Ponce De León, 1999).

Governments may play diverse roles: enforcing contractual agreements, creating regulatory caps, monitoring compliance, contracting service providers, providing technical assistance, and identifying priority conservation areas as a basis for funding allocation decisions. Some of these roles can be filled by NGOs, which may be more flexible and able to act more expediently. NGOs and stakeholder associations may also advocate on behalf of marginalized stakeholders, creating political pressure so that governments recognize rights and respond to the concerns of these groups.

Benefits tend to be more tangible and contractual arrangements more feasible when the scale is smaller and property rights and stakeholders are more easily defined. On a larger scale, it is harder to link cause and effect and to define rights and responsibilities. There is greater need to involve government and/or other intermediaries to facilitate transactions among numerous stakeholders and to establish priorities. However, this scale also offers a larger pool of buyers and sellers (Rose, 2002).

CASE STUDY 12

New York City watershed agreement

The City of New York is investing up to US$1.5 billion over ten years (to 2013) in several measures to protect the Catskill/Delaware and Croton watersheds and to avoid the expense of constructing a filtration plant, which was estimated to be US$9 to 11 billion, including operating costs for ten years. The investment is being financed through a 9 percent increase in charges to water users, which would have been at least double that amount if the filtration plant had been built. The funds are being used to implement an agreement among the City of New York, the United States Environmental Protection Agency and a coalition of watershed towns. More detailed reviews of the case can be found in Galusha (1999), Platt, Barten and Pfeiffer (2000) and Pires (2004).

The key components of the agreement are:

- acquisition of land or conservation easements near reservoirs, wetlands and watercourses;
- development and upgrading of infrastructure – including sewage systems, water treatment plants and storm-water management facilities – and stream corridor protection;
- an economic development bank – to support upstream development consistent with catchment protection – and environmental education;
- support for the implementation of best management practices on farms and in forests.

The agreement also gives the city greater authority to review and approve or reject potentially harmful projects and to set standards and other requirements pertaining to wastewater treatment plants, septic systems and storm-water control. Key to acceptance of the new, upstream land-use restrictions were a payment arrangement and the city's undertaking to acquire land only from willing sellers at fair market values. A separate agreement was reached with farmers, specifying that their participation in developing farm management plans and adopting conservation practices would be voluntary and that the programme would be managed by the farmers themselves. All regulations were suspended except that restricting wilful pollution.

The agreement was conditional on participation of 85 percent of the farms within five years and on achieving goals for protection of the entire landscape rather than of individual farms. These conditions were more than met (Appleton, 2004). Cost sharing is offered to forest landowners to encourage them to develop and adhere to forest management plans, which now cover 84 500 acres (about 34 210 ha). The agriculture and forestry component is governed by a Watershed Agricultural Council, which also supports and promotes small businesses based on farm and forest goods produced using best management practices (www.nycwatershed.org/).

CASE STUDY 13

Costa Rica's National Forestry Financing Fund

The Fondo Nacional de Financiamiento Forestal (FONAFIFO; National Forestry Financing Fund) compensates forest owners who adhere to approved management plans for services protecting freshwater, biodiversity and landscape beauty and for carbon storage. FONAFIFO is financed by selling these services to different types of buyers. Hydroelectric companies and municipalities may pay for watershed benefits, tourism agencies for landscape beauty, and foreign energy companies for carbon storage. Additional funds are derived from a fuel tax. The programme has been in place for five years, building on lessons learned and institutions established for an earlier ten-year payment for reforestation programme (Pagiola, 2002). FONAFIFO has expanded its range of activities, most recently in 2002 when agroforestry and indigenous reserves were added (Rosa *et al.,* 2003).

A recent assessment of FONAFIFO's social impacts in the Virilla watershed found it has had significant benefits in terms of strengthened capacity for integrated management of farm and forest resources, and has contributed to the protection of 16 500 ha of primary forest, sustainable management of 2 000 ha and reforestation of 1 300 000 ha, with spin-off benefits for biodiversity conservation and prevention of soil erosion. There are also high opportunity costs, however, particularly for smaller landowners, who tend to rely more heavily on small areas of cleared forest and to combine forestry with other activities such as shelter for cattle and shade coffee. Farmers with larger tracts receive greater advantages because they are able to maintain higher proportions of their land in forest.

Source: Miranda, Porras and Moreno, 2003.

PAYMENTS FOR ENVIRONMENTAL SERVICES IN PRACTICE – DEFINING WATERSHED SERVICES

The ability to demonstrate both the threats to existing services and the effectiveness of upstream land-use and management practices is key to building stakeholder confidence and maintaining the willingness to pay for services. These depend not only on the integrity of the ecosystem processes that support service provision, but also on the effectiveness of the institutional arrangements that ensure implementation of appropriate practices, and on assured access to benefits for those who pay for them.

However, the complexity and natural variability of watershed processes, which are dominated by randomly timed and extreme events, make it difficult, if not impossible, unequivocally to link all causes and effects. This requires monitoring and adjustment over time as lessons are learned. Making the inherent uncertainties explicit is even harder, but is critical to managing buyers' expectations and maintaining their cooperation in the long term. Uncertainty has a cost, which must be considered if the distribution of costs and benefits is to be equitable.

A review of case studies indicates that there is a general absence of scientific data to support the evaluation of trade-offs. A more detailed review of initiatives in Costa Rica by Rojas and Aylward (2003) found that most were based on conventional wisdom, secondary sources of information, and selective reference to forest hydrology literature affirming that protection of forests increases water yields, which is not always the case (Hamilton and King, 1983; Bruijnzeel, 2004; Calder, 1999). Payments are based on the opportunity costs of returning cleared land to forest cover, with no attempt to model relationships between land use and hydrology or to estimate the marginal value of water in specific consumption and production activities (Rojas and Aylward, 2003). Nor are the payments based on the expected costs of alternative courses of action, willingness to pay and to accept compensation, or consistency with comprehensive management plans (Tognetti, Aylward and Mendoza, 2005). Given the time and effort required to gather scientific information, reliance on these kinds of justifications may be unavoidable and even appropriate, provided that they are monitored.

Most payment initiatives have focused on links between upper watershed land-use practices and downstream urban water supplies and the sedimentation of hydropower dams and irrigation canals. However, it has generally been difficult to demonstrate the economic significance of impacts at this scale. Even when links between land use and hydrology can be identified and quantified, a recent literature review raises questions as to whether the magnitude of damages or benefits is likely to be economically significant. This depends largely on the downstream economic interests that rely on water and the scale of the impacts. Less attention has been given to local impacts within micro-watersheds, where land and water relationships can be better understood and stakeholders more directly engaged. Although the values placed on water quality improvement are modest, it has been suggested that land-use interventions for this purpose may be justifiable as part of an integrated community resource management strategy (Johnson and Baltodano, 2004).

Almost none of the existing PES schemes are based on both good science (proper scientific measurement of the impact of projects/policies) and good economics (reliable valuation of the benefits of these impacts).

INSTITUTIONAL CHALLENGES

When there are no institutional arrangements for ensuring access to benefits for those who pay the costs of management, economic value is only hypothetical and there is no incentive to take the actions needed to ensure service provision. Institutional arrangements are essentially “rules of the game” that resolve conflicts among competing demands for a limited resource; without them, the resource would be depleted or degraded. Key among these arrangements are various forms of property rights, decision-making processes and the intermediary organizations needed to reduce transaction costs when there are numerous buyers and sellers.

Property rights play an important role in economic incentives because they define who has access to benefits and who has responsibility for the costs of delivering those benefits. If the distribution of costs and benefits is not perceived as equitable, and if significant stakeholders are excluded or disadvantaged, they will have little incentive to cooperate. For example, without clear land title, upper watershed land users lack the authority to enter into contractual agreements and are thus unable to benefit from payments. They may also risk eviction as values are placed on services to which they have no formal rights (Landell-Mills and Porras, 2002). Some payments for watershed services have disproportionately benefited those who own larger tracts of forests or forest plantations, excluding smaller and marginalized landholders, who tend to occupy the steepest slopes, do not have large forest areas for which to be compensated, and face higher opportunity costs for foregone land uses on what little land they do own (Rosa *et al.*, 2003).

Property rights range from informal rights or norms recognized by users, to various forms of formally recognized public and private ownership by individuals, groups or government entities. Failure to control access is often mistakenly referred to as a common property situation, but is actually an open access situation in which no property rights are in effect (Ostrom, Gardner and Walker, 1994). A key problem in defining rights to watershed services is that the main upstream sources of off-site or downstream impacts are usually marginal and unproductive areas such as steep slopes, river banks, paths and roads. Private landownership does not create an incentive for implementing conservation practices in such areas, which cannot be expected to give landowners a significant return on investment. This makes these areas, in effect, situations of open access (Swallow, Garrity and van Noordwijk, 2001).

The use of payments as incentives in such situations is often accused of violating the "polluter-pays" principle. Given the low prices paid for agricultural commodities, however, direct payments for maintaining the landscape and water quality can be regarded simply as recognition of the value of providing ecosystem services. One way of addressing this is to maintain sanctions on wilful pollution (FAO, 2002) – an approach adopted in the New York City watershed agreement (Appleton, 2004) (Case study 12).

Buyers' acceptance and cooperation may ultimately depend on whether all stakeholders can participate in decision-making regarding fund allocation. For example, in Brazil, where a nationwide river-basin management policy has been adopted, domestic water users are willing to pay higher water fees if the revenue is invested in the basin where it was generated, and if they are able to participate in decisions on how it is spent (Porto, Porto and Azevedo, 1999).

One important obstacle to stakeholders' effective participation in water resources decision-making is the gathering and dissemination of information to support that decision-making. The site-specific nature of watershed services presents the institutional challenge of developing an integrated and site-based approach to assessment, which engages stakeholders in developing feasible options. This would also provides a basis for corrections as new information becomes available and lessons are learned.

CONCLUSION: KEY CHALLENGES IN DESIGN AND DEVELOPMENT

Because it is difficult to demonstrate and quantify land and water linkages on a large scale, the main focus is currently on small-scale pilot initiatives that could be scaled up as capacity develops. The Programa para la Agricultura Sostenible en Laderas de América Central is an example. This involves ten hillside pilot initiatives to improve small producers' land and water management in El Salvador, Honduras and Nicaragua, and is helping develop markets for watershed services through the local municipalities (Pérez, 2003). The programme's bottom-up approach is generally expected to ensure that regional-level organizations are more representative of and accountable to local livelihood interests. Many initiatives are also developing action research and learning approaches that support capacity building and knowledge exchange (IIED, 2004; Noordwijk, Chandler and Tomich, 2004).

Payments for watershed services will not solve all problems of watershed degradation, but can be an important component of a broader management strategy. They can also support a shift in water policy – from emphasis on the development of new sources of supply to the reallocation of existing supplies of water – to meet the fundamental needs of people and ecosystems and to recover costs. Ultimately, this is a governance challenge and should be regarded as a long-term process of developing the necessary institutional arrangements. The use of science to support site-based assessment presents both a research and an institutional challenge.

7. Recommendations

Water in adequate quantity and quality to meet human needs is essential, and forests have direct and indirect roles in providing such water. Managers of the forest estate should therefore adopt as many as possible of the guidelines given at the end of every chapter in this document. The following are additional recommendations for protecting and maintaining the world's precious water:

- Forest and land-use policies and programmes should be based on sound science rather than misperception. Key water supply areas and groundwater aquifer sites should be considered for forest retention, with minimum disturbance. Although tree cutting (of at least 20 percent of the canopy) produces temporary increases in water yield, there are trade-offs that must be considered, such as reduced water quality, increased erosion and impact on wildlife and other biodiversity. Any forest product removal in these areas should avoid soil compaction and bare soil exposure, to minimize surface runoff and concomitant erosion. Best practice watershed harvesting guidelines should be strictly followed. The effects of forest restoration on water yield also need to be considered.
- It is recommended that countries officially recognize the cloud or fog forest ecosystem in their forest classification systems, and plan for its conservation by establishing it as legally protected forest or designating it for protective purposes, by 2010. Techniques similar to those employed in UNEP-WCMC's global mapping can be used to estimate potential area in regions that lack ground or aerial surveys (section on Mountain cloud or fog forests in Chapter 4) (Bubb *et al.*, 2004).
- Planning authorities should identify slip-prone areas – perhaps using the criteria suggested from Megahan and King in the section on Forests on sites with high landslip risk in Chapter 4 – and red flag or zone them for forest retention or agroforestry/ sylvopastoral use with fairly dense tree cover. Such areas may then be part of the protective forest estate.
- It is recommended that each country undertake an assessment of its key riparian zones and classify them for conservation management, protection or restoration. Adequate legislation on riparian buffer zone maintenance should be established in each country; models are available from FAO. It is also recommended that countries report their national regulations or guidelines for maintenance in future FRAs.
- Swamp forests should be designated as environmentally sensitive areas where the maintenance of hydrological functions is a management and development priority. These forests have a key role as water regulators.
- Forested areas with saline subsoils or groundwater should not be cleared in

case this results in saline surface soil or saline drainage that affects off-site areas.

- To ensure optimum water quality, drinking-water supply catchments should have legal status as protected areas or be designated as protective forest.
- Payments for watershed services have significant potential and should be explored further. Such payments can be part of a broader management strategy and can support a shift in water policy to reallocate existing supplies. This is ultimately a governance issue, involving development of the necessary institutional arrangements. Site-specific assessment requires both research and institutional adjustments.
- It is hoped that by the time of the next FRA (2010) countries will be reporting substantial increases in both their areas of forest (and other wooded land) in protected areas and their areas of forest (and other wooded land) designated for protective purposes.
- Another measure of improvement for forests and water would be an increased area of certified forest. The criteria for certification always ensure water-friendly good practice, so increases in certification area would be good for water resources.

It is increasingly recognized that both the availability and the quality of water are strongly influenced by forests and that water resources in many regions are under growing threat from overuse, misuse and pollution. The relationship between forests and water is therefore a critical issue that must be accorded high priority. A key challenge for land, forest and water managers is maximizing the wide range of forest benefits without detriment to water resources and ecosystem function. To address this challenge, there is urgent need for better understanding of the interactions between forests/trees and water (particularly in watersheds), for awareness raising and capacity building in forest hydrology, and for embedding this knowledge and research findings in policies. There is also need to develop institutional mechanisms to enhance synergies in forests and water issues, and to implement and enforce national and regional action programmes (Calder *et al.*, 2007).

The most recently established political platform is the Resolution on Forests and Water, adopted in November 2007 by the Ministerial Conference for the Protection of Forests in Europe. This resolution has four parts: sustainable management of forests in relation to water; coordinating policies on forests and water; forests, water and climate change; and economic valuation of water-related forest services.

It is hoped that in the future the link between forests and water receives increasing attention at the national level and that decision-makers and experts in the water and forestry sectors increase their cooperation. For future FRAs, it is recommended that each country develop a list of national studies or publications on forests and water and the interplay between them.

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FAO FORESTRY PAPER

Forests and water

The availability and quality of clean water in many regions of the world is more and more threatened by overuse, misuse and pollution. In this context, the relationship between forests and water must be accorded high priority. Forested catchments supply a high proportion of the water for domestic, agricultural, industrial and ecological needs in both upstream and downstream areas. A key challenge faced by land, forest and water managers is to maximize the benefits that forests provide without detriment to water resources and ecosystem function. There is an urgent need for a better understanding of the interface of forests and trees with water and for embedding this knowledge in policies. This study, initiated in the context of the Global Forest Resources Assessment 2005, highlights the need for holistic management of complex watershed ecosystems taking into account interactions among water, forest and other land uses as well as socio-economic factors. It explains the role of forests in the hydrological cycle, with a particular focus on critical, "red flag" forest situations such as mountainous or steep terrain, river and coastal areas and swamp ecosystems, as well as the special case of mountainous small islands. It addresses the protection of municipal water supplies and emerging systems of payment for watershed services. This state-of-knowledge publication will be of interest to a broad range of technical experts, scientists and decision-makers.

ISBN 978-92-5-106090-2 ISSN 0258-6150
9 789251 060902
TC/M/I0410E/1/10.08/2000