3

SWIM Paper

Water-Resource and Land-Use Issues

I.R. Calder

SWIM

IWMI

System-Wide Initiative on Water Management

SWIM Papers

In an environment of growing scarcity and competition for water, increasing the productivity of water lies at the heart of the CGIAR goals of increasing agricultural productivity, protecting the environment, and alleviating poverty.

TAC designated IWMI, the lead CGIAR institute for research on irrigation and water management, as the convening center for the System-Wide Initiative on Water Management (SWIM). Improving water management requires dealing with a range of policy, institutional, and technical issues. For many of these issues to be addressed, no single center has the range of expertise required. IWMI focuses on the management of water at the system or basin level while the commodity centers are concerned with water at the farm and field plot levels. IFPRI focuses on policy issues related to water. As the NARS are becoming increasingly involved in water management issues related to crop production, there is strong complementarity between their work and many of the CGIAR centers that encourages strong collaborative research ties among CGIAR centers, NARS, and NGOs.

The initial publications in this series cover state-of-the-art and methodology papers that assisted the identification of the research and methodology gaps in the priority project areas of SWIM. The later papers will report on results of SWIM studies, including inter-sectoral water allocation in river basins, productivity of water, improved water utilization and on-farm water use efficiency, and multiple uses of water for agriculture. The papers are published and distributed both in hard copy and electronically. They may be copied freely and cited with due acknowledgment.

Randolph Barker
SWIM Coordinator

SWIM Paper 3

Water-Resource and Land-Use Issues

I. R. Calder

International Water Management Institute
P O Box 2075, Colombo, Sri Lanka

The author: Professor Ian R. Calder is the Director, Centre for Land use and Water Resources Research, at the University of Newcastle Upon Tyne, NE1 7RU.

This work was undertaken with funds specifically allocated to IWMI's Performance and Impact Assessment Program by the European Union and Japan, and from allocations from the unrestricted support provided by the Governments of Australia, Canada, China, Denmark, France, Germany, the Netherlands, and the United States of America, the Ford Foundation, and the World Bank.

Calder, I. R. 1998. *Water-resource and land-use issues.* SWIM Paper 3. Colombo, Sri Lanka: International Water Management Institute.

/ water resource management / water use / case studies / catchment areas / land use /hydrology / models / evaporation / soil moisture / GIS / decision support systems / water use / runoff / flow / forestry / deforestation / erosion control / rain / Africa / India /

ISBN: 92-9090-361-9
ISSN: 1028-6705

The International Irrigation Management Institute, one of sixteen centers supported by the Consultative Group on International Agricultural Research (CGIAR), was incorporated by an Act of Parliament in Sri Lanka. The Act is currently under amendment to read International Water Management Institute (IWMI).

Contents

CGIAR Centers

CIAT	Centro Internacional de Agricultura Tropical
CIFOR	Center for International Forestry Research
CIMMYT	Centro Internacional de Mejoramiento de Maize y Trigo
CIP	Centro Internacional de la Papa
ICARDA	International Center for Agricultural Research in the Dry Areas
ICLARM	International Center for Living Aquatic Resources Management
ICRAF	International Centre for Research in Agroforestry
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IFPRI	International Food Policy Research Institute
IIMI	International Irrigation Management Institute
IITA	International Institute of Tropical Agriculture
ILRI	International Livestock Research Institute
IPGRI	International Plant Genetic Resources Institute
IRRI	International Rice Research Institute
ISNAR	International Service for National Agricultural Research
WARDA	West Africa Rice Development Association

Abstract

This paper reviews perceived notions of the relationships between catchment land use and hydrology and explores whether much of the widely disseminated folklore, so often inextricably linked with issues of land use, is based on myth or reality. Gaps in our knowledge of the underlying processes in relation to land use and hydrology are identified. Our ability to apply this knowledge at different scales ranging from the plot to the catchment and regional scales are discussed and specific examples are drawn from Indian and African case studies. Methods for linking spatially distributed land-use hydrological models with economics and ecology through decision support systems are outlined and proposed as a framework for the integrated management of land and water developments at the catchment scale.

Water-Resource and Land-Use Issues

I. R. Calder

Introduction

The relationship between land use and hydrology is of interest worldwide. In many developing countries, extensive areas are undergoing land use change. The largest changes in terms of land area, and arguably also in terms of hydrological impacts, often arise from afforestation and deforestation activities (Calder 1992a) . While demands for agricultural land and firewood place increasing pressure on the dwindling indigenous forest resource, demands for timber and pulp are leading to increasing areas undergoing commercial afforestation with fast growing monocultures of often exotic tree species. Agricultural demands for irrigation water compete with those of conurbations and industry for water supply. Hydropower, often erroneously thought to have a neutral effect on water resources, because evaporation from hydropower reservoirs is not taken into account, is another big user of water in many developing countries, particularly those in southern Africa. Within the Zambezi basin in southern Africa, the flow of the Zambezi at Victoria Falls is approximately equal to the flow from the Kariba dam downstream; all the additional flow into Lake Kariba from the northward flowing rivers from Zimbabwe and the southward flowing rivers from Zambia can be considered as lost to evaporation.

Increasing industry, increasing urban populations without adequate sewage treatment facilities, and greater intensification of agriculture, while not significantly affecting the quantity of the resource, all pose problems for its quality. These are the problems faced by many developing countries when trying to maintain their water resources. New approaches to integrated water resources management are being developed. The concepts of demand management and valuing the resource in economic terms that allow competition between higher value uses such as industry and water supply to conurbations, as opposed to low value usage such as irrigation, are becoming increasingly accepted.

Land Use and Hydrology—Folklore and Myths

There still remains much folklore and many myths about the role of land use and its relation to hydrology, which hinder rational land use decision making. This is particularly true in relation to forestry, agroforestry, and hydrology, where claims by enthusiastic agroforesters and foresters may not always be supportable. Ong and colleagues (Ong et al. 1991) have explored five hypotheses related to agroforestry, crop production, and water use. They concluded that although the inclusion of trees in cropping systems can enhance the utilization of rainfall leading to increased overall productivity, because trees tend to compete with crops for moisture, this is often at the expense of reduced production from the agricultural crop.

Foresters have been suspected of deliberately propagating some forest hydrology myths. H. C. Pereira (1989) states:

> *The worldwide evidence that high hills and mountains usually have more rainfall and more natural forests than do the adjacent lowlands has, historically, led to confusion of cause and effect. Although the physical explanations have been known for more than 50 years, the idea that forests cause or attract rainfall has persisted. The myth was created more than a century ago by foresters in defense of their trees… The myth was written into the textbooks and became an article of faith for early generations of foresters.*

The vast majority of the hydrological evidence supports Pereira's view that forests are not generators of rainfall, yet this "myth," like many others in forest hydrology, may contain a modicum of truth that prevents it from being totally " laid to rest."

When scrutinized, much of this folklore is seen to be either exaggerated or untenable. For others we still require research to understand the full picture. Six aspects of widely propagated folklore in relation to forests and hydrology are considered in this paper:

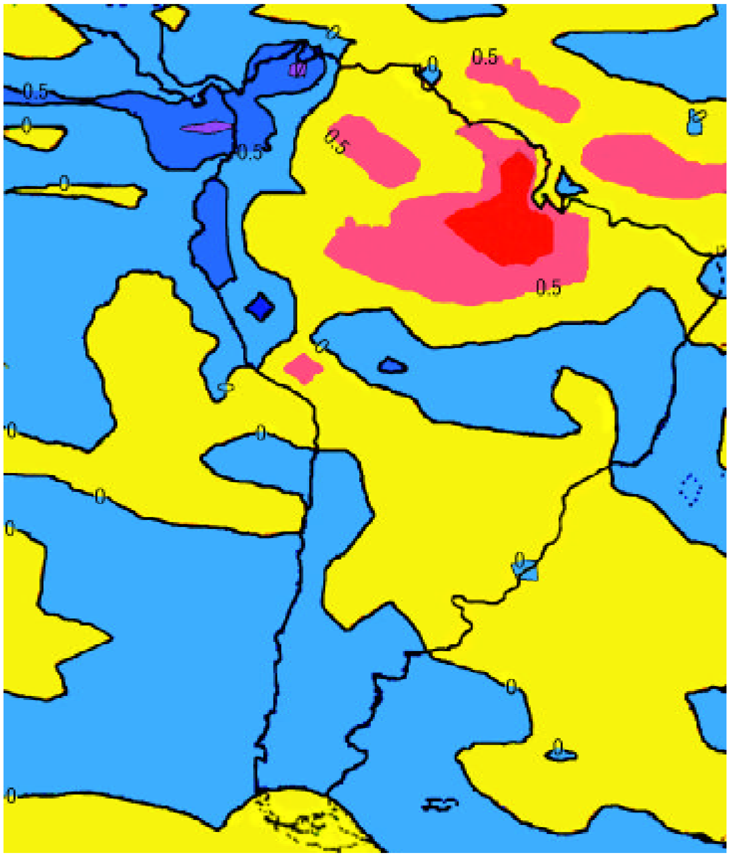
- Forests increase rainfall.
- Forests increase runoff.
- Forests regulate flows.
- Forests reduce erosion.
- Forests reduce floods.
- Forests "sterilize" water supplies—improve water quality.

Clearly, it is important to know what veracity can be attached to these statements for the proper management of water resources and land use. Many forestry projects in developing countries are supported because of assumed environmental and/or hydrological benefits, while in many cases the hydrological benefits may at best be marginal and at worst negative. The evidence for and against each of these widely articulated beliefs is taken in turn and appraised; the need for further research is also assessed.

1. *Forests Increase Rainfall?*

Pereira (1989) recognized this statement as a myth. However, there may be some situations where the presence of forests does lead to a small increase in rainfall. However, as detailed later, this small increase in rainfall input will nearly always be more than compensated by increased evaporation, leading to an overall reduction in water resources. Meteorological theory indicates that the height of trees will slightly increase the orographic effect, which will in turn lead to a slight increase in the rainfall. Modeling studies using mesoscale climate models have shown that some of the intercepted water retained by forest canopies and reevaporated will return as increased rainfall (Blythe, Dolman, and Noilhan 1994) but this result does not indicate a net increase in rainfall. Application of Global Circulation Models (GCMs) indicate that vegetation changes will have a regional impact on climate (Rowntree 1988). Use of these models in Amazonia shows that total removal of the Amazonian rain forest would affect rainfall patterns with reductions in the rainfall, particularly in the drier northeast of the continents, by about 0.5 millimeter per day on average (figure 1). For the whole of the

FIGURE 1.
Spatial variation of the annual change in rainfall (millimeters per day) over Amazonia resulting from complete removal of the Amazon forest: Predictions made by the Hadley Centre Global Circulation Model.



Source: Institute of Hydrology 1994.

Amazon basin, rainfall would be reduced by 6 percent (Institute of Hydrology 1994).

Similarly, GCM modeling studies for the Sahel (Xue 1997) indicate that past removal of the indigenous bush vegetation will have altered the spatial distribution of rainfall in a manner that bears a close correlation with observed changes in the distribution patterns (figure 2).

Research conducted in southern India (Meher-Homji 1980) indicates that annual rainfall over the last 100 years has NOT decreased despite the large-scale deforestation that has taken place as the dry deciduous forest has been converted to agriculture, although there is some evidence for a decrease in the number of rain days.

The issue is well summed up by Bands et al. (1987) quoting from experience in South Africa:

> *Forests are associated with high rainfall, cool slopes or moist areas. There is some evidence that, on a continental scale, forests may form part of a hydrological feedback loop with evaporation contributing to further rainfall. On the Southern African subcontinent, the moisture content of air masses is dominated by marine sources, and afforestation will have negligible influence on rainfall and macroclimates. The distribution of forests is a consequence of climate and soil conditions—not the reverse.*

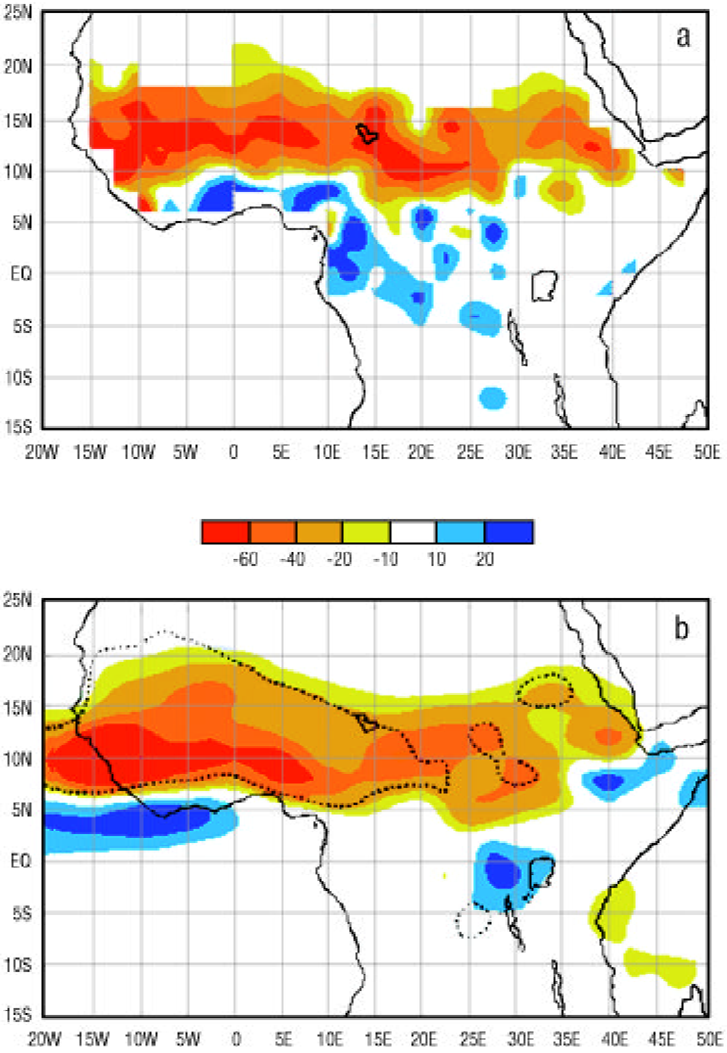
Conclusion: Although the effects of forests on rainfall are likely to be relatively small, they cannot be totally dismissed from a water resources perspective.

Research requirement: Further research is required to determine the magnitude of the effect, particularly at the regional scale.

2. *Forests Increase Runoff?*

A new understanding has been gained in recent years of evaporation from forests in dry and wet conditions based on process studies. These studies and the vast majority of the world's catchment experiments indicate decreased runoff from those under forests as compared with those under shorter crops. This knowledge has been gained from a host of different studies using a range of different techniques and methodologies. "Natural" lysimeters have been used to measure total evaporation while, of its components, transpiration has been determined using soil moisture measurements

FIGURE 2.
The observed change in the rainfall pattern (a) together with the spatial variability of the predicted change in rainfall (b) over Central Africa as a result of the Sahelian vegetation occurring over the last 30 years.



Source: Xue 1997.

(Bell 1976), micrometeorological and eddy correlation methods (Dyer 1961), plant physiological studies and tree-cutting studies (Roberts 1977, 1978), and heat (Cohen, Fuchs, and Green 1981), radioactive (Kline et al. 1970; Luvall and Murphy 1982), and stable isotope tracing methods (Calder 1991). The evaporation of intercepted precipitation has been determined by a number of techniques including interception gauges (Calder and Rosier 1976), gamma ray (Olsycka 1979; Calder and Wright 1986) and microwave attenuation methods (Bouten, Smart, and De Water 1991), "wet lysimeters," and rainfall simulators (Calder et al. 1996).

These studies indicate that in wet conditions, interception losses will be higher from forests than from shorter crops, primarily because of increased atmospheric transport of water vapor from their aerodynamically rough surfaces.

In dry (drought) conditions, the studies show that transpiration from forests is likely to be greater because of the generally increased rooting depth of trees as compared with shorter crops and their consequent greater access to soil water.

The new understanding indicates that in both very wet and very dry climates, evaporation from forests is likely to be higher than that from shorter crops and consequently runoff will be decreased from forested areas, contrary to the folklore.

The few exceptions, (lending some support to the folklore), are:

- Cloud forests where cloud water deposition may exceed interception losses.
- Very old forests: Langford (1975) showed that following a bushfire in a very old (200 years) mountain ash (*Eucalyptus regnans)* forest covering 48 percent of the Maroondah catchment, one of the water supply catchments for Melbourne in Australia, runoff was reduced by 24 percent. The reason for this reduction in flow has been attributed to the increased evaporation from the vigorous regrowth forest that had a much higher leaf area index than the former old ash forest.
- Observations and modeling studies of the evaporation from broadleaf forest in

southern England growing on chalk soils have been interpreted as showing reduced water use as compared with grassland (Harding et al. 1992). Further research is planned to investigate these results, exceptional in world terms, and to determine if these results are applicable to other regions of the UK.

Conclusion: Notwithstanding the exceptions outlined above, catchment experiments generally indicate reduced runoff from forested areas as compared with those under shorter vegetation (Bosch and Hewlett 1982).

Research requirements: Information on the evaporative characteristics of different tree species and soil type combinations is still required if evaporation estimates with an uncertainty of less than 30 percent are required. Both in temperate and tropical climates, evaporative differences between tree species and soil types are expected to vary by about this amount. For example, 30 percent differences in the water use of the same species of *Eucalyptus* growing on different soils have been recorded in southern India (Calder, Hall, and Prasanna 1993) while similar differences have been recorded between different tree species growing on the same soil type (Calder et al. 1997a). In the UK, further research is required to determine, at better than 30 percent uncertainty, the evaporation from different tree species/soil type combinations to determine the potential water quantity impacts of the proposed doubling of UK lowland forests (Calder et al. 1997b).

3. *Forests Regulate Flows—Increase Dry Season Flows?*

Although it is possible, with only a few exceptions, to draw general conclusions with respect to the impacts of forests on annual flow, the same cannot be claimed for the impacts of forests on the seasonal flow regime. Different, site-specific, often competing processes may be operating and the direction, let alone the magnitude of the impact, may be difficult to predict for a particular site.

From theoretical considerations it would be expected that:

- Increased transpiration and increased dry period transpiration will increase soil moisture deficits and reduce dry season flows.
- Increased infiltration under (natural) forest will lead to higher soil water recharge and increased dry season flows.
- For cloud forests, increased cloud water deposition may augment dry season flows.

Observations in the uplands of the UK (Robinson, Moore, and Blackie 1997) indicate that drainage activities associated with plantation forestry increase dry season flows both through the initial dewatering and, in the longer term, through alterations to the hydraulics of the drainage system. There are also observations from South Africa, that the increased dry period transpiration is reducing low flows. Bosch (1979) has demonstrated, from catchment studies at Cathedral Peak in Natal, South Africa, that pine afforestation of former grassland not only reduces annual streamflow by 440 millimeters but also reduces the dry season flow by 15 millimeters. Van Lill and colleagues (1980), reporting studies at Mokobulaan in the Transvaal, South Africa, showed that afforestation of grassland with *Eucalyptus grandis* reduced annual flows by 300–380 millimeters, with 200–260 millimeters of the reduction occurring during the wet summer season. More recently, Scott and Smith (1997), analyzing results from five of the South African catchment studies, concluded that percentage reductions in low (dry season) flow as a result of afforestation was actually greater than the reduction in annual flow.

Bruijnzeel (1990) discusses the impacts of tropical forests on dry season flows and concludes that the infiltration properties of the forest are critical in how the available water is partitioned between runoff and recharge (leading to increased dry season flows).

Conclusions: Competing processes, which may be operating in different parts of the hydrological cycle to either increase or decrease the magnitude of the impact, may result in either increased or reduced dry season flows. Effects on dry season flows are likely to be very site-specific. It cannot be assumed that it is generally true that afforestation will increase dry season flows; many studies indicate the contrary.

Research requirements: The complexity of the competing processes affecting dry season flows indicates that detailed, site-specific models will be required to predict impacts. The European Union is currently funding a research program with five European collaborators to understand the impacts within European conditions of sites and climates. In general, the role of vegetation in determining the infiltration properties of soils, as it affects the hydrological functioning of catchments through surface runoff generation, recharge, high and low flows, and catchment degradation, remains poorly understood. Modeling approaches that are able to take into account vegetation and soil physical properties, including the conductivity/water content properties of the soil, and possibly the spatial distribution of these properties, will be required to predict these site-specific impacts.

4. Forests Reduce Erosion?

If foresters are under suspicion of propagating the myth that forests are the cause of high rainfall in upland areas, then there may be equal suspicion of the universal claims of the benefits of forests in relation to reduced erosion. As with impacts on seasonal flows, the impacts on erosion are likely to be site-specific, and again, many and often competing processes are likely to be operating.

Conventional theory and observations indicate that:

- The high infiltration rate in natural, mixed forests reduces the incidence of surface runoff and reduces erosion transport.
- The reduced soil water pressure and the binding effect of tree roots enhance slope stability, which tends to reduce erosion.
- Windthrow of trees and the weight of the tree crop reduce slope stability, which tends to increase erosion.
- On steep slopes, forestry or agroforestry may be the preferred option where conventional soil conservation techniques and bunding may be insufficient to retain mass movement of soil.
- Management activities like cultivation, drainage, road construction, road use, and felling increase erosion.

The effects of catchment deforestation on erosion, and the benefits gained by afforesting degraded and eroded catchments will be very dependent on the situation and the management methods employed. According to Bruijnzeel (1990), “In situations of high natural sediment yield as a result of steep terrain, high rainfall rates and geological factors, little, if any, influence will be exerted by man.” Also, in drier land, situations where overland flow is negligible, little advantage will be gained from afforestation. Versfeld (1981) has shown that at Jonkershoek in the Western Cape of South Africa, land cover has very little effect on the generation of overland flow and soil erosion. On the other hand, in more intermediate conditions of relatively low natural rates of erosion and under more stable geological conditions, man-induced effects may be considerable. In these situations, catchment degradation may well be hastened by deforestation and there may also be opportunities for reversing degradation by well-managed afforestation programs.

Even in these situations, afforestation should not necessarily be seen as a quick panacea. In heavily degraded catchments, such as those on the slopes of the Himalayas, so much eroded material will have been mobilized already that, even if all the man-induced erosion could be stopped immediately, it would be many decades before there will be any reduction in the amount of material carried by the rivers (Pearce 1986; Hamilton 1987). The choice of tree species will also be important in any program designed to reduce erosion and catchment degradation.

Recent theoretical developments and observations (Hall and Calder 1993) confirm that drop size modification by the vegetation canopies of trees can be a major factor leading to enhanced splash-induced erosion. Although not generally recognized, this potential for increased erosion from drops falling from forest canopies was demonstrated almost 50 years ago by Chapman (1948). However, the importance of species in determining drop size and erosive impacts has not always been well understood. There have been claims that the drop size spectra of drops falling from vegetation are largely independent of vegetation type (Brandt 1989); in consequence, erosivity would be thought to be independent of the vegetation type. However, new insights have arisen from the use of modern optoelectronic devices, optical disdrometers, for measuring the size of drops falling from vegetation. Observations of the modified drop size spectra beneath canopies of different tree species with these devices (Hall and Calder 1993) and direct observations of erosion beneath teak plantations, suggest a different perspective from that of Brandt. Disdrometer observations of the below canopy drop size spectra beneath different tree species indicate that:

- The below canopy drop size is independent of the raindrop size falling on the top of the canopy.
- The below canopy drop size spectrum is a “characteristic” of the species.
- The drop size spectra vary widely between species. This can result in large differences in the potential for erosion; kinetic energies of drops falling from *Tectona grandis* (teak) can be as much as ***9 times*** greater than those from *Pinus caribaea* (Caribbean pine).

Conclusions: It would be expected that competing processes may result in either increased or reduced erosion from forests. The effect is likely to be both site- and species-specific. For certain species, e.g., *Tectona grandis*, forest plantations may cause severe erosion.

Research requirements: Although the Universal Soil Loss Equation (U.S. Department of Agriculture, Agricultural Research Service 1961) provides a practical solution to many problems associated with soil loss from agricultural lands, it may not be adequate for the prediction of erosion resulting from afforestation activities. Understanding the processes of controlling the erosive potential of drops falling from different tree species is not adequately appreciated and soil conservation techniques related to vegetation type, soils, and slope characteristics have not yet been fully developed. The role of vegetation as it determines erosion, infiltration properties, and subsequent catchment degradation is an important topic and one requiring further research.

5. *Forests Reduce Floods?*

It is a widely held view, propagated by foresters and the media, that forests are of great benefit in reducing floods. Disastrous floods in Bangladesh and northern India are almost always associated with "deforestation of the Himalayas." Similarly in Europe, floods are often attributed by the media to "deforestation in the Alps." However, hydrological studies carried out in many parts of the world do not support this view; for example, America (Hewlett and Helvey 1970), South Africa (Hewlett and Bosch 1984), UK (Kirby, Newson, and Gilman 1991; Johnson 1995), and New Zealand (Taylor and Pearce 1982). Generally, the hydrological studies show little linkage between land use and storm flow.

From theoretical considerations, it would be expected that interception of rainfall by forests reduces floods by removing a proportion of the storm rainfall and by allowing the buildup of soil moisture deficits. These effects would be expected to be most significant for small storms and least significant for the largest storms.

Field studies indicate that it is often the management activities associated with forestry such as cultivation, drainage, road construction, and soil compaction during logging, which are more likely to influence flood response than the presence or absence of the forests themselves.

Conclusion: There is little scientific evidence to support anecdotal reports of deforestation causing increased floods.

Research requirements: Carefully conducted controlled catchment experiments with different combinations of climate, soil, and species will be required to resolve this issue, but species impacts may not be as significant as often portrayed. Impacts of tree species may not be as significant as often portrayed. Management activities are probably paramount.

6. *Forests "Sterilize" Water Supplies—Improve Water Quality?*

Forests were historically the preferred land use for water supply catchments because of their perceived "sterile" qualities associated with an absence of livestock and of human activities. More recently, the generally reduced fertilizer and pesticide applications to forests compared with agricultural lands has been regarded as a benefit in relation to water quality degradation of runoff and recharge. Reduced soil erosion from natural forests can also be regarded as a benefit.

Offsetting these benefits, management activities such as cultivation, drainage, road construction, road use, and felling, are all likely to increase erosion and nutrient leaching. Furthermore, deposition of most atmospheric pollutants to forests is higher because of the reduced aerodynamic resistance of forest canopies compared with those of shorter crops. In high pollution (industrial) climates, this is likely to lead to both long-term acidification of the catchment and acidification of runoff.

Conclusions: Except in high pollution climates, water quality is likely to be better from forested catchments. Adverse effects of forests on water quality are more likely to be related to bad management practices rather than to the presence of the forests themselves.

Research requirements: Studies may still be required to determine the magnitude of the impacts for specific sites and the means to minimize adverse impacts.

Scaling Evaporation: Plot to Catchment and Regional Scale

Limits and Controls—Plot-Scale Measurements and Relationships

The physics of the evaporation process is well understood. Evaporation equations based on energy balance and aerodynamic transport concepts are central to most modern methods of estimating evaporation from different surfaces, whether these surfaces are natural vegetation, water, or man-made surfaces such as those of urban areas. These methods have been widely used in models that describe the spatial distribution of evaporation, both in GCMs and in distributed catchment models such as the System Hydrologique Europee (SHE) (Abbott et al. 1986) and more recent developments such as SHETRAN (Ewen, Parkin, and O'Connell 1997). The universality and potential accuracy of this approach is not questioned, but the applicability of the approach is sometimes limited by knowledge of the model parameters, particularly in their spatially distributed form.

Furthermore, approaches using the energy balance and aerodynamic transport equations place great emphasis on the importance of these climatic "demand-led" terms. In the temperate climates of the world where these evaporation equations were developed, this may be entirely appropriate. However, in many parts of the world, particularly in the very dry regions, the actual evaporation is perhaps only a small fraction of the demand and it may be more reasonable to estimate evaporation from considerations of limits on supply. In other regions, other processes may be limiting or more important in controlling evaporation.

As a supplementary approach, it has been proposed that "limit" type models may have application. Calder (1996a) suggested that broad estimates of the evaporation from forests in different regions of the world and the evaporative difference between forests and shorter crops could be estimated from knowledge of these limits identified as either *radiation, advection, physiological, soil moisture, tree size,* or *drop size* controls. The expected controls operating in four regions, the dry and wet, temperate and tropical regions of the world, are listed in table 1. Process studies generally carried out at the leaf, tree, and plot scales have identified many of the parameters that are required to operate these "limit" type models.

Wet Temperate

Results from studies carried out in the uplands of the UK illustrate some of the important controls on evaporation from vegetation growing in these wet temperate climates (Calder 1990; Kirby, Newson, and Gilman 1991; Johnson 1995).

Advection Limit

A "natural" plot lysimeter, operated at Plynlimon (mid-Wales), containing 26 spruce trees that were hydraulically isolated by containing walls and an impermeable clay subsoil, showed how important was the interception process from upland forest. On an annual basis, forest interception losses, determined by large plastic sheet net-rainfall gauges, were about twice those arising from transpiration, determined from the lysimeter and neutron probe measurements. The total evaporative loss, from both transpiration and interception, required a latent heat supply, which was supplied by large-scale advection and which exceeded the radiant energy input to the forest (table 2). The uplands of the UK, which are subject to a maritime climate typified by high rainfall, a high number of rain days per year and high windspeeds, are an example of a situation where large-scale advection of energy routinely occurs from moving air masses as they pass over wet forest covers. The high aerodynamic roughness of forest compared with shorter vegetation types allows the transport of heat to the forest surface from the air and the transport of water vapor from the surface into the atmosphere to occur at rates up to ten times higher than those possible from shorter vegetation. The utilization of advected energy is therefore much higher for forest and is the principal reason for the much higher evaporative losses from upland forests compared with shorter vegetation types. In the UK uplands, *advection* can probably be regarded not only as a major source of energy for forest evaporation but also as the principal limit on the evaporative process (table 1).

TABLE 1.
Principal limits and controls on evaporation for different land uses in different climates.

PRINCIPAL LIMITS ON EVAPORATION		
TEMPERATE CLIMATE		
Land use	Dry	Wet
Tall crop	Physiological Soil moisture	Advection
Short crop	Soil moisture Radiation	Radiation Physiological
TROPICAL CLIMATE		
Land use	Dry	Wet
Tall crop	Soil moisture Tree size	Drop size Physiological
Short crop	Soil moisture	Radiation

Radiation and Physiological Controls

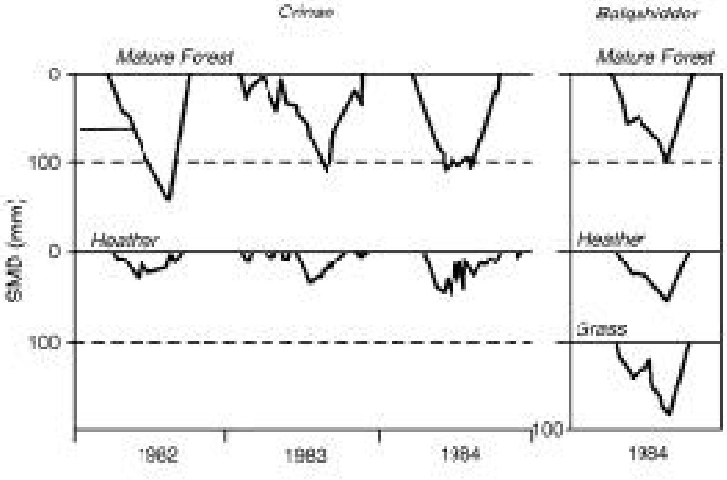
Shorter vegetation is less able to draw on advective energy to augment evaporation rates. For shorter vegetation, aerodynamic roughness is less and evaporation rates are more closely linked to the supply of radiant energy, i.e., they are radiation-limited. Stomatal controls, i.e., physiological controls on transpiration, also become more important. Soil moisture deficits recorded under heather *(Calluna vulgaris)*, grass, and coniferous forest at the Balquhidder and Crinan sites in Scotland are shown in figure 3. Modeling studies indicate (Calder 1990) that at these wet upland sites (annual rainfall 1,500 millimeters), with vegetation growing on generally *deep peaty soils*, soil moisture availability is not usually a limit on evaporation. The differences in the soil moisture deficits under heather and grass are principally a reflection of the increased physiological controls on transpiration imposed

TABLE 2.
Observations of the annual water use and energy balance of wet temperate and wet tropical forests.

Site	Rain (mm)	Transpiration (mm)	Interception (mm)	Total evaporation (mm)	Net radiation (mm equivalent)
Wet Temperate Wales Plynlimon, 1975 (Calder 1978)	2,013	335	529 (26%)	864	617
Wet Tropical Indonesia West Java Aug 80–July 81 (Calder, Wright, and Mudriyaso 1986)	*2,835*	*886*	*595*	1,481±12%	1,543±10%
Wet Tropical Brazil Amazonia, 1984 Reserve Ducke Forest, (Shuttleworth 1988)	2,593	1,030	363 (13%)	1,393	1,514

by heather as compared with grass. The much higher deficits recorded under forest are again a demonstration of the overriding importance of interception in determining forest evaporation in these climates.

FIGURE 3.
Soil moisture deficit (SMD) measured beneath mature spruce forest, heather, and grass moorland at Crinan and Balquhidder.



Source: Calder 1986.

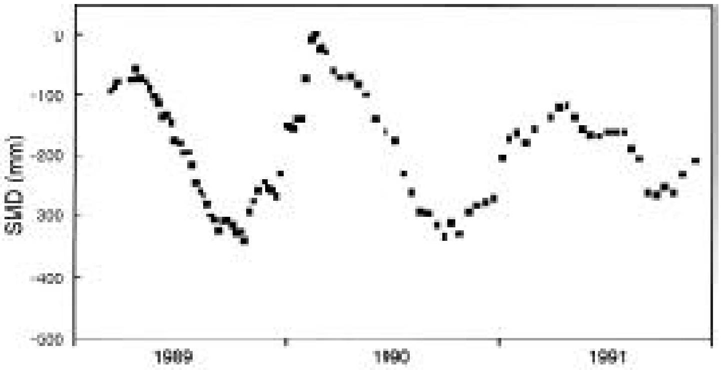
Dry Temperate

Physiological and soil moisture controls

Measurements of the evaporative and soil moisture regime under ash and beech forest in southern England were included as part of an investigation (Harding et al. 1992) into the hydrological impact of increased broadleaf plantations.

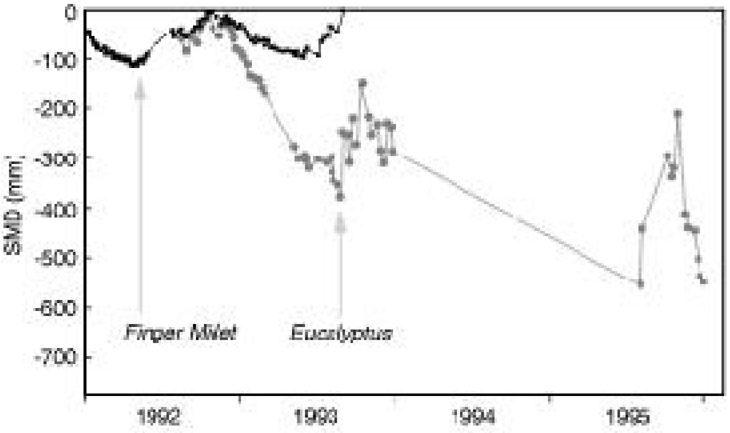
At these sites, evaporation was strongly influenced by physiological controls on transpiration imposed by the trees and soil moisture availability and, to a lesser extent, interception. Differences in available water to the forests were strongly related to soil type. For ash and beech growing on soil overlying chalk, the available soil water was essentially infinite (figure 4), whereas at the clay soil site, the value of the available water parameter was of the order of 280 millimeters. The extent of the physiological controls operating at these sites is the subject of current debate. It was claimed that the controls were sufficient to reduce the total

FIGURE 4.
Observations of soil moisture deficit (SMD) exceeding 350 millimeters under beech on a chalk site: Black Wood, southern England.



Source: Harding et al. 1992.

FIGURE 5.
Soil moisture deficit (SMD) recorded beneath Eucalyptus camaldulensis and Eleusine coracana (finger millet) at the Hosakote site, India.



evaporation from beech forest to a value less than that from grassland—a result unusual in a worldwide context but one, which if correct, has important implications for the water industry in the light of a proposed doubling of lowland UK forests.

Radiation and soil moisture controls

For grassland and other shorter crops, it is generally recognised that *radiation* controls, together with *soil moisture* controls, are the major determinants of evaporation. The Penman approach (Penman 1963), which takes account of the radiation control within the calculation of potential evaporation and the soil moisture control within a "root constant" function, has been shown to be quite adequate for calculating evaporation from short crops in generally dry temperate conditions.

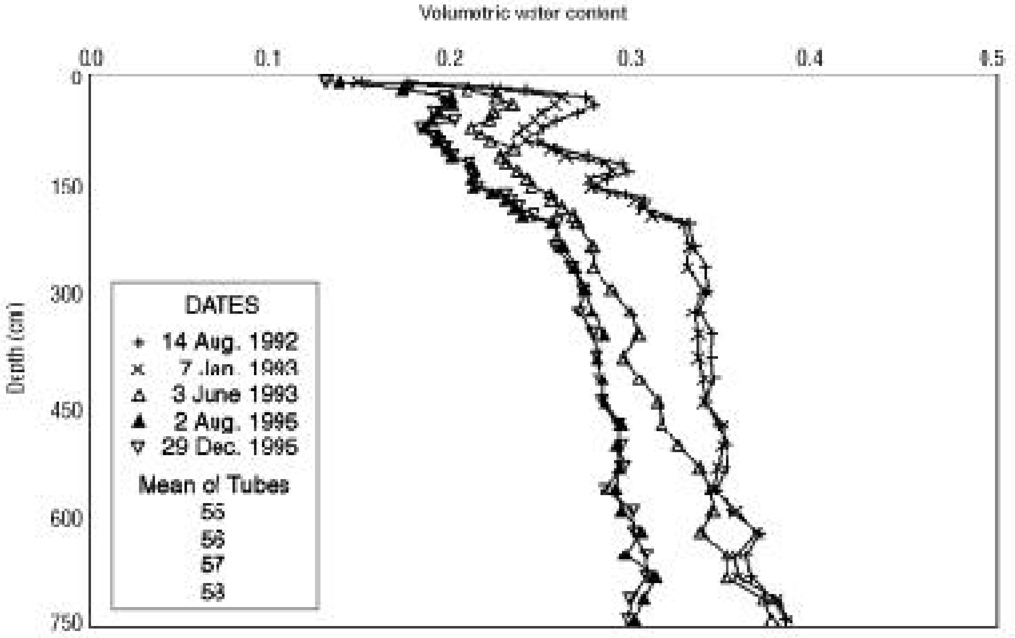
Dry Tropical

Soil moisture controls

As part of a study to investigate the hydrological impact of eucalyptus plantations in the dry zone of Karnataka in southern India, comparative studies were carried out on the evaporative characteristics and soil moisture deficits under eucalyptus plantation, indigenous forests, and agricultural crops. For all of the four experimental sites in different parts of Karnataka where investigations were carried out, *soil moisture* availability was found to be a major limit on evaporation for both agricultural crops and trees. For the annual agricultural crop studied, finger millet (*Eleusine coracana)*, the rooting depth was less than two meters and the available water was found to be 160 millimeters deep. This compares with 390 millimeters for most of the forest sites.

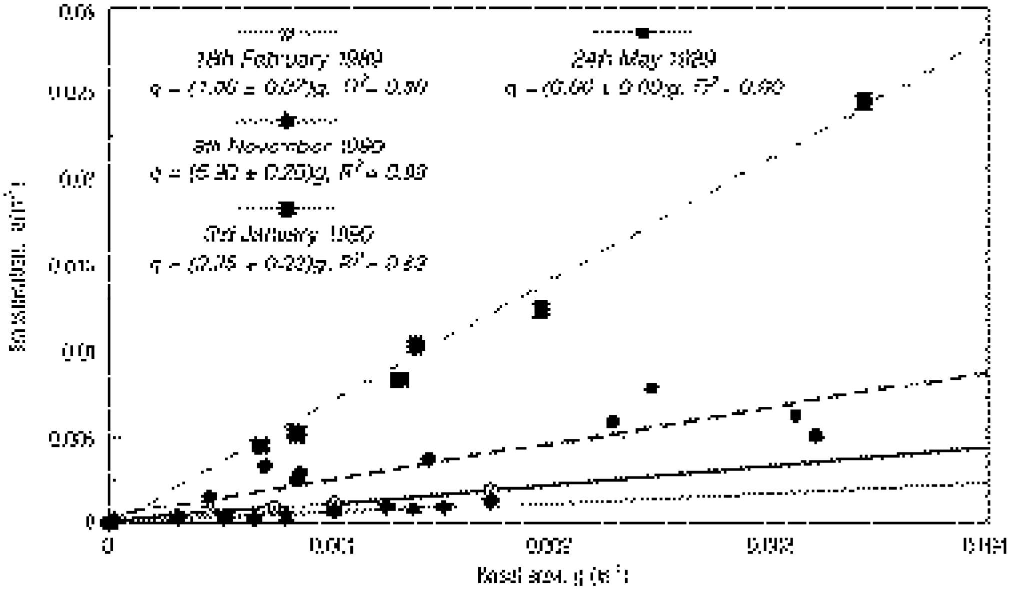
At one of the eucalyptus sites, the Hosakote experimental site of the Karnataka Forest Department, the roots are now known to extend to much greater depths. Recent studies using neutron probe measurement made to a depth of 8 meters on a "farmer's field" experiment (Calder et al. 1997a) have shown that not only can eucalyptus roots reach this depth but they can reach this depth within 3 years of being planted. Together with being able to evaporate essentially all the rainfall that enters the soil, these trees are able to extract

FIGURE 6.
Neutron probe observations of profile volumetric water content beneath Eucalyptus camaldulensis (plot 1) “farmer’s field” experiment, Hosakote, India, from the day of planting in August 1992.



Source: Calder et al. 1997a.

FIGURE 7.
Measured transpiration rates as a function of tree basal area (g) at the Puradal site prior to and after the monsoon (July–September), 1989.



Source: Calder 1992b.

approximately, an additional 100 millimeters of water from each meter depth of soil the roots penetrate. The concept of *soil moisture* availability cannot readily be applied at this site (figures 5 and 6). The deep rooting behavior of *Eucalyptus* species has also been reported in South Africa. Dye (1996) found root abstraction from a depth of 8 meter staking place from *Eucalyptus grandis.*

Reduced *soil moisture* availability was the principal reason why the annual evaporation from agricultural crops was generally about half that from either plantation or indigenous forest.

Tree size

These Indian studies also demonstrated a linear scaling relationship between transpiration rate and basal cross-sectional area (figure 7) for the relatively young plantation trees studied (less than 7 years old).

It would appear that although evaporative demand is clearly the driving mechanism for evaporation, for most of the year, it is not limiting, the primary controls being soil moisture availability and, for the tree crops, some factor relating to tree size. At the dry-zone sites in India, which experience an extended dry season, interception losses, which amount to less than 13 percent of the annual 800 millimeters rainfall, are not important in determining soil moisture deficits and are not a major component of the total evaporation.

The results from semiarid Karnataka, which indicate that evaporation is limited principally by soil water availability and plant physiological controls, are therefore in direct contrast to the observations from the wet uplands of the UK where evaporation is limited principally by atmospheric demand through *advection* and *radiation* controls.

Wet Tropical

Drop size controls

At wetter sites in the tropics, interception is a more significant component of the annual forest evaporation. From studies carried out in rain forest in Indonesia (Calder, Wright, and Mudriyaso 1986), the importance of rain drop size in determining interception losses from tropical forest was first realized. Application of a stochastic interception model, which explicitly took into account drop size, was required to describe the interception process in these conditions. This model shows that up to ten times as much rain may be required to achieve the same degree of canopy wetting for tropical convective storms, with large drop sizes, than would be necessary for the range of smaller drop sizes usually encountered for frontal rain in the UK. There are also results from studies using rainfall simulators, which show that the final degree of canopy saturation also varies with drop size, being greater for drops of smaller size.

Vegetation canopies also influence the drop size of the net rainfall; deeper layers in the canopy will be more influenced by the modified drop size spectrum falling from canopy layers above, than by that of the incident rain. Recent studies have shown that different vegetation canopies have very distinct canopy spectra (Hall and Calder 1993). For canopies with a low leaf area index, the interception characteristics would therefore be expected to be related more to the drop size of the incident rain, whereas for canopies with higher leaf area index, the characteristics would be less dependent on the drop size of the rainfall.

The advantages to be gained by incorporating the drop size dependence in interception models for use in tropical conditions were demonstrated by Hall and colleagues

(Hall et al. 1996) for a tropical forest site in Sri Lanka. The performance of the two layer stochastic interception model (Calder 1996b; Calder et al. 1996), which explicitly takes into account drop size, was very much better than conventional interception models in describing the initial wetting up phase of the storm, and hence the overall interception loss (Rutter et al. 1971). The drop size dependence of canopy wetting provides part of the reason why forest interception varies so much worldwide, and why interception losses from coniferous temperate forests are so much higher than from tropical forests (table 2). The model shows that canopy wetting will be achieved most rapidly and maximum canopy storage will be highest, leading to high interception losses overall, when the volumes of individual raindrops and drops draining from the canopy are small. These conditions apply for coniferous forests in the low intensity, small rain drop size climate of the uplands of the UK. By contrast, when both individual raindrop volumes and leaf drop volumes are large, canopy wetting will be achieved much more slowly, the final degree of canopy saturation will be less, and interception losses are likely to be much reduced. This situation is typified by tropical rain forest experiencing high intensity convective storms of large drop size.

Radiation limit

The wet evergreen forests of the tropics represent another situation where climatic demand is likely to limit forest evaporation. However, climate circulation patterns in the tropics do not favor large-scale advection of energy to support evaporation rates and here evaporation rates are likely to be closely constrained by the availability of solar radiation (table 2). As humid rain forest is able to convert, on an annual basis, virtually the equivalent of all the net radiation into evaporation, it is unlikely that any other land use will be able to evaporate at a higher rate. Conversion of forest to annual crops in these areas as well as in most other areas of the world is likely to result in increased annual streamflows.

Models based on the “limits” concept have now been applied for assessing forest impacts on water resources in both wet and dry climates of the world. Wet climate applications, where interception loss predominates, include studies in the uplands of Scotland (Price et al. 1995) and in New Zealand (Calder 1996a), on the Otago catchments (Fahey and Jackson 1997; Fahey and Watson 1991) of the South Island. Dry climate applications include a study, reviewed below, of how land use change in Malawi (southern Africa) has altered the water balance of Lake Malawi (Calder et al. 1995) and a regional study extending the Malawi study, through the use of GIS technology, to the Zambezi basin (Price et al. 1998). More recently, attempts have been made to make use of this knowledge for Integrated Water Resources Management by incorporating land-use evaporation models within Decision Support Systems.

Applications: Integrated Water Resources Management

Following the United Nations Conference for the Environment and Development (UNCED) held in Rio de Janeiro in 1990, most nations subscribed to the new principles that were established for the integrated management of land and water (see box).

An understanding of how land use and land-use change affect water resources is one component of the knowledge base required in applying principles of Integrated Water Resources Management. But this knowledge needs to be applied in the context of how land use and land-use change will also affect the environment, equity, the socioeconomics, and economics of basin inhabitants and ecological systems.

Some illustrations of the application of land-use evaporation models are described below together with suggestions as to how this knowledge can be incorporated within Decision Support Systems for implementing IWRM principles.

Lake Malawi Case Study

The level of Lake Malawi has undergone very considerable changes over the last 100 years. Various explanations have been put forward to account for these changes, including tectonic movement, blockage of the lake outlet, and linkages with sunspot cycles.

A water balance modeling study was carried out to determine the cause of these changes and to determine to what extent these changes in level might have been the result of land-use changes, the most significant of which has been the clearance of the dry deciduous miombo woodland for rainfed agriculture.

The model has been described in detail in an earlier paper (Calder et al. 1995). The evaporative component of the model considers the catchment to be composed of one of three surface types—forest, agricultural land, or water surface. The values for the model parameters relating to forests and agricultural crops were determined from the land-use evaporation studies carried out in India.

Using recorded rainfall data for the last 100 years, and assuming that the present relationship between lake level and the flow from the lake (the stage-discharge relationship) has been applied for the whole of this period, the model was operated to generate predicted lake levels. From 1896 to 1967, most of the major fluctuations in level, both seasonally and annually were well described (apart from a period in the 1930s when the stage-discharge relationship for the lake may have been affected following the prolonged period of no outflow in the early part of the century) by this model by using a value of 64 percent for the forest coverage of the catchment (figures 8 and 9). The overall agreement between prediction and observation indicates that variations in rainfall alone, without any other changes in either evaporative demand or the hydraulic regime of the lake, were sufficient to explain lake level changes during this period.

For the more recent period, model predictions that take into account a decrease in

Concepts and Principles of Integrated Water Resources Management

Integrated Water Resources Management (IWRM) involves the coordinated planning and management of land, water, and other environmental resources for their equitable, efficient, and sustainable use. IWRM programs need to be developed alongside, and not in isolation from, World Bank-encouraged Economic Structural Adjustment Programs and other sectoral programs. For IWRM strategies to be implemented, fragmentation of institutional responsibilities must be reduced.

IWRM objectives encompass the UNCED principles:

- Water has multiple uses, and water and land must be managed in an integrated way.
- Water should be managed at the lowest appropriate level.
- Water allocation should take account of the interests of all who are affected.
- Water should be recognized and treated as an economic good.

IWRM strategies seek to ensure:

- A long-term, viable economic future for basin dependents (both national and trans-national).
- Equitable access to water resources for basin dependents.
- The application of principles of demand management and appropriate pricing policies to encourage efficient usage of water between the agricultural, industrial, and urban supply sectors.
- In the short term, the prevention of further environmental degradation and, in the longer term, the restoration of degraded resources.
- The safeguarding of local cultural heritage and the local ecology as they relate to water management and the maintenance and encouragement of the potential for water-related tourism together with linkages between tourism and conservation.

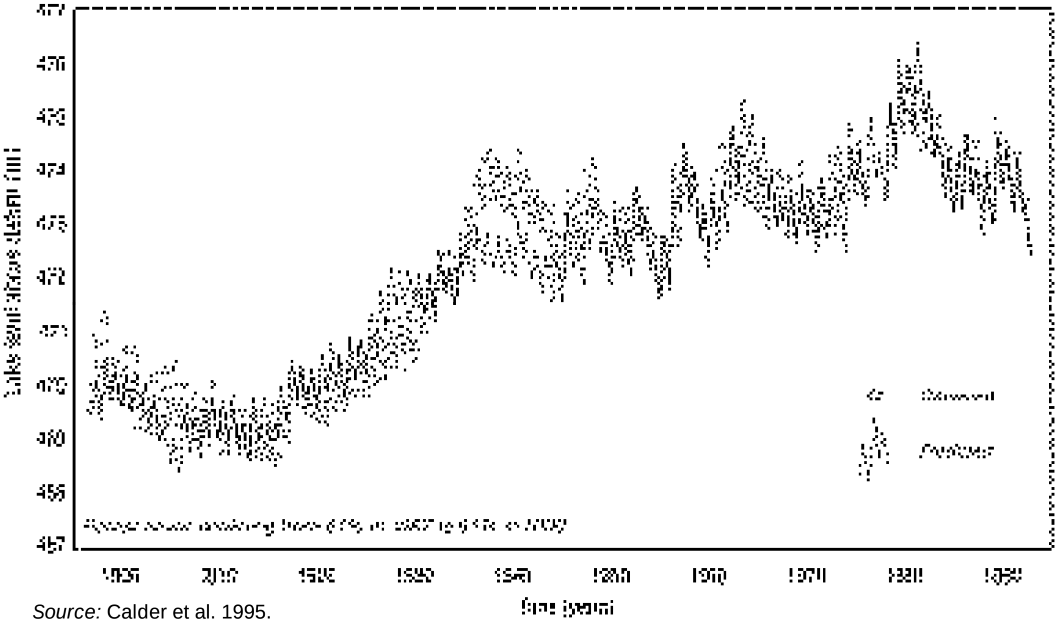
IWRM strategies should recognize that:

- Solutions must focus on underlying causes, not merely on their symptoms.
- Issues must be approached in an integrated way.
- In general, development of sound resource management and collective responsibility for resources will take place at the subregional or village level.

IWRM implementation programs should:

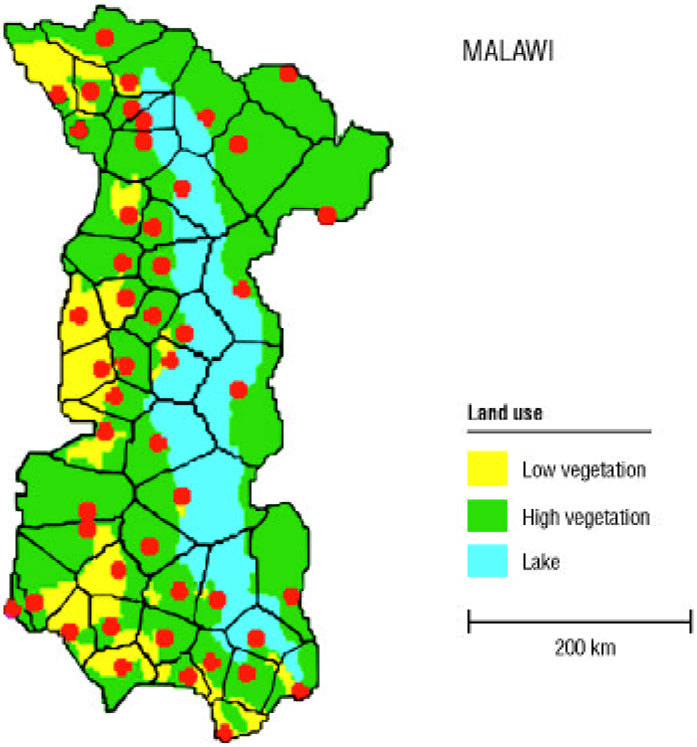
- Comprise an overall strategy that clearly defines the management objectives, a range of delivery mechanisms that enable these objectives to be achieved, and a monitoring schedule that evaluates program performance.
- Recognize that the development of Water Resources Management Strategies may require research to assess the resource base and, through the use of models and the development of Decision Support Systems, to determine the linkages between water resources development and the impacts on the environment, socioeconomics, equity, and ecology.
- Ensure that mechanisms and policies are established that enable long-term support to programs of environmental recovery.

FIGURE 8.
Changes in level of Lake Malawi—observed and predicted.



Source: Calder et al. 1995.

FIGURE 9.
Locations of rain gauges (used with the GIS version of the HYLUC model) and vegetation types on the Lake Malawi catchment.



forest cover of 13 percent over the period 1967 to 1990 (consistent with measurements of the decrease in forest cover for this period) agree well with both annual and seasonal observations. Without this decrease in forest cover, it is predicted that the lake level would have been almost 1 meter lower than that actually observed before the onset of the southern African drought of 1992. As the country is reliant on the lake for hydropower generation, fisheries, tourism, and transport, any further lowering of the lake level would have caused much more serious disruption, implying a significant benefit to water resources by the removal of the miombo woodland.

The model has also been used, in association with the development of a Water Resources Management Strategy for Malawi, to investigate how proposed irrigation developments would affect the water balance of the lake and lake level (Calder and Bastable 1995).

This modeling methodology has recently been extended through the use of GIS methods to allow the convolution of rainfall and climate patterns with patterns of land use both in Sri Lanka, the lowlands of the UK (Calder et al. 1997b), and in the Zambezi basin (Price et al. 1998). For the Zambezi basin, the change in mean annual runoff (MAR) expected as a result of a 1 percent reduction in the natural forest cover of the major sub-catchments ranges from zero for the Rioc (where MAR is zero) to 3.33 millimeters for Malawi (table 3).

These GIS developments should provide not only more accurate predictions of the hydrological impacts of land-use change but also a more general modeling approach for investigating forest and land-use impacts problems worldwide.

A general feature of these studies is that the conversion of indigenous forest to rainfed agriculture, whether in the wet or dry climatic regions of the world, is likely to result in an increase in annual runoff. Recognition of the impacts of land-use change is therefore important in both assessing and managing freshwater resources, whether at the local or regional scale.

TABLE 3.
Average change in mean annual runoff expected as a result of clearance of the natural forest for rain-fed agriculture on the major sub-catchments of the Zambezi.

Sub-catchments of the Zambezi	Catchment area (km^2)	Increase in mean annual runoff for a 1% reduction in natural forest cover (mm)
Lungwebungo, Kabombo, and tributaries	29,7938	2.87
Chobe	13,3593	0
Kariba (tributaries between Victoria Falls and Kariba dam)	22,3364	0.74
Kafue	15,7638	2.66
Luangwa	14,9438	2.86
Shire	15,7231	3.33
Lower Zambezi	23,7393	2.05

Source: Price et al. 1998.

Decision Support Systems (DSS)—Socioeconomics and Ecology

Although a great deal of thought and effort underlies the development of the UNCED principles and paramount importance is attached to them by governments and UN agencies, much less thought has been given as to how these principles can actually be implemented. Local agencies and organizations entrusted with their implementation are largely at a loss when it comes to knowing how to put implementing procedures in place. This is a problem not only for the developing world but also for the developed

Decision Support Systems—an Aid to Strategy Development

DSS can assist strategy developers by:

1. Defining the problem
2. Generating alternative solutions
3. Evaluating the alternatives
4. Indicating the best for implementation

Example application: What is the best water pricing policy to adopt?

1. ***Defining the problem:*** Consider what interests (stakeholders) will be affected?

* Basin economics?
* Equity?
* Environment?
* Ecology?
* Trans-national interests?
* Other?

- Consider the linkages?
- Construct "model" in DSS

2. **Generating alternative solutions:** Run "model" in DSS for different pricing policy scenarios and calculate impacts on "stakeholders."

3. **Evaluating alternatives:**

- ***Consider impacts in relation to each stakeholder***
- Consult with stakeholders
- Look for "incremental change" solutions
- Look for 'satisficing' solution rather than optimum

4. **Indicating the best for implementation:**

- Include "preferred" option in strategy

world where concepts such as stakeholder participation and demand management are still relatively new. Decision Support Systems have a role to play here. They not only provide mechanisms for testing the impacts of water resources management strategies on stakeholder interests (equity, environmental, ecological, and socioeconomic impacts), but also assist water resources managers by providing a focusing framework for defining stakeholder issues and interrelationships (O'Connell 1995).

Two "milestone" publications relating to DSS are the Journal of Hydrology, special issue, Volume 177, April 1966, and the book describing the results of the Natural Environment and Economic and Social Research Councils Land-Use Programme (NELUP) project (O'Callaghan 1996). NELUP was an innovative program designed to investigate, using modeling methodologies, the interactions between land use and economics, and ecology (O'Callaghan 1995). These publications describe both the ethos and philosophy underlying the DSS systems and describe "off the shelf" systems for immediate application.

Two of these, the "WaterWare" decision support system for river-basin planning (Jamieson and Fedra 1996) and the NELUP decision support system (O'Callaghan 1995), which relates more to the economic, environmental, and ecological issues relating to land-use change and water-resources planning, are now operational systems that have been tested in UK conditions. Although these systems have not so far been applied worldwide, their structure is sufficiently general for their usage in both the developed and developing world. These systems are also currently being developed to run on PC as well as Unix platforms (on which they were originally developed), which will make them more suitable in developing world environments. Developments are also planned to combine the components of these two systems together with the inclusion of a "limits concept land use" type evaporation models. This would allow the construction of "bespoke" systems, tailored to a particular country's needs. With economic, environmental, ecological, and water resources components built into these models, which truly reflect the particular developments within a basin, the catchment planner or agency responsible for planning developments will have the tools to hand to assist with the implementation of the UNCED principles.

Literature Cited

Abbott, M. B., J. C. Bathurst, J. A. Cunge, P. E. O'Connell, and J. Rasmussen. 1986. An introduction to the European Hydrological System – System Hydrologique Europeen (SHE) 1: History and philosophy of a physically-based, distributed modelling system. *Journal of Hydrology* 87: 45–59.

Bands, D. P., J. M. Bosch, A. J. Lamb, D. M. Richardson, B. W. Van Wilgen, D. B. Van Wyk, and D. B. Versfeld. 1987. Jonkershoek Forestry Research Centre Pamphlet 384. Private Bag X447 Pretoria 0001. Department of Environment Affairs.

Bell, J. P. 1976. *Neutron probe practice*. Institute of Hydrology Report No. 19. Wallingford, UK: Institute of Hydrology.

Blythe, E. M., A. J. Dolman, and J. Noilhan. 1994. The effect of forest on mesoscale rainfall: An example from HAPEX-MOBILHY. *Journal of Applied Meteorology* 33: 445–454.

Bosch, J. M. 1979. Treatment effects on annual and dry period streamflow at Cathedral Peak. *South African Forest Journal* 108: 29–38.

Bosch, J. M. and J. D. Hewlett. 1982. A review of catchment experiments to determine the effects of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55: 3–23.

Bouten, W., P. J. F. Smart, and E. De Water. 1991. Microwave transmission, a new tool in forest hydrological research. *Journal of Hydrology* 124: 119–130.

Brandt, J. 1989. The size distribution of throughfall drops under vegetation canopies. *Catena* 16: 507–524.

Bruijnzeel, L. A. 1990. *Hydrology of moist tropical forests and effects of conversion: A state of knowledge review.* UNESCO International Hydrological Programme. Paris: UNESCO.

Calder, I. R. 1978. Transpiration observations from a spruce forest and comparison with predictions from an evaporation model. *Journal of Hydrology* 38: 33–47.

Calder, I. R. 1986. The influence of land use on water yield in upland areas of the U.K. *Journal of Hydrology* 88: 201–212.

Calder, I. R. 1990. *Evaporation in the uplands.* Chichester: John Wiley & Sons Ltd.

Calder, I. R. 1991. Implications and assumptions in using the total counts and convection-dispersion equations for tracer flow measurements - with particular reference to transpiration measurements in trees. *Journal of Hydrology* 125: 149–158.

Calder, I. R. 1992a. Hydrologic effects of land-use change, ed. in chief D.R. Maidment. *Handbook of Hydrology* 13.1–13.50.

Calder, I. R. 1992b. A model of transpiration and growth of Eucalyptus plantation in water-limited conditions. *Journal of Hydrolology* 130: 1–15.

Calder, I. R. 1996a. Water use by forests at the plot and catchment scale. *Commonwealth Forestry Review* 75(1): 19–30.

Calder, I. R. 1996b. Dependence of rainfall interception on drop size: 1. Development of the two-layer stochastic model. *Journal of Hydrology* 185: 363–378.

Calder, I. R. and H. G. Bastable. 1995. *Comments on the Malawi Government Water Resources Management Policy and Strategies.* Report to ODA. Wallingford, UK: Institute of Hydrology.

Calder, I. R., R. L. Hall, H. G. Bastable, H. M. Gunston, O. Shela, A. Chirwa, and R. Kafunda. 1995. The impact of land use change on water resources in sub-Saharan Africa: A modelling study of Lake Malawi. *Journal of Hydrology* 170: 123–135.

Calder, I. R., R. L. Hall, and K. T. Prasanna. 1993. Hydrological impact of *Eucalyptus* plantation in India. *Journal of Hydrology* 150: 635–648.

Calder, I. R., R. L. Hall, P. T. W. Rosier, H. G. Bastable, and K. T. Prasanna. 1996. Dependence of rainfall interception on drop size: 2. Experimental determination of the wetting functions and two-layer stochastic model parameters for five tropical tree species. *Journal of Hydrology* 185: 379–388.

Calder, I. R., I. Reid, T. Nisbet, and M. R. Robinson. 1997b. *Trees and Drought Project on Lowland England.* Project proposal to the Department of the Environment. Wallingford, UK: Institute of Hydrology.

Calder, I. R. and P. T. W. Rosier. 1976. The design of large plastic sheet net-rainfall gauges. *Journal of Hydrology* 30: 403–405.

Calder, I. R., P. T. W. Rosier, K. T. Prasanna, and S. Parameswarappa. 1997a. *Eucalyptus* water use greater than rainfall input – a possible explanation from southern India. *Hydrology and Earth Systems Sciences* 1(2): 249–256.

Calder, I. R. and I. R. Wright. 1986. Gamma-ray attenuation studies of interception from Sitka spruce: Some evidence for an additional transport mechanism. *Water Resoures Research* 22: 409–417.

Calder, I. R., I. R. Wright, and D. Murdiyarso. 1986. A study of evaporation from tropical rainforest—West Java. *Journal of Hydrology* 89: 13–33.

Chapman, G. 1948. Size of raindrops and their striking force at the soil surface in a red pine plantation. *Eos Transactions of the American Geophysical Union* 29: 664–670.

Cohen, Y., M. Fuchs, and G. C. Green. 1981. Improvement of the heat pulse method for determining sap flow in trees. *Plant, Cell and Environment* 4:391–397.

Dye, P. J. 1996. Climate, forest and streamflow relationships in South African afforested catchments. *Commonwealth Forestry Review* 75 (1): 31–38.

Dyer, A. J. 1961. Measurements of evaporation and heat transfer in the lower atmosphere by an automatic eddy correlation technique. *Quarterely Journal of Royal Meteorological Soceity* 87: 401–412.

Ewen, J., G. Parkin, and P. E. O'Connell. 1997. SHETRAN: A coupled surface/subsurface modelling system for 3D water flow and sediment and solute transport in river basins. Under consideration for *Water Resources Research*.

Fahey, B. D. and R. Jackson. 1997. Hydrological impacts of converting native forests and grasslands to pine plantations, South Island, New Zealand. *Agricultural and Forest Meteorology* 84: 69–82.

Fahey, B. D. and A. J. Watson. 1991. Hydrological impacts of converting tussock grasslands to pine plantation, Otago, New Zealand. *Journal of Hydrology (N.Z.)* 30: 1–15.

Hall, R. L. and I. R. Calder. 1993. Drop size modification by forest canopies - measurements using a disdrometer. *Journal of Geophysical Research* 90: 465–470.

Hall, R. L., I. R. Calder, E. R. N. Gunawardena, and P. T. W. Rosier. 1996. Dependence of rainfall interception on drop size: 3. Implementation and comparative performance of the stochastic model using data from a tropical site in Sri Lanka. *Journal of Hydrology* 185: 389-407.

Hamilton, L. S. 1987. What are the impacts of deforestation in the Himalayas on the Ganges-Brahmaputra lowlands and delta? Relations between assumptions and facts. *Mountain Research and Development* 7: 256–263.

Harding, R. J., R. L. Hall, C. Neal, J. M. Roberts, P. T. W. Rosier, and D. K. Kinniburgh. 1992. *Hydrological impacts of broadleaf woodlands: Implications for water use and water quality.* British Geological Survey Project Report 115/03/ST and 115/04/ST for the National Rivers Authority. IH, Wallingford, UK: Institute of Hydrology.

Hewlett, J. D. and J. M. Bosch. 1984. The dependence of storm flows on rainfall intensity and vegetal cover in South Africa. *Journal of Hydrology* 75: 365–381.

Hewlett, J. D. and J. D. Helvey. 1970. Effects of forest clearfelling on the storm hydrograph. *Water Resources Research* 6 (3): 768–782.

Institute of Hydrology. 1994. *Amazonia: Forest, pasture and climate - results from ABRACOS.* Wallingford, UK: Institute of Hydrology.

Jamieson, D. G. and K. Fedra. 1996. The 'WaterWare' decision-support system for river-basin planning. 1. Conceptual design. *Journal of Hydrology* 177: 163–175.

Johnson, R. C. 1995. *Effects of upland afforestation on water resources: The Balquhidder experiment 1981-1991*. Institute of Hydrology Report No. 116, pp.73. Wallingford, UK: Institute of Hydrology.

Kirby, C., M. D. Newson, and K. Gilman. 1991. *Plynlimon research: The first two decades*. Institute of Hydrology Report No.109. Wallingford, UK: Institute of Hydrology.

Kline, J. R., J. R. Martin, C. F. Jordan, and J. J. Koranda. 1970. Measurement of transpiration in tropical trees with tritiated water. *Ecology* 51:1068–1073.

Langford, K. J. 1976. Change in yield of water following a bushfire in a forest of *Eucalyptus regnans. Journal of Hydrology* 29: 87–114.

Luvall, J. R. and C. E. Murphy. 1982. Evaluation of the tritiated water method for measurement of transpiration in young *Pinus taeda* L. *Forest Science* 28: 5–16.

Meher-Homji, V. M. 1980. Repercussions of deforestation on precipitation in Western Karnataka, India. *Aech. Met. Geogph. Biokl.,* Series B 28: 385-400.

O'Callaghan, J. R. 1995. NELUP: An introduction. *Journal of Environmental Planning and Management* 38(1) 16pp.

O'Callaghan, J. R. 1996. *Land use. The interaction of economics, ecology and hydrology.* London, UK: Chapman & Hall.

O'Connell, P. E. 1995. *Capabilities and limitations of regional hydrological models.* Keynote Paper. "Scenario Studies for the Rural Environment," (143–156). The Netherlands: Kluwer Academic Publishers.

Olszycka, B. 1979. Gamma-ray determinations of surface water storage and stem water content for coniferous forests. Ph.D. Thesis. Scotland: Department of Applied Physics, University of Strathclyde.

Ong, C. K., J. C. W. Odango, F. Marshall, and C. R. Black. 1991. Water use by trees and crops. Five hypotheses. *Agroforestry Today* April-June: 7–10.

Pearce, A. J. 1986. *Erosion and sedimentation*. Working paper. Honolulu, Hawaii: Environment and Policy Institute.

Penman, H. L. 1963. *Vegetation and hydrology*. Technical communication 53. Harpenden: Commonwealth Bureau of Soils.

Pereira, H. C. 1989. *Policy and practice in the management of tropical watersheds.* Boulder, Colorado, USA: Westview Press.

Price, D. J., I. R. Calder, and R. C. Johnson. 1995. *Modelling the effect of upland afforestation on water resources.* Institute of Hydrology report to the Scottish Office. Wallingford, UK: Institute of Hydrology.

Price, D. J., I .R. Calder, O. Shela, A. Chirwa, and H. Williams. 1998. Investigation into the impact of changing forest cover upon the water resources of the Zambezi Basin. Submitted to *Tree Physiology*.

Roberts, J. M. 1977. The use of "tree cutting" techniques in the study of the water relations of mature *Pinus* sylvestris L.: 1. The technique and survey of the results. *Journal of Experimental Botany* 28: 751–767.

Roberts, J. M. 1978. The use of the "tree cutting" technique in the study of the water relations of Norway spruce (Picea abies (L.) Karst.). *Journal of Experimental Botany* 29:465–471.

Robinson, M., R. E. Moore, and J. R. Blackie. 1997. *From moorland to forest: The Coalburn catchment experiment.* Institute of Hydrology and Environment Agency Report. Wallingford, UK: Institute of Hydrology.

Rowntree, P. R. 1988. Review of general circulation models as a basis for predicting the effects of vegetation change on climate. In *Forests, Climate and Hydrology: Regional impacts,* pp.162–192, ed. E. R. C. Reynolds and F. B. Thompson. UK: Kefford Press.

Rutter, A. J., K. A. Kershaw, P. C. Robins, and A. J. Morton. 1971. A predictive model of rainfall interception in forests 1: Derivation of the model from observations in a plantation of Corsician pine. *Agricultural Meteorology* 9:367–384.

Scott, D. F. and R. E. Smith. 1997. Preliminary empirical models to predict reduction in total and low flows resulting from afforestation. *Water S.A* 23: 135–140.

Shuttleworth, W. J. 1988. Evaporation from Amazonian Rainforest. *Proceedings of the Royal Soceity of London.* B. 233:321–346.

Taylor, C. H. and A. J. Pearce. 1982. Storm runoff processes and sub-catchments characteristics in a New Zealand hill country catchment. *Earth Surface Processes and Landforms* 7:439–447.

U. S. Department of Agriculture, Agricultural Research Service. 1961. *A universal equation for predicting rainfall-erosion losses.* USDA-ARS Special Report 22–6.

Van Lill, W. S., F. J. Kruger, and D. B. Van Wyk. 1980. The effects of afforestation with *Eucalyptus grandis* Hill ex Maiden and *Pinus patula* Schlecht. Et Cham. On streamflow from experimental catchments at Mokobulaan, Transvaal. *Journal of Hydrology* 48:107–118.

Versfeld, D. B. 1981. Overland flow on small plots at the Jonkershoek Forestry Research Station. *South African Forestry Journal* 119:6pp.

Xue,Y. 1997. Biosphere feedback on regional climate in tropical north Africa. *Quarterly Journal of the Royal Meteorological Society* 123:1483–1515.

SWIM Papers

1. *Accounting for Water Use and Productivity.* David Molden, 1997.

2. *How to Manage Salinity in Irrigated Lands: A Selective Review with Particular Reference to Irrigation in Developing Countries.* Jacob W. Kijne, S.A. Prathapar, M.C.S. Wopereis, and K.L. Sahrawat, 1998.

3. *Water-Resource and Land-Use Issues.* I.R. Calder, 1998.

INTERNATIONAL WATER MANAGEMENT INSTITUTE
P O Box 2075 Colombo, Sri Lanka
Tel (94-1) 867404 • Fax (94-1) 866854 • E-mail IIMI@cgnet.com
Internet Home Page http:/ /www.cgiar.org/iimi

CGIAR

ISBN 92-9090-361-9

ISSN: 1028-6705