

# ASB Lecture Note 7

## Forest watershed functions and tropical land use change

Pendo Maro Susswein, Meine van Noordwijk and Bruno Verbist



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# Towards integrated natural resource management in forest margins of the humid tropics: local action and global concerns

Meine van Noordwijk, Sandy Williams and Bruno Verbist (Editors)

Humanity stands at a defining moment in history. We are confronted with a perpetuation of disparities between and within nations, a worsening of poverty, hunger, ill health and illiteracy, and the continuing deterioration of the ecosystems on which we depend for our well-being. However, integration of environment and development concerns and greater attention to them will lead to the fulfilment of basic needs, improved living standards for all, better protected and managed ecosystems and a safer, more prosperous future. No nation can achieve this on its own; but together we can - in a global partnership for sustainable development. (Preamble to the United Nations' Agenda21 on Sustainable Development; <http://www.un.org/esa/sustdev/agenda21chapter1.htm>).

## Background to this series of lecture notes

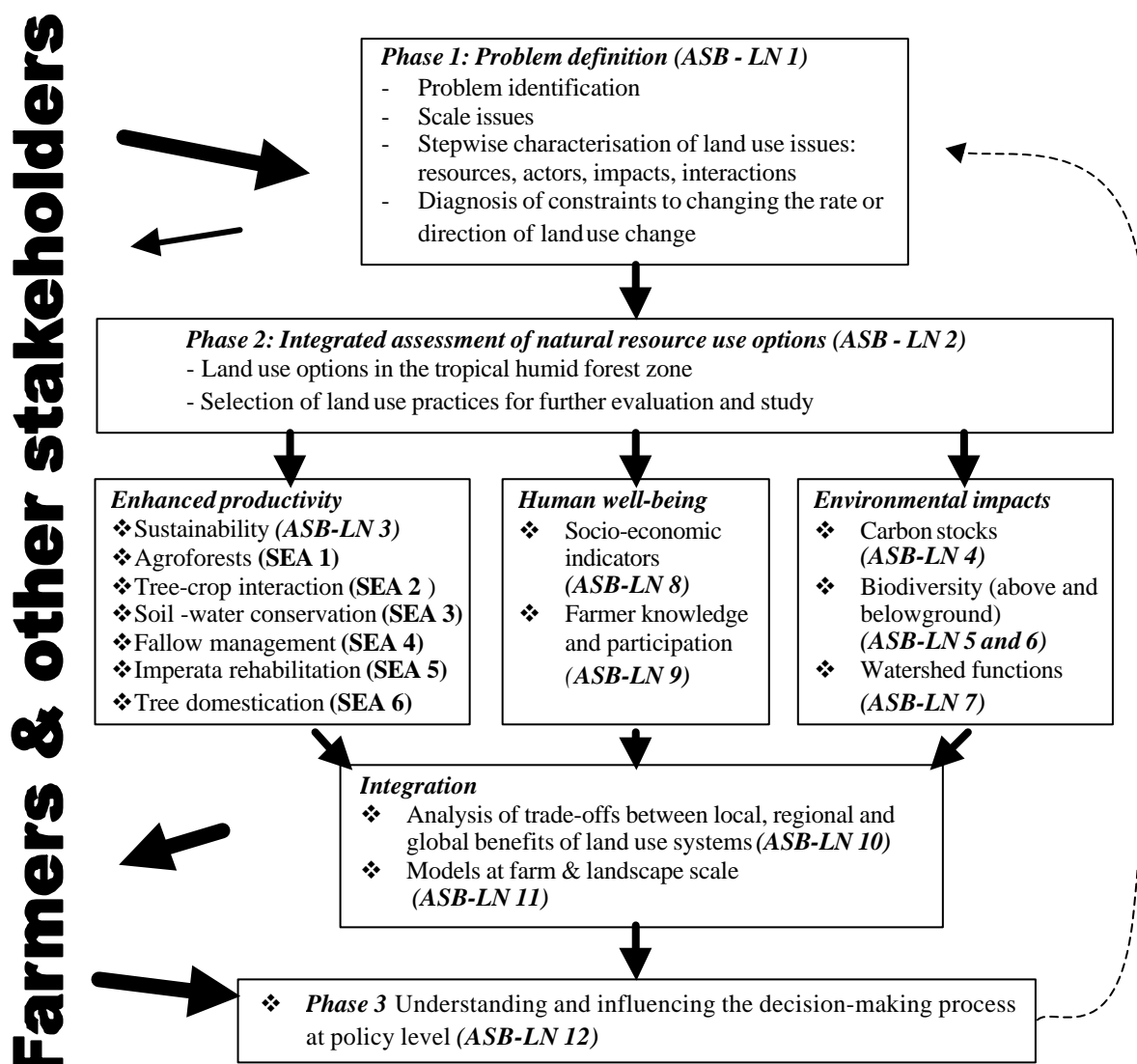
Much of the international debate on natural resource management in the humid tropics revolves around forests, deforestation or forest conversion, the consequences it has and the way the process of change can be managed. These issues involve many actors and aspects, and thus can benefit from many disciplinary perspectives. Yet, no single discipline can provide all the insights necessary to fully understand the problem as a first step towards finding solutions that can work in the real world. Professional and academic education is still largely based on disciplines – and a solid background in the intellectual capital accumulated in any of the disciplines is of great value. If one wants to make a real contribution to natural resource management issues, however, one should at least have some basic understanding of the contributions other disciplines can make as well. Increasingly, universities are recognising the need for the next generation of scientists and policymakers to be prepared for interdisciplinary approaches. Thus, this series of lecture notes on integrated natural resource management in the humid tropics was developed.

The lecture notes were developed on the basis of the experiences of the Alternatives to Slash and Burn (ASB) consortium. This consortium was set up to gain a better understanding of the current land use decisions that lead to *rapid* conversion of tropical forests, shifting the forest margin, and of the *slow* process of rehabilitation and development of sustainable land use practices on lands deforested in the past. The consortium aims to relate local activities as they currently exist to the global concerns that they raise, and to explore ways by which these global concerns can be more effectively reflected in attempts to modify local activities that stabilise forest margins.

The Rio de Janeiro Environment Conference of 1992 identified deforestation, desertification, ozone depletion, atmospheric CO<sub>2</sub> emissions and biodiversity as the major global environmental issues of concern. In response to these concerns, the ASB consortium was formed as a system-wide initiative of the Consultative Group on International Agricultural Research (CGIAR), involving national and international research institutes. ASB's objectives are the development of improved land-use systems and policy recommendations capable of alleviating the pressures on forest resources that are associated with slash-and-burn agricultural techniques. Research has been mainly concentrated on the western Amazon (Brazil and Peru), the humid dipterocarp forests of Sumatra in Indonesia, the drier dipterocarp forests of northern Thailand in mainland

Southeast Asia, the formerly forested island of Mindanao (the Philippines) and the Atlantic Congolese forests of southern Cameroon.

The general structure of this series is



This latest series of ASB Lecture Notes (**ASB-LN 1 to 12**) enlarges the scope and embeds the earlier developed ICRAF-SEA lecture notes (**SEA 1-6**) in a larger framework. These lecture notes are already accessible on the website of ICRAF in Southeast Asia: <http://www.icraf.cgiar.org/sea>

In this series of lecture notes we want to help young researchers and students, via the lecturers and professors that facilitate their education and training, to grasp natural resource management issues as complex as that of land use change in the margins of tropical forests. We believe that the issues, approaches, concepts and methods of the ASB program will be relevant to a wider audience. We have tried to repackage our research results in the form of these lecture notes, including non-ASB material where we thought this might be relevant. The series of lecture notes can be used as a basis for a full course, but the various parts can also 'stand alone' in the context of more specialised courses.

## Acknowledgements

A range of investors (or ‘donors’) have made the work of the ASB consortium possible over the past years, some by supporting specific parts of the program, others by providing core support to the program as a whole. These lecture notes build on all these investments, but were specifically supported by the ASB Global Steering Group, with funds provided by the Asian Development Bank, the World Bank via the CGIAR, by ICRAF core funds, by the Netherlands' Government through the Direct Support to Training Institutions in Developing Countries Programme (DSO)-project and by the Flemish Office for Development Cooperation and Technical Assistance (VVOB). Both biophysical and policy research was supported by a Regional Technical Assistance Grant from the Asian Development Bank. Many researchers and organisations have contributed to the development of ideas, collection and synthesis of data, and otherwise making the program what it is today. A team at the International Centre for Research in Agroforestry (ICRAF), consisting of Kurniatun Hairiah, Pendo Maro Susswein, Sandy Williams, SM Sitompul, Marieke Kragten, Bruno Verbist and Meine van Noordwijk developed these lecture notes. A first test of their suitability was provided by a course on ‘Ecology for Economists’ organised by the Economy and Environment Program for Southeast Asia (EEPSEA) program – we thank David Glover, Hermi Francisco and all participants to that course for their suggestions. Key researchers within the consortium provided support and agreed to act as co-authors on the various chapters. Editorial comments on draft forms of the various lecture notes were obtained from Fahmuddin Agus, Georg Cadisch, Min Ha Fagerström, Merle Faminow, Roeland Kindt, Chun Lai, Ard Lengkeek, Jessa Lewis, Chin Ong, Per Rudebjer, Goetz Schroth, Douglas Sheil, Fergus Sinclair, Sven Wunder and others. Overall responsibility for any shortcomings in the lecture notes remains with the editorial team.

## ASB-consortium members

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## Lecture Note 7

# FOREST WATERSHED FUNCTIONS AND TROPICAL LAND USE CHANGE

By Pendo Maro Susswein, Meine van Noordwijk and Bruno Verbist

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# I. Objectives

- to challenge a popular paradigm relating to the role of forests in watershed functions
- to illustrate how various watershed functions relate to the water balance
- bring an understanding of the interaction between land use/land cover change and watershed functions

## II. Lecture

### 1. Introduction

World-wide there is mounting interest in the relationship between land use and water resources. This has come about mainly because most developing (and developed) countries are experiencing a degradation of land and water resources, whereas the need for these resources is increasing. Land use practices and forest conversions have been implicated in causing a degradation of watershed functions. In the humid tropics, deforestation and the resulting shifting cultivation and fallow cycles have been singled out as the major causes of the destruction of watershed functions. Is this really the case? Research elsewhere is beginning to question this simplistic view of looking at the relationships between forest functions and their effects on watersheds.

The old paradigm on deforestation and watershed functions proposes *reforestation* as the solution to the problem of *deforestation*. This has resulted in the use of scarce financial resources on 'tree-planting' programs, which have seldom if ever actually restored 'forest watershed functions', as a recent review by the International Hydrology Program revealed. Before we can find the solution to the degradation of soil and water resources, we must first identify the problem, its causes, effects and the inter-linkages between the different factors. Our understanding of the hydrological cycles, forests and their role in the hydrological cycle will be important in enabling rational decision-making at different levels.

### 2. Myths and elusive realities

Consider the following statements about forest watershed functions (Calder, 1999):

- Forests increase rainfall
- Forests increase runoff
- Forests regulate flows
- Forests reduce erosion
- Forests reduce floods
- Forests 'sterilise' water supplies – improve water quality

**Are these myths or reality?**

#### Exercise

- What is *your* understanding of watershed functions?
- Divide the class into two groups, those for and those against the given statements. Discuss the reasons for your answers, in view of your understanding of forest watershed functions.

The view of forests as ‘good’ and deforestation as ‘bad’ for watershed functions has been blindly and widely accepted and propagated for decades without a clear understanding of the role of land use and land use changes in relation to the hydrological cycle and watershed functions (see Boxes 1, 2, 3). This lecture note aims to clarify the role of forests in watersheds, thus challenging this old paradigm.

We have all probably heard or read that, the removal of forests and/or deforestation, will have a negative impact on the flow of waterways, the volume of water in waterways, cause floods, cause desertification, reduce rainfall, cause erosion, damage to wildlife habitats and degradation to watershed areas, among others (UNCED, 1992\*<sup>1</sup>; Calder, 1999). Is this the case?

**QUESTION:** What do you think will be the impact of ‘reforestation’ on the watersheds in each of the cases in Boxes 1, 2 and 3? Explain.

### **Box 1. Failure of the Way Rarem Scheme: Deforestation or Design Error?**

The Way Rarem Scheme is an ambitious project set up 15 years ago to dam water for downstream rice irrigation, in the western Kota Bumi watershed area in Lampung, southern Sumatra (Indonesia).

During a regional meeting (in 1999) to discuss watershed functions, the manager of this scheme complained about not having enough water in the dam and that the rice farmers downstream were not getting enough water for their rice irrigation. The reason for this, he said, was “... the observed deforestation upstream is causing a reduction of water flow into the dam”. The solution, he proposed, was “reforestation of the upland areas, so as to increase water flow into the dam...”

*What is your view on this statement? Discuss his statement in relation to your understanding of the role of forests on watershed functions.*

*The facts:*

- a closer inspection of the Way Rarem scheme by an engineer found that the project had miscalculated the size of the watershed area, and therefore the amount of water that could be captured from the watershed, by 30 – 40 %. The result was construction of a dam with a larger capacity than needed and the overestimation of the amount of water available for rice irrigation downstream. In anticipation of this irrigation scheme, the rice farming area had increased.
- In addition, 1997 was a drought year (El Niño), so there was an overall reduction in rainfall countrywide, and a reduction of waterflow in most watersheds in the country, regardless of local land use. So naturally, the water quantity in the dam had been relatively low since then.

The manager is right in his observations (deforestation and reduced waterflow), however, the causal link that he made between his observations was inaccurate. From this example we see that although it is easy to make deductions about two observations, we should strive to find all possible reasons that might explain observed phenomena before making general conclusions about ‘cause-effect’ relationships. This is especially important in the management of watersheds and water resources in general, if sustainable use of natural resources is to be promoted and conflicts between the different users is to be avoided.

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<sup>1</sup> Cited in Calder (1999)

## **Box 2: Floods in Jakarta: the setting, the problem and the reality.**

### **The Setting**

Jakarta has been described as an ‘all of Indonesia rolled into one’ urban sprawl of over 9 million people (Turner, 1999). People from all over Indonesia come to Jakarta to make a living, setting up lodgings within the already congested city and on the city’s outskirts. Despite the scarcity of land, construction of houses is still taking place. In addition, the daytime population of the city swells dramatically as more people from the surrounding towns (Bogor and Puncak) come to the city to work. The result is traffic congestion, air pollution, smog, increased temperatures, and their resulting ill-effects on health.

The pressure of the population on the environment is enormous. This has implications for water resources, in the provision of an adequate supply of good quality drinking water, the increase in water pollution from household and industrial waste and for the hydrological processes.

### **The Problem**

Floods. The city is experiencing seasonal floods following heavy rains. **It is generally believed that deforestation upstream** (in Puncak), is the main cause of the floods downstream in Jakarta. Is this true?

### **The Reality**

Jakarta, as other capital cities on the mouth of a river, is built on what is geomorphologically a floodplain – so flooding is ‘natural’. An increase in the quantity of water in the city’s canals and drainage systems has been caused by both an increase in wastewater from the increasing population and from industries. This, coupled with the fact that most of these channels are blocked by solid waste (for example plastic bags), causes them to burst their banks under the strain and release large quantities of water which flood the surrounding areas. This is especially marked during heavy rains when the volume and pressure of the water has increased. In the past a system of ponds was used as an overflow, replacing the natural wetlands along the river that had already been converted into housing developments. Now, however, the ponds have largely been filled in for more directly profitable land use.

### **The Conclusion**

Deforestation does play a major role in increasing the probability of flooding, because the removal of trees results in more water flowing into the watershed, increasing the water flow and volume of waterways. In this example, deforestation was not the main culprit, although it may have had a slight influence on the quantity of the water flowing downstream. The flooding situation in lowland Jakarta, was a direct result of the interaction between rainfall and the carrying capacity of the drainage systems and canals in and around the city.

“ Truly widespread flooding is usually the result of an equally large field of extreme rain, occurring at a time when soils have become wetted up by previous rains. In such cases, the process of run-off generation is governed by soil water storage capacity rather than topsoil infiltration opportunities. The presence or absence of a well-developed vegetation cover has become of minor importance” (Bruijnzeel, 1990: 180).

Construction of more roads, drainage channels and concreted areas and houses (for the swelling population) have reduced the infiltration rate of soils in Jakarta, increasing surface run-off, and the risk of flooding. Rising quantities of water, especially after a heavy storm, lead to an amplified potential for flooding, as the water is not able to infiltrate into the ground.

### BOX 3. 'Conflicting Perceptions'

#### Do Land Use Changes in the Himalayas Affect Downstream Flooding? – Traditional Understanding and New Evidence (Hofer, 1998).

Every year during the monsoon season, the Himalayan region appears in the headlines because of large-scale flooding in the plains of the Ganga and the Brahmaputra in India and Bangladesh. Peasants in and around Nepal are being blamed for the floods. They are blamed for causing deforestation in the Himalayas, which leads to devastating inundation, particularly in Bangladesh. The hypothesis regarding the impact of human activities in the Himalayas on the ecological processes in the lowlands can be summarised by the following (superficially convincing) sequence: population growth in the mountains – increasing demand for fuelwood, fodder and timber – uncontrolled forest removal in more and more marginal areas – intensified erosion and higher peak flows in the rivers – severe flooding and siltation on densely populated and cultivated plains of the Ganga and Brahmaputra. These apparently convincing conclusions have been subscribed to too carelessly by some scientists and adopted by many politicians and journalists in order to identify the so-called culprits (Hofer, 1998).

The following paragraphs show how different people view the same environmental issue (floods) from very different perspectives.

1. **Farmers** – the people affected:

- are not interested in knowing whether it is the Himalayas or the Meghalaya Hills which are responsible for the floods
- view floods as just part of the life to which their ancestors, and they themselves, have learnt to adjust.

This view is reflected in one of their local sayings, 'People do not die if there are floods, people die if there are no floods.' No floods mean no crops, as floods bring fertile soils, which sustain crops, to their farms. The main problem for them is actually river erosion, which takes away the fertile silt.

2. **Politicians** – the decision-makers:

- believe floods are a problem because of the suffering they bring to people
- believe floods should be solved/eliminated by large projects involving expensive foreign aid.

3. **Engineers** – the ('scientific') solution providers:

- floods are simply a problem of high water volume, to be controlled by technical measures (for example, dams).

4. **Journalists** – the reporters of floods to the rest of the country and world:

- floods provide dramatic headlines, good for selling their story
- western media believe floods are the main problem in Bangladesh. Not the case!
- foreign media tend to misrepresent the real environmental problem in Bangladesh, that of river erosion, by not giving enough coverage to it
- the media in Dhaka (the capital city) reports on the real problem of river erosion, which the foreign media tends to miss.

**Suggested group work:** this case can be used for a role-play where four groups adopt different perceptions on an issue. A team of students (group 5) is sent out to interact with them. This example can be adapted to local conditions and to a local environmental issue. Discuss the findings.

Forests do indeed have an important role in relation to watershed functions and environmental protection in general. However, new evidence suggests that forests are not necessarily 'good' for all watershed functions (Bands *et al.*, 1987<sup>2</sup>; Calder, 1999).

A positive correlation has been found between the presence of forests and a slight increase in **rainfall**. However, this small increase in rainfall is normally compensated for by increased evaporation, so the overall effect is a reduction in water resources. In addition, the effect of forests on rainfall is dependent on the maritime influence. Narrow landmasses (for example Southern Africa, Southeast Asia), are more influenced by the moisture content of the marine air masses rather than by inland air masses. By contrast, in continental areas, forests form part of the hydrological cycle through increased evaporation and rainfall (Bands *et al.*, 1987\*). From a water resources perspective, the role of forests on rainfall is quite significant.

Forests have been found to reduce **runoff**. There are two reasons for this. Firstly, forests have long, well developed root-systems, which penetrate deep into the soil in search of water; as such they are large consumers of water, especially in the dry season. The effect of this is a reduction in the availability of ground water and thus a reduction in run-off. Secondly, in comparison to shorter stature vegetation, forested areas are likely to have more evaporation than areas with shorter crops (because the trees have long roots, more access to soil water, and thus there is more water lost through evaporation); consequently, forests reduce the runoff in catchment areas (Bosch and Hewlett, 1982\*). This is contrary to the widely accepted 'myth' that deforestation causes a reduction in watershed run-off, and thus a reduction in the quantity of water in reservoirs and that available for irrigation purposes downstream.

Observations in different parts of the world have shown that the relationship between forests and increased **water flow** is not necessarily a positive one (Boost, 1979\*; Van Lill *et al.*, 1980\*). Furthermore, effects on dry-season flow have been found to be very site-specific, with other competing processes playing a major role in either increasing or decreasing dry-season flow. In terms of **erosion**, forests play both a positive and negative role. On the positive side, forests reduce the incidence of surface run-off, which in turn reduces erosion transport. Forest canopies can also 'slow down' the speed of raindrops before they hit the soil thus reducing the soil water pressure. However, the positive effects are both site-specific and species-specific. Afforestation is not necessarily the answer, especially when the soil has undergone severe degradation (Pearce, 1986\*; Hamilton, 1987\*). Research in different global sites: America, South Africa, UK and New Zealand - has shown no direct linkage between deforestation and **floods** (Hewlett and Helvey, 1970\*; Hewlett and Bosch, 1984\*; Kirby *et al.*, 1991\*; Johnson, 1995\*; Taylor and Pierce, 1982\*; Box 2). What are implicated, however, are the management activities associated with logging, such as drainage, road construction and soil compaction and also the cultivation activities which may follow logging; these will most likely influence flood response rather than the absence or presence of forest vegetation.

There is an urgent need to re-think conventional wisdom. By challenging these old paradigms, we will be able to bring about an understanding of the truth, which relates to the effects of land use change on watershed functions. This will enable better management of water resources, better decision-making and a better understanding of the effects of forests and deforestation on water resources.

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<sup>2</sup> \* Cited in Calder (1999).

### 3. Forest concepts

A rapid conversion of forests raises concerns over the maintenance of watershed functions that influence the livelihoods of people downstream. However, the perception that only natural forests are able to maintain these functions is an over-simplification. It is proposed that some farmer developed agroforestry mosaics may be as effective in protecting watershed functions as the original forest cover (van Noordwijk, 2000). Before looking at the functions of forest it is important to understand what constitutes a forest.

#### 3.1 What is a forest?

Generally, a forest is perceived as being a collection of trees. This is evident in reforestation projects, whose efforts are focused on tree planting as a means of ‘regenerating’ degraded and/or deforested forests. Contrary to this popular belief, a forest is not a tree, but an ecosystem with different components and functions (see box below). The role of forests on watershed functions is dependent on these different aspects of forest as an ecosystem.

‘Forest’ implies:

- a vegetation (trees, understorey plants)
- a soil condition (good infiltration, high macroporosity)
- a landscape with few ‘channels’ and many irregularities
- a ‘state of mind’ of the perceivers...

#### 3.2 Forest watershed functions

Forest watershed functions include:

- maintenance of high quality water
- regulation of water quantity
- maintaining water-sediment balance in watersheds

Quantitative statements are needed for the way ‘watershed functions’ depend on the amount and type of forest and the various land use practices that can follow forest conversion. Watershed functions are based on the three aspects of forests (above, in box) that together dominate the impact on the flow and quality of water. The following sections show how the three aspects of ‘forest’ influence the flow and quality of water:

##### a) Vegetation

- Trees and understorey vegetation, with a minimum fraction of area cover dominating the more common definitions of forest;
- trees are better at maintaining transpiration rates throughout the year than most other plants, and their annual water consumption often exceeds that of other vegetation;
- tree canopies intercept more rainfall than other vegetation and this is returned to the atmosphere by direct evaporation (NB in specific conditions, however, ‘cloud forest’ vegetation (trees plus their epiphytes) can intercept water from clouds and mist and thus generate net water flows into the soil, BUT these forests can only account for a very small percentage of global forest cover (Calder, 1999)).

## b) Soil conditions

Forest soils, which typically have a high surface infiltration rate and substantial macroporosity (due to soil biological activity and tree root turnover) facilitate deep infiltration, and also sub-surface lateral flow of water.

## c) Landscape

A landscape with a rough, uneven surface, including depressions and swamps, provide temporary water storage and sediment filter functions and very few 'channels' (pathways for rapid surface runoff).

These three aspects of the forest differ in their impact on total annual flow, dry season flow, storm flow and water quality, they differ between forest types and they differ in the way and rate at which they are affected by forest conversion and can be subsequently recovered in 'reforestation'. The generic term 'forest watershed functions' thus needs further specification before we can judge the impacts of forest conversion. Both the type of forest converted and the type of land use to which it is converted determine whether the overall impact on 'forest watershed functions' is negative, neutral or even positive. With regard to the 'broad' definition of 'forest' given above, 'deforestation' can be considered as a loss of forest function.

## 3.3 Deforestation as gradual loss of 'forest functions'

Forest conversion is not a black-or-white deforestation process. It can result in a gradual loss of 'forest functions' as landscape evolves into agroforestry mosaics. Existing institutions and policies are largely based on a forest - agricultural land use dichotomy. This may lead to an unnecessary sense of conflict. This issue is of particular relevance where supposed 'watershed protection functions' have been the basis for the regulation of access (as for example in Indonesia and Thailand). The key presumption of this lecture note is that *some farmer-developed agroforestry mosaics are as effective in protecting watershed functions as the original forest cover, and hence a substantial share of current conflicts between state forest managers and local population can be resolved to mutual benefit* (Van Noordwijk, M., 2000).

Deforestation can be regarded as the loss of 'forest functions' as natural forests are replaced by other land use systems. National and regional concern for forest conservation and reforestation most often focuses on the loss of the watershed functions of natural forests. While some land uses may be as good as natural forest in this regard, land use systems differ significantly in their ability to supply these watershed functions. Loss of watershed functions can be a combination of:

- A. on-site loss of land productivity as a result of erosion,
- B. off-site concerns about water quantity:
  - B1. annual water yield,
  - B2. peak (storm) flow,
  - B3. dry season base flow,
  - B4. groundwater recharge or depletion,
- C. off-site concerns about water quality, including siltation of reservoirs.

A is primarily an issue for upland farmers, whereas B and C are mainly the concerns of downstream interest groups, who may be adversely affected as natural forest is converted into agricultural land uses.

The hydrological functions of forests appear to have been erroneously attributed to the trees rather than to other aspects of a forested landscape, especially their role in recharge



of groundwater leading to base-flow, supplying water in the off-season. (Bruijnzeel, 1990; Calder, 1998; Jakeman *et al.*, 1998<sup>3</sup>). Changes in stream flow (increased stream flow) after deforestation have often been noted, but this may be due to 'opening up' the landscape and 'improved drainage', reducing 'surface roughness', rather than to removal of trees *per se*. If 'reforestation' returns trees to a landscape but does not block off all roads, create swamps, and return surface roughness, it may have a negative effect on downstream water availability, as additional transpiration and interception losses from tree canopies (on average about 300 mm/year) are sustained. In considering the role of agroforestry landscape mosaics it is thus essential to pay attention to both the relative tree cover and to the 'surface roughness', as it consists of a series of 'filter' elements in the landscape. Models developed at ICRAF and elsewhere (Rose and Yu, 1998; Van Noordwijk *et al.*, 1998) show that the position of these filters in a landscape is at least as important as their spatial extent.

#### 4. Watershed functions – who is interested in which function?

The main functions of watersheds are to provide an adequate and regular quantity of water, to reduce the amount of soil movement and to provide a good supply of high quality drinking water (see box below).

Watershed function	Importance (example)
<b>Water quantity</b> Reliable (high) total water yield High dry-season flow Low peak-flow <b>Soil movement</b> Low sediment load Few landslides/mudflows <b>Good water quality:</b> Drinking water, Fish & other biota 'cool' water no sub-soil salt movement	<ul style="list-style-type: none"> <li>• filling up lakes &amp; reservoirs</li> <li>• in absence of lakes</li> <li>• flooding risk in lowland</li> <li>• reservoir life-time</li> <li>• villages in valley</li> <li>• direct source of drinking water</li> <li>• fishermen, biodiversity conservation</li> <li>• ricefields (N. Thailand)</li> <li>• groundwater flows (Australia)</li> </ul>

A deterioration in water quality, for example an increase in turbidity, will have an immediate negative impact on water users. However, in terms of quantity, there is a timelag between the time an activity occurs, until the time its effects on water quantity become noticeable. It can take up to ten years or more to detect any observable changes in the quantity of water in watersheds, long after the effects of the particular activity have been masked by others or have disappeared. It is thus difficult to isolate the cause of reduction of water quantity, as it requires experiments that last for long periods of time.

Figure 1 shows the environmental service functions of watersheds and the processes that influence them. From this diagram, it can be seen **that water quality** (on the right-hand side of the figure) is dependent on quick flow and stream base flow. Quick-flow is influenced by the following hydrological processes: run-on, lateral-inflow, run-off, and lateral-outflow, while stream base flow is influenced by percolation. **Total water yield** is dependent on quick flow and stream base flow and deep recharge. Any activity that

<sup>3</sup> Cited in van Noordwijk *et al.* (2000).

affects these processes will have an impact on the environmental service function of watersheds that are dependent on them.

The term ‘environmental service function’, in this context, is taken to correspond to ‘watershed functions’. Land use change effects on the hydrological processes (Figure 2) will cause an impact on the water balance, which will affect watershed functions. The example on water quality above illustrates this process. The same is true for all other watershed functions.

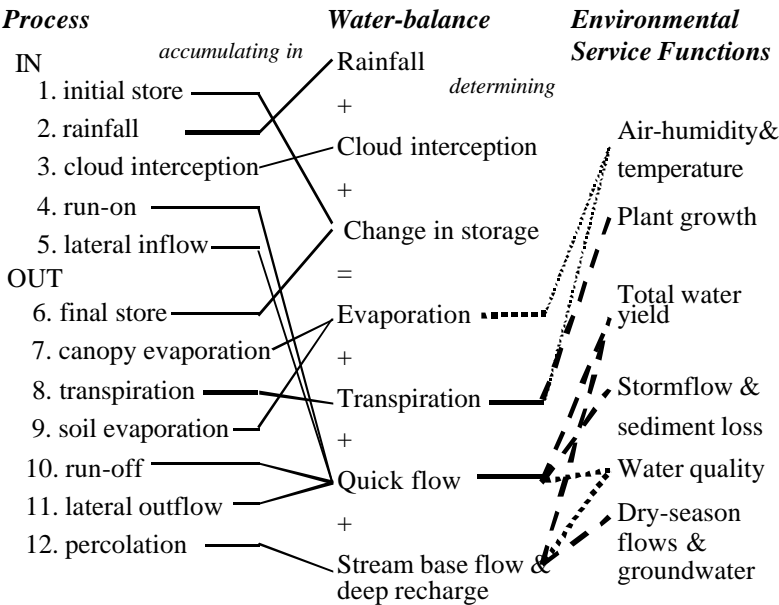


Figure 1. Land Use Change Effects on Hydrological Processes (see glossary at the end for a definition of terms used)

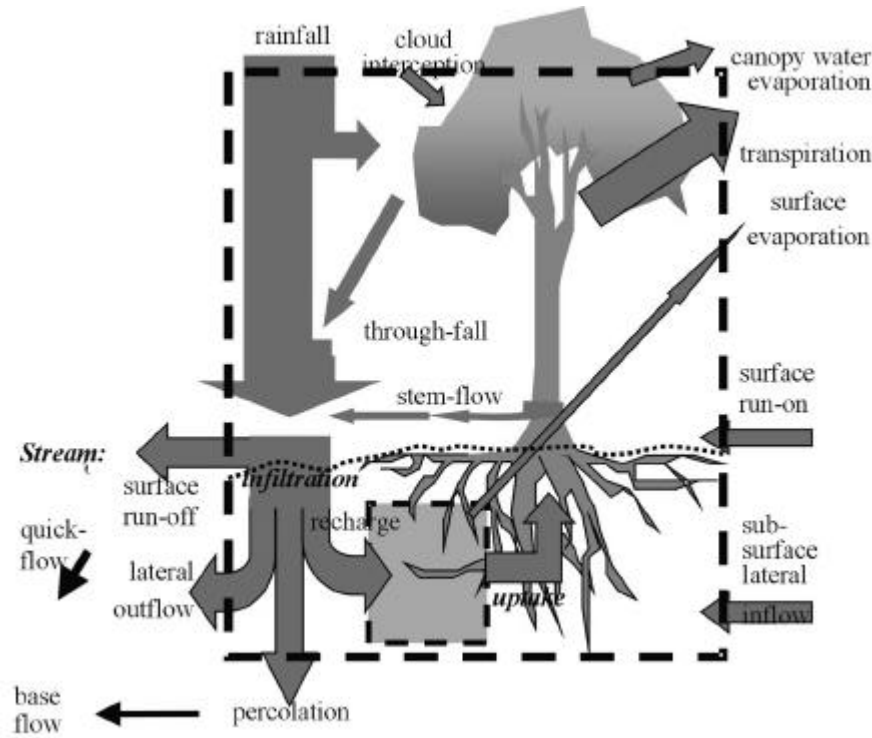


Figure. 2 Hydrological processes at the plot level – forest watershed functions.

Watershed functions serve both upstream and downstream users. Any activity upstream, which has an effect on the watershed, will have an effect on the water users downstream. Interactions between upstream and downstream occur at many levels:

- water is flowing from high to low elevation, so land use in the source area affects downstream conditions more than vice-versa; traditionally river banks are favoured agricultural lands, because of the combination of soil fertility and easy transport; modified river flow regimes (peak as well as base flow) have an effect on this type of land use; more modern sectors, such as irrigation-based agriculture in the lowland peneplain, depend on reservoirs and/or constant river flow from the uplands,
- major towns and trading centres, and thus centres of political power, are traditionally located at the mouths of rivers, giving a pre-dominantly 'downstream' perspective on policies; towns are the main beneficiaries of electricity generated from dams and reservoirs in the uplands and are directly concerned with the life expectancy of such reservoirs,
- people can obtain their livelihoods in both the uplands and lowland peneplains; they can migrate into foothills and mountains when conditions there appear to be more attractive than elsewhere, or (at least at household level) they may depend on resources in both landscapes.

On the basis of such relations, institutions and mechanisms are needed to ensure that the different interests are addressed and that open conflict can be avoided or at least kept at manageable levels. This is a question of equity as well as a question of effective natural resource management.

Past 'watershed projects' were often conceived on the rather naïve assumption that soil and water conservation would be in everybody's interest, and that everybody would, or should, carry part of the costs required for the common good. The new perspective on sources and filters, on losers and beneficiaries, should coincide with a renewed search for adequate institutions and regulations linking local and regional benefits.

## **5. Plot-level water and sediment balance**

Rainfall over the land surface provides input for recharging the soil with water, replenishing groundwater reservoirs and providing run-off in streams and rivers (see Figure 2). Some of this rainfall will be absorbed and evaporated into the atmosphere by the forest vegetation canopy. The evaporation occurs via three pathways (Calder, 1999):

- interception – that portion of rainfall held on vegetation surfaces and re-evaporated before it reaches the ground
- transpiration – water absorbed through roots and evaporated via the leaf stomata
- evaporation from bare soil.

A small part reaches the forest floor directly without touching the canopy. This is 'through-flow'. The remainder reaches the floor as crown drip and via trunks as 'stem-flow', the latter resulting in a concentration of water at the base of the stem. In certain climatic and topographic conditions it may take on dramatic proportions, capable of washing away litter and topsoil. Through-flow can have an impact on soil erosion. The amount of splash erosion induced by through-flow hitting the forest floor is governed by the degree to which the ground surface is covered by litter or undergrowth rather than by the erosive power of raindrops (Wiersum, 1983\*\*). Surface run-on is that water which comes from the neighbouring plot, while surface run-off is that leaving the

‘experimental’ plot. Subsurface flow is that water which flows just below the ground surface and infiltrates through different soil layers (see Figure 3).

Infiltration is the passage of water through soil layers, into the soil for recharging groundwater, for plant uptake, as surface flow, and for ‘recharging’ waterways. In principle, infiltration can affect the rate of surface run-off and flood response. The higher the rate of infiltration the less water available for surface run-off. In practice, this effect is dependent on land management activities associated with forestry. Rainwater that flows rapidly reaches the stream flow of waterways.

The effects of forest conversion on the water and sediment balance at plot level is shown in Figure 3. The explanation of what happens to the sediment-water balance at the plot level is given in the box (right).

Generally, upon forest clearing there is a marked increase in water yields (Bruijnzeel, 1990).

**In recently burned forest the following is evident:**

- an increase in surface evaporation due to lack of forest cover
- increased surface run-off
- increased erosion, greater under conditions of intense tropical rainfall and steep terrain
- severe losses of soil nutrients via erosion

**Regrowth forest:**

These ‘mimic’ the function of natural forests. However, due to the differences in tree species size and composition, their effect on the hydrological process may differ slightly from that of natural forests. An example of a regrowth forest could be an agroforest.

**Degraded forest:**

- forest functions are destroyed or severely compromised
- there is a marked increase in soil evaporation
- an increase in surface run-off, increasing potential for floods
- increase in soil erosion, especially after heavy storms and on steep slopes

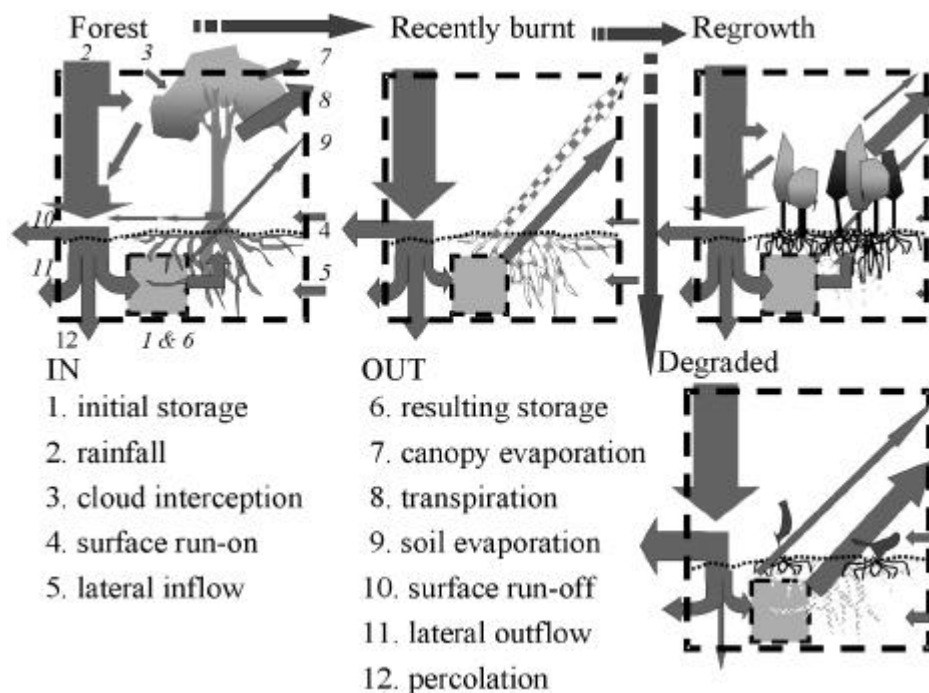


Figure 3. Schematic components of the water-balance at plot level, for forests, recently opened and degraded land

## 6. Landscape level connections in water and sediment flow: channels and filters

The way a landscape functions does not only depend on the sum of all the ‘plots’ in the landscape, but also on the ‘lateral flows’ of water, nutrients, soil, fire and organisms that relate them (Vos and Opdam, 1993\*\*; Forman, 1995\*\*; van Noordwijk, 1999\*\*). These lateral flows can be promoted by ‘channels’ (such as roads or streams) and reduced by ‘filters’ (such as strips of vegetation along contours, or otherwise perpendicular to the direction of the lateral flow), whose functions include interception, long-term storage or transformation (e.g. from nitrate into gaseous forms of nitrogen).

In order to predict soil erosion effects at the watershed level we first need an assessment of the effectiveness of filters. Filter efficiency depends on lateral transfers between sources and sinks. Total filter efficiency of a landscape depends on the radial or directional transport velocity, the total density of emitters and filters and the vegetation as a function of time. Filters in this general sense can include a range of landscape elements: depressions, cut-off drains, ditches, embankments, vegetated strips, hedgerows and riparian vegetation. The spatial positioning of filters is important in relation to their effectiveness.

Filter effectiveness can be defined as some function of radial distance – thus the overall effect at any given filter density can be compared with that of the same number of filters in a regular spacing.

Distribution patterns of filters:

- regular spacing – most efficient distribution
- random distribution – slightly less efficient than regular spacing
- extremely clustered distribution – overall efficiency reduced by 40%.

Examples of human-made channels are drainage channels from domestic and industrial drainage schemes, roads, irrigation canals, compaction channels formed following land disturbance caused by actions such as logging, and channels caused by poor land management techniques. Such channels may be major factors in causing soil erosion, land degradation and increasing the risk of flooding.

The term filter is used here in a generic sense to be anything that can intercept a lateral flow. Typically, filters occupy a small fraction of the total area and have a large impact per unit of area occupied. They can thus be regarded as keystone elements of a landscape. Filter elements are easily overlooked in remote sensing approaches, but should be the focus of research if we want to understand how the landscape functions as a whole. Closely coupled to the issue of filters and flows is the question of whether spatial pattern matters.

When land use practices affect lateral flows, the impacts of plot-level land use decisions on external stakeholders can be complicated. Conservation or establishment of filters to interrupt problematic lateral flows may be attractive and practical options for mitigating such impacts, compared with elimination of the ‘root causes’.

### 6.1 Stabilizing and regenerating landscape filters

A wide array of landscape elements has now been recognised as potentially having ‘filter’ functions, intercepting lateral flows of earth, water, gases, fire or organisms. Filters, however, can get saturated and start to leak or let subsequent inflows pass through, and for their long term functionality they depend on:

- near-infinite storage capacity in a stable form, or
- frequent regeneration of their filter capacity by disposal of the filtered material.

Opportunities for disposal depend on the material filtered (Table 2). For example, among the nutrients N can leave a filter zone in gas form ( $N_2$  or  $N_2O$ ), while P, K and other nutrients can only be removed with the organic material or mineral soil that stores them.

Agroforestry practices can contribute to long-term filter functions in as far as they involve the long term stabilisation of captured sediment flows (in new soil formation processes), in sufficient off-take of nutrients in tree products or litter transfers, or by allowing breakdown of biocides. Wetland sites with or without trees may provide an environment for gaseous N losses. Little direct study has been made of the sediment filter zones in landscapes recently derived from forests, but the relatively wet sites rich in organic matter can be expected to be ‘hot spots’ for emissions of greenhouse gases. The ‘light’ fractions of soil macro-organic matter, that are most easily moved in surface flows of water, have a shorter turnover time than heavier fractions (Van Noordwijk *et al.*, 1998b).

Table 2. Scheme of how three aspects of forests are affected by human disturbance and how this in turn modifies the water balance

	Causes and effects of disturbance	Terms of water balance affected	Recovery-time
Trees	logging & fire reduce tree cover	interception, transpiration	water use can recover in 1-3 year, LAI and interception in 4-10 year; tree biomass will take decades and species composition a century or more
Forest soil	compaction, decline of infiltration rate due to loss of macropore formation	rate of surface infiltration, percolation and subsurface lateral flow, surface evaporation	surface permeability can be restored in < 1 year, soil macroporosity may take decades
Forest landscape	paths, tracks and roads lead to quickflow, levelling and swamp drainage reduces surface buffer storage capacity	time available for surface infiltration, percolation and subsurface lateral flow	channels can be closed, and surface roughness restored rapidly through specific actions

Table 3. Characterisation of mechanisms for initial capture, long term storage and outflows for a range of lateral flows

Lateral flow	Initial capture	Long term storage (increased residence time)	Outflows
1. Topsoil & surface litter	run-on infiltrates or slowed down to allow sedimentation	terrace build up	terrace collapse and landslides
2. N	surface flows as for 1, or subsurface flows of water entering filter zone	biomass, SOM	biomass export, denitrification, SOM & litter transfer
3. P + other nutrients	(sub)surface flows as for 1 and 2	sorbed & fixated biomass, SOM	biomass export. SOM & litter transfer
4. biocides	as for 1 and 2	sorption	(microbial) breakdown

## 6.2 Techniques for measuring the effectiveness of filters

Empirical tests of the effectiveness of filter elements consist of measurements of the surface sediment flows upstream and downstream of a range of potential filter types in the landscape, and calculating the apparent filter effectiveness as:

$$\frac{(\text{Sediment yield before filter} - \text{Sediment yield after filter})}{(\text{Sediment yield before filter})}$$

A number of measurement devices have been used for such studies:

- a narrow (2 cm diameter) hole in the ground with a pipe, where one measures the level of sedimented soil at regular intervals,
- a wider (15 cm diameter) hole with a 'coffee filter' that capture the sediment above a specified mesh size from the incoming overland flow,
- a proportional sampling device for overland flows that channels a 2% sample of the flow into a container for further analysis.

The last device measures overland flow of water as well as soil particles, the first two only measure soil movement. As long as results are expressed relative to those at different positions, the 'filter effect' does not appear to depend much on the specific device used. Initial measurements in Sumber Jaya (Sumatra) showed that the filter effectiveness of grassy field boundaries and similar landscape elements ranged from 30 to 95%, indicating that estimates of sediment flow not acknowledging such effects can be wrong by a factor 0.5 to 20.

## 7. Combined effects of forest conversion

### 7.1 Logging

The effects of logging on watershed functions have more to do with land disturbance and soil degradation than with the cutting of trees. Access roads to the forest may act as channels, which in cases of heavy rain act as sediment transporters, as well as increasing run-off. In the humid tropics, logs are transported via streams, causing damage to riparian strips. One of the consequences of this is increased sediment in the streams, which has implications for watershed users downstream, in terms of providing good quality water and in terms of reservoir sedimentation.

### 7.2 Slash-and-burn forest conversion, crop/fallow systems, and degradation

Shifting cultivation as practised in most humid forest margins involves clearing the land, usually using slash-and-burn techniques, for agriculture and/or food production, followed by periods of fallows when the land is left uncultivated to 'rejuvenate' (see Lecture note 2). After a number of years, depending on the length of the fallow, the land is planted again. During the cropping phase of shifting cultivation or after conversion to pasture (or grasslands – see Lecture note 2), depletion of soil nutrients manifests itself in a more or less rapid decline in crop yields. Fallowing the land allows it to 'rest', and the soil fertility can be restored. The length of the fallow needed to restore fertility depends on the climatic and soil factors, with longer periods needed in areas of high erosion and leaching potential. Shortening the fallow periods or intensifying land use will eventually result in the degradation of soil and land resources. The effects of soil degradation on the hydrological processes have been discussed earlier (see Figure 3). Removal of forest cover during the land-clearing phase results in a disruption of the following hydrological processes: canopy evaporation, evaporation,

transpiration, interception and stem-flow (Figure 2). The impact of this on the water and sediment balance at the plot level is depicted in Figure3.

### **7.3 Roads and villages**

The presence of roads and villages can have several cumulative effects. The people, livestock and agricultural activities associated with a village all require water (of different qualities and quantities) and also for transport of waste products from the village. Drainage systems are generally used for irrigation, transport of wastewater and for transport of storm-water; thus they act as channels. Roads can act as channels, transporting water and sediment downstream. In the presence of degraded or 'poor' soils, this type of transport may lead to rill erosion and increased sedimentation downstream.

### **7.4 Irrigated crops**

Irrigated horticultural crops, (mainly different types of vegetables), require water of a high quality, and in high quantities. Forest conversion in the watershed areas will impact on both these properties of watershed functions that are necessary for crop irrigation. The use of sprinkler irrigation as is practised in Thailand (horticulture projects), is dependent on the quality of water, and its sediment load. Increased sedimentation, as a result of land use changes upstream, will have an impact on the sprinkler systems, causing blockages and reducing their technical efficiency. Less water will thus be available for crop cultivation.

### **7.5 Dams**

Dams and their associated reservoirs are constructed to capture (and store) water for different purposes, such as irrigation and hydroelectricity generation. Dams are dependent on both the water quantity and the sediment load of the water entering the dam. Whereas increased volumes of water (as in increased run-off) are desirable for dams, reduced flows may result in a reduced quantity of water behind the dam. The implications of this are in the generation of hydro-electricity (e.g. in Kenya, due to droughts in most of the country, the reservoir supplying water to the city of Nairobi, among others, was so reduced that water and electricity supply to the city were disrupted for several months. Periods of 'blackouts' and non-availability of tap water became the norm).

Sedimentation is a major concern for dams and reservoirs. Increased sediment loads flowing into the reservoir reduce the volume of a reservoir, and thus its capacity. Over time, this shortens the lifetime of a reservoir, as it becomes filled up with silt. Silt also reduces the lifetime of electricity generating turbines, in cases of hydroelectric power generation.

### **7.6 Irrigated ricefields as potential filters**

Overland flows of water and sediment can be intercepted by a wide range of vegetative filters, and thus a non-forest landscape with strategically placed filters can maintain acceptable waterflows. Ricefields can act as vegetative filters by intercepting sediment flow and using the fertile silt as a source of nutrients. In this way sediment eroding from upland areas may be captured by ricefields. This is not only beneficial for the rice farmers, but it also helps reduce the amount of soil that will reach the downstream users. However, soil erosion in the upland areas is still a problem as it reduces soil nutrients (topsoil is lost), and causes land degradation. More research is still needed to investigate



to what extent rice fields are also effective during major rainfall events, as these usually cause the most damage.

## 8. Landscape typologies

In order to understand forest watershed functions at the landscape level, it is necessary to first make a classification of landscape types or stages in typical dynamic processes. In a schematic form, most agriculturally-used landscapes have undergone a gradual process of intensification (Figure 4) with a gradual loss of the 'forest functions' in soil and water balances, leading to concerns A, B and C (section 2.3; van Noordwijk *et al.*, 1998). The five stages in a typical dynamic process identified in Figure 4 will be used here as the **classification** of landscape types in order to understand the interactions between the different landscape typologies and watershed functions.

When patches of forest are opened for shifting cultivation, the storm flow increases slightly, while the net-sediment loss and the dry season base flow do not show a significant change (type II, Figure 4). Trees are large consumers of water. In their absence, the storm-flow increases noticeably. This supports the view that although forests have a positive role to play in watershed functions, their absence is not necessarily detrimental to these functions. This is in line with previous findings discussed in earlier sections of this lecture note. Intensification of land use and shortening of fallow cycles results in an increase in crop production at the expense of natural forest (type III). Intensification of land use reduces soil productivity and fertility, and as such may induce soil degradation and soil erosion. Surface flow is also increased on degraded soil, and so is the amount of sediment reaching watersheds.

Watersheds respond to changes in landscape patterns in a non-linear pattern. The responses of watersheds to changes in landscape patterns are dependent on the presence and positioning of trees and other vegetation (filter effects), and their responses are different between the different landscapes. Landscapes with trees are able to maintain relatively low net sediment loss. Reasons for this depend on different factors, but the obvious one is that agroforestry techniques can have a positive and negative effect on watershed functions, whereas physical barriers only contribute to erosion control (for example: Landscape IV, Figure 4).

Combinations of a lack of filters, deforestation and land intensification result in severe soil erosion (no filter effect), and increased run-off (no forest cover), and an increase in the sediment load of watersheds (type IV). This has implications for water quality for domestic uses, as well as for sedimentation in reservoirs. Restored agroforestry landscapes with permanently vegetated contour strips reduce the incidence of soil erosion and the resulting sediment loss.

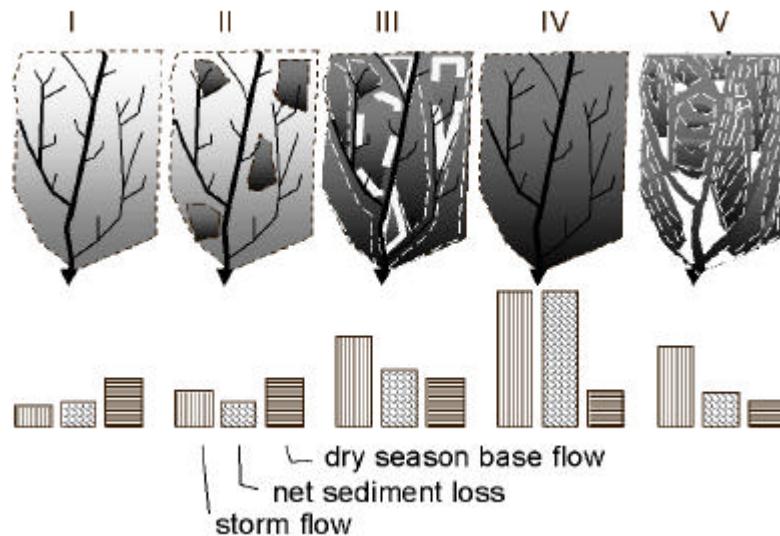


Figure 4. Schematic development of the landscape in a sub-watershed and its effects on storm flow, net sediment loss and dry-season base flow: I. original forest cover, II. patches of forest opened for shifting cultivation, III. intensification of land use has brought most land into cultivation, except for riverine borders and hedges along paths, IV. reclamation of all 'wastelands' has removed all filter strips causing a disproportional rise in net sediment loss, V. restored agroforestry landscape with permanently vegetated contour strips and riparian woodlands.

### Spatial arrangements of land uses within the landscape

The 'segregate-integrate' debate was introduced in lecture note 1: to attain the twin goals of productivity (food, timber, other products/raw materials etc.) and maintenance of environmental services (watershed functions, C stocks, biodiversity, etc.) what is the best spatial arrangement of land uses in the landscape? Would a fully segregated landscape, where natural undisturbed forests are kept separate from lands where intensive high-input agriculture is practised, be most efficient at achieving the two goals? Or would a fully integrated landscape, composed entirely of a mosaic of crops, trees and small forest patches be best (see Figure 5)?

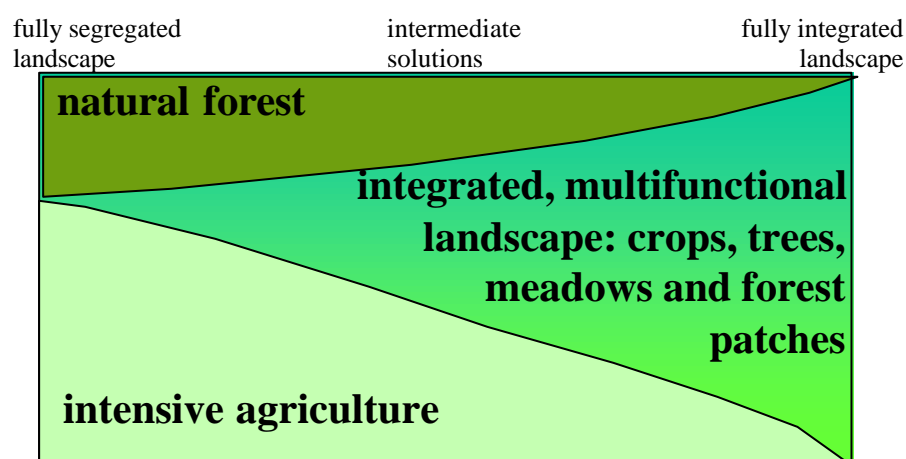


Figure 5. Segregated and integrated landscapes.

We can now summarise the consequences of segregated or integrated land-use options for the issues of watershed functions and soil conservation (Tables 4 and 5).

Table 4. Summarising watershed functions for segregated or integrated landscapes (see lecture note 1)

Segregated - Agriculture	Segregated - Natural forest	Intermediate solutions	Integrated - Agroforestry mosaic
High water yield but infiltration capacity tends to decline, more run-off	Ideal where clean water is desired, total water yield relatively low, base-flow component high	Limited options for correcting subsurface lateral flows	Many options for lateral flow interactions in fine-grained mosaics

Table 5. Summarising soil conservation aspects of segregated or integrated landscapes

Segregated - Agriculture	Segregated - Natural forest	Intermediate solutions	Integrated - Agroforestry mosaic
Problematic on sloping land	No problems (but logging can be very damaging)	Problematic, but strategically located riparian forests can act as sediment filters	Many options for local sedimentation

## 9. Models

### 9.1. Modelling vertical and lateral flows of water

Well-spaced trees or other permanent vegetation along contours can be effective in reducing erosion. What is their effect on crop production?

The overall effect is likely to be a balance of short- and long-term changes and will include negative effects through competition between the hedgerows/woody vegetation on the contours and the crops, as well as positive effects via maintenance of soil fertility. Tree-soil-crop interactions in hedgerow intercropping on flat land already are a complex of positive and negative interactions (van Noordwijk *et al.*, 1998). Whereas hedgerow intercropping on flat land has not lived up to previous expectations, contour hedgerows on sloping land are supposed to have positive effects on crop fields (Sanchez, 1995) although the yield increase may still not be worth all the labour invested in pruning the trees (Garrity, 1996). The WaNuLCAS model for predicting water, nutrient and light interactions in agroforestry systems (van Noordwijk and Lusiana, 1998) can be used to explore some of the interactions at process level. The model is set up for spatially zoned tree-crop systems and can be easily adapted to sloping lands, to model vertical and lateral flows of water. Another model that can be used to measure these interactions is the 'FALLOW' model. These are both discussed below.

#### 9.1.1 The WaNuLCAS model

The WaNuLCAS model (Van Noordwijk and Lusiana, 1999; 2000) can be used to explore agroforestry options for long term landscape filter functions as it includes runoff-run-on and the relevant subsurface flows of water, retention on sorption sites, uptakes by trees and other vegetation and an organic matter balance. The model can be used to explore impacts of the width and spacing of the filter strips on capture and residence time, and describe the nutrient balance on a medium time scale (5 - 20 years), depending on tree management practices.

The model has three types of control which can determine the pathway of waterflows, and which can be modified by the user to explore the effect of different factors. These controls are:

- soil surface and its restrictions to infiltration, if rainfall intensity exceeds current infiltration rate, water will accumulate on the surface and as soon as the storage capacity determined by local 'roughness' and slope is exceeded, it will start to run-off over the surface ('infiltration-limited runoff'),
- the soil profile with its macropores that allows water to reach deeper layers, recharge the soil to field capacity and percolate to the subsoil; in many tropical soils clay content increases with depth, and saturated conductivity decreases. This situation leads to the possibility of lateral subsurface flows on slopes, that can contribute to the 'quickflow' of streams. 'Saturation overland flow' occurs if the local storage and percolation capacity of the soil is exceeded. Under certain conditions a 'perched water table' may be formed, leading to saturation overland flow before the whole soil profile is rewetted,
- subsoil hydrological properties, leading to 'baseflow' of streams and/or recharge of deep aquifers.

The first two of these processes are under direct influence of land cover and can change from a 'forest' to a 'degraded' condition.

### 9.1.2 'FALLOW' Model

This model is described fully in lecture note 11.

## 9.2 Scaling up from the plot to the watershed level

### 9.2.1. Quantifying erosion: the USLE and GUEST equations

As mentioned before, quantifying erosion and especially the scaling up was (and still is!) a tricky thing to do. Most commonly the empirical USLE (*Universal Soil Loss Equation*) is used to quantify erosion:

$$SY = R * K * L * S * C * P$$

Whereby SY = Sediment Yield; R = Rainfall factor; K = Soil erodibility factor; L = slope Length; S = Slope gradient; C = Crop-management factor; P = Erosion Control Practice factor

It is based on mostly American research at plot level on moderate slopes.

Application of the USLE to quantify erosion at the watershed level, generally overestimates erosion and gives notoriously high errors (up to 2000 %) (Van der Poel and Subagyono 1998)! Scaling up from plot to slope or (sub)-catchment level is done using the (again empirical) Sediment Delivery Ratio (SDR).

$$SY = SDR * A$$

Whereby SY = Sediment yield; SDR = Sediment delivery ratio; A = area in km<sup>2</sup>

$$SDR = 33.65 * A^{-0.23}$$

This approach does not take into account the spatial distribution of various land-use types and thus the effects of filters can hardly be measured with this method. USLE was

in fact designed to quantify erosion at plot level. The 'sediment delivery ratio' itself does depend on scale, and when we consider larger areas it may be only 5%. In that case one would like to know where the other 95% of sediment stays behind in the landscape and how likely it is it will remain there.

The physical 'GUEST' equation is expected to be more accurate and uses a set of equations that describe the underlying physical processes of erosion (Rose and Yu 1998). GUEST stands for Griffith University Erosion System Template.

$$\bar{c}_t = k^b Q_{eff}^{0.4b} \exp(-k_s C_s)$$

$$\text{with } k = \frac{F s S L^{\frac{2}{5}}}{(s / r - 1) f} \left( \frac{\sqrt{S}}{n} \right)^{\frac{3}{5}}$$

Parameters are  $\beta$  = Erodibility parameter;  $Q_{eff}$  = effective run-off rate;  $C_s$  = Surface Cover contact fraction;  $n$  = Surface Roughness coefficient (Manning);  $F$  = fraction of stream power of overland flow used in erosion ( $\sim 0.1$ );  $s$  = Sediment density ( $\text{kg/m}^3$ );  $\rho$  = water density ( $\text{kg/m}^3$ );  $S$  = Slope;  $V$  = velocity of flow (m/s);  $w$  = mean settling velocity of sediment (m/s)

This equation is unfortunately more complex and more 'data hungry'.

### 9.2.2 Scaling up using the USLE and GUEST equations

In a case study for Sumberjaya watershed in Lampung, Sumatra, both equations were compared at different levels of scale: plot (20 m x 20 m), slope (20 m x 500 m) and (sub)-catchment (2 km x 4 km) level (Schmitz and Tameling, 2000).

Both methods were compared in a virtual environment in the form of PCRaster, a dynamic GIS-program, which is suitable for modelling overland flow. All three levels of scale were modelled in this program, with a grid/raster size of 20 m x 20 m.

Scenarios were created to be able to compare the results for the land-use types at each level of scale of both equations in PCRaster (a dynamic GIS-software developed at the University of Utrecht, Netherlands). Different scenarios represented different combinations of land-use types.

Input data for the models were mainly derived from literature, since there was little information available for the Sumberjaya area itself. Thus the run-results should be interpreted in a more qualitative, rather than quantitative way.

#### *Plot level scenarios*

At plot level, various land use scenarios were compared for a constant slope of 15 % and same soil type or K-value (0.15). The GUEST equations seem systematically to underestimate the erosion (in ton/ha) for all land uses, which can be attributed to the inaccuracies of how some of the parameters (Manning coefficient, erodibility  $\beta$ , ..) could be determined from the literature (Fig. 5).

However, it could also be that the USLE is systematically overestimating erosion levels! Accurate measurements in the field should give us some stronger conclusions. The modelling exercise revealed which parameters it is important to measure accurately.

Following plot level scenarios were chosen, because they occur regularly in the study-area:

- (1) Clean weeded coffee
  - (a) Without filter
  - (b) With filter 1 (terrace)
  - (c) With filter 2 (grass-strips)
  - (d) With filter 3 (two months weeded)
- (2) Unweeded coffee
- (3) Coffee in multistrata
- (4) Natural forest
- (5) Sawah = irrigated rice field
- (6) Calliandra forest
- (7) Belukar = young secondary regrowth of forest
- (8) Vegetables
- (9) Bare soil

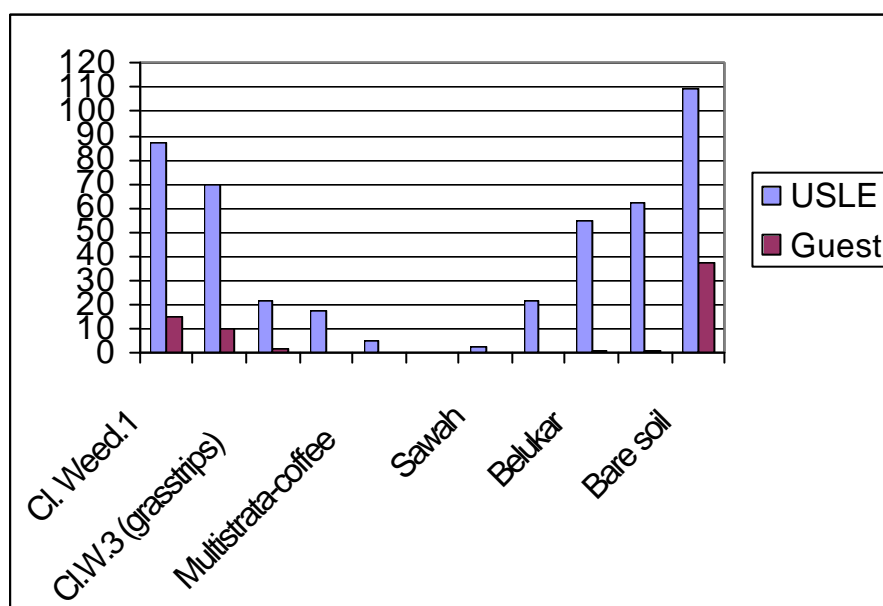


Figure 6. Erosion at plot level for various land use types (ton/ha)

### *Slope level scenarios*

The slope used each time was 500 m long and 20 m wide, so consisted of a downhill sequence of 25 grid cells of 20 x 20 m (equivalent to the plot size used above).

The list below represents the slope-level scenarios. One scenario consists of a combination of land-use types considered above. The combinations are given from the top of the slope down to the valley bottom.

1. natural forest/ bare soil/ clean weeded coffee/ sawah; with different subscenarios for the different types of clean weeded coffee mentioned above.

2. natural forest/ bare soil/ clean weeded coffee/ multi strata coffee/ sawah
3. natural forest/ multistrata coffee/ sawah
4. natural forest/ unweeded coffee/ sawah
5. natural forest/ calliandra/ sawah
6. natural forest/ vegetables/ sawah
7. natural forest/ belukar/ sawah

The different types of land-use are distributed over multiple plots, for instance in scenario 1a, the distribution is:

Land-use Type	Length of slope (m)	Number of plots
Natural Forest	80	4
Bare Soil	180	9
Cleanweeded coffee without Filters	200	10
Sawah	40	2
Total	500	25

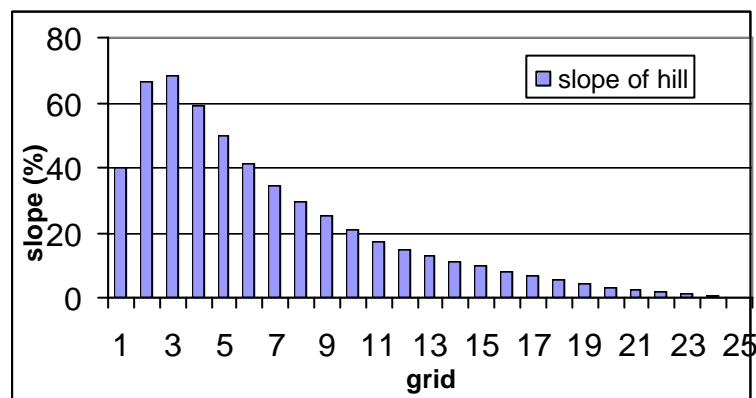


Figure 7. The varying slope for each of the above 25 cells

Figure 8 gives the results for the USLE. Especially scenario 3 to 5 seem to give low erosion yields.

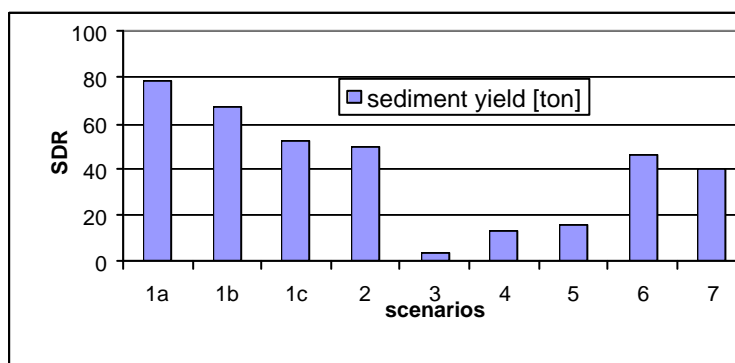


Figure 8. Sediment yield at the bottom of a slope using the USLE equation

For the same slope the GUEST equation always gave a very low (almost incredible) erosion yield: very close to 0 (zero) ton/ha. This was mainly due to the large sedimentation capacity of the last two sawah plots at the end of the almost flat slope. Hardly any sediment would 'leak' through these 'filter' plots. Especially the gentle slope in the last 2 grid cells seemed to play a crucial role.

The USLE does not account for these effects, because the result is based on an average erosion value over the whole area. It would not make a difference if the filter elements were located at the bottom of the slope or on top of the hill!

### *Catchment level scenarios*

The catchment level simulations involved following scenarios (fig. 9), whereby the different land use map scenario's were overlaid with a digital elevation model as can be seen in fig. 10 and 11. Scenario 1 was made to compare the USLE and GUEST equation. Scenarios 2 and 3 were developed to study the effect of filter elements with the GUEST equation. Scenario 3 had strips of 2 cells sawah (as filters) along the rivers.

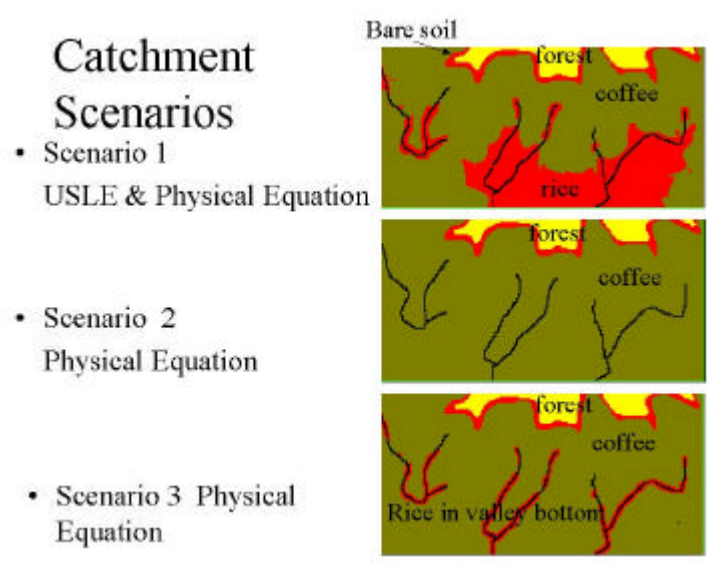


Figure 9. Landuse scenarios compared at the catchment level

Comparing scenario 1 for both the USLE and GUEST equation gave following results (Fig 10 and 11):

Comparing results following observations can be made:

- The difference between both equations is far less at the catchment level then at the plot or slope level. This is largely because of the increased sediment yield for the physical equation. The higher figure is caused by the large amount of run-off on the steep slopes without 'filter elements' near the outflow points at rivers.
- It is striking that the erosion 'hot spots' are in completely different areas depending on which equation one uses! This would imply dramatic consequences for if and where soil and water conservation interventions should be undertaken, as until now these interventions are only based on one approach.
- The USLE is sensitive to convex slopes and catchment size: the larger the catchment, the larger the absolute erosion result. The USLE is completely insensitive to the spatial distribution of land use types.



- The GUEST equation is sensitive to convex slopes, the distribution of land use types and filter elements and the frequency of big rainfall events. Catchment size is far less important for the GUEST equation.

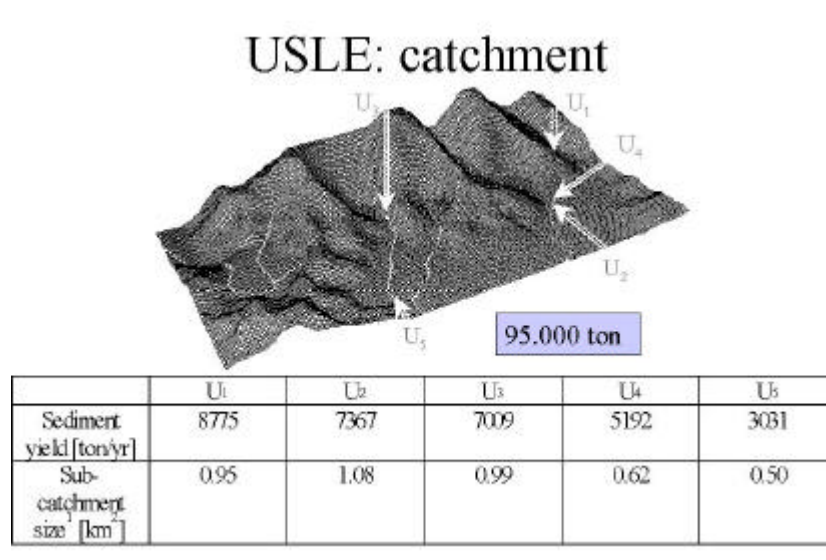


Figure 10. Erosion results and 'hot spots' in a catchment using the USLE for scenario 1. Over the whole grid, the grid cells where sediment would yield are the outer boundaries of the grid and the rivers. These were defined as potential end points for the sediment 'traveling' through the landscape. The five grid cells with the highest sediment yield are listed in figure 10 and 11.

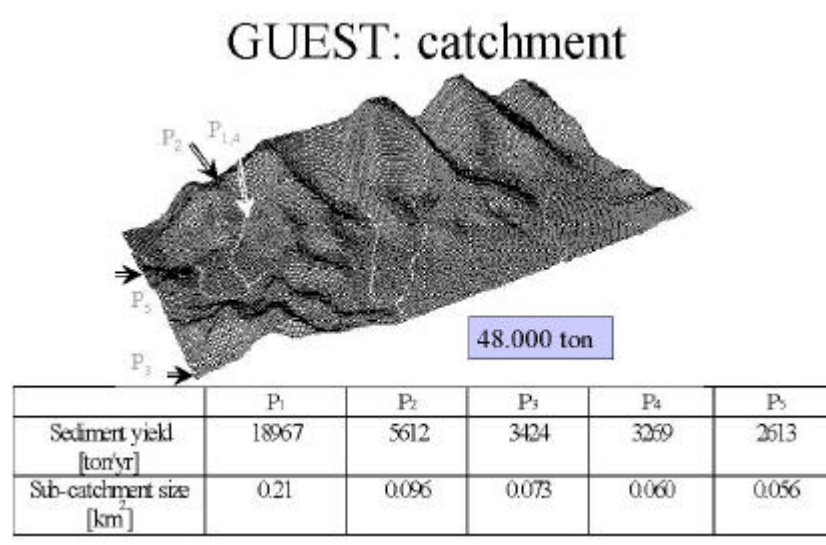


Figure 11 Erosion results and 'hot spots' in a catchment using the GUEST for scenario 1

Scenario 2 gave a higher total sediment yield (57,456 ton/yr compared to 47,656 ton/yr) because of the lack of filter elements. Scenario 3 gave only a marginal higher figure (48.338 ton/yr), although it had far less filter elements (sawah) than scenario 1. This is a clear indication that it is not so important how many filter elements there are in the landscape, but far more important is where they are spatially located! It seems crucial that filter elements are close to the inflow points to the river.

This type of approach could be modified e.g. by adding roads, small footpaths, ... to the virtual landscape.

### *Conclusions from this case study*

1. USLE is a relatively easy equation to use, but scaling up is problematic. It doesn't capture spatial heterogeneity or landscape mosaic. The output is a sum of erosion from homogeneous units corrected for the area by the Sediment Delivery Ratio.
2. The more complex GUEST equation needs more accurate data in this case study, but is more promising in being able to help answer the questions posed in the introduction! It captures lateral flows and spatial heterogeneity! It needs better and more reliable data, than are currently available in many areas.
3. At plot level: e.g. erodibility of various soil types and their infiltration capacity
4. At the catchment level: More research is needed to find out to what extent sawah or irrigated rice fields can operate as an effective filter. The approach illustrated (with 'hot spot' locations) above can help in locating where the most effective place in the landscape would be to put those filters. More research is needed to what extent small roads and footpaths function as channels or even 'highways' for sediment transport.

## **10. Conclusion**

In conclusion, forest conversion to other land uses can affect watershed functions in a number of ways. Land use changes at the 'source' or upland areas of watersheds have effects on the users of the water downstream. As can be seen from the various examples, the perceptions of the different stakeholders in a watershed often dominate the ways in which they deal with each other. Thus, watersheds involve multiple users and decision-makers that are not affected equally by the introduction of watershed development technology. Such technologies (such as soil erosion prevention measures) are likely to fail if their costs to various stakeholders are not linked to the benefits they deliver. There is a need to get the facts right: What are the actual sources of erosion? Do current remedies target the right problem? More insight in e.g. the effects of scaling up or the range of (in) accuracy can help.

A 'scientific based' watershed approach can help contributing more objective facts to the discussions between the various stakeholders and perhaps go even so far in bringing suggestions for revisions of current legislation in some countries. Is the most appropriate location of watershed protection forest really on the (generally steeper) upper slopes? Or would a more appropriate location be in valley bottoms, which are currently often dedicated to irrigated rice cultivation?

## **III. Reading Material**

### **Textbooks**

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- Bruijnzeel LA. 1990. Hydrology of Moist Tropical Forests and Effects of Conversion: A State of Knowledge Review. *UNESCO International Hydrological Programme*; a publication of the Humid Tropics Program and International Institute for Aerospace Survey and Earth Sciences.
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- Penning de Vries FWT, Agus F and Kerr J. (eds.), 1998. Soil Erosion at Multiple Scales. Principles and Methods for Assessing Causes and Impacts. CABI Publishing in association with the International Board for Soil Research and Management (IBSRAM). 390 pp.

## Book chapters

- Garrity DP. 1996. Tree-crop-soils interactions on slopes. In Ong, C. K. and Huxley, P.A. (eds.). *Tree-Crop Interactions – a Physiological Approach*. CAB International, Wallingford, UK. pp. 299-318.
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## Scientific journal articles

- Sanchez P. 1995. Science in Agroforestry. *Agroforestry Systems* 30, 5 – 55.
- Van Noordwijk M, Tomich T and Verbist B. 2000. "Negotiation support model for integrated natural resource management in forest margins and in landscapes with trees: can they solve local as well as global problems?" Conservation Ecology: 18 pp.

## Reports / Manuals

- Schmitz K and Tameling A. 2000. Modelling erosion at different scales, a preliminary 'virtual' exploration of the Sumber Jaya watershed. Enschede, ICRAF, Bogor, Indonesia and University of Twente, Enschede, The Netherlands: 84.
- Turner P. 1999. Java. Behind the Temples, Volcanoes and Fertile Plains. Lonely Planet Publications Pty Ltd., Australia.
- Van der Poel P and Subagyono K. 1998. National watershed management and conservation project, the use of the universal soil loss equation in the RTL process. Bandung, Indonesia.
- Van Noordwijk M and Lusiana B. 1998. WaNuLCAS, a Model of Water, Nutrient and Light Capture in Agroforestry Systems. International Centre for Research in Agroforestry (ICRAF), Bogor, mimeograph.

## Websites

- International Hydrological Program: <http://www.unesco.org/water>
- Karssenbergh, D.J., 1996. PCRaster manual. Department of Physical Geography, Utrecht University, The Netherlands (check also at <http://www.pcraster.nl>)
- River Systems Research Group: <http://boto.ocean.washington.edu/>
- World Commission on Dams: <Http://www.dams.org>

## IV. Mini-Glossary

**Base flow:** Part of the discharge, which enters a stream channel from groundwater. It is the more or less permanent flow supplied to drainage channels by rather invariable sources

**Cloud interception:** Condensation of water vapour on surfaces exposed to mist or clouds, e.g. of trees covered by epiphytes, leading to water dripping to the soil surface

**Infiltration:** the rate of movement of water into the soil

**Interception:** (1) the process whereby the downward movement of precipitation is interrupted and redistributed, or (2) the amount of water lost to soil moisture by this process, often expressed as a percent

**Overland flow:** surface run - off

**Perched water table:** The water table of a relatively small groundwater body lying above the general groundwater body.

**Percolation:** Downward movement of water in a non-saturated zone

**Quick flow:** Part of the discharge, which enters a stream channel almost directly during and shortly after a rainfall event

**Radial or directional transport velocity:** the speed with which particles are moved along a certain direction

**Run-off:** transport of water out of a (catchment) area or experimental plot

**Run-on:** transport of water into a (catchment) area or experimental plot

**Saturated conductivity:** Saturated flow occurs when the soil water pressure is positive; that is, when the soil matrix potential is zero (satiated wet condition). In most soils this situation takes place when about 95 percent of the total pore space is filled with water. The remaining 5 percent is filled with entrapped air.

**Saturation overland flow:** Shallow widespread surface runoff caused by reduced infiltration of rain during saturation by a rising groundwater table

**Sediment delivery ratio:** A measure of the sediment actually reaching a stream or lake expressed as the quantity of material reaching a specific point in a drainage system divided by the quantity actually eroded in the catchment above the same point

**SOM:** Soil organic matter

**Subsurface flow:** water, which flows just below the ground surface and infiltrates through different soil layers

**Subsurface run-off:** water that moves through the aerated portion of the soil to the stream and behaves more like overland flow than base flow

**Surface run-off:** water that runs across the top of the soil without infiltrating in the soil

**Watershed (catchment):** the natural or disturbed unit of land on which all of the water that falls (or emanates from springs), collects by gravity, and fails to evaporate, runs off via a common outlet

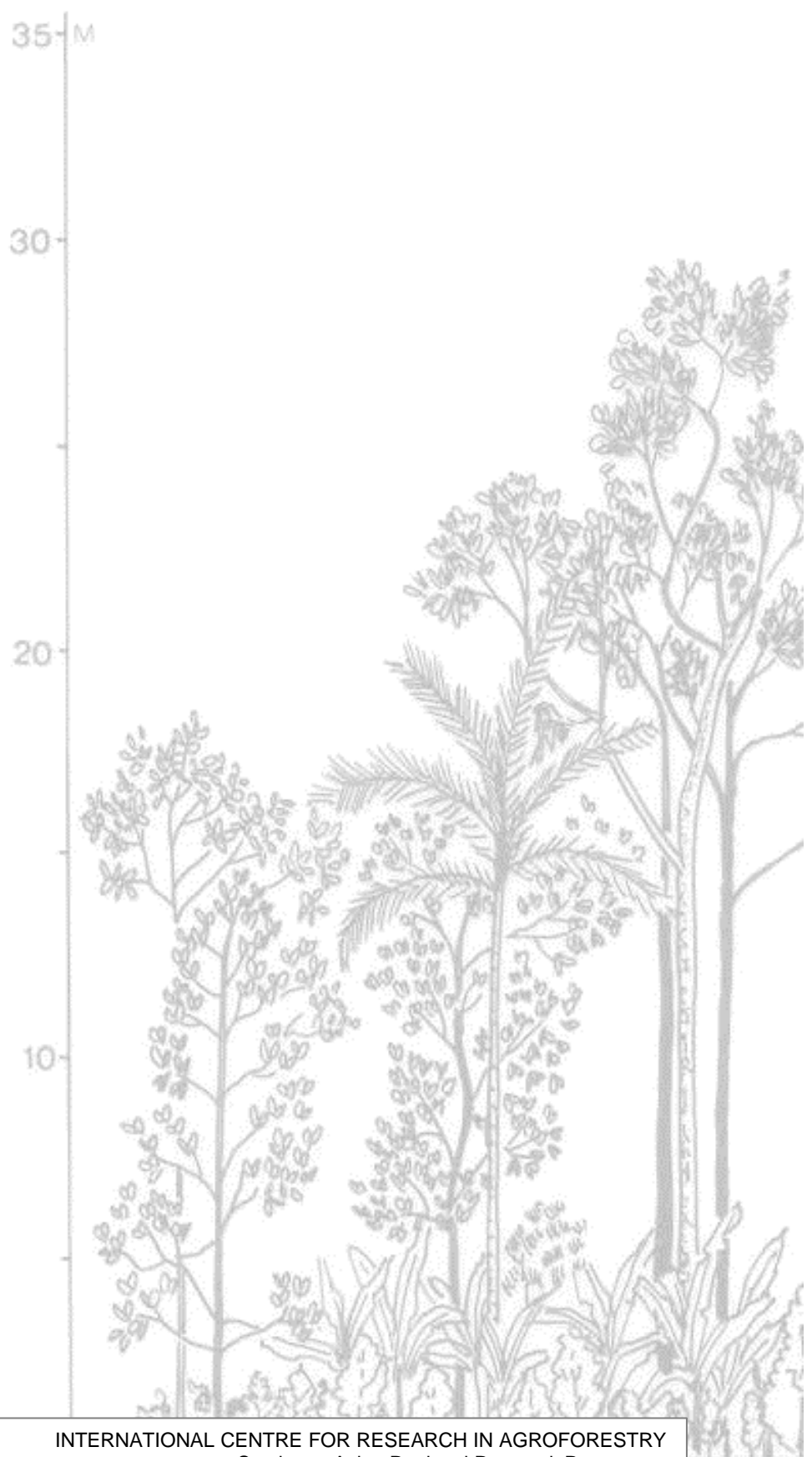
**Water table:** the upper surface of the groundwater reservoir

## Contents of this series of lecture notes

1. Problem definition for integrated natural resource management in forest margins of the humid tropics: characterisation and diagnosis of land use practices  
*by: Meine van Noordwijk, Pendo Maro Susswein, Cheryl Palm, Anne-Marie Izac and Thomas P Tomich*
2. Land use practices in the humid tropics and introduction to ASB benchmark areas  
*by: Meine van Noordwijk, Pendo Maro Susswein, Thomas P Tomich, Chimere Diaw and Steve Vosti*
3. Sustainability of tropical land use systems following forest conversion  
*by: Meine van Noordwijk, Kurniatun Hairiah and Stephan Weise*
- 4A. Carbon stocks of tropical land use systems as part of the global C balance: effects of forest conversion and options for 'clean development' activities.  
*by: Kurniatun Hairiah, SM Sitompul, Meine van Noordwijk and Cheryl Palm*
- 4B. Methods for sampling carbon stocks above and below ground.  
*by: Kurniatun Hairiah, SM Sitompul, Meine van Noordwijk and Cheryl Palm*
5. Biodiversity: issues relevant to integrated natural resource management in the humid tropics  
*by: Sandy E Williams, Andy Gillison and Meine van Noordwijk*
- 6A. Effects of land use change on belowground biodiversity  
*by: Kurniatun Hairiah, Sandy E Williams, David Bignell, Mike Swift and Meine van Noordwijk*
- 6B. Standard methods for assessment of soil biodiversity and land use practice  
*by: Mike Swift and David Bignell (Editors)*
7. Forest watershed functions and tropical land use change  
*by: Pendo Maro Susswein, Meine van Noordwijk and Bruno Verbist*
8. Evaluating land use systems from a socio-economic perspective  
*by: Marieke Kragten, Thomas P Tomich, Steve Vosti and Jim Gockowski*
9. Recognising local knowledge and giving farmers a voice in the policy development debate  
*by: Laxman Joshi, S Suyanto, Delia C Catacutan and Meine van Noordwijk*
10. Analysis of trade-offs between local, regional and global benefits of land use  
*by: Meine van Noordwijk, Thomas P Tomich, Jim Gockowski and Steve Vosti*
- 11A. Simulation models that help us to understand local action and its consequences for global concerns in a forest margin landscape  
*by: Meine van Noordwijk, Bruno Verbist, Grégoire Vincent and Thomas P. Tomich*
- 11B. Understanding local action and its consequences for global concerns in a forest margin landscape: the FALLOW model as a conceptual model of transitions from shifting cultivation  
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*by: Martua Sirait, Sandy Williams, Meine van Noordwijk, Achmad Kusworo, Suseno Budidarsono, Thomas P. Tomich, Suyanto, Chip Fay and David Thomas*



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