The impact of forest conversion on hydrology

A synthesis of French work in West Africa and Madagascar

by Sylvain Adokpo Migan

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IHP-V Project 6.1

Foreword

In pursuance of the selected topic for the IHP Humid Tropics Programme (UNESCO) concerning 'The impacts of land-use conversion on hydrology', the present work synthesizes forest hydrology work in French-speaking West Africa and Madagascar. The monograph includes:

- a review of forest hydrology work, principally that conducted by ORSTOM (formerly the Office de la Recherche Scientifique et Technique Outre-Mer, now known as L'Institut Français de Recherche Scientifique pour le Développement en Coopération, French Scientific Research Institute for Development in Cooperation) and CIRAD (Centre de Coopération International en Recherche Agronomique pour le Développement, Centre for International Co-operation in Agricultural Research for Development; previously known as the Centre Technique Forestier Tropical (CTFT));
- detailed information concerning available research data, including special mention of the state of existing stored data.

I am grateful to Dr Mike Bonell of the International Hydrology Programme (IHP), UNESCO, for having given me the opportunity to produce this synthesis and for his help and advice throughout the study.

The present monograph would not have been possible without the help of research seniors. Acknowledgements and regards are due to Professor Michel Mietton (CEREG URA 95 CNRS of Louis Pasteur University of Strasbourg), Professor Jean Luc Piermay (Geography Institute URA D-902 CNRS of Louis Pasteur University of Strasbourg) and Dr Jean-Marie Fritsch (Hydrology Laboratory/ORSTOM Montpellier) for their regular follow-up and advice.

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Sylvain Adokpo Migan

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Introduction

The environmental impact of anthropogenic activities on tropical forests has today become a vital issue, owing to the growing pressures being exerted on tropical forests. The question of the hydrological consequences of deforestation (i.e. the modification of the forest ecosystem, or the conversion to other types of land use) is a principal theme of applied research and training within the global IHP Humid Tropics Programme (IHP-IV subproject H.5-1; IHP-V project 6.1).

In October 1994 an IHP workshop was held in Abidjan, Côte d'Ivoire, with the principal objective of establishing a West African regional programme of applied research and training to address practical water and land management issues. One of the four themes selected was the hydrological impact of tropical forest conversion because both Ghana and Nigeria were establishing research programmes on this subject at the time. Most of West Africa is French-speaking, however, and the problem of access to previous research undertaken in the region, notably by the French Scientific Research Institute for Development in Cooperation (ORSTOM) and the Centre for International Co-operation in Agricultural Research for Development (CIRAD-Fôret) was raised at the Abidjan workshop. Consequently, the drafting of a synthesis in English of forest hydrology previously undertaken in French-speaking countries of both West Africa and Madagascar was one of the recommendations of this workshop.

Moreover, it was also recognized that, at the global level, there may be insufficient appreciation of French forest hydrology in the tropics because a lot of work was either not published in English-language international journals or published only as 'in-house' reports. Thus it was hoped that any synthesis would also be of value not only to English-speaking West Africa but also to the wider international community.

The current synthesis is not intended to be yet another descriptive approach to the mechanisms and functioning of hydrology in tropical moist forest, but rather a review of past literature focusing on the hydrological impacts of anthropogenic disturbances in the tropical forest environment, in French-speaking West Africa and also extended to Madagascar. An additional objective is to report on the existing data archives and their quality for further analyses.

The result of extensive research within the respective libraries and archives of ORSTOM and CIRAD-Fôret, the current synthesis should nevertheless be considered as only a preliminary to more in-depth studies. It is hoped that a more exhaustive version of the present document will be published in the not-too-distant future.

1. Physiography of West African humid tropics

1.1 The important geomorphologic features

West Africa is an ancient platform of Precambrian geology, generally worn and monotonous, but displaying nevertheless some relief:

- the Fouta Djallon in Guinea, which continues parallel to the coast via the Guinean-Liberian ridge until Mount Nimba (1854 m);
- the Atakora range, stretching SSW–NNE from Ghana to Niger, and culminating at Mount Agou, in Togo, at an altitude of about 1000 m;
- the Jos Plateau in Nigeria, which reaches 2010 m at its highest point.

In places, there are more geologically recent formations, which are represented by vast sedimentary basins. These formations are tabular (Benin, Burkina Faso, Voltaian Basin in Ghana, Niger and Togo) or folded and metamorphic (Dahoman, Gourma).

The most characteristic landscape is of undulating relief, with less pronounced plateaux of gneissoid granite ground or volcanic schist. These plateaux present frequently hardpans and are grouped into two or more, or stepped in a piedmont.

1.2 The weathering of crystalline and crystallophylian bedrock in West Africa

The magmatic and metamorphic formations of West Africa are, in general, covered with a weathered rock layer which represents the result of a physico-chemical disintegration due largely to two climatic factors: water and temperature. The thickness of this layer varies, as a rule, according to latitude, diminishing for example from Côte d'Ivoire in the direction of the Sudanese latitudes. Local variations occasionally appear according to the geological facies and the geomorphology. This thickness, which is often between 10 m and 20 m in gneissoid granite, can reach and even surpass a depth of 40 m in the schist of Côte d'Ivoire.

1.3 The humid tropical soils of West Africa

Within the weathered rocks layer previously described, the humid tropical soils are essentially ferralitic soils. They consist of well-developed A, B and C horizons, and are dominated by 'sesquioxides' of iron and aluminium and kaolinite-type clay. These soils often penetrate deeper than 10 m and have a distinctive red colour.
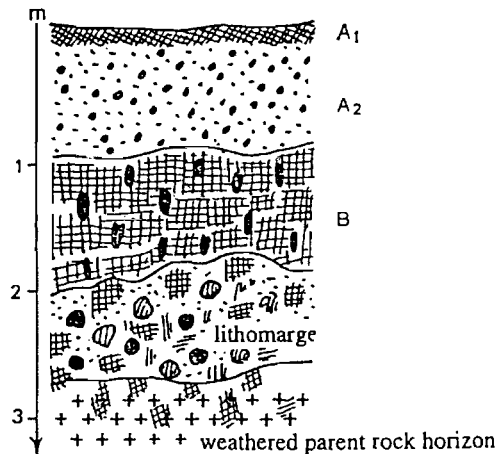
Figure 1. Ferralitic soil profile (George, 1993)

A typical soil description is as follows:

*   Horizon A_1, not very deep (10–20 cm): forestry mull with very rapid mineralization; the mineralization of these organic reserves is an important factor for the soils in our area of study. The region as a whole is subject to strong climatic influences accentuated by humidity, heat and the intense energy of the rains, which favour the mineralization of organic materials and damage the physical properties of superficial horizons (Charreau, 1972; Humbel, 1974). The pedological ferralitic covering is therefore no more than a completely weathered skeleton, an area relatively favourable to farming but almost completely devoid of mineral reserves (Roose, 1983).
* A_2, washed, rich in gravel
*   B, deep, compact, clayey enriched in iron and alumina, with abundant kaolinite;
*   A clayey lithomarge (kaolinite), called 'speckled zone' or 'veined clay' because of the existence of iron hydroxides.
*   An arena or côarse weathered rock *in situ*, of a variable depth, where the structures of the parent rock are roughly preserved.

The multiphase process, which leads to the formation of the ferralitic soils, is characterized by sudden weathering at the primary levels, due to neutral or alkaline hydrolysis freeing the iron, the alumina and the silica. The extent of the ferralitization is linked to the drainage conditions and to the nature of the parent rock. In the humid tropics of West Africa, the fact that the substrata is frequently an acidic rock alleviates somewhat the ferralitization process (the silica still present combines with the alumina, producing a crystallization after diagenesis of kaolinite, abundant where drainage is poor or scarcer where drainage is good).

The question of the different soil types must be approached here in terms of characteristics of drainage of the surface layers which represent the most relevant factor for differentiating between the catchment hydrological systems (Fritsch 1993). Three categories of soil have been identified and retained (Fritsch, 1993; Lal, 1993; Roose, 1975):

*   soils with good vertical drainage;

- soils with bad vertical drainage, the formation of a perched watertable and a dominantly lateral circulation of water;
- soils with considerable fluctuation in watertable, with the emergence of groundwater at the surface during intense rainy periods.

These soils are precariously balanced from both a chemical and structural point of view. Under the forest cover, this balance is only maintained by soil biology. These soils are made up of plant remnants and nutritional elements from various biological activities concentrated near the surface and are recycled continuously by the forest (Roose, 1983). The plant cover represents the most effective protection against erosion (Goujon et al., 1968).

When the forest is removed, the recycling of organic materials stops. The amount of carbon in the soil is reduced, the nutritional elements weakly retained by the kaolinitical clay are leached, the biological activities are reduced, whilst the macroporosity collapses and the structure in the surface layers becomes degraded (Nye and Greenland, 1964; Charreau and Fauck, 1970; Roose, 1981).

1.4   The types of anthropogenic influences within the forest environment in West Africa and Madagascar

In Africa, and especially in West Africa and Madagascar, the evolution of farms is achieved much more by extending cultivated surfaces rather than by improving yield (Roose, 1983). Human influences lead in most cases to a degradation of the forest which is generally done by:
- setting fire;
- overgrazing;
- clearing;
- careless cultivation neglecting soil conservation (Goujon et al., 1968).

However, man can also be the source of restoration, through judicial forest area protection, projects of overgrowth and reforestation (Goujon et al., 1968).

Examples of colonization of forest areas for farming are numerous in West Africa, where even 'protected' forest does not escape the actions of clearing. Examples of soil occupation are seen through the percentage changes of cultivated fields within the forest boundaries, clearly illustrating this development. For example, in the Korhogo basin only 15 % of the surface area was occupied by cultivated fields in 1962; this percentage had risen to 64 % by 1975 (Albergel and Gioda, 1986). The same goes for several other forest areas subjected to clearing in West Africa (Adokpo Migan, 1993; 1994).

1.4.1   The different types of clearing

With regard to the study of hydrological impacts of forest conversion, it is very important to provide precise details of the nature of clearing which preceded the new use of the soil.

1.4.1.1 Traditional clearing

Clearing is manual without working the soil and entails progressive burning of the plant material, respecting the roots system and the structure of the surface horizons (Moreau, 1982). The degradation of the soil is limited and does not become apparent until between three and five years thereafter (following deterioration of the roots network). The abandonment of such clearing methods generally leads to an invasion by weeds and predators rather than to a reduction in chemical fertility (Jurion and Henry, 1967).

1.4.1.2 Manual or semi-mechanized clearing

Clearing is manual or semi-mechanized with a view to practising intensive perennial shrub cultivation with covering plant or forest fresh overgrowth: the burning is limited to small wood and enriches the surface layer of earth if it is done outside the rainy season. The unloading of the large wood is very limited. The roots system is preserved along with the structure of the soil (Roose, 1983).

The degradation of the soil is reduced in these conditions and a balance favourable to shrub cultivation (planting cacao-tree, coffee-tree and hevea) can be established in return for a poor supply of fertilizer (Tranh Thanh Canh, 1972; Roose, 1980).

1.4.1.3 Mechanized clearing (annual cultivation)

Clearing is mechanized for annual cultivation conversion. In this case it is much more harmful, because it entails the transportation of all the plant material on the distant windrows of 50–150 m, the soil becomes compact and the roots are extracted, followed by the subtitling and the delicate preparation of seedbed.

This method causes most failures (abandonment of the degraded ground after two to three years of cultivation). Furthermore, this type of clearing deprives the soil of its mineral and organic stock (including the plant material brought together on the windrows); the earth is exposed to the rigour of the sun and capping of the soil by intense rains. In addition, soil erodibility is increased (Roose, 1983).

1.4.1.4 Mechanized clearing (perennial cultivation)

Clearing with a view to perennial cultivation is mechanized using powerful tractors, but the work is done outside the rainy season. The large wood is unloaded as windrows in the spaces between the lines after burning, which allows the soil to recover a plant cover either through forest fresh overgrowth or through the sowing of leguminous plants (Roose, 1983). If the mechanized clearing for the perennial cultivation conversion is not done in this way, the degradation of the soil can reach serious proportions both spatially and temporally, since the packing under the heavy engines and the destruction of the surface layers have long-term effects.

2. Climatic characteristics of humid tropical forest in West Africa

The part of West Africa under study here is characterized by three climatic sub-areas from the equatorial hot, humid climate in the South to the typically Sudanese climate in the North.

These climatic variations are obviously expressed through such common climatic parameters as temperature, rainfall (Map 1) and evapotranspiration but also through the surface hydrology and the plant cover. From South to North there is also a progression from rainforest to savannah. Whilst the forests are declining at a much faster rate because of the degradation arising from anthropogenic influences, the savannahs are affected by a combination of anthropogenic and climatic factors.

2.1 Aerological conditions

Often not sufficiently categorized, the synoptic conditions are highly significant when defining the climatic conditions of West Africa. It is important to recognize that West Africa owes its climatic characteristics to boreal trade (oceanic winds, and continental winds called 'harmattan') on the one hand, and to the Atlantic monsoon (resulting from the deviation of the lower stratum of the southern winds) on the other hand, these two flows being separated by the meteorological equator (commonly designated in literature as the Inter-Tropical Convergence Zone or Inter-Tropical Front).[1]

The advanced or retracted position of this front over the continent and the aerological structure it presents at each stage of its extension determines the different conditions for 'raingenesis'. In the South of West Africa, in Côte d'Ivoire for example, the monsoon flow persists during the greater part of the year, except during the 'long dry season' (December to February). In the South of the country the proximity of the ocean and forest cover confine the higher temperatures to the savannah.

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1. There has been considerable debate within climatological literature as to the appropriate term to use for this system. Manton and Bonell (1993) provided an overview of this subject and elected to use the term 'northern monsoon sheerline' for the described system here. Nowadays, 'front' is out of favour, but possible in some African literature.

2.2   The conditions for rain-genesis

It has been established that a principal source of precipitation in West Africa comes from the Atlantic Ocean and as part of the south-west monsoon. Nevertheless, the structure of the 'Inter-Tropical Front' structure at different times of the year is a controlling factor for the precipitation potential.

Thus, in the south of West Africa (around the latitude 5° North), three different aerological structures of the meteorological equator occur, offering therefore three different conditions for 'rain-genesis'.

1. The most northern structure of the meteorological Equator, the I. T. F. structure (Figure 2), is unproductive (non-rainfall), due to the sudden discontinuity of the humidity between the lower layers of the western monsoon and the 'harmattan' of the East which surmount the monsoon. Thus the cloudy formations are sheared or evaporated. Consequently, 'non-rain' is the rule, despite an abundant potential for precipitation. The unproductive conditions are temporarily cancelled during the passage from East to West of an 'eastern heavy shower' (*ligne de grain* in French) constituted from clouds with vertical development of the cumulonimbus type. Linked to these perturbations, the rainfalls are brief, strong, mainly stormy, but relatively scarce.

2. The 'central' structure of the meteorological Equator, the I. C. Z.[2] (Intertropical Convergence Zone) structure, which is situated over the continent in the medium layers straight above the moist layer of monsoon (Figure 2), is the axis of confluence between the upper stratum of the southern trade winds and the boreal trade winds raised above the monsoon. These two flows pull towards the I. C. Z. The concentration of energy from the convergence of North and South flows transforms this axis structure into dense cloud formations (mainly composed of altocumulus and altostratus). Rainfall is abundant, continuous and on the whole not stormy but with more intense areas of activity. The I. C. Z. represents the culmination point of the 'eastern heavy shower' of the I. T. F. Structure.

3. To the south of the I. C. Z. is found the standard structure of the trade winds, characterized by its rigorous layering; shearing of the wind and contrasting characters make this structure unproductive. Its penetration into the south of West Africa in mid-summer (notably in August, see Figure 2), is reflected in the short dry summer season (August) in the coastal zones.

One can conclude that the latitudes close to the geographical Equator experience three structures of the meteorological Equator with two passages of the I. C. Z. structure (central structure). By contrast, those areas at the northern boundaries of the area of study only experience two of the three structures previously depicted; with a single rainy season that corresponds to the installing of the I. C. Z. structure over three months (July to September).

2.3   The West African humid tropics and their vegetation

For Anglo-Saxons, the humid tropics concept defines the three sub-types of the tropical climate (humid, sub-humid and wet-dry).

The *humid* sub-type corresponds to the Guinean domain in the geographical distribution and climatic domain applied to the African continent. It includes the zone located with over 1,600 mm isohyet where the tropical rain forest grows into hyper tropical rain forest. In the zone incorporated between 1,600 mm and 1,200 mm isohyet, the mesophile forest grows.

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2.   The I.C.Z. is equivalent to the Maximum Cloud Zone (MCZ) mentioned in Merton and Bonell (1993).
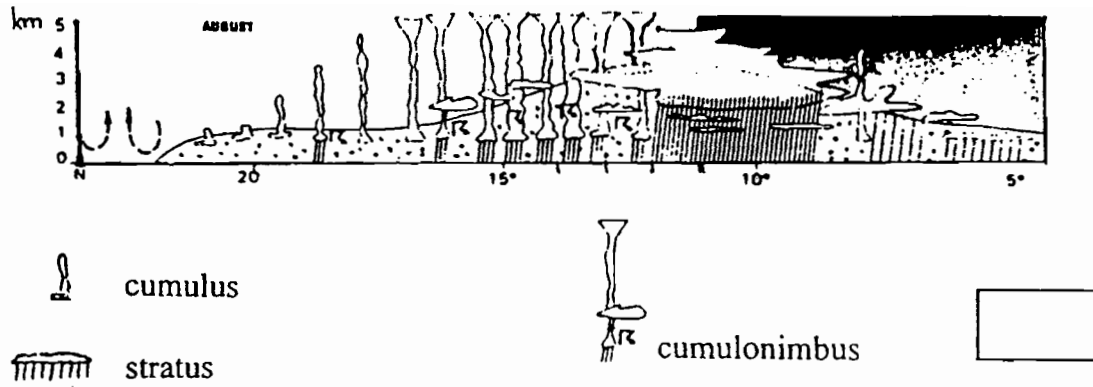
Figure 2. Overall structure of I.T.F. (around the latitude 5° North in August)

The *sub-humid* sub-type concerns the sub-Guinean and sub-Sudanese domains. These represent, in terms of vegetation, an area between the Guinean and Sudanese domains. The first one is characterized by strips of mesophile forest and wide meshes of savannah, overlapped by 'gallery forest'. Always organized in strips in the relatively less rainy areas, the sub-Sudanese sector appears as a juxtaposition of forest and savannah formations. Some authors classify these as 'light forest' with more or less a closed canopy. The parts located south of the Sudanese domain have something in common with this latter sector.

The *wet-dry* sub-type corresponds to a thoroughly Sudanese climatic domain, i.e. equally exposed to the continental trade winds and the African monsoon (here included between 700 mm and 1,000 mm with a total number of rainy months included between 4.5 to 7). This location endows a hydrological regime where the river hydrograph has only one peak, with a slight shift during the rains. Typically, this sector is the seat of the dry savannah forest overhanging a layer of high grass. Savannahs appear as discontinuous bands and become more or less dense as the latitude increases.

These medium characteristics are subject to an important inter-annual variability which mainly affects the rainfall, notably in a reduction of the annual total (Map 1). It is important to underline here the tendency over the last decade for precipitation to decline, which has affected not only the Sudanese domain but also the more southern domains of West Africa.

Oceanic trade wind domain

Continental trade wind
("Harmattan")

700

1000

wet-dry climate

1600-1800

1000

humid climate

sub-humid climate

700

humid climate

1600

1600

———— Isohyet (annual average) mm

⋮⋮⋮⋮ montane climate

— — — Northern limit of bi-modal pluviometric regime (with 2 rainy seasons)

— — — Eastern limit of oceanic trade wind
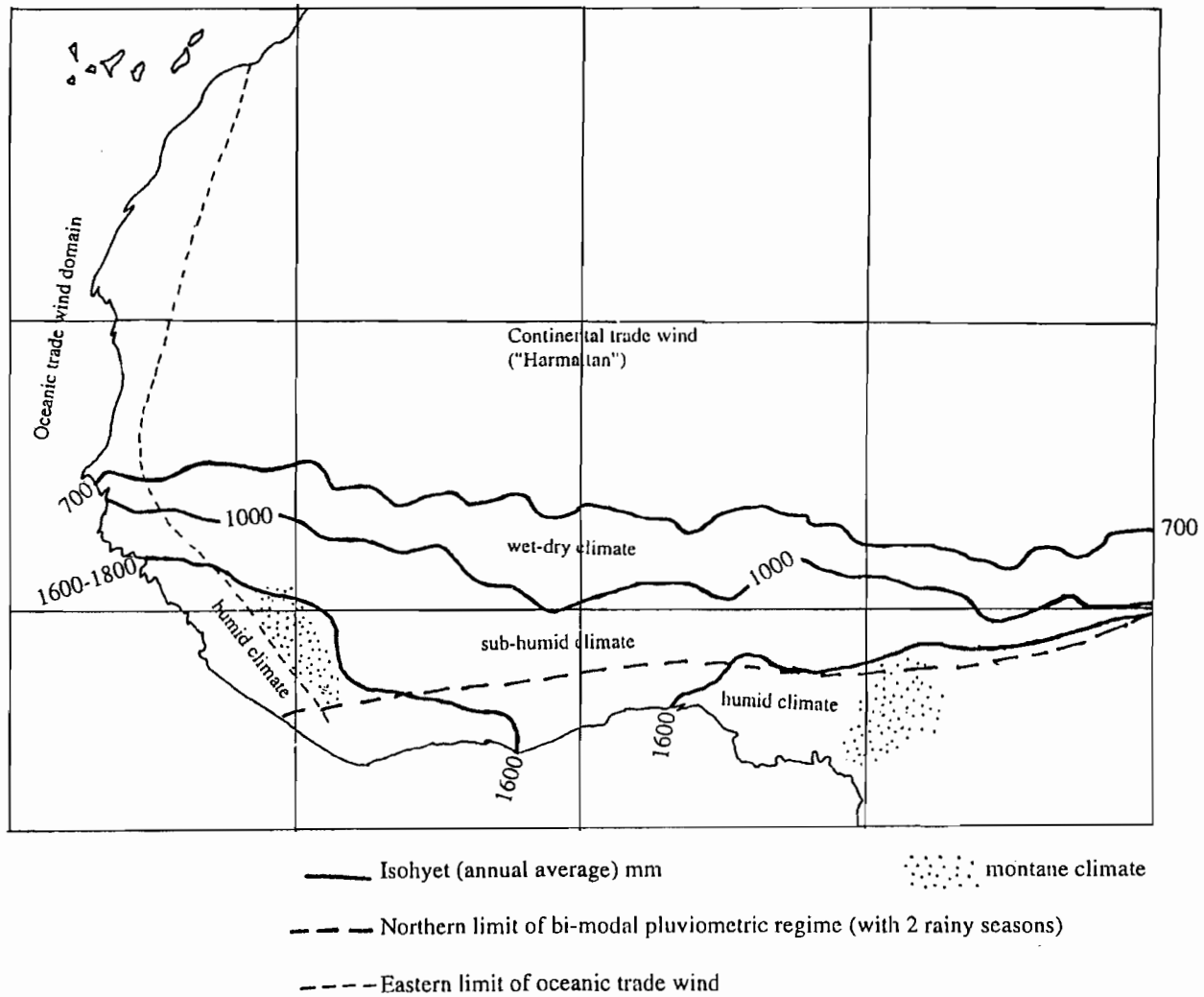
Map 1. Climatic zones of West Africa
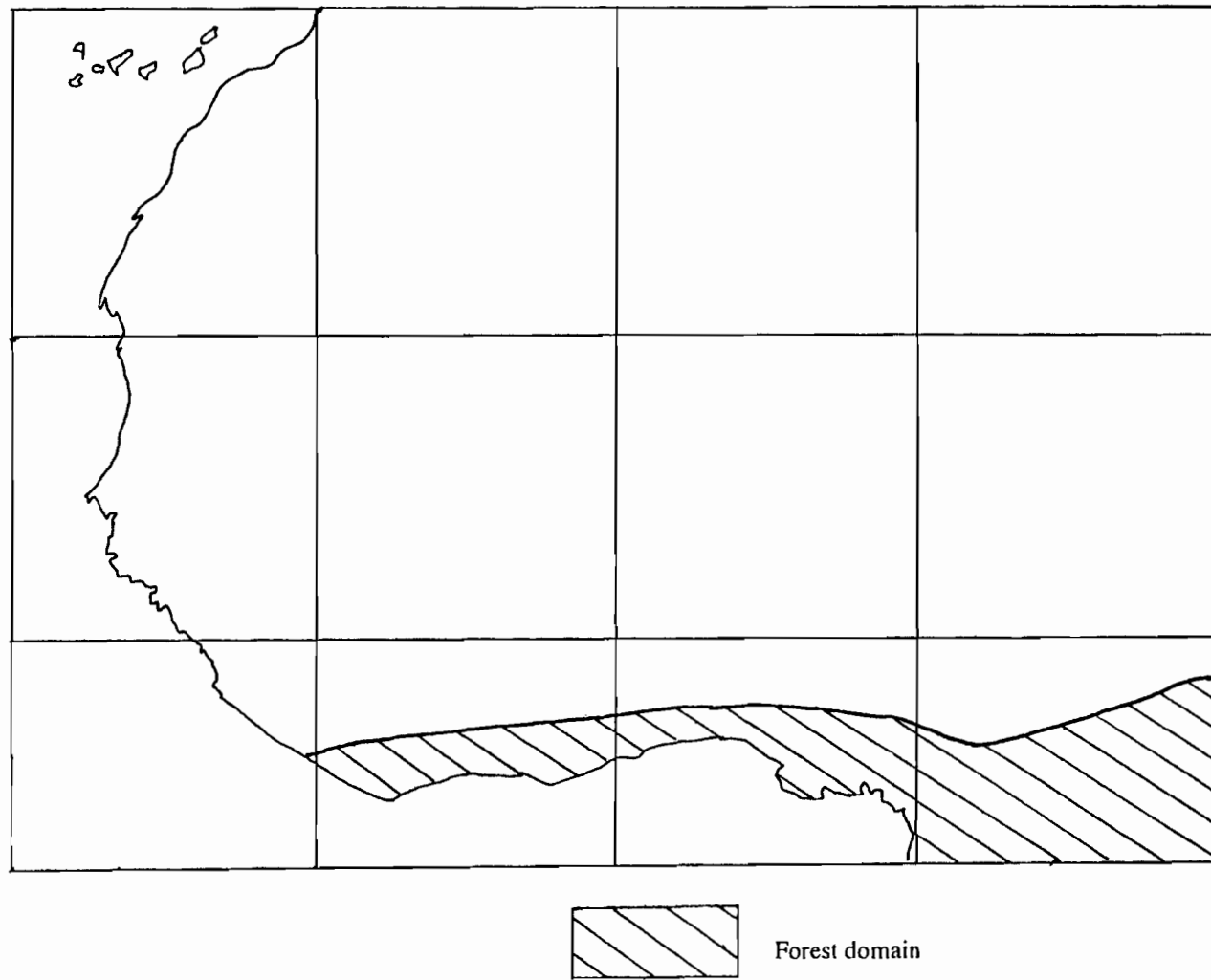
Map 2. The forest domain in West Africa

3. Forest hydrological processes in humid tropics

The aim of this chapter is not to undertake a detailed study of forest hydrological processes in West Africa, but rather to clarify from the outset certain terms which are open to confusion when describing forest hydrological systems.

We will begin with the precipitation that represents the water input from the hydrological systems of the tropics:

- *'direct' or 'free' throughfall:* the part which (depending on the density of the vegetation) penetrates directly to the forest floor without being intercepted by the canopy (Rutter et al., 1971);
- *interception loss:* a large part of that received by the canopy returns to the atmosphere as water vapour, during and immediately after the storm (Bruijnzeel and Wiersum, 1987); this term has been the subject of several controversies in scientific literature and should be used with caution;
- *crowndrip:* the part that does not evaporate but which reaches the forest floor soil by the dripping of the canopy when the maximum moistening capacity of the canopy and the trunks has been reached (Leyton et al., 1967);
- *stemflow:* the part that does not evaporate but which reaches the forest floor soil by the branches and trunks when the maximum moistening capacity of the canopy and the trunks has been reached (Leyton et al., 1967).

The sum of direct throughfall, crowndrip and the stemflow is commonly called net precipitation (Helvey and Patric, 1965).

In practice it is difficult to estimate separately the direct throughfall and the crowndrip, but this distinction is very useful when modelling the interception processes. It is also useful when differentiating between gross interception loss (i. e. incident rainfall minus net rainfall) and the net interception loss (i. e. the gross loss minus the saving in transpired water). Such differentiation introduces the idea that leaves covered with a film of water do not transpire. The energy necessary for transpiration is largely consumed to evaporate the water on the leaves. Then whilst intercepted water is being evaporated, there will be a saving in water normally taken up for transpiration according to the surrounding evaporative constraints (Burgy and Pomerol, 1958; Rutter et al., 1971; Rutter, 1975; Gash, 1979).

Interception has been measured in the forest basins of Perinet (Madagascar) over the
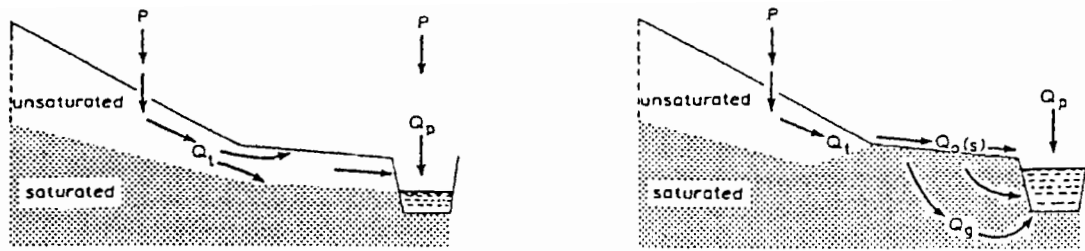
Figure 3. Flow paths of the sources of streamflow (adapted from Ward, 1984)

course of four measurement campaigns (1963–1964 to 1966–67). These measurements enabled the CTFT researchers to estimate the above different processes:

- the gross interception (i. e. difference between the depth of rainfall collected outside the cover and under cover) represented 14 % of precipitation;
- the amount of rain flowing the length of the trunks, expressed in percentage terms of the rainfall, was 2 %, which enabled the net precipitation to be calculated (Goujon et al., 1968). We shall return to the mechanism of measurement in Chapter 5.

The net precipitation (i. e. the rainwater arriving at the soil surface) meets a filter system that determines the preferred pathway for reaching the stream channel (Bruijnzeel, 1990).

As a result of the different delivery pathway of water input (precipitation), the stream-flows reflect periods of sudden increase associated with the rainy event and longer periods of the progressive decrease in the flows, corresponding to the draining of the water stored in the hillside basins. The immediacy of streamflow response suggests that part of rainfall will follow a rapid route to the stream channel, thus producing the quickflow. The water arriving more much slowly corresponds to the baseflow (Ward, 1984), otherwise known as delayed flow.

In the case where the intensity of the rains over the forest exceeds the soil infiltration capacity, the unabsorbed excess runs off as Hortonian Overland Flow (Hortonian) or as infiltration excess (flow path Qo Figure 3). The infiltrated part depends on the vertical and lateral hydraulic conductivity, on the local characteristics of the soil moisture content and on the slopes, and can therefore take one of the numerous possible routes leading to the stream channel (Figure 3).

In the case (relatively rare) where the soil is essentially composed of deep deposits, homogeneous and permeable, the water will tend to travel vertically towards the saturation zone and hence adopt a move lateral path towards the stream channel (flow path Qg in Figure 3). Otherwise, the permeability reduces with depth. Most of the water then percolates vertically until it meets an obstruction like clayey B-horizon or a bedrock, when it is deflected laterally (Weyman, 1973; Guelh, 1983). Usually this lateral flow in the soil profile is referred to as throughflow or interflow (Kirkby and Chorley, 1967, flow path Qt in Figure 3).

The throughflow generally travels slowly through the pedological matrix, feeding near-saturated sections around the stream channels and contributing therefore to the maintenance of baseflow of the stream. These near-saturated zones in a catchment often act as the major sources of quickflow during rainstorms (Dietrich et al., 1982; Nortcliff and Thornes, 1984).

The mechanism of quickflow production reflects the prevailing geomorphologic and pedological conditions (Walsh, 1980; Ward, 1984; Burt & Butcher, 1985). In other cases, the quickflow is generated through the formation called riparian groundwater ridge (Ward, 1984), which may rise to the surface and induces what is called Saturation Overland Flow (Dunne, 1978; flow path $Qo(s)$ in Figure 3). In such situations an important portion of the quickflow will be provide by the freshly fallen rainwater. Proof is provided by the lowness of solute concentrations in flowing water (Bruijnzeel, 1983) and in floods, which in the latter case depends on the rainstorm intensities.

However, when the steep hillslopes with deep permeable soils overlie impermeable bedrock limit a narrow flood plain, there will be little scope for saturation overland flow, neither in the valley bottoms nor on the hillsides themselves. The quickflow will be then dominated by rapid throughflow contributions (Harr, 1977; Dunne, 1978; Cales, 1982). A peak in streamflow may occur immediately or several days after the storm, directly depending on the depth and initial moisture status of the soil and the size of the storm (Hewlett and Nutter, 1970; Sklash et al., 1986).

The immediacy of streamflow response to rainfall on the sites without appreciable overland flow of any type has been explained in part by the fact that the throughflow travels quickly enough through the upper soil horizons to reach the stream channel during the storm (hence the term sub-surface stormflow) and in part by the important role played by the decayed root network, animal burrows and other macropores in this type of flow (Whipkey, 1965; Mosley, 1982). It is very often the small or medium storms which give rise to this intermediate flow (Rodier, 1976). For larger storms, there can be a type of flow either over the leaf litter, on the forest floor or within the dead leaves complex or at its contact with the soil. This hypodermic flow is much more rapid than sub-surface stormflow (Rodier, 1976).

Except in these situations where the soil porosity and sub-surface pipes are favourable, rates of water movement through the soil matrix are generally too slow to allow freshly fallen water to reach the stream during a storm event as throughflow (Dunne, 1978). Hewlett and Hibbert put forward the concept of translatory flow or a push-through mechanism whereby each new addition of rain on a hillside displaces an approximately equivalent amount of 'old' water, leading in this way to the oldest water exiting from the bottom of the slope into the stream. Several studies have proved the scope of this push-through mechanism in ideal conditions for the generation of rapid sub-surface flow (high rainfall, short and steep slopes and highly permeable soils) (Pearce et al., 1986; Sklash et al., 1986).

However, a displacement of stored soil water by an equivalent volume of 'new' rainfall can only be expected if the moisture storage capacity of the pedological matrix is nearly full. In drier conditions, each 'new' rainfall will be used firstly to refill the soil moisture store before being able to displace existing moisture This implies of course that the push-through mechanism will occur more frequently after a period of rain, and/or on the lower and more humid areas of the slopes (Ward, 1984).

Obviously not all of the water infiltrating into the soil emerges as streamflow, a lesser part of it being taken up by the vegetation and returned to the atmosphere as a result of the plant transpiration. In this context the term of evaporation (ET) beneath forest will be used to indicate the sum of transpiration (i. e. evaporation from a dry canopy) and interception (i. e. evaporation from a wet canopy). Evaporation from the litter and soil surface is minimal in the humid tropics and depends on the density of the forest cover (Jordan and Heuveldop, 1980; Roche, 1982).
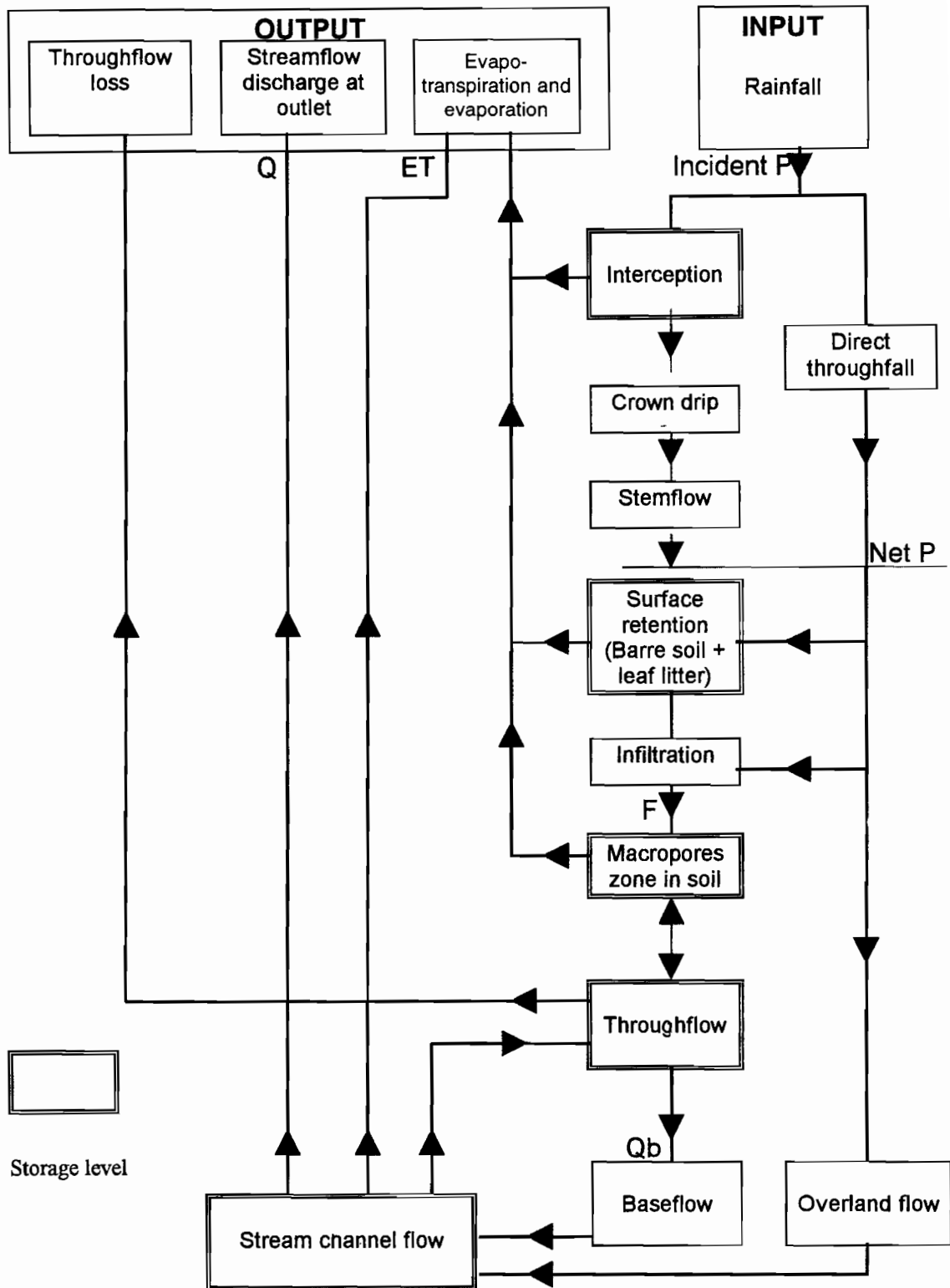
Figure 4. Hydrological cycle of a forested catchment (adapted from Douglas 1977 and Chuzeville, 1990)

4. Hydrograph and rainfall characteristics of humid tropical forest in West Africa and Madagascar

There are few water balance studies on forest basins in West Africa and Madagascar. Only two have been studied in any detail. The first concerns the Côte d'Ivoire basins of Korhogo and Sakassou (Camus and Berthauld, 1972), the other was undertaken on the Tafaina basin in Madagascar (Pourrut, 1968). In the Côte d'Ivoire study, ORSTOM approached the task through short-period comprehensive water balance measurements for later testing in a distributed model (Rodier, 1974). In this way, a better understanding of the processes of infiltration and soil and groundwater movement was obtained. However, the most important problem remained that of obtaining an independent estimation of the actual evapotranspiration (Rodier, 1974).

In a longer-term study, it would be necessary to carry out a data analysis for selected small experimental basins showing:

1. the amount of water yield versus rainfall and hydrograph separation to determine stormflow and delayed flow (both expressed in mm and as a percentage of rainfall);
2. the statistical relationship between quickflow (stormflow) and maximum intensities of storm rainfalls over a varying time base.

This exercise has not been undertaken within the geographic area of coverage.

On the other hand, this will not be enough to characterize the forest basin hydrograph for the entire climatic zones studied. Furthermore, the characterization of the floods remains to be improved (Bailly et al., 1974). Nevertheless there are large numbers of recorder raingauges which could allow the development of typical intensity-duration curves for durations of less than one hour in West Africa (Rodier, 1974). It has been also possible, by examining the flood hydrograph, to assess a few characteristics:

*   lag time,
*   rising time
*   peak flow relating with volume of surface runoff.

This type of study has enabled the effects of forest cover on the type of flood (i.e. hydrograph characteristics) to be evaluated. However, it should be noted that application of unit hydrograph theory is largely applied in experiments (see the ORSTOM studies in Chapter 5) but can be uncertain for small basins (Bailly et al., 1974).

It being beyond the scope of the present monograph to elaborate a detailed analysis of hydrographs, the only remaining option has been to synthesize existing data.

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5. Hydrological impacts and forest conversion

This chapter presents the effects of partial or complete removal of a forest or forest conversion on the main hydro-climatic parameters (rainfall and water yield), and also the methods of comparison used to estimate the impact of land use changes in West Africa and Madagascar.

5.1 Effects on the climate

These effects concern the diverse climatic changes and the impacts on local precipitation which may occur with forest clearing.

5.1.1 Changes in local climatic conditions and consequences

Changes in local climatic conditions (greater exposure to the sun, much higher soil temperature resulting in an increase in evaporative demand of the atmosphere) at soil level following forest clearing have consequences which range from the decomposition of organic matter to a change in the infiltration characteristics of the soil upper layers and erodibility. Furthermore, there is a reduction in microbial and soil fauna activity. Such changes occur due to a different partitioning of available energy arising from the decrease in evaporation (i. e. latent heat) after forest conversion to another plant covering (grassland or agricultural crops) less fitted to exploit soil moisture during dry periods. Large-scale conversion could influence the local and regional patterns of circulation of air and precipitation (Monteny and Casenave, 1988 and 1989). On the other hand, there is a limited data base to elaborate on this issue.

5.1.2 Effects on rainfall

Two approaches, one direct the other indirect, have been followed by researchers estimating the influence exerted by vegetation on rainfall-genesis: the direct approach consists of analysing time series of rainfall and the corresponding vegetation data. The aim is to link annual rainfall with vegetation cover relating to clearing or conversion. Rigorous analysis is required of long observation periods of well-equipped catchments. In addition, synoptic climatological considerations need to be taken into account in this kind of analysis. In West Africa, Côte d'Ivoire is apparently the only country able to offer such data.

The indirect approach involves computer simulation of climatic effects from land use changes. Such computer simulation studies have been concentrated mostly on the Amazonian basin, West Africa by and large having been neglected (Potter et al., 1975; Lettau et al., 1979; Lettau et al., 1979; Henderson-Sellers and Gornitz, 1984; Henderson-Sellers, 1987; Wilson et al., 1987; Dickinson, 1984, 1988 and 1989; Sellers et al., 1986 and 1989; Dorman and Sellers, 1989; Shuttleworth et al., 1990; Shukla et al., 1990). All of these studies have worked on updating and improving Land Surface Parametrisation (LSP) and the Global Circulation Models (GCM).

The origin of change in the precipitation regime has not been clearly proved by either of the above methods. Such changes may have an internal origin (due to conversion) or external origin (linked to global warming, see surface temperature anomalies).

Thus, in West Africa, important progress remains to be made in the field of forest–atmosphere interactions and climatic effects of forest conversion (Baldy and Stigter, 1993). However, results recently obtained in other regions make it difficult nowadays to entertain the idea put forward in Congo (Central Africa) that forest clearing exerts an insignificant influence (Bernard, 1953).

5.2   Effects on water yield

Compared with other types of soil, forest soils (litter roots and soil matrices) present special characteristics. For example, they are noteworthy for their large infiltration and water storage capacities, even if much of the water is consumed more to satisfy the needs of the forest than to sustain the streamflow regime.

5.2.1   Methodological comments

As Bruijnzeel (1983) underlined, the question of the effects of forest conversion on flows must be split into its two facets:
*   effects on water yield (i.e. total streamflow)
*   effects on the seasonal distribution of flow.
From a methodological point of view, the simple comparison of streamflow totals for catchment areas with different land use types may lead to wrong interpretations for several reasons. The complexity of the mechanisms involved cannot be clarified by simply comparing streamflow in recently converted forest catchment. Furthermore, the size of catchment may influence the water yield, for example, the case of lower streamflow totals suggesting considerable leakage in small catchments covered with Eucalyptus robusta in Madagascar (Bailly et al., 1974). In addition, leakage between adjoining catchments or losses in the sandy shallows from upstream to downstream may influence the water yield. Another problem is the well known effect of spatial and temporal variability of precipitation in tropical areas.

One way to minimize these potential problems is to use the so-called 'paired catchment

method' (Hewlett and Fortson, 1984; Fritsch, 1994), which entails the hydrological comparison of two (or more) catchments of similar size, geology, slopes, exposure and vegetation and which are situated next to one another. One of the catchments will be left unchanged and acts as the 'control catchment'. The other(s) will be the experimental or treatment catchment(s) (Roche, 1981 and 1982).

The experiment takes place in two phases:

1. the calibration phase, which may take several years depending on the rainfall variability. The objective is to develop an equation (linear regression or double mass curve) which links the streamflows of the two types of catchment.

2. the treatment period during with the land use changes are made to the treatment catchment. The degree to which equations derived during the calibration period change after the land is put to different use is a measure of the effect of the latter.

This type of experiment may take a decade (calibration, clearing, site preparation, planting, maturing of the new vegetation) (Bruijnzeel, 1990). Nevertheless, this does not preclude the results obtained from being influenced by the geological and pedological specific site conditions of study areas or from being due to scale effect (Fritsch et al., 1987; Dano, 1990).

At the conclusion of this bibliographical survey, it became apparent that none of the studies carried out in West Africa and Madagascar had developed this comparative method of evaluating the impacts of land use changes on water yield. Some studies had approached this method without fully pursuing the protocol. In paragraph 5.2.6.2, such a development is described in Madagascar (Ibiza, 1975).

Many hydrological studies in the forests of West Africa have been led by ORSTOM with a view to satisfying one of the main demands of the countries, that is, the prediction of rare events, most notably the ten-year return period flood. This information is required for the numerous civil engineering works (bridges, dam, storage basin) within the framework of a weak hydrometrical network. Commonly it has been necessary to use other sources of information such as rainfall data for the estimation of water yields of representative basins and to extrapolate the calculations towards the desired flow (Casenave et al., 1982).

In Madagascar, researchers of CTFT (CIRAD-Forêt) assessed water yield in terms of the influence of various forest covers on catchment discharges, runoff coefficients and peak runoff during the flood periods. The experiments were undertaken between 1963 and 1973.

Thus, the aims were not really those of a comprehensive evaluation of the impacts of forest conversion on water yields. However, the methods and techniques used, whether for reconstituting the extreme flows of forest catchments or for evaluating the influence of diverse forest covers on water yield, deserve to be included in the present synthesis.

5.2.2 Forest catchment and water yield in West Africa: ORSTOM experiments

Most of the studies undertaken by ORSTOM on forest catchments in West Africa have been carried out in Côte d'Ivoire, commencing with the Ifou basin in 1995. Since then, seventeen groups of basins (41 catchments) have been studied (Casenave et al., 1982). The extent of these basins is less than 200 km² and they do not have a rainfall–discharge gauge series for statistical studies or modelling. In this case, the only way of evaluating the characteristics of extreme events was to transpose rainfall/runoff data from representative basins. Such a strategy enabled the reconstitution of rare frequency floods from high rainfall as well as for other precipitation events (Rodier, 1976). This estimation method used by ORSTOM in small forest basins only dates from 1976. Before that date, the limited basins studied and the heterogeneous characteristics of their response did not allow precise calculations to be made (Rodier, 1976; Casenave et al., 1982). A principal problem to be solved just before the beginning of the important pro-

gramme of flooding estimation in West African forest and basins was the characterization of surface global permeabilities. For this reason, ORSTOM pursued the rainfall simulating programmes on small plots from 1977 until 1985.

5.2.2.1 Objectives

The objectives may be defined in the following way:
- in some projects, the objective was to characterize the global permeability of different basins in order to determine the runoff of an unknown forest basin following simple pedological criteria (Rodier, 1976; Casenave et al., 1982)
- in others, the effects of the extension of cultivated areas on the water yield in savannah zones having been previously studied (Camus et al., 1976; Albergel and Gioda, 1986), the objective was to use the data collected on plots to reconstitute the floods observed on a basin scale linked with hydro-pluviometric gauge measurements.

5.2.2.2 Use of the rainfall simulator

Before the large number of parameters influencing the hydrodynamic behaviour of soils, which makes it necessary to study these under natural rainfall conditions, considerable attention has been given to the use of the rainfall simulator. The latter allows the reproduction at will of storm characteristics (intensity, duration, total depth), the control of soil moisture by successive spraying and the testing of different types of soil or surface state (soil + covering) (Chevallier, 1989). On the other hand, it is important to emphasize here that the surface area covered (1 m²) raises the critical problem of representativeness or measurement replicability. The main results are listed in two main papers (Asseline and Valentin, 1977; Casenave et al., 1982).

5.2.2.3 Methods used

The ideal method for calculating the ten-year return period flood would consist in adjusting the rainfall–water yield model from a daily rainfall data of about 40 years. Nevertheless, the systematic transposition of such a method in a forest zone where, moreover, the pluviometric information is often of a poor quality, has not been possible (Rodier, 1976).

Method 1: Determination of ten-year return period water yield
Before explaining the procedure used, it is important to note the solutions and practical norms adopted for the determination of flows on forest basins by ORSTOM researchers:

Separation of forest flood hydrograph
A simplified solution has been used for resolving the problem of the flood hydrograph separation. It has been considered that floods only start when the hydrograph separates significantly from the tangent to the preceding limb of flood wave. The hydrograph presents the recession as an almost straight line then curves to show a less pronounced decrease. It is the termination of what is called forest surface runoff. Surface runoff ends in the middle of this curved section and not at the end. One joins this figurative runoff end point to that which represents its beginning as defined above by a straight line. This process in only applicable to major floods.
- the time that passes between these two points is the base time;
- the time included between the starting point of the flood flow and the peak flow is the rising time.

The extent of the area between the hydrograph and the straight separating line defines the vol-

ume of runoff necessary for calculating the runoff coefficient *Kr*. All these operations are done according to the standard unit hydrograph method of Sherman (1931) with some modifications as outlined in Roche (1983).

The accepted standards for unit hydrographs
The accepted standard for unit hydrographs (it must be stated here that this is an adaptation to western Africa of Sherman hydrograph theory. It should be stated also that this is a cooking recipe applicable for a practical implementation of Sherman's method without any 'heavy' computing method. It may have been developed and explicited in *Hydrologie de Surface* (Roche, 1983, Masson Ed.).

The following method for determining a standard hydrograph is usually applicable to small drainage basins typically with less than 50 km² drainage. The assumptions are the following:

(a)   Hydrographs generated by storms which can be considered as homogeneous over the basin and whose duration is approximately shorter than half the rising time of the flood are considered as having the same shape (the different hydrographs are afinne curves). The duration of the storm is limited to that part with high intensity. Such selection is usually obvious for storm events in dry tropical Africa, but much more complicated for monsoon rainfalls. For the former short rainfall event, it is considered as a pulse for the rainfall–runoff process, whose resulting hydrographs can be combined using a linear process.

(b)   A longer duration storm has to be split into several storms matching the previous criterion (duration of less than half the rising time of the hydrograph) and the resulting hydrographs are combined (added) with lag times equal to the time separating centres of gravity of each storm.

(c)   Each basin has a specific type of hydrograph defined by three characteristics:
• the area of the hydrograph (i.e. the volume of runoff)
• the base time
• a factor K (Q_{max}/M, see below paragraph 5) which determines the geometry of the hydrograph (its sharpness) and depends on the watershed characteristics (shape, type of slopes, geology, soils, vegetation, drainage pattern, etc.).

Determining the ten-year return period rainfall
1.   One estimates the value of the ten-year return period rainfall. This is usually the result of a statistical computation for a single rainfall station (located on the watershed or sufficiently close to it to assume that the result is applicable to any raingauge on the watershed).

2.   The probability of observing a specific rainfall value across an area of several km² or several tens of km² (the drainage basin area) is less than the probability of this same amount of rainfall at a single point (which is the result of the previous statistical adjustment). It can be said also that, for a given return period, the rainfall over a drainage basin is less than for a single station (even assuming that the overall watershed has the same average rainfall). This areal reduction coefficient is therefore used to reduce the value of the 'point' rainfall (Roche, 1963). The ten-year return period rainfall for a storm concerning the complete basin area is noted *Pa*.

3.   One has to transfer the amount of the ten-year storm rainfall into a very basic hyetograph 'model' according to the characteristics of such storm events in the region, either in the form of one single storm matching criteria (a) above, or in the form of several successive elementary storms. The statistics of time-duration of rainfall in very short time steps is a useful tool to achieve such modelling.

4.   The knowledge of some physical characteristics of the basin (e.g. slope, geology) allows an estimation of the runoff coefficient Kr, corresponding to the ten-year return period (Rodier, 1976).

5.   In the same synthesis one may find diagrams or formulae allowing the estimation of the base time Tb, according to specific geomorphological variables as in (4). It is then possible to calculate M (average runoff discharge for the ten-year return period flood during a time equal to base time Tb).

$$M = Pa^* Kr/Tb \ (Pa \text{ in m}, Tb \text{ in sec.}, M \text{ in } m^3.s^{-1})$$

6.   After obtaining the value of K ($K = Q_{max}/M$) corresponding to the basin, the peak discharge of the ten-year return period flood Q_{max} is then determined.

7. Q_{max} corresponds to the surface runoff (assuring the prevalence of the hortonian overland flow). It should be pointed out that the preceding methodology was not applicable to the land conditions for which it was developed, i.e. small basins in the Sahel or the Sahelo-Sudanian zone (poor vegetation, thin soils, crusting on the surface).

8.   In the case of drainage basins having a very responsive behaviour or in the case where the 'model' taken for the storm duration determines an event which does not satisfy condition (b) above (i.e. the duration of the storm is significantly longer than half of the rising time of the hydrograph), the storm has to be split into several successive smaller storms, each of them associated with a unit hydrograph, which are combined to obtain the peak discharge, according to (b).

9.   In summary, the calculation of the ten-year return period flood requires the following information:
     (a) the ten-year return period storm
     (b) the areal reduction coefficient
     (c) the runoff coefficient Kr corresponding to the ten-year return period flood
     (d) the base and rising time (Tm, Tb)
     (e) the K coefficient ($K = Q_{max}/M$)

Thus the ten-year return period is obtained by compiling existing rainfall recordings in the area and statistical adjustments. All other parameters have to be estimated from diagrams as presented in Rodier (1976).

Method 2: Evaluation of water yield change following conversion

The method used to reconstitute floods using the rainfall simulator on plots is spatialized. One must ultimately proceed to the fixing of a correlation model between the reconstituted floods using simulated rainfall and those actually observed (Albergel and Gioda, 1986).

The evaluation procedure

This is made of up 5 stages:

1.   The drawing up of surface states or a soil map is necessary to fix the weighting of each plot in a model. In this geographical representation of the spatial variability of the environment, ORSTOM researchers use zonal thematic maps established from land surveys, photo-interpretation and sometimes satellite imagery (Landsat or Spot). Computer processing enables such information storage and their various uses (comparison, overlay) (Chevalier, 1989). It is necessary to note that this surface state characterization is not really possible for a forest. Under the same rubric, the topographic map assumes a greater importance, which can then be a useful tool for various calculations after computer digitization (Chevallier, 1989).

2.	The selected plot sites should represent the main soil surface conditions of the studied basin.
3.	The protocol of simulated rains reproduces the precipitation at annual and ten-year return period frequencies.
4.	Under a seasonal climate, the simulated rain campaign takes place in the dry season in order to have a minimum soil moisture before the first precipitation.
5.	The examination and interpretation of the collected data are followed by a modelling exercise to reconstitute floods from the simulated rains; those with which such simulated floods are then correlated are directly measured.

Whatever the differences in approach, the two above-mentioned methods attempt to establish similar links, viz.:
•	The linkage between measured basin runoff and that obtained from the use of the simulator. To do this, the forest basins studied in the classic way have been tested with the simulator on a topo-sequence, the latter being representative of different types of soil in the basin.
•	The linkage between the results obtained from the simulator with the physico-chemical characteristics of the soils studied (Casenave and Valentin, 1985; Albergel and Gioda, 1986).

5.2.2.4 Location and characteristics of the basins studied

Studies of soil hydrodynamic behaviour have been carried out on small representative basins. The representativeness is linked to the climate, geology, relief and land-use (e.g. natural vegetation, cultivation) (Chevallier, 1989).

The different basins studied are located in the humid and dense forest zones of the Guinean domain, except those of Amitioro (and especially of Ifou), the latter being part of the semi-deciduous forest zone (Casenave et al., 1982).

The investigated basins we subdivided into three types: I, II and III (determined according to the nature of their topography and soil). They have respectively a high, medium and low slope position, except those of Nion and Agbeby which have only two (I and II: a high and low position on the slope respectively).

A more detailed description of the basins may be found at the end of this chapter under (5.3).

5.2.2.5 Link 1: Simulator – rain

This operation begins with a surface runoff test at each of the sites of the different basins. The objective is to define for each studied basin the vulnerability of the investigated soils to surface runoff according to their physico-chemical characteristics.

The grouping of the soil types linked with the above types is not always obvious. According to ORSTOM researchers, in almost the entire forest zone of Côte d'Ivoire, the soil may be classified into three categories principally controlled by their topographical location on the catchment slope (Casenave et al., 1982).
•	Horizon and clayey surface layer or at a very shallow depth. The direction of dominant water flow is vertical.
•	Usually on the hillslope, sometimes at medium elevation or in the lower third of the slope, there is a sandy layer on top of the gravely horizon which thickens and disappears at the bottom of the slope. This morphology changes the hydrodynamics of stormwater transfer and causes it to be more lateral and superficial. The soils (red

Catchment	Site I	Site II	Site III
Tai[5] catch. 1	9.4	62.3	28.3
Tai[5] catch. 2	10.8	65.5	23.7
Tai[5] catch. 3	12.1	70.2	17.7
Manso[4]	20.0	67.0	13.0
Loué[10]	75.0	20.0	5.0
Agbéby[8]	92.0	7.0	
Amitioro I[7]	10.0	60.0	30.0
Amitioro II[7]	10.0	70.0	20.0
Nion I[9]	58.0	38.0	4.0
Nion II[9]	85.0	14.0	1.0
Ifou[6]	49.6	44.2	6.2

(#) number of cross-reference for the description of the basins, see page 48.

ferralitic on the upper slope and those more yellow farther down the slope) are less permeable than those ferralitic soils at the summit.

• At the bottom, there are the hydromorphic soils, whose hydrodynamics depends on the season. These are the soils that initiate most runoff during the heavy or light rainy seasons. The following table shows the percentages of the basin surface occupied by the soils corresponding to the different test sites.

From the so-called Lr curves (based on parameters Pu and IK) for bare soil, it is possible to extract the value of the depth of overland flow for a given amount of rain and the IK variable according to the climatic setting of the regions studied (Rodier, 1976; Casenave et al., 1982); where:

Pu = rainfall of a given depth

IK = an index of soil moisture in the middle of the rainy season, which depends upon the annual rainfall amount and the temporal distribution of the rains.

Table 2 (adapted from Casenave et al., 1982) shows the values of the depth of surface runoff expressed in mm obtained during these experiments for:

Pu = 100 mm

IK = 50

(IK = 20 for the Ifou basins)

Table 2 illustrates the extreme variability for the same type of soils to generate overland flow. Also it is clear that the hydromorphic soils strongly account for most overland flow generated.

5.2.2.6 Link 2: Simulator–basin

The simulator–basin link is based on the information and data obtained from tests at the sites described above. The objective is to be able to link the measured depth of overland flow as measured by the simulator to the runoff coefficients of the basin for a rainfall of 120 mm (the latter being calculated in the classical way). The global sum (addition of each site's value) of depth of overland flow Lr(100, 50) of a basin, multiplied each time by the percentage of surface area in the basin occupied by the corresponding soil, seems to correlate with the Kr120 of the basin.

TABLE 2. Depth of surface runoff (mm) synthesis, by sites for the different forest basins studied (Côte d'Ivoire)

Catchment	Site I	Site II	Site III
Tai[5]	64.0	75.0	88.0
Manso[4]	71.0	85.0	90.0
Loué[10]	33.3	5.8	11.5
Nion I[9]	53.0	4.0	52.0
Nion II[9]	18.5	3.0	52.0
Agbéby[8]	0.75	1.9	
Amitioro[7]	0.0	1.5	54.5
Ifou[6]	12.0	1.8	70.0

(#) number of cross-reference for the description of the basins, see page 48.
Source: adapted from Casenave et al., 1982.

TABLE 3. Synthesis of the results obtained from all the basins studied in Côte d'Ivoire

Catchment	Lr.S (Site I)	Lr.S (Site II)	Lr.S (Site III)	$\sum$ Lr.S	Kr120
Tai[5] catch. 1	602	4673	2490	7765	57.0
Tai[5] catch. 2	691	4913	2086	7690	52.0
Tai[5] catch. 3	774	5265	1558	7597	53.0
Manso[4]	1420	5695	1170	8285	59.0
Loué[10]	2498	116	58	2672	30.0
Agbéby[8]	69	13		82	3.0
Amitioro I[7]	0	90	1635	1725	21.0
Amitioro II[7]	0	105	1090	1195	12.5
Nion I[9]	3074	152	208	3434	34.0
Nion II[9]	1573	42	52	1667	16.0
Ifou[6]	595	80	434	1109	7.0

(#) number of cross-reference for the description of the basins, see page 48.
Source: adapted from Casenave et al., 1982.

$$\sum Lr.S = (Lr1.S1) + (Lr2.S2) + ...(Lr.Sn) = f(Kr120)$$

Lrn = depth of surface runoff (mm) of bare soil at site n, for a rainfall of 100 mm and an IK index of 50.
Sn = percentage of the basin surface occupied by the soil represented by site n.

Table 3 synthesizes the results obtained from all of the basins studied in Côte d'Ivoire. It has been adapted from Casenave et al., 1982; note that the values for the basin of Taï are provisional.

Moreover, in 1994, the Tropenbos Foundation published a synthesis of the information on the entire Taï National Park, realized by Riezebos et al.; up until now this synthesis has not been available for consultation.

The semi-logarithmic plot of the $\sum Lr.Sr$ values with regard to the corresponding values of $EQ f(Kr120)$ shows that, for all the basins of a $Kr120 > 5$ %, the points line up without any significant scattering.
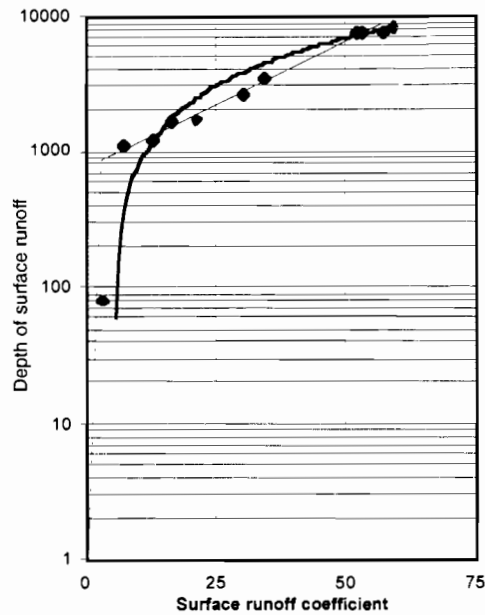
Figure 5. Correlation between the depth of surface runoff extracted from $\sum Lr. Sr$ curves and the corresponding f(Kr120) values

The fact that the basins with a $Kr120 < 5$ % do not line up here is explained by their insufficient number (only one in the case of this study).

The method which consists in summing up all the contributions from different sections of the catchment is justified by the fact that the depth of surface runoff cannot be absorbed during its transfer. This is because the soils the surface runoff encounters are less and less permeable as one moves downstream (Casenave et al., 1982). The same does not hold for all the forest zone of West Africa and the opposite situation from that found on the savannah may even be found, with nearly the entire depth of surface runoff being absorbed in uphill slope areas and therefore not arriving at the basin outlet (Casenave and Valentin, 1988).

5.2.2.7 Reconstitution of surface runoff depth

This concerns the relation between the simulator and the soil characteristics. This relation entailed researching the links between the infiltrated depth figures and the main characteristics of the soil, such as texture, structure and the percentage of organic material or clay (Casenave et al., 1982).

The infiltrated depth Li have been extracted from $Lr(Pu, IK)$ curves.

$$Li = 100 - Lr(100, 50)$$

Ten characteristic variables of the three groups of soil previously classified have been defined and analysed in relation to Li in a matrix of correlation coefficients to all the variables taken two by two to discover the variables which are best linked to Li.

To alleviate the heterogeneity of the reactions of the basins studied, a classification according to the supposed permeability was carried out. From the infiltration depth, it was possible to assess the depth of surface runoff then the $Lr.S120$ values (for rainfall of 120 mm) which allow the calculation of $Kr120$.

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TABLE 4. Comparison of depth of surface runoff figures reconstituted from the soil characteristics*
and measured values

Catchment	Site	Reconstituted Lr	Gauged Lr
Taï	I	72.0	64.0
	II	94.3	94.0
	III	67.5	88.0
Loué	I	31.9	33.3
	II	6.7	5.8
	III	11.9	11.5
Nion II	I	0.0	6.5
	II	4.8	3.1
Agbéby	I	12.3	0.75
	II	4.0	1.9
Amitioro	I	8.7	0.0
	III	58.6	54.5

* As indicated above, ten characteristic variables of the soil have been taken into account (aggregates, coarse grained sand, clay and organic matter) as being able to influence the infiltration. The determination of the aggregate rates is done from a dried soil at 35 °C. The aggregates taken in account are those of 0.2–2 mm size and include therefore the coarse grained sands. Given that the 'real' aggregates not showing the same characteristics as the coarse grained sands, could be destroyed, many types of variables have been used:

$Ag\,A$: percentage of water stable aggregates after alcohol pretreatment;

$Ag\,E$: percentage of water stable aggregates without alcohol pretreatment;

$Ag\,B$: percentage of water stable aggregates after benzene treatment which stabilizes the structure, except for soils rich in organic matter;

$Ag\,A - SG$: percentage of 'real' aggregates after alcohol treatment. This variable is generally linked to the rate of clay;

$Ag\,E - SG$: percentage of 'real' aggregates without pretreatment;

$Ag\,B - SG$: percentage of 'real' aggregates after benzene pretreatment. This variable proves the role of organic matter;

$$\overline{Ag - SG} = \frac{(Ag\,A - SG) + (Ag\,B - SG) + (Ag\,E - SG)}{3}$$

SG: percentage of coarse grained sands (particles with a total size of 200 μ to 2000 μ;

Arg: percentage of clay (particles with a size between 0–5 μ);

$M.O.$: percentage of organic matter.

The different attempts to link the values of infiltration depth and those characterizing the texture of the soil have been inconclusive, except for the rate of coarse grained sands and the percentage of clay. On the other hand, the figures characterizing the soil structure are closely linked to the infiltration depth, just as they characterize the percentage of organic matter (Casenave et al., 1982).

Table 5 below represents the general summary of the water yield in the forest basins studied in West Africa (essentially in Côte d'Ivoire). It shows, on the one hand, the permanent characteristics of each basin:

S: Basin area in km²

P: Average annual rainfall in mm

$P4m$: Total rainfall in mm for the four most humid months

Ig: the global index of slope, average slope in m/km, which describes imperfectly all the topographic characteristics that could influence the water yield.

The same table also presents information on the ten-year return period storm, the $\overline{P_{10}}$ depth and the depth of the ten-year return period storm divided by the basin area value $\overline{P_{10}}$, the ratio of $\frac{P_{10}}{\overline{P_{10}}}$ is the area reduction coefficient or factor.

Lastly it presents the characteristics of the ten-year return period flood, Kr, Tm, Tb, k and $Kr120$ (i.e. the runoff coefficient for the storm showing the same characteristics as the ten-year return period storm but with a depth of 120 mm). Tm, Tb and k correspond to the ten-year-return period storm or to an impulse of rain with high intensity; if the basin is too small, it may be necessary to split the rainfall into individual storms (Rodier, 1976). Note that $k = P_{max}/P_{average}$.

A final column Qo gives the baseflow observed at each basin for the storms whose hydrograph has been used to calculate K (see paragraph in Section 5.2.2.3). The maximal discharge observed was each time $Q_{max} + Qo$.

It should be noted that Qo is linked to S, the permeability and the degree of soil saturation; this parameter provides a useful assessment of the potential occurrence of flood discharge. Thus, Qo is added with caution to the maximal discharge of surface runoff.

TABLE 5. Forest basins water yield in West Africa (Côte d'Ivoire)

Catchment	S (km²)	P (mm)	P4m (mm)	P_{10} (mm)	$\overline{P}_{10}$ (mm)	Ig (m/km)	KR (%)	KR_{120} (%)	Tm (h)	Tb (h)	k	Qo (m³/s)
Sitou	27.8	1770	1000	120	104	5.50	62.0	62.0	11.00	22	2.30	2.10
Manso	88.0	1770	1000	120	98	3.94	59.0	59.0	14.00	32	2.60	8.40
Bafo	26.7	1770	1000	120	104	6.50	59.0	59.0	8.00	20	1.80	1.20
Nion I	75.0	1800	1005	121	102	5.90	34.0	34.0	20.00	70	2.06	2.50
Nion II	12.1	2000	1110	140	130	40.00	18.0	16.0	5.00	12	2.70	2.00
Gboa	12.3	2200	1385	200	100	73.00	33.0	30.0	3.00	9	2.20	1.60
Loué	18.4	2200	1385	200	100	70.00	33.0	30.0	2.20	9	2.50	2.70
Amitioro I	170.0	1365	1365	117	90	3.30	21.0	21.0	13.00	32	2.38	4.00
Amitioro II	2.75	1365	1365	117	112	20.00	12.4	12.5	1.66	7	1.87	0.20
Agbéby	11.0	2150	1420	220	202	10.00	7.0	3.0	3.50	11	1.69	0.91

Source: Rodier, 1976.

5.2.2.8 Other examples of water yield study undertaken by ORSTOM

Other attempts at studying flows which continue to use hydro-pluviometric correlation have taken place in Madagascar. The example of the grassland conversion to cultivation of the 'Hauts-Plateaux' in Madagascar during the first half of the 1960s deserves to be highlighted.

The analysis centred on the following:
* flood rising time,
* flood recession time,
* comparison of depth of surface runoff between two basins of different plant cover.

As with the West African study, empirical mathematical laws were established through hydro-pluviometric correlation, taking the following form (Ibiza, 1975):

$$C - L = aT + S(1 - lK) + H$$

$(C - L)$ represents the amount of water infiltrated during the storm, i.e. the difference between the storm gross amount (C) and depth of surface runoff during the flood.

The term aT, where T is the duration of the storm, represents the amount of water which has infiltrated under maximal saturation soil conditions. This infiltration is constant and (a) represents the average capacity of absorption of the basin.

$S(1 - lK)$ is a fraction of the amount of water S needed to enable the first surface layer of the soil to change from an unsaturated to a saturated state.
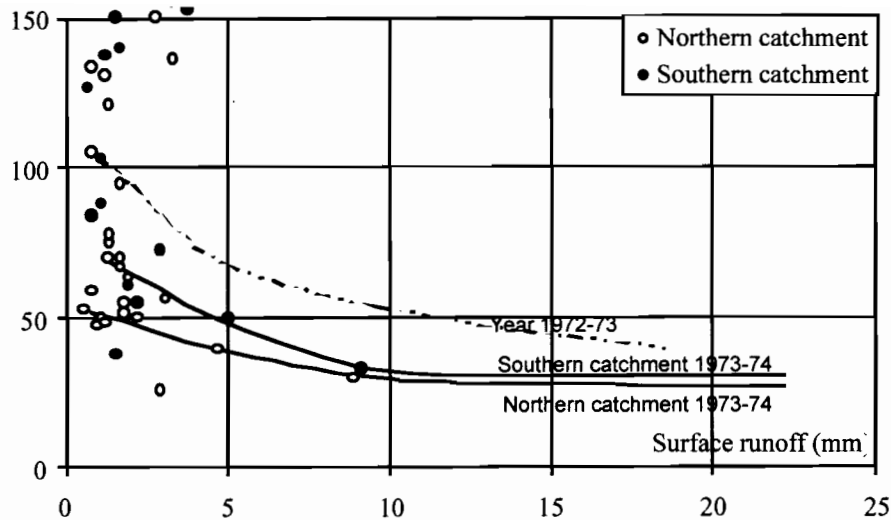
Figure 6: Comparison of rising times of the flood in Madagaskar (experimental catchment of Ambatomainty)

The fraction $(1 - IK)$ balances the amount S according to the shape of the storm (K coefficient) and in particular according to the rain that fell prior to the storm of interest.

H is a symbolic variable representing an amount of water that moistens the surface part of the soil at the start of the rainy season.

This study provides a means (Figure 6) of detecting the minimum rising time for small storms for each basin linked with the volume global surface runoff. Figure 8 shows the comparative situation for the two basins. Between 1972 and 1973, the two basins were in the natural state (bare meadows of vivacious grasses). By contrast, between 1973 and 1974, the southern basin was subject to a 'late burning', while the northern basin was exploited in accordance with Madagascar's traditional cultivation practices.

5.2.2.9 Few limitations linked to rainfall simulator use in West Africa

As already described, the method consists of summing the contributions of surface water runoff from the different zones of the slope during its organized drainage progression down-stream. Nonetheless, the simulator cannot be used to calculate directly the flood volume even if the global permeability of the basins were known because of the scale factor. This also includes the issue of variable sizes of drainage basins (Albergel et al., 1986; Chevallier, 1989).

Measurements taken within the natural vegetation area using the rainfall simulator present several difficulties. Correlations were attempted between the depth of surface runoff extracted from the characteristic curves, natural vegetation area and the $Kr120$ values taken from the classical experiments. Despite many attempts to link the results, it was not possible to obtain a good correlation. This led many researchers to note that the measurements taken were not fully representative of the role played by the vegetation throughout the basin. Although adjusted, the punctual values of measurements did not allow the transformation processes induced by the vegetation to be assessed (Casenave et al., 1982).

Despite the relation between the reconstituted depth of surface runoff and that actually measured (see Figure 7), the quality of reconstitution from soil properties using the rainfall simulator still has to be applied with great caution (Chaperon, 1977; Casenave et al., 1982; Chevallier, 1989).

mesured depth of surface runoff (mm)
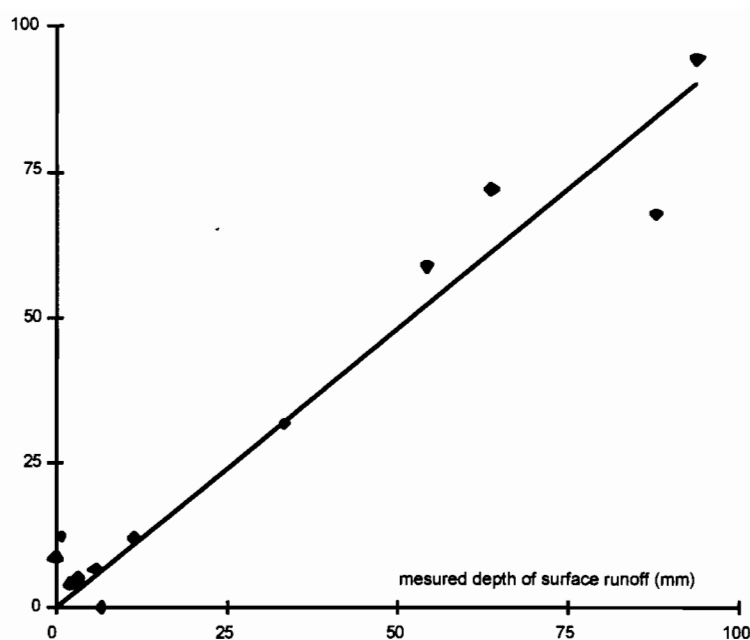
Figure 7. Relation between the reconstituted depth of surface runoff and measured depth of surface runoff

These experiments were all carried out in small basins (less than 200 km²). There appears to be a large gap in knowledge of changes in the water yields occuring in basins of between 500 km² and 2000 km². The gaps in research centre largely on three issues:

- spatial distribution of rainfall during convective storms;
- rainfall–runoff relationship investigations;
- investigation into the influence of antecedent soil moisture on the surface runoff during each storm (Rodier, 1974).

The representation of a type-hydrograph has also not been studied for this range of scale.

5.2.3   Forest basins and water yield: experiments conducted by CIRAD (ex CTFT)

Among the catchments studied in Madagascar, only those in Perinet Analamazaotra are located in the tropical forest zone (on the eastern cliffs of this island) (Goujon et al., 1968). Since 1974, this region has been known as Andasibé (Sarrailh and Rakotomanana, 1978).

5.2.3.1 The main objectives of the experiments

There were two principal objectives. Firstly, the influence of vegetation cover on water yield and especially on the water balance was studied between 1962 and 1972. The initial phase of experiments (1962–1966) consisted in maintaining the existing forest on the one side and in letting it regrow after a *tavy* (burning cultivation) on the other side (Goujon et al., 1968). The researchers carrying out the study measured the influence of various types of vegetation cover on water yield and storm runoff (Bailly et al., 1974). Secondly, the effects of forest area conversion into farming land were studied. This point is not discussed in this chapter, as the discussion concerns only surface runoff and soil loss (Bailly et al., 1974).

5.2.3.2 Basins studied

Investigations were made into seven catchments:
- four in natural forest (Ampangalatsary basin)
- one planted with 50-year-old eucalyptus robusta, with a density of 420 trees per hectare and height varying from 25 m for the dominated stratum to 45 m for the superior stratum (Betsakotsako basin).
- two in a *tavy* area which included the recovery of secondary shrub vegetation (so-called *savoka*) (basin of Marolaona) (Goujon et al., 1968; Bailly et al., 1974).

These basins are described in detail at the end of this chapter. It is however important to note that the surface area of these basins varies from 7 ha to just over 100 ha.

5.2.3.3 Method used

The measurements used to establish the water balance were carried out in all the basins mentioned above between 1962 and 1972 then in the basins with natural forest vegetation (Ampangalatsary basin) and those with eucalyptus (Betsakotsako basin) (Sarrailh and Rakotomanana, 1978).

To measure stemflow, a rubber water-collection apparatus was girdled around the trunk of selected trees. The water was collected and measured after each rainfall. Several rain-gauges were installed, some in the eucalyptus planting and others outside or above the cover in order to be able to compare the incident rainfall total and the depth of water having fallen through the trees as throughfall (Goujon et al., 1968).

5.2.3.4 Results obtained

Table 6 shows the water balance results obtained after 8 or 12 years of measurements and shows the influence of the various forest vegetation covers on water yield in the eastern cliff of Madagascar (Perinet, now called Andasibé).

TABLE 6. Average water balance of Perinet catchment (mm) (Madagascar)

Overflow shoot	Area (ha)	Rainfall	Off flood flow	Base flow in flood flow	Total	Storm flow (total runoff)	Total flow (total runoff)	Runoff coefficient	Years of measurement
D1	9.18	2170	489	16	505	45.7	551	25.4	12
D2	7.14	2186	556	31	587	58.7	646	29.6	12
D3	38.88	2162	677	29	706	50.8	757	35.0	12
D4	100.96	2139	761	32	793	57.0	850	39.7	12
D5	13.26	1664	194	15	209	51.8	261	15.7	12
D6	7.27	1885	675	27	702	125.0	828	43.9	8
D7	31.50	1880	676	34	710	156.0	867	46.1	8

D1–D4: natural forest basin
D5: eucalyptus basin
D6–D7: secondary shrub basin

The division of water yield presented here is somewhat different from that normally presented in ORSTOM studies. This is simply due to differences in training.

Baseflow: depth of runoff representing the total volume of flow during the flood as well as during the 'out of flood' period. The calculation is made by taking the average between the

baseflows before and after the flood. This volume is expressed in mm (equivalent depth of water measured in order to be compared to the depth of rainfall) (Sarrailh and Rakotomanana, 1978).

Surface runoff: the depth of runoff during a flood minus the baseflow. It includes the direct surface runoff and sub-surface flow. In the area of secondary shrub vegetation, this level reached values greater than double the values observed from the natural forest (Sarrailh and Rakotomanana, 1978).

Total flow: the total amount of water at the catchment outlet. It increases in the same way as baseflow with the size of the surface area of basins in connection with the natural forest basins as well as with secondary shrub. The water yield is clearly less, whatever the surface area for the eucalyptus-covered basin as compared to the natural forest. The highest yields are recorded in secondary shrub areas (Sarrailh and Rakotomanana, 1978).

The above remarks will be discussed further below, including the controversial influence of eucalyptus on water yield.

5.2.3.5 The effects of forest vegetation

In general, it has been established that forest vegetation considerably decreases the maximum runoff coefficient. It regulates considerably water yield and contributes towards a reduction in specific discharges of exceptional floods (Bailly et al., 1974).

It is clear however that natural forest and eucalyptus trees evapotranspire to a greater extent than secondary shrub vegetation (Bailly et al., 1974). The influence of eucalyptus trees is therefore open to debate.

A statistical study of low flows has shown that eucalyptus trees cause a depletion of flows in four out of seven years; such effects have not been observed in the natural forest where, even in the driest of years, a flow was still observed (Sarrailh and Rakotomanana, 1978). Although the evapotranspiration could not be estimated with acceptable accuracy for a given depth of precipitation, an estimate was made in comparison with the average rainfall observed within the basins studied in Madagascar.

TABLE 7. Comparison of various types of vegetation evapotranspiration (ET) values in Madagascar

	Rainfall (P) = 1907 mm (Catchment 1964–1976)	Rainfall (P) = 1752 mm (Meteo. station 1928–1977)
ET Eucalyptus	1345 mm	1255 mm
ET Natural forest	1170 mm	1090 mm
ET Secondary shrub catchment	1025 mm	1000 mm

Table 7 shows a greater consumption of water in the eucalyptus forest. Such differences should have an effect on the discharge of low water and touch on the problem of what influence reforestation may have. It is important to know whether the consumption of water in fast-growing plantations exceeds that of the natural forest they replace.

The species of tree used (pine, eucalyptus . . .) are often indicated as the cause of the decrease in water yield of the basins. Despite the findings of experiments relative to interception and runoff (Goujon et al., 1968), and relative to evapotranspiration and water yield (Sarrailh and Rakotomanana, 1978), there is still no scientific evidence of a greater consumption of water in a eucalyptus forest. According to several analyses, the smaller water yield of Bestakotsako basin as compared to the natural forested basin has been attributed to catchment leakage (Bruijnzeel, 1990).

It is important to mention, on the other hand, the outstanding study made by Monteny et al. in 1986, which reported that a mature plantation of hevea had led to an increase in water yield of between 100 mm/year and 300 mm/year.

5.2.4 Comments on the water yield regime

Studies of the influence of vegetation cover on the forested basin water yield regime are scarce. The above-mentioned study is the exception which shows the influence of distinct consumption of eucalyptus forest on low water discharge.

5.2.4.1 Floods

As mentioned in Chapter 3 on processes, the storm response in a small catchment depends on climatic interactions with geological factors, as well as soil and land use.

Change in the predominance of sub-surface flow through transformation in Hortonian Overland Flow (HOF – flow path Q_o, Figure 3) could considerably accelerate the immediacy of hydrological response of a basin after the change in land use. However, topographical factors (such as the basin morphology) and geological factors may affect runoff to a greater extent than any change in the vegetation cover (Bruijnzeel, 1990).

When the natural hydrological response is greatly influenced by Saturation Overland Flow (SOF – flow path $Q_o(s)$ Figure 3), the response to a storm in terms of runoff in the basin is already near the limit of what is physically possible (Fritsch, 1983). It essentially depends on the type of subsoil rather the properties of surface horizons which may be changed easily (Bonell et al., 1981).

Between the two hydrological response situations depicted above, there are many others that can be fitted to hillslopes. The general response diagram is outlined in Figure 8:
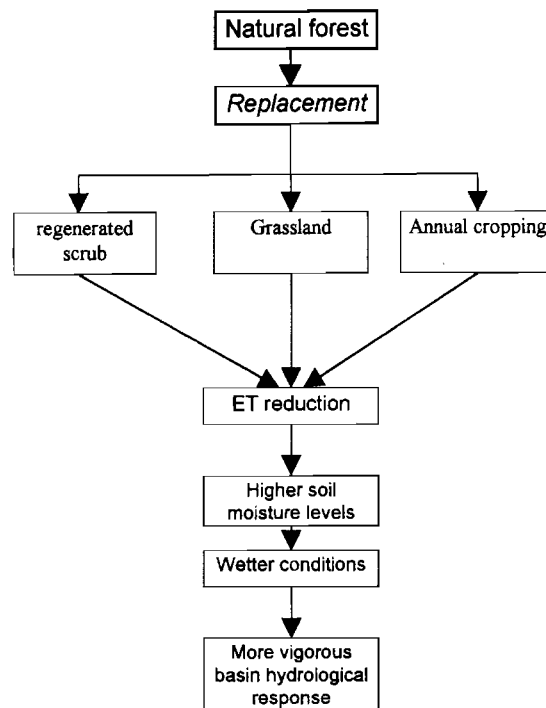
Figure 8. Diagrammatic representation of catchment's hydrological response

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5.2.4.2 Dry season flows

Near the latitude of the northern limits of our study area, any decrease in low flows induced by the changes in soil use are of additional importance.

Often, a link is made between the decrease in water yield during the dry season (here much more pronounced) and the reduction in natural vegetation (more open savannah than forested), which limits the soil moisture storage capacities. This may appear to be contrary to the previous response in Figure 8, which shows the impacts on water yield of a replacement of tall vegetation.

However, there are three reasons for this:

1. under drought conditions, forest removal decreases infiltration opportunities and increases the depth of surface runoff, particularly the stormflow component, which exceeds the amount of water contributing to baseflow;
2. the net changes in the evapotranspiration values with the reduction in tall vegetation;
3. as some studies have underlined, the reduction in infiltration may be due, among other factors, to:
   - the increase in the zones occupied by impervious surfaces, such as roads and villages (Ruslan and Manan, 1980; Reid and Dunne, 1984; Rijsdijk and Bruijnzeel, 1990);
   - open cast mining (Bandyopadhyay and Vandana Shiva, 1987);
   - overgrazing after forest removal (Gupta et al., 1974, 1975; Dunne, 1979);
   - improper agricultural practices (Hardjono, 1980; Lal, 1983). These situations are widespread in West Africa and potentially contribute to disruptions in the water yield.

5.2.5 Modelling considerations

Modelling considerations concern the relationship between rainfall-discharge using different levels complexity. Their application to the hydrological observations and experiments undertaken on the small basin is essential to the processes interpretation (Chevallier, 1989). There are several types of models:
- *deterministic* (as opposed to stochastic), with non-random variable.
- *conceptual* (as opposed to empirical), describing the physical phenomena with variable degree of precision.
- *inclusive* or *lumped*, without any modulation regarding to the local situation.
- *distributed* (as opposed to inclusive), which contain algorithms to represent various processes in order to obtain the results regarding the whole geographical entity studied (Chevallier, 1989).

When concerning rainfall–runoff the only examples of modelling by ORSTOM were connected with experiments carried out in savannah zones of West Africa rather than in forested zones. These modelling experiments are named the ERREAU and ECOULEES programmes (Servat, 1995). The objectives were to evaluate methods which gave estimations of water inputs in savannah region and to determine the annual and monthly depth of runoff throughout the West African savannah zone.

The models were created from systematic investigations when concerning the correlation between model parameters and the different ways of characterizing the catchment (physiographical, climatic, and soil occupation). Despite all this, there remain considerable challenges in relation to the application of most equations to predetermining model parameters for use in catchments not already measured (Servat, 1995).

5.2.6 Different experimental methods of catchment comparison

Several methods and techniques have been used to compare the hydrodynamic behaviour of catchment with various types of vegetation cover. These are listed below:

5.2.6.1 The representative experimental basin and its limits

As we have seen in the section concerning ORSTOM experiments in relation to estimating the water yield, the representative experimental basin is the focal point of all operations. It was in this type of basin that simultaneous measurements of rainfall and of discharge were taken. This enabled the determination of water input–output operators and the extrapolation of the results to other similarly representative basins (Casenave, 1988).

In order to measure the effects of changes in land use, simulations were carried out (changes in agricultural use . . .) in order to study the basin reactions to rainy events. The first attempts at this type of experiment were carried out in 1953–1954 (Casenave, 1988). We have already examined how this technique works. However it is not the best way to evaluate the impact of land use changes on the water yield and soil loss parameters. Moreover, the so-called representative basins have a limited application as the results they provide are only reliable for small basins (surface area < 200 km²) (Rodier, 1976).

In addition, the rainfall–discharge relationship established for a given period is not necessarily applicable for subsequent periods of time. For example, the extension of cultivated areas and the protracted decrease in rainfall quoted in the Korhogo basin in Burkina Faso caused ORSTOM researchers to re-evaluate their calculations formerly established for this same basin (Albergel and Gioda, 1986). The conversion to cultivation, or even a simple change in farming technique, may cause drastic changes in surface states; hence the need for new calculations.

As for the Korhogo basin, it was necessary to separate the observation periods of the hydrological analysis into several sub-periods corresponding to the different stage in the evolution of surface states (Camus et al, 1976). Without this, no in-depth comparison would have been possible, with the exception of comparison between specific water yields (Albergel and Gioda, 1986).

5.2.6.2 The paired catchments

The study closest to the paired catchment principle of evaluating the influence of anthropogenic disturbances on the water cycle and the bioecological balance is that reported by Ibiza (1975). This study was undertaken between 1972 and 1974 in Madagascar.

In this study, two similar catchments of around 30 ha, situated side-by-side in the same climatic area (annual rainfall of 1700 mm) were used. The northern catchment was converted, the other remaining undisturbed (Southern Ambatomainty catchment). Measurements of different hydrological components were taken in both basins (surface runoff, changes in soil moisture, change in the watertable level), as well as measurements of sediment transport (Ibiza, 1975).

Although conducted in the paired catchment savannah zone, this methodology has been useful for studying the influence of anthropogenic activity. Unfortunately, the effects of burning on the water yield and sediment transportation were studied separately and did not follow the traditional paired catchment methodology of calibration followed by conversion of one of the catchments.

5.2.6.3 The comparison technique used by the CTFT

Although the paired catchment method was not used in the Perinet basin, the technique used to compare the influence of different types of vegetation on the hydrological cycle deserves some mention, disregarding the problems linked to basin size differences.

By establishing the correlation between annual rainfall and annual water yield, it is possible to remove from the water yield that part linked to the rainfall variability and even to distinguish the families of regressions.

Several elements may be used to explain the differences in the behaviour of the basins studied. According to Sarrailh and Rakotomanana (1978) who carried out this experiment, differences observed in the comparison of water yield of two basins with near-similar soils (disregarding their vegetation cover) are caused by the surface area effect which affects the results in three different ways:

- the shape of the basin;
- the average steepness of the basin;
- leakage caused by infiltration and scale effect (Sarrailh and Rakotomanana, 1978).

Influence of the basin shape
If the compactness of the basins (measured by the Gravelius compactness coefficient) varies, the shape of the basin plays an important role: the longer the basin, the greater the area exposed to differences in evaporation (Sarrailh and Rakotomanana, 1978).

Influence of the average steepness of the basin
This factor increases the surface runoff as the steepness increases (Sarrailh and Rakotomanana, 1978).

Infiltration leakage and scale effect
Smaller basins release less water than larger ones because there is a tendency towards a greater proportion of water infiltrating the smaller basins which does not pass through the gauging station (Sarrailh and Rakotomanana, 1978).

In fact, total water yield for a given surface area is estimated using an interpolation. The method used consists of looking up in the graph the parallel lines which are closed, the regression straight and studying the link between the ordinate at the origin of these lines and the basin's surface area (see Figure 9).

Taking into account the effect of the surface area, and with similar pedological material, it will not be possible to compare two basins with different vegetation cover unless these basins have a similar surface area; the comparison may also be done by adjusting the water yield of a non-forested basin to that obtained in the case of a forested catchment if they had the same surface area (Sarrailh and Rakotomanana, 1978).

The interpolation technique
Thus, it is apparent that the size of the basin plays an important role in the comparison of catchments and it will not be possible to compare two basins with different vegetation cover unless these basins have a similar surface area (Sarrailh and Rakotomanana, 1978).

The technique consists of two main stages and takes as its base the regression equations ($Q = aP + b$) of rainfall (P) and water yield (Q), calculated for the different basins:

1. Using the graph, a satisfactory slope of equation line is established from a new value of a from the equation used to estimate the flow by the regression method mentioned above;
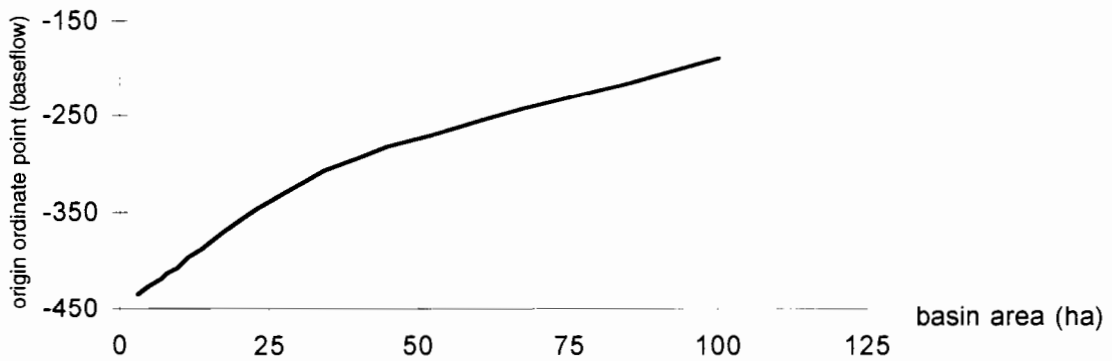
Figure 9. Abacus showing the interpolation of water yield from the catchments with different types of vegetation cover

2.   During this iteration process, the value (*a*) is recalculated from the initial value of the total flow. This means that the constants (*b*) – *baseflow* – will take values appropriate for interpolation.

Given that *Q(forest)* = *aP* + *b*, *b*, the new ordinate value may be calculated as:

$$b' = a' \cdot P - Q$$

where *a'* = graphic representation of (*a*) new value
P = rainfall value
Q = total flow.

The technique is completed by adjusting the interpolation abacus which allows the value of the ordinate at the origin of the correlation straight *D* = *f(P)*

This interpolation technique allows the water yield of a basin in natural forest to be compared with another type of vegetation cover. This is done by fixing the ordinate at the point of intersection of the curve with the abscise line corresponding to the surface area of the basin. The equation of the curve may then be calculated: *E* = *a'P* + *b'*.

This formula allows the water yield under forested basin conditions to be calculated and the result to be compared with the actual water yield measured.

Using this technique in Madagascar allowed the evaluation of the influence of the vegetation cover on water balance for the basins with different covering. This was done by adjusting the surface area of the different basins in order to consider them as having the same extent then tracing on the graph the runoff deficit curves (the values of the runoff deficit are only comparable when the rainfall is similar) (Sarrailh and Rakotomanana, 1978).

At first sight, the interpolation technique offers a means of comparison, but there are several problems with the method linked to the size of the basins studied in West Africa and Madagascar. None of the forested basins studied has a surface area greater than 1 km² in Madagascar or greater than 200 km² in West Africa. This means that this technique needs to be reviewed meticulously before being confidently applied to larger basins.

5.3 The forest basins or catchments studied in Madagascar and in West Africa

(1) Catchment of Ampangalatsary – Perinet (natural evergreen montane forest)
This is a large catchment in natural forest, called B.V.4. A subdivision into three secondary catchments was made. The gradients are somewhat symmetric and quite steep (up to 55 %) on both sides of the main thalweg.

Main physical characteristics of Ampangalatsary catchment (Perinet)

Catchment	Area (ha)	Max. length of main thalweg (m)	Gravelius coefficient
D1	9.18	365	1.13
D2	7.14	400	1.04
D3	38.88	1000	1.09
D4	100.96	2825	1.84

(2) Catchment of Betsakotsako – Perinet (Eucalyptus forest)
The catchment is covered in Eucalyptus trees and has a roughly rectangular shape. Maximum gradient (40–45 %).

Main physical characteristics of Betsakotsako catchment (Perinet)

Catchment	Area (ha)	Max. length of main thalweg (m)	Gravelius coefficient
D5	13.26	580	1.26

(3) Catchment of Marolaona (secondary shrub vegetation)
This basin is also roughly rectangular and is covered in secondary bush scrub and shrub. Gradients are severe (around 35–45 % close to ridge line).

Main physical characteristics of Marolaona basins (Perinet)

Catchment	Area (ha)	Max. length of main thalweg (m)	Gravelius coefficient
D6	7.27	250	1.19
D7	31.50	950	1.25

(4) Basin of Manso (5°42' N., 4°06' W.)
With a surface area of 81 km², this basin is very compact and may be compared to a 9 km by 9 km square. Some 70 % of the basin is covered by natural forest (Yapo). This forest is very dense and is typical of Mapanian hygrophilous forests.

The topography is quite gentle with gradients in general of less than 10 %. The soils at the bottom of the thalweg are hydromorphic and contain the watertable, which rises during the rainy season causing an overflow of water in the flood channel and the generation of a large flood plain. However, the hillside is generally occupied by yellow and red ferralitic soils and has a gritter and clayey horizon.

(5) Basin of Taï (5°50' N., 7°20' W.)

This basin, with a surface area of 37.6 km², has two experimental basins of 1.4 km² and 1.2 km². Both are covered in dense, evergreen forest. The longitudinal gradients are low while the transversal gradients are quite steep and may reach 90 m/km.

There are two types of soil present:
- hydromorphic soils in the shallows and at the foot of slopes.
- higher, there are red and yellow ferralitic soils, more often with a gritty, clayey horizon.

(6) Basin of Ifou (7°08' N., 3°54' W.)

This basin of 38.2 km² has a geological substrata consisting of clayey schist which makes a deep penetration of infiltrated water into the basement easier. The watercourse (superior watercourse of Ifou) has quite a clear and meandering bed, but the vegetation has a great deal to tone down the runoff.

The vegetation cover is a second-rate mesophile forest mixed with many plantations. Depending on the topography, three types of soils may be distinguished:
1. on the plateaux: ferralitic soils, with ironpan at shallow depth (10–30 cm);
2. on the slopes: red and yellow ferralitic soils with deep concreting;
3. in the thalweg and at the foot of some slopes: hydromorphic soils.

(7) Basin of Amitioro (5°49' N., 4°52' W.)

A 170 km² basin with steep gradients (10 m/km) which decrease to 3.5 m/km as one moves downstream. The trough-shaped valleys have a transversal gradient of between 5 % and 25 % in the upper basin and between 3 % and 8 % in the lower basin.

The soils are of a red ferralitic type with a gritty surface horizon. On the slopes, there are the same types of soils but with colluvium recovering of the gritty surface horizon depicted above. The shallows (30 % of the basin surface area) are occupied by the hydromorphic soils.

(8) Basin of Agbéby (5°25' N., 4°13' W.)

A 11 km² basin consisting of numerous deep valleys, which make the basin seem hummocky. The transversal gradients are all greater than 5–10 % and may reach 40 % at the top of the basin, while the ridges hardly pass the 100 m level. The vegetation is natural dense forest, a large part of which is occupied by coffee and palm tree plantations. Concerning the soils, the whole of the basin is covered by ochre or red clayey sands from Tertiary continental, typical of the whole coastal strip of Côte d'Ivoire and other coastal countries of West Africa. The more or less ferralitic soils stemming from this are very leached and have a high permeability.

(9) Basins of Nion (7°22' N., 7°33' W.)

There are two basins here, with different surface areas. Nion I covers 62.4 km²; Nion II 10 km². In general, the relief is quite pronounced. The vegetation cover is that of an old forest that has been largely converted for cultivation. The ferralitic soils (red and brown-red on colluvium) on granite, enriched with magnesian limestone, cover almost the entire basin, but there is a lot of variation in the distribution of these soils.

(10) Basins of 'Mont Tonkoui' (7°23' N., 7°36' W.)

The relief in these two forest basins is very hummocky (Gboa 12.3 km² and Loué 18.4 km²). The average altitude is 700 m, the highest point in the first one being 1073 m and in the second 1189 m. The longitudinal gradients are steep. The transversal gradients attain as much as 400 m/km. Soils are mainly red and yellow ferralitic and have developed on granite.

During the experiments, the Loué basin was covered almost completely by forest while Gboa had been largely converted for cultivation.

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6. Hydrological sediment load and soil erosion

Before dealing with the question of the impact of the land use changes on sediment load and erosion, it would be useful to give some definitions in order to avoid semantic confusion about the different terms used in this chapter.

6.1   The different erosion dynamics: a succinct review

Three types of erosion are commonly distinguished, mostly by geomorphologists and biogeographers for tropical forests (Rougerie, 1960). These also have some application to savannah regions (Mietton, 1988).

(1) Elementary erosion at the microscale ('elementary' applies to the limited movement of matter or ablation rather than large movements). The causes of this type of erosion are as follows:
•   Rainfall through the splash or soil capping and disintegration under the impact of raindrops including the effects of throughfall in the forest (Rougerie, 1960).
•   Elementary diffuse overhead flow as a thin trickle, discontinuous in both time and space; even over a long time-scale, a slope may be completely swept away by the process.
•   Overhead flow as a thin plate which may occasionally cover the whole slope. Under the latter condition, the process is known as sheetflow. Sheetflow is more associated with arid and semi-arid environments than with forests.

The thin trickling erosion may lead to rill erosion in some areas. Rill erosion is the beginning of concentrated surface runoff overland flow and is characterized by linear erosion: minor linear incision of centimetrical to decimetrical order widthwise and in depth. The rills have a concave shape or a 'U' form when they become gullies. The difference in shape is linked mainly to the nature of the matter dissected and to the age of incision.

(2) Gully erosion: Gullies are more advanced linear incisions of metric order widthwise and in depth and appear where the runoff is concentrated (in valleys, in shallows or at the foot of a slope). If these gullies are not treated soon after their genesis, increases in their size may lead to progressive wall collapses which may hinder any attempts to repair the damage (Morgan, 1986).

(3) Mass movement: this process concerns wholescale displacement of debris from slopes, but it is outside the limits of our study here.

A point to remember is that there is a distinction made between the term 'ablation' and on-site erosion, which refers to a transfer of matter at field or catchment scale, and the larger meaning of the term 'erosion', which consists in a combination of the process of ablation, transportation and downstream sedimentation. Very often, only some of the eroded matter in upstream will enter the drainage network; the rest will move in a discontinuous way on small alluvial cones. This can happen, for example, at the outlet of incisions at the foot of a slope or in a more widespread way in shallows or in flood-plains. This materiel which has already been moved may de reloaded again after the heavy storms or may be colonized by vegetation and form stable topographical features for several years (Tricart, 1972; Trimbe, 1981).

As the likelihood of a deposit of material increases with the size of a basin, the relationship (sediment delivery ratio) between the material eroded on site and the total amount of sediment loaded by a course of water decreases significantly with the size of the basin (Walling, 1983; 1988). It is clear that the effects of erosion are seen sooner on site than further downstream. It may take several decades before a decrease in ablation upstream leads to a decrease in the contribution of sediments downstream in the flood-plains of large rivers (Pearce, 1986).

6.2   Forest cover as a form of protection: some main points

Before tackling the main studies and their evaluation of the impact of land use changes on soil losses, it might be useful to define the protective role played by forests in the processes of erosion.

The forest ecosystem is more efficient than a simple farming system in two aspects. Firstly, a forest increases the level of soil fertility to its highest level and helps to concentrate the range of substances necessary, in humus-bearing horizons, for the development of plants and for various other biological processes. This may be proved by the presence of well-balanced levels of material in the soil surface horizons in forests or savannah areas (Roose, 1980)

As we will see, any losses are to a large extent compensated for by the arrival of new matter (rainfall, dust and above all biological elements) because only forest and forested fallow are capable of restoring the fertility of soil surface horizons to the highest level (Laudelout and Van Bladel, 1967). Biological processes and turnover are swift under forest conditions; this allows for the concentration of nutritive substances on the surface, as well as the formation of a relatively stable and airy fine structure (soil density is often less than 1 % and total porosity greater than 60 %, two-thirds of which is macroporosity) (Roose, 1983).

Whatever the type of natural and non-converted forest or savannah, it is clear that the maximum levels of surface runoff $(KRAM = 0.1 - 5.5$ %) and erosion $(E = 10 - 500$ kg ha^{-1} year^{-1}) are moderate even on the steep slopes (up to 65 %), in spite of the heavy rainfall experienced in such environments $(RUSA$ from 600 to more than 1200) (Roose, 1980).

The results obtained from the Perinet basins show in the same way that the maximum levels of catchment runoff stay very high (70 %) in the area of savoka vegetation (secondary shrub vegetation) while in forested zones the levels are very low (1–3 %). This is so because, in the area of savoka vegetation, water moves over the non-rotted plant layer rather than infiltrating the soil (Goujon et al., 1968). Elsewhere, soil losses are minimal if they occur at all.

In general, it has been established that forest cover acts as a form of protection against soil losses and changes in the state of soil due to erosion and drainage. However, as we will see, other types of a non-forest vegetation cover may play a similar role.

6.3 The apparatus and methods used in the different studies

ORSTOM researchers and other institutions have carried out numerous studies on the effects of forest conversion and mechanical cultivation, and on forest and tropical soils (Fauck et al., 1969; Chaperon and Fauck, 1970; Siband, 1972; Blic, 1976; Blic and Moreau, 1979; Roose, 1980). A deterioration in the state of soils after conversion was underlined by many of these (Nye and Greenland, 1964; Roose, 1980). There are three explanations for this:
* the mineralization of organic matter in severe and hot climates;
* erosion;
* the leaching of nutrients.

The experimental apparatus used to measure overland flow and the associated soil losses originates from methods used in the USA by the Soil Conservation Service (elementary plots and experimental representative basin or catchment).[1] These may be straightforward and less expensive to study, but the results obtained cannot be practically applied to larger catchments or basins (Goujon et al., 1968; Roose, 1973–1980).

We will synthesize the main studies measuring soil and water losses since the beginning of the 1960s in West Africa and Madagascar. The results obtained are not only taken from experiments in erosion plots (a few hundreds of square metres), but also from observations made in larger plantations on ferralitic soils in Côte d'Ivoire, as well as in the south of the Hauts-Plateaux region and along the eastern coast of Madagascar (Goujon et al., 1968; Bailly et al., 1974; Ibiza, 1975; Roose 1980–1988). The potential for more intense rainfall on an event basis in the regions studied *(RUSA* = 1200 to 450) increases with the increase in annual rainfall and the concentration of rainfall in a single season. Gradients only rarely rise above 20 % (Roose, 1983).

Too often, erosion is evaluated using a single comparison of annual total weight of equivalent dry earth between the plots. Other studies have however calculated the correlation between the volume of the flood and the weight of the equivalent dry earth as a suspended deposit for each flood (Ibiza, 1975). The statistical correlation obtained is inaccurate but continues to be used as a means of comparison.

Besides the studies carried out at an experimental plot, erosion in several other basins was studied by ORSTOM (Sakassou, Sarki and Godola). Erosion was quite pronounced (earth losses of between 1.4 and 1.8 t ha^{-1} year^{-1}). In these basins, it was observed that there was a significant relationship between the total weight of earth removed in the basin by each storm and:
* depth of surface runoff,
* the first 20 minutes of rainfall,
* the time between the start and the maximum strength of the storm,
* the sum of the precipitation since the start of the rainy season(Rodier, 1974).

Another significant relationship was noted between the (t ha^{-1}), the slope index,[2] clay and silt content and the percentage of cultivated area. This could allow the extrapolation of results obtained (Rodier, 1974).

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1. Experimental plots and representative catchments may be split into two sections: an experimental field of study and a collector system (see *Bois et Forêts des Tropiques,* No. 119, May–June 1968, p. 5.)
2. The slope index is a number characterizing the relief of a given basin. The most used index is given by:

$S = D.L/A$

where D = isohypse interval
L = total length of contour lines
A = basin surface area
expressed in homogeneous units.

6.4 Results

The experiments discussed here were conducted on small plots. They were carried out in order to measure the effects of changes in the forest environment. Some of these types of changes were highlighted in Section 1.4 above. The results are listed according to the different techniques used, *viz.* the more traditional techniques (manual clearing with or without burning), followed by the more modern techniques (mechanized clearing). A comparison is also made over time for the same plot and in relation to space for neighbouring plots.

The 'slash and burn' agricultural technique is commonly used in our geographic area of study and has been widely studied. It will therefore be discussed below.

6.4.1 The hydrological impact of the burning cultivation technique

Numerous studies have considered the impact of burning on overland flow and soil losses in the humid tropics of West Africa and Madagascar (Goujon et al., 1968; Roose, 1973–1980; Bailly et al., 1974; Sarrailh and Rakotomanana, 1978; Pedro and Kilian, 1986).

The results of the effects of burning on overland flow and soil losses presented here are in part taken from the experiments undertaken by CTFT in the montane forest region in Madagascar (Bailly et al., 1974). Other results are taken from experiments carried out in the Hauts-Plateaux region in the same country (Goujon et al., 1968).

The measurements were taken in the Marolaona basins (Perinet) in a region of undulating relief. Maximum altitudes in this region vary between 930 m and 1095 m above sea level. It has a humid climate with more than 200 days or 1700 mm of rain per year. Two seasons are usually distinguished, according to temperature and to the type of rainfall:

- Hot season, beginning in September and finishing in April/May, when high rainfall events of long duration can be associated with tropical cyclones or other well-organized meteorological systems.
- The 'dry' season when low rainfall events of long duration can occur associated with the SE Trade Winds. Thick fog and cold nights are also a common occurrence (Bailly et al., 1974).

In order to test the impact of burning cultivation on erosion and overland flow, three elementary catchments were set up in 1963 in the Marolaona basins:

1. catchment 71 of 1.36 ha, left as control catchment and covered in secondary forest vegetation in mid-growth (old savoka);
2. catchment 72 of 1.77 ha, farmed along contour lines, with anti-erosion windrows and associated plantation of fruits;
3. catchment 73 of 1.73 ha, traditional *tavy* farming (rain paddy farmed after burning) for the first two years and kept in fallow after that.

Each catchment was equipped with gauging apparatus (flow and soil).[1] The experiments were carried out until 1971–72 (Bailly et al., 1974).

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1. Type H calibrated rating tank (US Soil Conservation Service)
   - 2 feet in catchment 71
   - 2.5 feet in catchments 72 and 73, and raingauges.

TABLE 8. Annual surface runoff (mm) 1963/1964–1971/1972: Marolaona (Perinet)

Year of measure-ment	Rainfall (mm)	Surface runoff (mm)		
		Basin 73 (Tavy)	Basin 72 (Cultivation)	Control Basin 71
1963/64	1780	198.1	266.4	346.5
1964/65	1975	35.1	79.8	150.4
1965/66	1556	0.0	1.3	3.5
1966/67	1510	0.2	3.1	7.7
1967/68	1906	18.6	50.4	107.2
1968/69	1781	1.1	29.0	63.1
1969/70	2277	23.1	50.6	91.6
1970/71	2057	92.0	136.2	204.7
1971/72	2141	141.0	187.0	318.4
Average	1887	56.6	89.3	143.7

Source: Bailly et al., 1974.
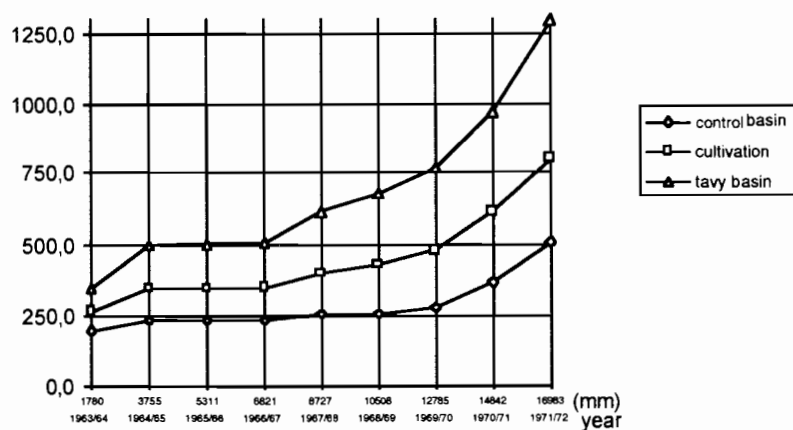
Figure 10. Cumulated global surface runoff versus rainfall. Marolaona (Perinet) (Bailly et al., 1974)

TABLE 9. The impact on soil losses. Mass wasting (kg of wet sediment/ha): Marolaona basins (Perinet)

Year of measure-ment	Mass wasting (kg/ha)		
	Basin 73 (Tavy)	Basin 72 (Cultivation)	Control Basin 71
1963/64	9000	1700	0
1964/65	170	16	5
1965/66	0	0	0
1966/67	0	0	0
1967/68	6	12	25
1968/69	3	0	0
1969/70	1	91	9
1970/71	0	5	0
1971/72	46	2	0
Total	9226	1826	39

Source: Bailley et al., 1974.
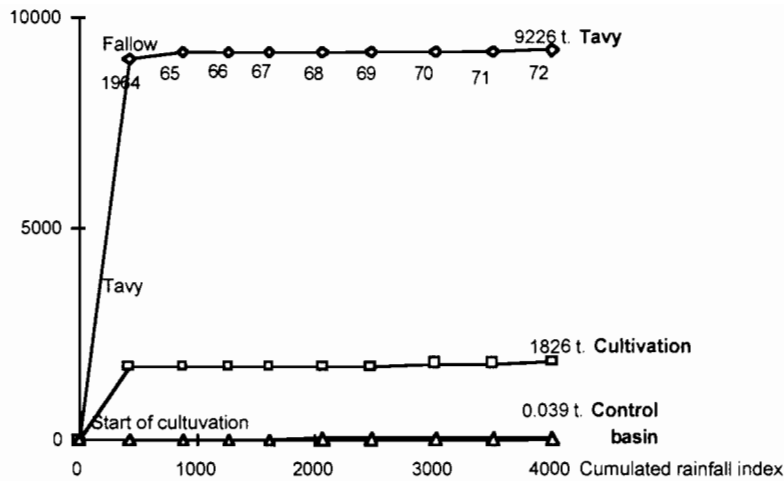
Figure 11. Cumulated sediment loss (kg/ha) versus cumulated rainfall index (Perinet) (Bailly et al., 1974)

Measurements were taken between 1961 and 1966 in the Hauts-Plateaux region in Madagascar in order to evaluate the impact of destruction of vegetation by fire on overland flow and soil losses. From a climatic point of view, annual rainfall in this region reaches an average of 1700 mm and is concentrated within five months (November to March). The pronounced dry season varies in duration from one year to the next (Bailly et al., 1974).

The following table gives results from a plot of 150 m². It was previously an area of grassland which was burnt at the end of dry season on two consecutive years (1961 and 1962) then in 1964 and 1966.

TABLE 10. **The impact of burning on overland flow *f* and soil losses (Manankazo, Madagascar).**
Plot of 150 m². Slope = 23 %.

Year	1961–62		1962–63		1963–64		1964–65		1965–66	
Plot of catchment (C or T)[1]	C	T*	C	T*	C	T	C	T*	C	T
Rainfall (mm)	1506	1506	1893	1893	1851	1851	2092	2092	1413	1413
Annual runoff (mm)	56	103	112	235	108	123	97	299	35	40
Annual runoff (% of rain)	4	7	6	12	6	7	5	14	2	3
Maximum runoff (% of rain)	31	44	29	33	32.7	38	35.1	54	30	28
Earth losses (t/ha)	0	2	0	2	0	0	0	3	0	0

1. C = Control plot (bushy and covered with *Loudetia*)
   T = Treatment catchment
*   Vegetation destruction by fire.
Source: adapted from Goujon et al., 1968.

The comparison of the results of treatment-plot versus control-plot shows that, during the periods 1963–64 and 1965–66 when there was no burning, maximum overland flow remained high, but the total annual overland flow and the average overland flow decreased. Soil loss only commenced after burning.

Elsewhere measurements were also taken in another experimental plot which was burnt every year around the mid-October (end of dry season) from 1961. An increase in surface runoff and a significant increase in soil losses only appeared after the third year after the first treatment (Goujon et al., 1968).

TABLE 11. The impact of burning on the annual surface runoff and soil losses (Lac Alaotra, Madagascar). Plot of 100 m². Slope = 36 %.

Year	1960–61		1961–62		1962–63		1963–64		1964–65		1965–66	
Plot of catchment (C or T)[1]	C	T	C	T	C	T	C	T	C	T	C	T
Rainfall (mm)	869	896	1181	1181	1029	1029	1233	1233	1141	1141	861	861
Annual runoff (mm)	69	–	49	88	40	42	138	107	100	79	31	26
Annual runoff (% of rain)	8	–	4	7	4	4	11	9	9	7	4	3
Maximum runoff (% of rain)	29	–	26	28	21	24	57	50	50	40	48	30
Earth losses (t/ha)	0	0	0	0	0	0	0	1.4	0	0.3	0	0.9

1. C = Control plot (covered with Aristida and no-burned); T = Treatment catchment.
Source: Adapted from Goujon et al., 1968.

Some conclusions may de drawn from each of these studies. Where burning cultivation technique takes place, the deterioration is mainly biological which is linked to the disruption of mesofaunal and microfloral activities and the maintenance of the aeration structure of humus bearing horizons. Clearing prevents accumulation of further organic matter inputs in the form of litter on the field. The subsequent denudation and burning processes accelerate mineralization of organic matter stored in the vegetal and also in the soil surface humus-bearing layers. The mineralization of the humus, the roots and surface plant remains continues over several years (Roose, 1983).

6.4.2 The effects of manual clearing: findings from a plot in Adiopodoumé (Côte d'Ivoire)

This first example illustrates the impact of forest conversion to annual cultivation or to bare soil using traditional methods.

Table 12 is taken from experiments on plot No. 6 in Adiopodoumé (Côte d'Ivoire). The plot is 15 m long and has a gradient of 23 %. It is located in secondary rain forest, with ferralitic soils on Tertiary sands, and was investigated over 10 years (Roose, 1973; 1977; 1983).

TABLE 12. Runoff and earth losses before and after clearing (case of Adiopodoumé)

	1960 Forest	1961 Forest	1962 Forest	1963 Forest	1964 Forest	1965 Forest	Median forest 1956–1965	1966a cassava on mounds	1967b peanut on flat land	1968 baresoil	1969 baresoil	1970 baresoil
Rainfall (mm)	1898	2289	2773	2434	1674	2300	2321	1496	1673	2084	1951	1655
RUSA	–	–	1927	1358	1084	1673	–	614	990	861	989	1251
K_{RAM} %	0.6	0.4	0.1	0.2	0.5	0.6	0.5	18.3	25.0	24.7	26.1	31.2
K_{RMAX} %	2.7	3	1	3.4	3.9	7.3	3.2	75	77	65	76	68
Total erosion (t ha⁻¹ year⁻¹)	0.013	0.021	0.013	0.007	0.052	0.227	0.052	162.4	427.3	622.3	564.2	746.6
S/E %	100	100	100	100	100	100	100	5.7	1.7	2	2.6	2.7

S/E = The ratio between material eroded in fine suspension (loaded from catchment to sea) and total erosion (fine and coarse, i.e. sands and aggregates which may be deposited at the foot slope and form colluvium); in dense forest only the fine particles raised up above the litter by the mesofauna are prone to migrate (S/E = 100 %).
Source: adapted from Roose, 1983.

It is clear that even manual clearing in harsh sub-equatorial climates and on steep gradients (such as 23 %) causes an increase in overland flow and in soil losses:

- the annual average of storm-runoff coefficient $KRAM$ increases from 0.5 % to 20 % or even beyond 25 % on selected cultivated or bare soils;
- the maximum unit storm–runoff coefficient KR_{MAX} increases from 3 % to 70 %;
- the negligible soil losses under natural environmental conditions, a few tenths of a kilogram per hectare per year are multiplied by a much greater factor (> 1000): $E = 400$–750 t ha^{-1} year^{-1}!

Manual clearing accelerates erosion which in turn removes the entire humus-bearing layer. If we consider the two years of cultivation, erosion seems to be distinctly moderate during the first year in cassava cultivation and the second year in areas of peanut farming. It is however difficult to attribute this change to a causal factor, for example a better preservation of the soil structure, because the aggressiveness of the climate considerably increases over the same period, and the farming practices are not the same (farming on mounds and on flat land).

It must be remembered that these results, which clearly show the hazards of even manual clearing, were however specific to chosen sites which had well-defined climate and morphopedological characteristics. It is not always the case that traditional manual conversion has exacerbated such erosion effects. Collinet (1979) showed from an experiment in a catchment of large forest of Taï in the south of Côte d'Ivoire that the erosion does not go beyond 300 kg ha^{-1} year^{-1} after manual clearing and traditional planting of montane rice, even though there has been a marked increase in overland flow.

6.4.3 The effects of mechanized clearing: findings from an experimental plot in Divo (Côte d'Ivoire)

This is a region situated in the central west of Côte d'Ivoire and characterized by a dense semi-deciduous secondary forest distinguished by the height of the canopy and by the abundance of undergrowth; a thin layer of litter covers the soil all year round (Roose, 1981).

Table 13 outlines the main figures related to overland flow and soil erosion before (1967–1970) and after clearing (1971–1974). The observations were made from a 35 m long plot with a 30 % gradient (Roose and Jadin, 1969; Roose, 1983). The forest was cut down in 1971 by mechanical saw, slightly burnt and converted to a cacao tree plantation. Planting followed the contour lines after the removal of the existing stumps. This meant that the soil was practically never denuded. Therefore the mineralization of organic matter storage during burning was reduced and the organic inputs did not stop, although they were considerably reduced.

TABLE 13. Runoff and earth losses before and after clearing (made in 1971)
(Case of Divo, E.R.L.O. plot near I.F.C.C. station)

	Semi-deciduous forest				Cacao plantation plus forest fresh regrowth				Median
	1967	1968	1969	1970	1971	1972	1973	1974	1967–74
Rainfall (mm)	1242	1955	1211	1436	1220	1291	1388	1375	1333
RUSA	607	1100	500	848	599	684	795	659	672
KRAM %	0.5	1.4	0.5	1.0	0.3	0.4	0.4	0.4	0.4
KR_{MAX} %	2.9	6.0	4.6	6.1	1.2	1.5	2.4	1.7	2.7
Erosion (kg/ha)	503	644	128	191	133	73	58	98	130
S/E	73	38	23	29	8	22	45	33	24

Source: adapted from Roose, 1983.

According to these findings, no major change was observed. Both overland flow and soil erosion remained negligible after this type of forest conversion despite the rainfall aggressiveness index (Median $RUSA$ = 672). According to Roose (1983), the density of the forest and the cacao trees was apparently similar and the covering nature of this plantation would explain a negligible rate of soil erosion and level of overland flow. The levels could even be lower than those observed in the forest!

The comparison of annual climate data does not add any further explanation, except for 1968 when the rainfall aggressiveness index increased by 50 %, leading to the highest value of erosion recorded. Thus, a more detailed comparison of climate data is needed on a daily basis for the extreme events rather than on a yearly basis (annual rainfall, global annual aggressiveness) (see Chapter 8). Similar results were observed in relation to erosion and runoff in the Anguédédou plantation of hevea on a gradient of 30 %. Here, there is clayey sand and very desaturated ferralitic soils (Roose et al., 1970; Tran Thanh Canh, 1972).

Thus, it is possible to manipulate or convert forest land without damaging it, through the appropriate selection of crops and adapted cultivation techniques.

6.4.4 Measurements of parallel soil erosion and surface runoff on neighbouring plots

Table 14 outlines the figure relating to erosion and runoff on neighbouring plots with natural vegetation cover and bare or cultivated earth, taken one or more years after clearing. The values shown are the medians (Example: 0.052 t ha^{-1} year^{-1} for the forest plot of Adiopodoumé with a gradient of 20 %), or are the values for a single year (570 t ha^{-1} year^{-1} on bare earth in 1969), or are intervals (Example of Divo).

TABLE 14. Compared values of surface runoff and soil erosion of neighbouring plots with natural vegetation or bare earth or cultivated after clearing

Sites	Slopes	Mean annual runoff %			Erosion (t ha^{-1} year^{-1})			Source
		Natural environment	Baresoil	Cultivation	Natural environment	Baresoil	Cultivation	
Adiopodoumé	4.6	–	35	–	–	60	–	Roose,
(Côte d'Ivoire)	7	0.1	33	0.5–30	0.017	138	0.1–100	1973–79
ORSTOM,	11	0.3	–	–	0.034	–	–	
1954–75	20	0.5	24	–	0.052	570	–	
	65	1.2	–	hevea	0.455		hevea	
Anguédedou (Côte d'Ivoire) IRCA/ORSTOM 1966–69	29	–	–	0.3–1 (hevea)			0.06–3 (hevea)	Roose, 1970
Azaguié (Côte d'Ivoire) IRCA/ORSTOM 1966–74	14	0.4–5.5	–	5.5–12 (banana)	0.05–1.4	–	0.7–4.5 (banana)	Roose, Godefroy, 1977
Divo (Côte d'Ivoire) IFCC/ORSTOM 1967–74 (cacao)	10	0.5–1.4	–	0.3–0.4 (cacao)	0.1–0.6	–	0.06–0.1	Roose, Jadin, 1970–79
Korhogo (Côte d'Ivoire) ORSTOM, 1967–74	3	1–5	25–40		0.01–0.160	3–9	–	Roose, 1975–79
Agonkamey (Benin) ORSTOM, 1964–69	4.4	0.1–0.9	17 after clearing	20–35	0.3–1.2	17–28 after clearing	10–85	Verney Volkoff Willaime, 67 Roose, 73, 76

Planting a crop reduces the dynamics of surface material transfers compared to observations made in areas of bare earth. However, it is important to underline that this decrease in surface runoff and in erosion takes place in very variable proportions according to the cultivation techniques used and the proportion of vegetation cover. The structural state of the soil surface at the time of the most erosive rainfall also plays an important part. Not only is there a reduction in the surface water and soluble debris transfers, but some land use changes may lead to negligible levels of erosion and overland flow, which may even be inferior to the values obtained under forest conditions (see Table 13). This refers in particular to grassland, banana plantations, shrub crops associated with covering plants and mulched cultivation (Roose, 1983).

The various erosion impacts on different types of surface states are expressed through a factor C. This includes not only the influence of the vegetation cover but also the influence of farming techniques used and represents the ratio between the erosion measured under a given type of farming and that measured on a neighbouring bare soil plot (Roose, 1980). Table 15 lists the values for the C factor depicted above for the different surface states, crops and vegetation cover. C is very low ($C < 0.001$) when the risks of soil losses are negligible, whilst a value of 1 is reached for a bare earth surface state. Between these two extremes, there is a whole range of values corresponding to the various types of situation.

TABLE 15. Factor C for a range of crops/farming and surface states in West Africa

	C (average annual value)
Bare soil	1
Forest, dense thicket, well-mulched farming	0.001
Savannah and good conditions grassland	0.01
Savannah or grassland burnt or over-pastured	0.1
Slow growth covering plant late crop	
first year	0.3–0.8
Fast growth covering plant or advanced crop	
first year	0.01–0.1
Slow growth covering plant late crop	
second year	0.01–0.1
Maize, millet, sorghum (according to harvests)	0.4–0.9
Plateau rice/intensive farming	0.1–0.2
Cotton, tobacco in second cycle	0.5–0.7
Peanut plant (according to harvests and the date of planting)	0.4–0.8
Cassava, first year/yam (according to the date of planting)	0.2–0.8
Palm trees, hevea, coffee, cacao and covering planting	0.001–0.3
Pineapple (according to the gradient) advanced planting	0.001–0.3
with burnt residue	0.2–0.5
with buried residue	0.1–0.3
with surface residue	0.001–0.01
Pineapple on partitioned ridges of earth (gradient 7 %),	
late planting	0.1

Source: adapted from Roose, 1977.

6.5   Conversion and the rates of erosion

Conversion often leads to a state of imbalance caused by an increase in soil losses, mineralization of the reserves and a decrease in biological inputs (Roose, 1983). As was indicated above, this general statement needs to be qualified with some caution in relation to the different methods of farming and clearing.

The rates of erosion following land use changes may be synthesized as follows:

There is an increase in erosion following clearing: although the initial impact is weak, because of the residual organic matter which helps maintain the stability of the soil complex and the infiltration capacity (Wiersum, 1985), the subsequent rate of degradation increases during the first few years. This slows down to reach a new balance at the end of between 5 to 15 years depending on the farming system (Roose, 1983).

The impact of erosion becomes dramatic after the layer of litter has been removed and the soil stripped bare (Roose, 1973, 1980). It becomes more pronounced as well with repeated disturbances such as burning, frequent weeding or even in the case of discontinuous farming (Bailly et al., 1974; Goujon et al., 1968; Roose, 1983). On the other hand, earth losses are reduced rapidly with perennial shrub farming (Roose, 1980).

Figure 12 clearly shows the erosive force after clearing and when farming has begun on ferralitic soils. It also shows the importance of the influence of slope on soil losses.
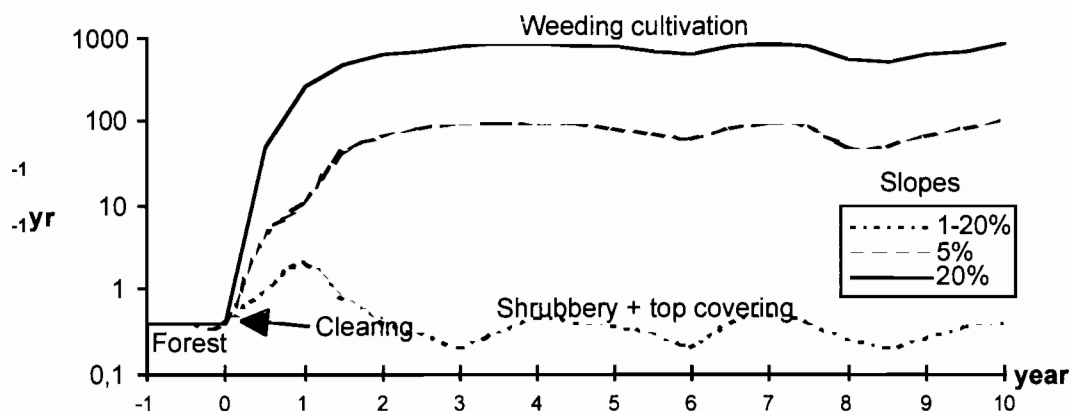

Figure 12. Erosion rhythms of ferralitic soils after conversion (clearing and cultivation) (Roose, 1982)

6.6   Limits of the studies reviewed

Several writers have underlined the fact that it is difficult to replicate on a small plot the real conditions of pasture or cultivation burning which normally takes place on a larger scale. It is practically impossible to feed animals the young shoots which grow after burning on a small area of land (Goujon et al., 1968). Therefore, the results obtained from plot studies will be less than in reality. They may allow for comparisons and therefore allow an interesting study of the problems caused by erosion, but they cannot be representative of an entire catchment, no matter what the size (Goujon et al., 1968).

The time span of measurement also presents some problems. The rapid degradation of the chemical and physical properties of surface horizons of tropical soils leads to an increase in the rates of soil losses caused by erosion and drainage. Although this has been shown by many studies, not many projects have analysed such effects over a sufficiently long period of

time. Also, important physiographic information (for example the proportion of natural or converted vegetation cover) or climatic information (such as occurrence or non-occurrence of rare events which may control in large part the results from the experimental plots) is not given. Such details can only be found from campaign annual reports and these are not easily accessible.

It is also important to emphasize that the majority of studies devoted to erosion concentrate to a large extent on changes in the transport of solid matter following forest conversion within small basins. Nevertheless, some vital lessons were drawn from experiments within elementary basins as well as from plots. One was the recognition of the need for a soil land use capability classification in order to establish a more appropriate strategy for land use allocation to reduce past erosion loss rates (Goujon et al., 1968).

7. Available hydrological data

This chapter describes the pluviometric and hydrometrical data base controlled by the Hydrology Laboratory (Laboratoire d'Hydrologie) of ORSTOM. There are more than 100,000 equivalent years of data spread over 4400 observation stations.

7.1 Available data and their source

The available data in ORSTOM's Hydrology Laboratory are of three broad types which are distinguished as follows:
- instantaneous water yield measurements (considered as instantaneous) characterized by a pair 'measured water yield-associated gauge height';
- instantaneous or average water yield over a certain period: these are rarely measured directly, but are calculated from gauge height with a stable-discharge table (also available);
- rainfall gauge height read on the limnimetrical scale or noted by rain recorder (further described below).

The data from the above three categories are always a positive number between 0 and 150,000. The standard unit used is 1/10 of a millimetre and the maximum cumulate duration length is normally a year.

7.1.1 Pluviometric data

The above rainfall (pluviometric) data concern the depth of rainfall observed over a time interval and may be split into two categories:
- Raingauge data (fixed time interval of 24 hours);
- Rain recorder data, data taken from a numeric table established from the daily, weekly, biweekly or monthly pluviograma. These pluviograma are obtained from a rain recorder equipped with an unrolling drum or table. These data are taken at variable time intervals.

7.1.2 The sources of ORSTOM data

There are two sources of the stream (of river) flow hydrometric and pluviometric data available at ORSTOM.

Direct sources: results obtained directly from the observational network-connected watercourses in French-speaking countries of Africa; and observation made during studies of experimental basins from 1952 onwards (Jaccon and Travaglio, 1990).

Indirect sources: the data mainly originate from the national records of the African countries' pluviometric network.

7.2 ORSTOM's data banks and their problems

The two types of data described above are stored in data banks.

7.2.1 The ORSTOM laboratory data banks

Two independent data banks were computerized from 1967 onwards. They are managed by two programmes: HYDROM (Cochonnean, 1978) and PLUVIOM (Raous, 1990), which have been developed within ORSTOM. These programmes exist both for use on a main frame and later, modified, for use on a personal computer (PC). They allow data to be consulted and extracted, and also facilitate the exchange of information between users.

7.2.2 Present-day problems linked to the data banks

The creation of data banks at ORSTOM was a big step forward in the formatting of basic data for regional studies. For the data banks to be efficient, they have to be regularly updated. Unfortunately, since 1979–1980, the data base has been weak because:
1.   in 1980, ORSTOM ceased managing the observation systems in Africa. Therefore any updates are subject either to a bilateral Convention or to study contracts;
2.   the direct data entry operations have become too costly for the Hydrology Laboratory of ORSTOM to maintain (Jaccon and Travaglio, 1990).

The only solution to these problems is to promote an efficient collection of data by competent departments in the countries concerned and to establish an efficient data exchange mechanism between these countries. Some steps have been taken in this direction, but the countries concerned need to agree on the political bases for such data exchanges.

7.2.3 Present-day policy of ORSTOM

The updating of data bank management systems (with data concerning paired daily rainfall–discharge measurements) by ORSTOM in collaboration with other institutions (namely OMM, AGRHYMET and ASECNA) has allowed the creation of data banks in a lot of African countries. These data banks are either national (National Hydrological Departments) or regional (Inter-state Organizations).

The states manage their collection systems and own their own data. The compatibility of the formats and the programmes allows some co-operation (Jaccon and Travaglio, 1990).

Therefore the present approach in the Hydrology Laboratory is to promote this policy,

which consists in trying to collect and enter into data banks all recorded data. This policy would facilitate the exchanges of data and enable periodic updates, especially for data with interesting amplitude and representative regional figures (Jaccon and Travaglio, 1990).

7.2.4 Conventions and accomplishments

Amongst the achievements in the updating of data from African countries, it is important to mention the work carried out by the tripartite CIEH-ASECNA-ORSTOM Convention. This Convention led to the updating of the pluviometric data bank of the 13 Member States (Benin, Burkina Faso, Cameroon, Centrafrican Republic, Chad, Congo, Côte d'Ivoire, Gabon, Mali, Mauritania, Niger, Senegal and Togo) for the period 1966–1980 (Jaccon and Travaglio, 1990). This high standard of work (full-files, work report and pluviometrical yearbook published by country) was carried out at the end of a four-year study (1985–1989).

As for the work in progress, there is the FRIEND-AOC project. The aim of the latter is to assemble in a comprehensive and easily up-datable format all the daily rain and discharge data from the West and Central African countries. This will help to establish a better level of collaboration between the countries and organizations involved (ORSTOM, UNESCO, OMM, ASECNA, AGRHYMET). FRIEND-AOC is currently under the supervision of ORSTOM. The implementation plan of this programme was released following a meeting organized by ORSTOM in December 1995 in Benin.

7.2.5 Synopsis of the available data

For each of the two data banks, (pluviometric and hydrometric), there is a file showing the location characteristics of each measurement site. The information stored in this file is of a descriptive nature (Jaccon and Travaglio, 1990). It indicates:
- the name of the measurement station,
- the geographical location,
- the equipment used,
- the date the apparatus and the records were set up.

As already stated in Section 7.1.1, it is possible to find out the depth of simple daily rainfall (fixed time interval of 24 hours) for the majority of West African stations or sites.

Concerning hydrological process studies, rain recorder data which allow the calculation of maximum intensities over a variable time basis are the most important for application in research. Search data are less numerous than the simple daily rainfall amounts. The criteria used to quality-control this type of data in the following tables have to take into account the time resolution of the data obtained after processing.

Therefore the quality of the data is directly linked to the recording equipment present in the stations. Data are judged to be of good quality when it is possible to process them up to a time basis of 5 minutes (daily unrolling drum or table) and they are fine enough to be able to follow the progress of the storm (flood) hydrograph. The weekly unrolling drum records do not allow processing with a time basis of less than 30 minutes and therefore these are judged to be of medium quality. For some stations, these data are taken from bi-weekly or monthly unrolling drum records. The information given by this type of data is obviously of much less fine time resolution than the former. This rain recorder data may be extracted and processed from programmes created within ORSTOM (PLUVIOM and more recently ARES (ex-POH126) in a PC version).

8. Research recommendations

The following recommendations for further research became evident during the compilation of the present report.

1. In relation to the evaluation of the effects of land-use changes on the local climate (soil temperature, exposure to the sun) following conversion, there seem to be several areas needing attention:

    *   There is a need for rigorous studies to compare temperature and decreases in vapour pressure recorded above the forest canopy and at the same height above deforested areas.

    *   There is a need for an evaluation of the types of radiation emitted from the forest canopy and from other types of surfaces. The only existing studies in this area are those done by Monteny and Casenave (1988; 1989). The latter provided some figures for the amount of reflection (20 %) when the forest is converted to multi-cultivation (Monteny, 1986) and 12 % for a humid tropical forest (Monteny and Casenave, 1988). The study by Baldy and Stigter (1993) is also a useful point of reference.

2. In relation to the rigorous evaluation of conversion or land use change impact on the water yield and soil losses, studies based on the classic paired catchment methods over a long period are lacking in French-speaking Africa.

3. In future studies, an important aspect needing attention is the number of years it takes for a return to pre-disturbed water yields following natural regrowth of vegetation after clearing.

4. It is also important to consider the lack of studies on the effects on water yield of 'slash and burn' shifting cultivation or of the conversion of natural forest to annual farming. As these are the two practices most often used in our study area, it would be mandatory to consider their effects.

5. There is also a lack of studies linking water yield for different types of vegetation cover. A more reliable description of soil types with land use cover is needed in future studies.

6. It is important to mention here that, in our geographic area of study where climatic variability extremes are normal, the seasonal distribution of watercourse flow is more

important than the simple total annual flow. Therefore, it would be interesting to know if the reforestation of degraded land will restore dry season flows or not.

7. The conversion of natural forest to plantations is not a panacea for preventing land degradation. In our study area, there is evidence that anthropogenic activity encourages a higher rate of mineralization of ferralitic soils. This implies that degradation is practically unavoidable when faced with this type of climate and soil conditions. However, there are several measures which may be taken to slow down the rate of degradation:

   - the use of more conservative methods of clearing (with respect of the humus-bearing horizon, the root network, progressive on-site burning);
   - the use of farming methods which protect most of the soil through plant cover (associated cultivation or shrub farming with undergrowth);
   - the use of farming techniques which are well adapted to the physical environment (Roose, 1983);
   - covering the soil to protect it against raindrop compaction and to decrease the rate of soil mineralization (Fournier, 1977; Roose, 1980).

   While the preceding solutions may not be enough to prevent degradation and facilitate biological activity, they do however considerably reduce erosion, especially when shrub farming (with undergrowth) gives the vegetation cover (Ollagnier et al., 1978, palm trees; Cunnigham, 1963, cacao plants; Moulo, 1974, banana plants; Tran Than Canh, 1972, hevea).

8. In parallel to the need for land use hydrology to evolve is the need for greater utilization of geographical information systems in connection with soil classification, soil arability, vegetation cover and status of land in terms of degradation.

9. There is a need to strengthen (especially at the Agency level within the countries concerned) the FRIEND-AOC project aimed at the creation of functional data banks and a greater exchange of centralized information. In relation to this, the BADOIE (Inter-State data bank) experiment, which is already at an advanced stage, is an act to follow. Additional measures aimed at collecting and exchanging information within the African countries need to be encouraged.

10. It is also necessary to encourage rigorous field research pertaining to medium-sized and large basins. There is practically no existing information for this type of basin in West Africa or Madagascar. Most research has concentrated thus far on experimental plots or on smaller basins (less than 200 km^2).

There is a shortage of high-quality, short-time resolution data related to rainfall–runoff and associated process hydrology studies. Therefore, basic pluviometric and watercourse hydrometric networks must be strengthened.

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