# Impact of land use change on the hydrology and erosion of rain forest land in South Cameroon

M.J. Waterloo
J.C. Ntonga
A.J. Dolman
A.B. Ayangma





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ABSTRACT

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Rainfall, water, sediment yields and evaporation were quantified in three catchment areas with undisturbed rain forest, selectively logged forest, and forest with shifting cultivation respectively. Despite a considerable regional variation in rainfall (1700-2300 mm $a^{-1}$), annual evaporation rates were similar (1209-1314 mm $a^{-1}$). The impact of land use practices on water yield is negligible compared to the effect of rainfall. The sediment yield increased from 56 kg $ha^{-1}$ $a^{-1}$ for undisturbed forest to 105 kg $ha^{-1}$ $a^{-1}$ for forest with agriculture and to 564 kg $ha^{-1}$ $a^{-1}$ for selective logging. The simulated soil erosion increased by more than 1000 kg $ha^{-1}$ when skid tracks were constructed on slopes exceeding 10°.

Keywords: agriculture, catchment area, forestry, rainfall, sediment, soil, water

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P.O. Box 125, NL-6700 AC Wageningen (The Netherlands)
Phone: 31 (317) 474200; fax: 31 (317) 424812; e-mail: postkamer@sc.dlo.nl



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# Contents

## Preface

The Tropenbos Cameroon Programme (TCP) was established in 1992 by the Cameroonian Ministry of Environment and Forests (MINEF) and the Dutch Tropenbos Foundation to provide scientific knowledge on which a management plan for the rain forests in South Cameroon could be based. The implementing agencies are the 'Institut de la recherche Agronomique (IRA)', the 'Office National de Développement des Forêts (ONADEF)', the Tropenbos Foundation and the Wageningen Agricultural University (WAU). Several of the fourteen interrelated projects dealing with economical, sociological, agronomical, forestry, hydrological, ecological and soil issues are funded through project PD 26/92 of the International Tropical Timber Organisation (ITTO). The involvement of the Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO) started in 1991 during the formulation phase of the programme to assist in the preparation of a document describing the various proposed research projects (Foahom and Jonkers, 1992). Upon request of the Tropenbos Foundation, SC-DLO became the leading agency for the forest land inventory and land evaluation study (Lu1 project) after approval had been obtained in 1994 from the competent Cameroonian Authority, the National Committee Tropenbos Foundation and the Board of the Tropenbos Foundation.

The hydrological study is one of the components of the Forest Land Inventory and land Evaluation (Lu1) project carried out by SC-DLO and coordinated by the Tropenbos Cameroon Programme in Kribi, Cameroon. The study started in June 1995, when the field hydrologist (Dr. M.J. Waterloo) was recruited for a fourteen months period to set up the study under supervision of the senior hydrologist (Dr. A.J. Dolman). A counterpart (Dr. J.C. Ntonga) and a technician (Mr. A.B. Ayangma) of the 'Centre de Recherches Hydrologiques' of the 'Institut de Recherches Géologiques et Minières (CRH-IRGM)' were identified and joined the SC-DLO field hydrologist in August 1996 and January 1997, respectively. The involvement of SC-DLO was reduced when Dr. M.J. Waterloo left the project at the end of his contract in July 1996 and the counterpart became responsible for the study. Dr. M.J. Waterloo returned to the research area on a backstopping mission for SC-DLO in November - December 1996.

This report deals with the results of the hydrological study at the end of the first year of data collection. Since the study is expected to continue until January 2000, the results presented in this report should be considered preliminary. However, they provide a fair indication of the changes in the hydrology after low intensity conversions of rain forest to selectively logged forest or to shifting cultivation.

In Cameroon, many people have contributed to the hydrological study. We are grateful to the administrative staff at the Tropenbos Cameroon Office in Kribi, and to Wim van Driel, Martin Zogo and Hannah Mokome in particular, who took care of the increasingly difficult task of managing the logistics and finances of the fourteen projects.

We should also like to thank Marcel Mva, who assisted throughout the study period with the collection of field data and who acted as an interpreter between the scientists and the local population.

Scientific support was obtained from Yves Nestor Nangmo from the University of Dschang and Menno Ruppert from the University of Utrecht, who carried out studies on the soil physical properties and rainfall interception, respectively.

Special thanks to Gerard Hazeu and Barend van Gemerden who made their soil and vegetation data available.

The drivers of the Tropenbos Cameroon Programme, Jean Owona, Sylvestre Tchoungui, Johanes Djon Djon, Theodore Atangana and Gervais Meyo did a very good job of driving us around safely under often difficult conditions.

The observers of rainfall and river water levels, Bile Sylvain Bruno, Lambo Jean Paul, Mba Michel, Mva Jean Jacques, Mvondo Jean Louis, Ngbwa Rivel Nestor, Nguiamba Isaac, Njock Simeon, Nna Jean Claude, Oba Joseph, Oyono Fernand, Touandop Augustin and Zamadjo Didier should be complimented for having worked throughout the study period without missing a single day, thereby providing continuous rainfall and waterlevel records.

Last, but not least, we are very grateful for the hospitality and cooperation provided by the entire population of the research area.

## Summary

A hydrological study has been carried out in South Cameroon by the DLO Winand Staring Centre for Integrated Land, Soil and Water Research and the 'Centre de Recherches Hydrologiques' of the 'Institut de Recherches Géologiques et Minières'. The study aimed to assess the impact of land use change on the hydrology and erosion in rain forest. The results should contribute to the development by the Tropenbos Cameroon Programme of a land management plan promoting sustainable land use.

The spatial distribution of rainfall was not uniform over the research area due to orographic effects. The central part of the area, where the elevation increases from about 100 m a.s.l. to 600 m a.s.l., received distinctly higher rainfall (2100-2300 mm) than the western lowlands (ca. 1700 mm) and eastern uplands (ca. 1700 mm) between September 1995 and August 1996. The interception loss in the rain forest canopy at Biboo - Minwo amounted to 35% of incident rainfall, whereas that by a cassava field near Ebom was less at 15% of incident rainfall.

Two types of river water could be distinguished based on electrical conductivity (EC) data collected from 30 streams. The first type was observed in the western lowlands and had an EC of 40-80 $\mu S\ cm^{-1}$. The second type, with a lower EC of 14-35 $\mu S\ cm^{-1}$, was observed in the central part and eastern uplands. The differences in EC could be caused by differences in weathering processes, soils and bedrock.

Agriculture and selective logging both affected soil physical properties. The permeability of the soil was high at 28 $m\ d^{-1}$ for undisturbed forest soils in the Biboo - Minwo catchment and decreased sharply to 3 $m\ d^{-1}$ upon disturbance of the soil by skidders. Bulk density and soil compaction were lowest in undisturbed forest soils (975-1047 $kg\ m^3$) and highest on skid tracks (1297 $kg\ m^3$). Top soil aggregates collected in undisturbed forest were stable, but the stability decreased considerably after disturbance of the soil by skidders. Differences between the forest soils and soils under shifting cultivation were less distinct with somewhat lower cohesion values observed in the latter. The litter layer in undisturbed primary forest at Biboo - Minwo had an average dry mass of 7600 $kg\ ha^{-1}$.

The annual rainfall and water yield for three small catchments varied between 1733-2219 mm and 419-1010 mm, respectively. Annual evaporation values were fairly similar in spite of differences in rainfall and land use, ranging from 1209 in the forested Biboo - Minwo catchment to 1314 mm in the Nyangong catchment, which was partly under shifting cultivation. In the present situation with low-intensity land use conversions, the spatial distribution of rainfall, rather than the type of land use, must be considered as the main factor determining the observed variation in annual water yields in the research area.

Sediment concentrations and the annual sediment yields were affected by land use. The lowest concentrations were found for the undisturbed forest cover (Songkwé),

whereas the highest were found for the forest - shifting cultivation land use (Nyangong). The sediment yields were low at all sites, but increased in the order undisturbed forest (56 kg $ha^{-1}$) < forest - shifting cultivation (105 kg $ha^{-1}$) < selectively logged forest (564 kg $ha^{-1}$ ). The latter value may be an underestimate because storm flows were not sampled in sufficient detail.

Preliminary results of the modelling of stormflow, erosion and sediment yield from the Biboo - Minwo catchment with the LImburg Soil Erosion Model (LISEM) have been included as a first approximation for the changes following selective logging of undisturbed rain forest. At present, the model could not yet be properly calibrated because detailed soil data were not yet available. As such, the results presented below should be considered as indicative only. A 48 mm storm was selected for modelling. The measured discharge, peakflow and sediment yield were 2.3 mm, 1.4 $m^3 s^{-1}$ and 1.4 kg $ha^{-1}$, respectively. Comparison of the model results for undisturbed forest with those for selectively logged forest indicated that the discharge total, the peakflow and the sediment yield increased significantly after selective logging from 0.4 mm to 1.3 mm, 0.7 $m^3 s^{-1}$ to 2.7 $m^3 s^{-1}$ and from 12.3 kg $ha^{-1}$ to 39.0 kg $ha^{-1}$, respectively. The bulk of the increased soil erosion originated from the construction of skidder tracks on slopes exceeding 10°. On these slopes, the simulated soil erosion increased with more than 1000 kg $ha^{-1}$, with a maximum of 140,000 kg $ha^{-1}$ on a slope of 17°, after the construction of the track.

Micrometeorological data were collected from July 1996 onwards in a 30 m mast in secondary forest with a height of about 22 m. The data indicated that the daily average temperature, humidity and radiation totals did not show much variation over the four months period. The wind direction was predominantly southwest. A relation was established between the incoming shortwave radiation and the net radiation through regression analysis and this relation compared well with those found for rain forests elsewhere in the humid tropics. The temperature fluctuation energy balance method was used to calculate the evaporation on August 7, 1996 and the result (2.9 mm) compared well with the annual daily average (3.3 mm) obtained with the water balance method for the adjacent Songkwé catchment.

The results presented in this report do not give rise to great concern for the effects of the present low-intensity land use changes on the regional hydrology. However, in view of the increase in sediment concentrations observed after selective logging of rain forest or conversion to agriculture (shifting cultivation), special attention should be given to the protection of village water supply areas to guarantee the water quality. Modelling results indicate that construction of roads and tracks on slopes steeper than 10° should be minimized to prevent excessive erosion and corresponding decreases in the water quality through high sediment concentrations.

# 1 Introduction

## 1.1 Backgound

Due to economic and population pressures, rain forests in South Cameroon are increasingly being exploited, either for commercial purposes (e.g. selective timber harvesting, oil palm and banana plantations) or for subsistence farming (shifting cultivation). To avoid the biophysical degradation of the area as a result of these activities, calls have been made by the Cameroonian Ministry of Environment and Forests (MINEF) for the development of a land management plan, which should promote and establish sustainable land use in these areas.

As scientific data on which such a management plan could be based were lacking, the Tropenbos Cameroon Programme was initiated by MINEF and the Tropenbos Foundation in 1992. Research in fourteen interrelated projects of the programme was carried out by the Wageningen Agricultural University, the 'Institut de Recherche Agronomique (IRA)', the DLO Winand Staring Centre for Integrated Land, Soil and Water Research (SC-DLO) and the 'Centre de Recherches Hydrologiques' of the 'Institut de Recherches Géologiques et Minières (CRH-IRGM)'. Funding for the projects was provided by the International Tropical Timber Organisation (ITTO, project PD 26/92) through the 'Office Nationale de Développement des Forêts (ONADEF)' and by the Tropenbos Foundation.

The objective of the Tropenbos Cameroon Programme was to develop strategies and methods to provide a scientific basis for decisions regarding sustainable land use alternatives for the rain forest area. The programme attempts to achieve this goal by combining information obtained from studies of the biophysical environment, with those obtained from studies of the social, political and economical environments. All research activities are carried out in two concessions of the 'Houthandel Gebr. Wijma en Zonen B.V.' timber company, which cover 1916 $km^2$ of rain forest in South Cameroon.

One of the studies contributing to the development of a land management plan is the Forest Land Inventory and Land Evaluation (Lu1) project. This project is geared towards carrying out a land evaluation study in the Tropenbos Cameroon Programme (TCP) research area, and should provide the biophysical background on which decisions regarding sustainable land use alternatives in the area can be based. Within the framework of this study, a reconnaissance scale (1 : 100,000) inventory on landforms, soils and vegetation has recently been carried out and the preliminary results have been published by Van Gemerden and Hazeu (1997). More detailed studies of the relationships between landforms, soils and vegetation are presently carried out in four small catchments, which were selected to reflect the physiographical range of the whole study area. The landform, soil and vegetation studies are complemented by hydrological, ecological and agronomical studies. The results of these small-scale biophysical studies will be combined with the data obtained from the large-scale inventory to define and locate a number of land mapping units. The most important land utilisation types and their specific requirements on the biophysical, social and economical environments will be defined using information obtained by the Lu1 study team as well as information made available for this purpose by other disciplines within the Tropenbos Cameroon Project. Finally, the land utilisation types (and their specific requirements) will be matched with the qualities of the land mapping units to produce a map depicting land suitability classes for the whole study area.

The hydrological study is carried out by the CRH-IRGM, in collaboration with SC-DLO. The present report provides an overview of the progress of the study after completion of the first year of data collection (August 1995 until December 1996). During this period, a research proposal has been formulated, study sites were selected and instrumented, and a hydrological model was selected and tested. In addition, the Cameroonian counterpart (Dr. J.C. Ntonga) received basic training in the use of geographical information systems (ARC/INFO, PC-RASTER) and in hydrological modelling (LISEM model).The CRH-IRGM should continue the study in collaboration with the DLO Winand Staring Centre (Dr. A.J. Dolman) and Dr. M.J. Waterloo, who returned for a mid-term evaluation in December 1996.

## 1.2 Objectives

It is well-known that changes in land use affect the total water yield, the runoff distribution pattern (Bosch and Hewlett, 1982; Bruijnzeel, 1990, 1993; Malmer, 1993; Fritsch, 1993; Waterloo, 1994; Sahin and Hall, 1996), as well as the sediment yield (Douglas, 1967, 1968; Baharuddin, 1989; Bruijnzeel, 1990; Abdul Rahim and Zulkifli, 1994). Clearfelling of tropical rain forests, whether for timber harvesting or for agricultural purposes, and subsequent burning of the slash generally causes an increase in the annual water yield as a result of a decrease in rainfall interception and transpiration losses. The effect becomes less marked as soon as the area becomes covered by closed-canopy secondary forest vegetation. Changes in the runoff pattern (e.g. decrease in baseflows) have been observed in some cases where the soil had severely been disturbed, limiting percolation to deeper ground water reservoirs during periods with high rainfall (Bruijnzeel, 1990). Changes in water yield or runoff distribution are less obvious in areas where forests are selectively logged, which is the common practice in South Cameroon. In general, no significant changes have been observed when less than 20% of the area was affected by logging (Gilmour, 1977a; Subba Rao et al., 1985; Sahin and Hall, 1996). Sediment yields from areas covered with undisturbed forest are usually lower than those of areas with similar physiography under other land use systems (Douglas, 1967). A conversion from forest to another type of land use therefore usually causes an increase in the river water sediment concentrations, with the magnitude of which depends mainly on the intensity of soil disturbance during and after the conversion (Bruijnzeel, 1990).

The aim of the hydrological study was to assess the sensitivity of the hydrology of the rain forest area to changes in land use (Dolman and Waterloo, 1995). This includes changes in the water yield, runoff distribution and water quality in terms of sediment load as a result of land use changes, as well as the identification of areas sensitive to erosion. The results presented in this report provide a better understanding of the impact of land use conversions on the hydrology and will contribute to the formulation by the Tropenbos Cameroon Programme of a management plan promoting sustainable land use and may also be used to establish guidelines for the proper management of the rain forests in South Cameroon.

To achieve this goal, studies on rainfall distribution, catchment water use and sediment yield were initiated in areas with contrasting land use (undisturbed forest, selectively logged forest and shifting cultivation). A physically-based distributed-parameter hydrological and soil erosion model (LImburg Soil Erosion Model, LISEM, De Roo et al., 1994) was selected to predict the sensitivity of the area to land use changes with respect to the water and sediment yield. The model has yet to be adapted to the specific environmental conditions of the study area to allow future extrapolation of the results to cover the TCP area using a geographic information system.

## 1.3 Outline

This report provides preliminary results of the hydrological component of the Forest Land Inventory and Land Evaluation study of the Tropenbos Cameroon Programme. Chapters one to three provide background information on the Tropenbos Cameroon Programme and the hydrological study in particular, on the study area and on the methods used for data collection. The hydrology of the area is discussed in detail in chapter four, which provides information on the rainfall distribution, soil properties, water and sediment yield. The preliminary results of the hydrological modelling of selective logging in the Biboo - Minwo catchment are discussed in chapter five, whereas chapter six gives a brief overview of the micrometeorology. A discussion of the results and some preliminary conclusions are provided in chapter seven.

# 2 Physiography

## 2.1 Location, topography and drainage system

The Tropenbos Cameroon Programme area is located in humid tropical rain forest in South Cameroon (South Province, Departments of Ocean and Ntem). The area consists of two concessions (Nos. 1600 and 1790) of the 'Houthandel Gebroeders Wijma & Zonen B.V. (GWZ)' timber company (Wijma-Douala SARL), which cover an area of 1916 $km^2$. The concessions are situated between the villages of Lolodorf (3°14'N, 10°44'E) in the North, Adjap-Essawo (3°02'N, 10°52'E) in the East, Akom II (2°48'N, 10°34'E) in the South and Bipindi (3°04'N, 10°25'E) in the West (see Fig. 1).

A gradual transition from lowland in the West to upland in the East occurs in the TCP area, as shown in Figures 2 and 4, where the topography and a WNW-ESE elevation profile have been presented, respectively. The elevation ranges from about 60 m a.s.l. near Bipindi, to up to 1057 m a.s.l. in the Bingalanda mountain range near Nyangong. The topography ranges from undulating to rolling in the lowland area, but changes to steeply dissected in the more mountainous areas in the Southeast. Isolated hills, which are several hundreds of meters higher than the surrounding area and which have slopes exceeding 50°, occur in both the lowland and upland areas (Van Gemerden and Hazeu, 1997), as is illustrated by the slope map presented in Figure 3.

The area is drained by four major rivers, of which the Lokoundjé river is the largest. This river enters the research area at Lolodorf and drains the northern part of the area (Fig. 1). The second largest river is the Tchangué river which drains the central part of the area and confluents with the Lokoundjé just south of Bipindi. The southwestern part of the area is drained by the Songkwé river, whereas the south-eastern part is drained by the Biwomé river. The flow direction of the larger rivers is predominantly from the north-northeast to the south-southwest, reflecting the regional pattern of faulting. The drainage system can be considered coarse dendritic to trellised. The stream density, as determined for a combined surface area of 73 $km^2$ (Saa and Biboo-Minwo research areas), is 1.6 km $km^{-2}$.

## 2.2 Climate and hydrology

The climate is humid tropical with two distinct wet seasons (August - November, March - May) and two dry seasons in a year, associated with the movement of the intertropical convergence zone over the area. The average annual rainfall generally decreases in an eastern direction, ranging from 2836 mm $year^{-1}$ in Kribi (n = 45 yrs) to 2096 mm in Lolodorf (n = 25 yrs) and 1719 mm in Ebolowa (n = 48 yrs; Olivry, 1986). In Lolodorf, maximum monthly rainfall averages 375 mm in October and 263 mm in April. Dry season values are well below 100 mm $month^{-1}$.

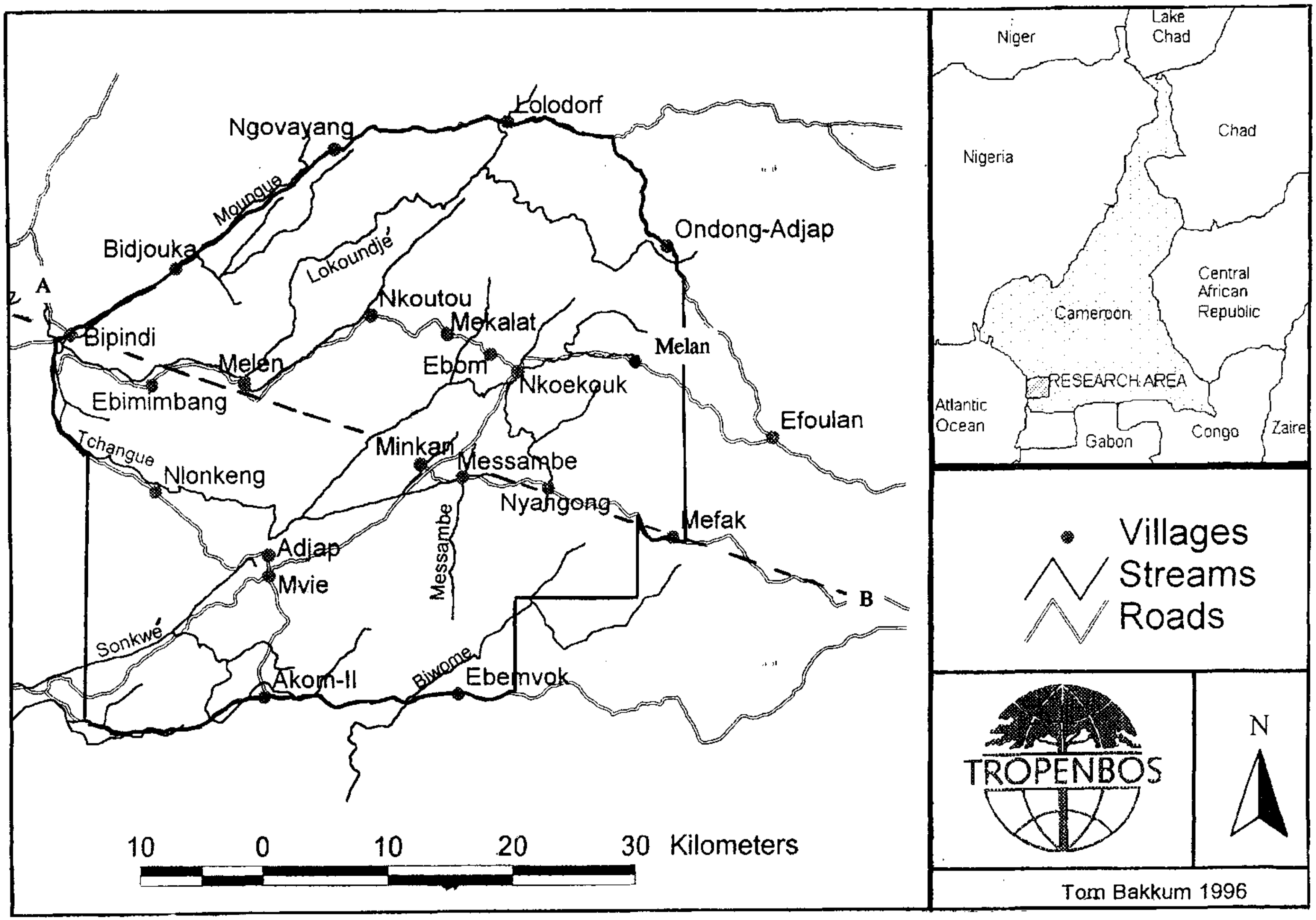



*Fig. 1 Map of the Tropenbos Cameroon Programme research area showing the main rivers, the infrastructure and the location of the profile A-B*

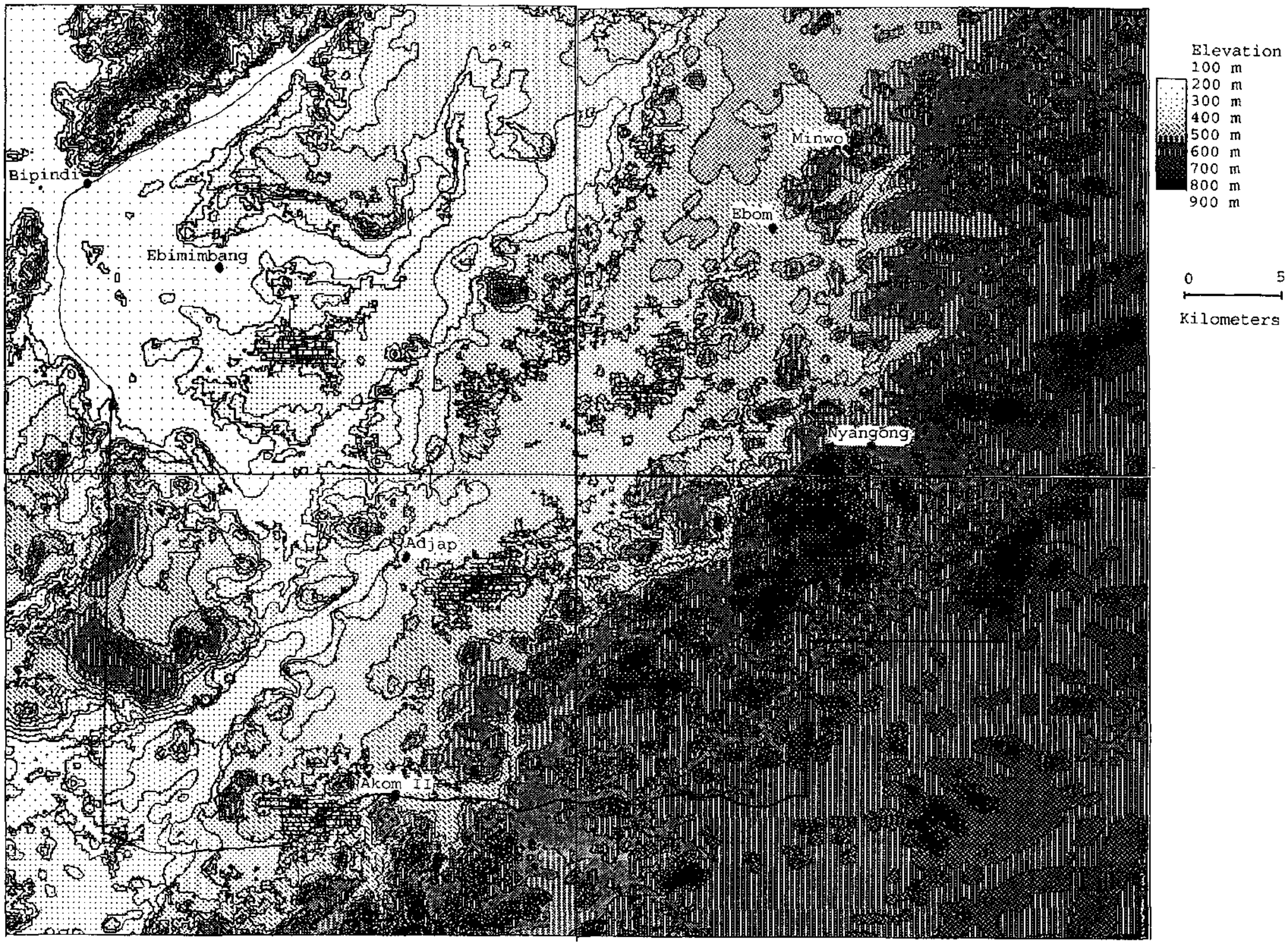



*Fig. 2 Topographical map of the Tropenbos Cameroon Programme research area*

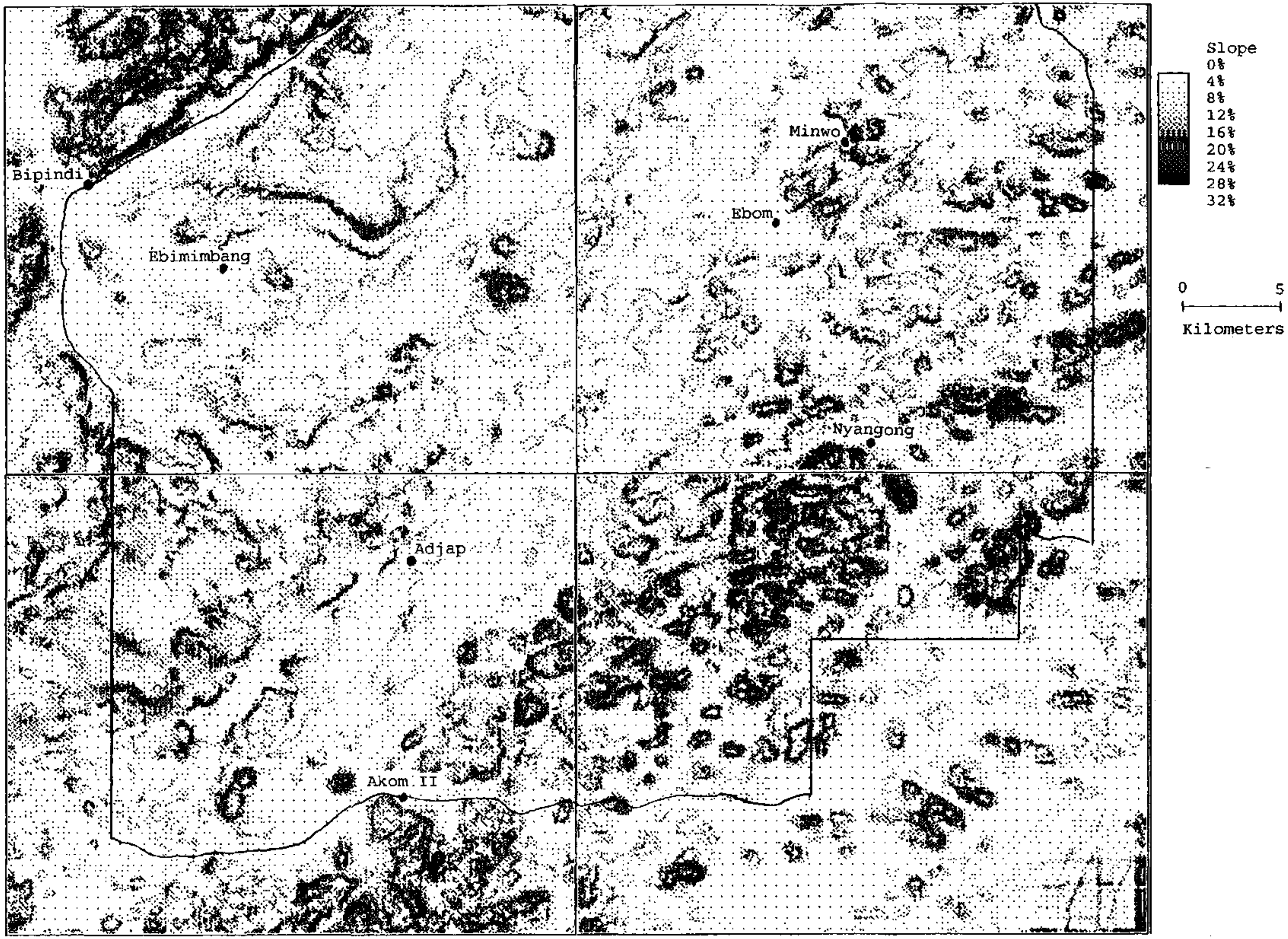



*Fig. 3 Slope map of the Tropenbos Cameroon Programme research area*

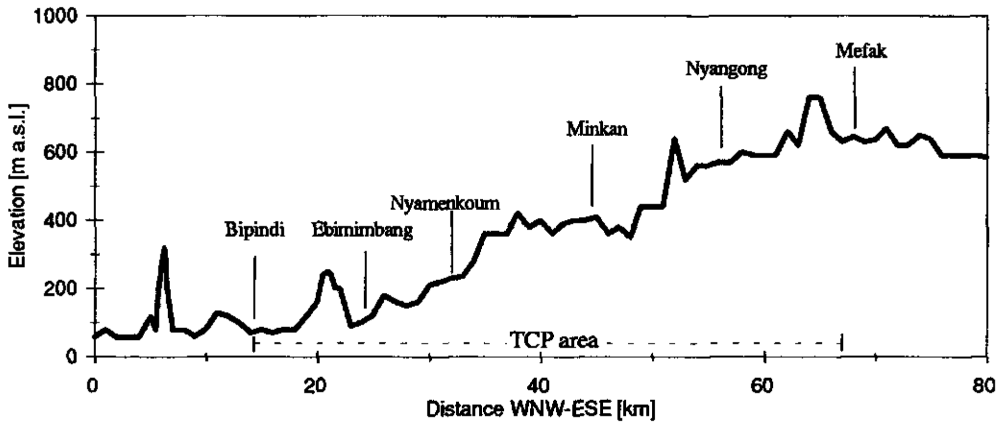



*Fig. 4 WNW-ESE profile (see Fig. 1 for location of profile A-B) through the Tropenbos Cameroon Programme research area*

The air temperature shows little variation over the year with minimum monthly values of 25.0 °C and 22.9 °C in August and maximum values of 27.5 °C and 25.0 °C in March in Kribi (10 m. a.s.l.) and Ebolowa (628 m a.s.l.), respectively (Olivry, 1986). The relative humidity is high throughout the year, with minimum monthly values varying between 70% and 78% in Kribi and between 62% and 74% in Ebolowa. Wind speeds are generally low, being less than 4 m $s^{-1}$ for 98% of the time. However, high wind speeds may occur during the passage of squall lines associated with large thunderstorms. The wind direction is predominantly Southwest to West (Olivry, 1986).

Hydrological data were not available for the TCP research area at the initiation of the project. However, data collected by CRH-IRGM at Lolodorf for the Lokoundjé river (draining the area north of the TCP area, basin area 1150 $km^2$) and those collected near Kribi for the Kienké (partly draining the TCP area, basin area 1435 $km^2$) and Lobé rivers (draining the area south of the TCP area, basin area 2305 $km^2$) may be used to provide rough estimates of the quantities of annual runoff and evaporation in the area.

The discharge patterns of the rivers strongly reflect the seasonal rainfall pattern discussed above, with maximum values being observed in October and May, and minimum values in February and August. The long-term (1950-1977) monthly average discharge of the Lokoundjé river at Lolodorf ranged from 8 $m^3$ $s^{-1}$ in February to 65 $m^3$ $s^{-1}$ in October. Corresponding values for the Kienké (1955-1977) and Lobé (1953-1977) rivers ranged between 16 $m^3$ $s^{-1}$ and 121 $m^3$ $s^{-1}$ and 21 $m^3$ $s^{-1}$ and 284 $m^3$ $s^{-1}$, respectively (Olivry, 1986). The long-term average annual discharge of the Lokoundjé river at Lolodorf amounted to 773 mm. Higher annual values of 1082 mm and 1397 mm were observed for the Kienké and Lobé rivers, respectively. This may be attributed to higher rainfall inputs received by these more coastal basins, as compared to that of the Lokoundjé basin. Based on data collected at very few rainfall stations, Olivry (1986) estimated the long-term annual rainfall input to the Lokoundjé river basin at 1880 mm, whereas those for the Kienké and Lobé basins were both estimated at 2425 mm. This implies that runoff coefficients are in the range of 41% (Lokoundjé river) to 58% (Lobé river). Long-term annual evaporation values, obtained with the water balance method using the rainfall and runoff values quoted above were rather similar for the three basins, ranging from 1025 mm for the Lobé basin to 1107 mm for the Lokoundjé basin and 1345 mm for the Kienké basin (Olivry, 1986). It should be noted that the errors in the evaporation totals may be considerable due to the uncertainties in the annual rainfall inputs into the basins.

## 2.3 Geology and soils

The TCP research area is located on the Precambrian shield, which is the most extensive geological formation in Cameroon. The shield consists mainly of metamorphic rocks (gneisses, micaschists, quartzites) and old volcanic intrusions (diorites, gabbro) (Franqueville, 1973). The geology of the TCP area reflects that of the overall Precambrian shield. The rocks are mostly acid gneisses, the composition varying between light-coloured quartzites, quartz-biotite-muscovite gneisses and granite gneisses to darker coloured pyroxene-rich gneisses. Basic ferro-magnesian amphibolite, diorite or gabbro intrusions occur locally within the more acid rock formations. These intrusions are mostly oriented in an NE-SW direction in discontinuous bands along the main faults (Bilong, 1992). Four erosional planes can be distinguished, with elevations increasing from 50-100 m a.s.l. in the western part to 200-300 m and 400-500 m in the central part and 600-800 m a.s.l. in the eastern part (Fig. 2).

Based on drainage characteristics and texture, four soil types have been distinguished in the area (Van Gemerden and Hazeu, 1997). Poorly drained soils were commonly found in the river valleys and adjacent swamp areas throughout the research area. These soils were characterised by a thin, sometimes peaty, A-horizon and a mottled B-horizon showing phases of oxidation-reduction (gley). The texture was often sandy to gravelly with clay interlayers. Following the FAO classification system, such soils were classified as Gleysols or Fluviosols (Van Gemerden and Hazeu, 1997).

The moderately-well to well-drained soils were subdivided into sandy soils (Ebimimbang soil type), clayey soils (Ebom soil type) and very clayey soils (Nyangong soil type).

The Ebimimbang soil type occurred mainly in the lowland area (50-350 m a.s.l.) between the Lokoundjé and Tchangué rivers near Ebimimbang. It was a yellowish-brown sandy clay loam soil with a sandy (60-90% sand) A-horizon and a soil depth rarely exceeding 2 m. It was the most nutrient-rich soil type in the area and has been classified as Acri-xanthic, Acri-Plinthic or Plinthic Ferralsol.

The Ebom soil type had a higher percentage of clay (20-60%) with the minimum clay content in the upper horizon. It was a yellowish-brown to strong-brown soil developed on gneisses and had a depth exceeding 1 m. This soil type was common in the central part of the area at elevations between 350 m and 600 m a.s.l. and has been classified as a Xanthic or Plinthic Ferralsol.

The Nyangong soil type was a deep to very deep clay soil with a sandy clay loam to sandy clay topsoil (clay content of 35-80%, with the lower value observed in the A-horizons). The colour was yellowish to strong-brown. This soil has developed on fine grained gneisses and was deep to very deep. It has only been observed in the eastern part of the area at elevations above 500 m a.s.l. and has been classified as a Xanthic Ferralsol. More detailed descriptions of the landforms and soil types have been presented in Van Gemerden and Hazeu (1997).

## 2.4 Vegetation and land use

The vegetation in the TCP area consists mainly of humid tropical rain forest. Selective logging of the more accessible forests has presumably not affected their structure and floristic composition to a large extent because logging intensities remained invariably low.

The western and central lowlands (elevation lower than 700 m a.s.l.) are covered by evergreen lowland rain forest. The canopy of the lowland forest can be subdivided into four structurally different levels, which usually show a gradual transition from one level to the next. The crowns of emergent trees, often surpassing 60 m in height, form the highest level and cover 20-30% of the soil surface. Mature trees with their canopy level at 25-40 m form the second layer and their crowns cover 60-80% of the surface. Shrub and herb layers may reach heights of 3-6 m and 1 m, respectively, and their foliage covers 40-60 % of the surface. Climbers (lianas) are abundant in the canopy and in gaps where light conditions are favourable to their growth. The lowland rain forest can be characterised by the presence of *Dialium* spp., *Calpocalyx dinklagei*, *Hymenostegia afzeillii* and *Saccoglottis gabonensis* (Van Gemerden and Hazeu, 1997) and is relatively rich in commercial timber tree species, of which *Lophira alata* (Azobé), *Cynometra hankei* and *Saccoglottis gabonensis* are the most important. A separate swamp-type of vegetation is common in the relatively broad valley bottoms where soils are close to saturation during most of the year (Foahom and Jonkers, 1992).

The eastern, more mountainous part of the TCP area (700-1050 m a.s.l.) is covered by sub-montane forest, which is characterised by a low, irregular canopy at 15 to 20 m height, occasionally reaching a height of 35 m, with a foliage cover of 70-80%. The shrub layer (3-7 m), which in some instances replaces the tree layer as canopy, varies from closed to very open. The herb layer is closed and may reach heights of up to one meter. The canopy is often climber infested and the presence of epiphytic mosses give these forests the appearance of 'cloud forests'. The broad-leaved trees, probably both evergreen and deciduous, are branched at low heights and have an irregular stem shape. The forest can be characterised by the presence of *Drypetes* spp., *Anisophyllea polyneura*, *Maranthes glabbra* and *Scorodophloeus zenkeri*. These sub-montane forests are not of great interest for commercial timber exploitation because of their inaccessibility (steep slopes) and the irregular shape of the stems of the few timber species (Van Gemerden and Hazeu, 1997). Hunting and gathering of non-timber forest products are therefore the most important human activities in these forests.

The more easily accessible lowland forests have been selectively logged by any of the various timber companies that have operated in the area over the past decades, or constitute of old regrowth on abandoned fields used in the shifting cultivation system by the local population for their subsistence. The latter type of forest is usually located in a zone of several kilometres wide along the main roads and villages. More detailed descriptions of the various vegetation types and land use practices have been presented by Van Gemerden and Hazeu (1997).

Selective logging has been practised for decades in areas of which the slopes did not exceed 20°. The intensity of logging is rather low at about 1 tree $ha^{-1}$. The extraction is restricted to the bole of the tree (with an average diameter of 1.16 m), and the slash is left in situ to decompose. The most important commercial tree species extracted from the area are *Lophira alata* (Azobé, over 60% of the extracted volume), *Erytrophleum ivorensis* (Tali), *Pterocarpus insoyauxii* (Padouk), *Distemonanthus benthamianus* (Movingui) and few redwood species. The trees are felled with chain saws, after which the bole is separated from the slash. The extraction is mechanized and is done by teams consisting of two skidders (Caterpillar 528) and one bulldozer (Caterpillar D7). The damage afflicted to the forest during logging and timber extraction (gaps, tracks and roads) covers roughly 7% of the area logged (Pers. comm. G.J.R. van Leersum, 1996). These gaps, skid tracks, and to a lesser extent the landings, are rapidly invaded by vines, climbers and pioneer tree species such as *Musanga cecropoides* and, although at a much lower intensity as the former, by *Lophira alata*.

Agricultural activities are generally restricted to the lower slopes and valley bottoms where shifting cultivation practises have lead to the presence of fields, weed infested thickets and secondary forest vegetation along the main roads and around villages. In the shifting cultivation system, the farmer clears small plots (usually not larger than two hectares at a time) of secondary forest, or occasionally virgin rain forest, from most of the vegetation. This is followed by burning of the slash at the end of the dry season and planting at the onset of the wet season. The usual practice is to plant a combination of crops at the same time. The most important food crops are cassava, coco-yam, banana and plantain, peanuts, maize and yams. Cocoa has traditionally been the most important commercial crop. More recently however, large commercial plantations of oil palm and plantain have been established in the area. The fallow succession consists mainly of *Chromolaena odorata* in fields of up to five years old, *Musanga cecropoides* and other fast-growing pioneer trees in seven to nine year old fields, followed by a dominance of slower growing tree species in older fields. The length of the fallow period varies greatly, ranging from a minimum of three years on more fertile sites to up to twenty years on less productive sites, with an average of about twelve years (Pers. comm. L. Nounamou, 1996).

## 2.5 Study catchments

Hydrological measurements were made in three key catchments (Songkwé, Nyangong and Biboo-Minwo catchments). These catchments were selected after an extensive field survey of the soils, vegetation and hydrology had been completed by the land evaluation study team to assure the representativity of the sites with respect to the larger project area. Topographic maps of the three catchments are presented in Figure 5. In addition to these catchments, a fourth catchment (Saa catchment) was selected by the land evaluation team for detailed soil and vegetation studies to cover the full range of soils and vegetation types in the TCP area. A short description of the physiography of the catchments is given below.

### 2.5.1 The Songkwé catchment

The Songkwé catchment is located northwest of the village of Adjap-Mvié and covers a surface area of 2.7 km$^2$. The elevation ranges from 310 m at the discharge measurement site (2°55.16'N, 10°32.60'E) to just over 440 m at the top of the catchment. Slopes are fairly steep, with maximum values of over 22° on the hills forming the catchment boundary. The rock consists mainly of light-coloured gneiss and the soil has tentatively been classified as belonging to the Ebom soil type (Section 2.3).

The vegetation consists for a large part of primary or old-secondary rain forest and has a species composition typical for the lowland rain forest in the area. The height of emergent trees is well over 40 m, even in the area affected by shifting cultivation, where some of the large trees have not been cut to provide shading for the crops. Few small agricultural fields are presently in use, and these are mostly located along the road in the southernmost part of the catchment area. Their influence on the hydrology of the catchment is negligible.

### 2.5.2 The Biboo - Minwo catchment

The Biboo - Minwo catchment is located 7 km northeast of Ebom and covers a surface area of 7.7 km$^2$. The elevation ranges from about 430 m at the discharge measurement site (3°06.48'N, 10°44.32'E) to 719 m on top of a hill in the center of the basin. Slopes are moderately steep to steep, with maximum values of up to 50°. Soils have tentatively been classified as belonging to the Ebom soil type, although the Nyangong soil type may also be found on the hillslopes in the catchment. Rock outcrops are common on hills and in the river valleys.

The vegetation consists of primary forest on the hills, where the steepness of the slopes does not allow for timber harvesting or shifting cultivation, and of primary or old-secondary forest in less accidented terrain. The forest has a species composition typical for the transition between lowland rain forest and lower montane rain forest. Less accidented areas (37% of the total catchment area) were selectively logged between May 1995 (eastern part of the catchment) and August 1996 (south-western part). The logging intensity in these areas was about 1 tree $ha^{-1}$, resulting in a value of 0.4 trees $ha^{-1}$ for the whole catchment. Trees were felled with a chain saw and the boles were extracted using a team consisting of two Caterpillar skidders (528) and one bulldozer (D7). The skid track density in the selectively logged area was 3.9 km $km^{-2}$. Skid tracks covered 2% of the logged area, but the area covered by tracks showing severe disturbance and compaction of the soil was significantly smaller at 0.6% of the logged area, or 0.2% of the total catchment area. There was no indication of recent agricultural activity in the area.

### 2.5.3 The Nyangong catchment

The Nyangong catchment is located south of Nyangong village and drains part of the Bingalanda mountain complex. The basin area is 6.8 $km^2$ and the elevation ranges from 550 m near the discharge measurement site (2°58.11'N, 10°45.18'E) to about 1010 m. Slopes are steep, often reaching values of above 45°. Rock outcrops are abundant. The rock consists of fine grained gneisses with intrusions of quartzite. The soil may be classified as belonging to the Nyangong soil type.

The main vegetation types are primary and old-secondary rain forest on the steeper slopes, and lower montane forest on the hill tops above 800 m a.s.l.. About 35% of the catchment area is affected by agriculture (Pers. comm. M. Yemefack, 1996), but this area includes abandoned fields which are covered with young secondary forest. The area presently under agriculture may cover less than 10% of the catchment area. Shifting cultivation and cocoa plantations are commonly found along the larger river valleys, where slopes are less steep. However, several agricultural fields have recently been established within primary forest on steep hillslopes at higher elevations (above 700 m a.s.l.).

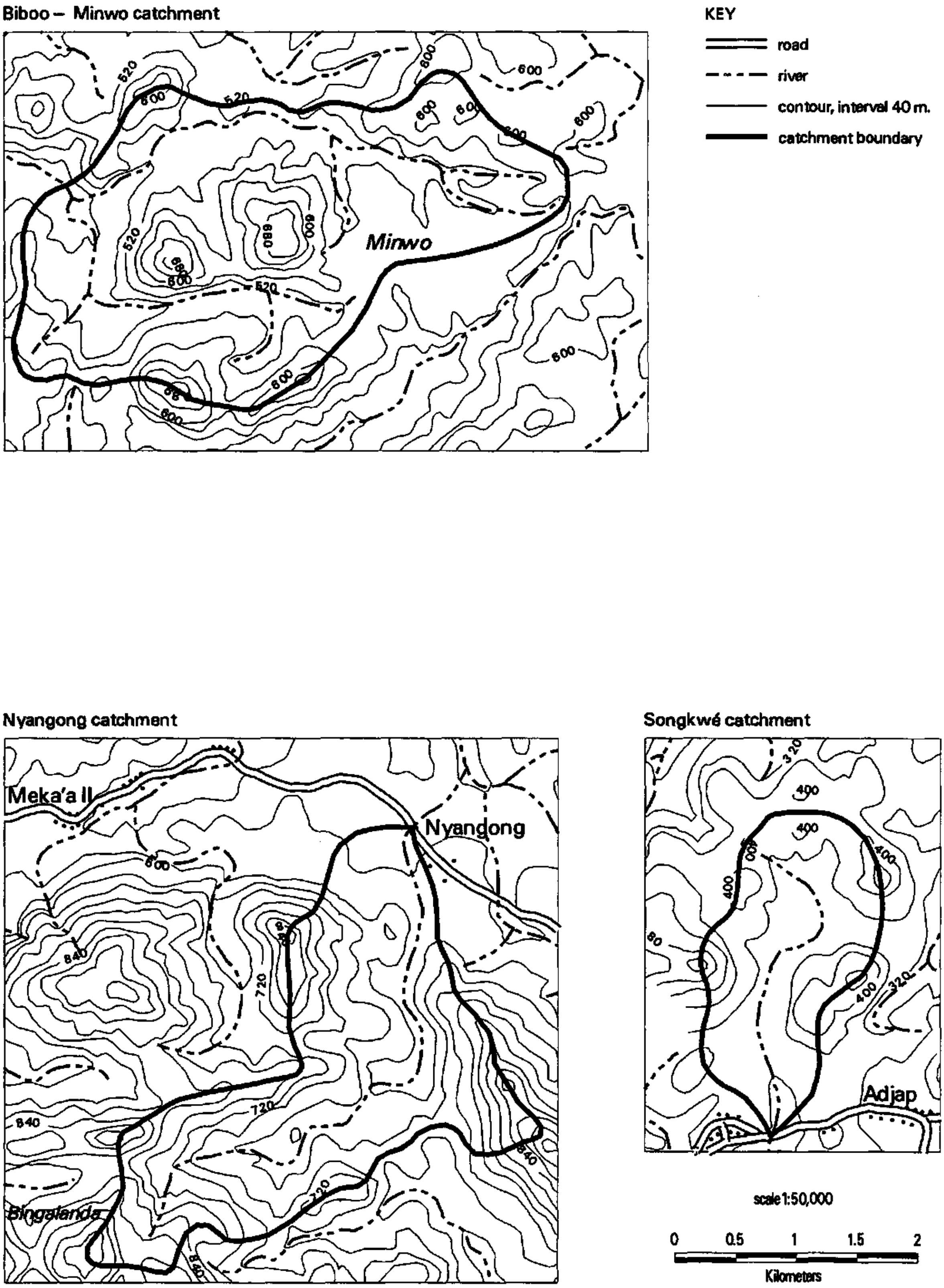



*Fig. 5 Topographic maps of the Biboo - Minwo, Nyangong and Songkwé catchments.*

# 3 Methods

## 3.1 Field data acquisition

The regional rainfall pattern has been established from daily data collected at eleven rainfall stations. Nine rain gauges (Productive Alternatives Inc., capacity 230 mm) were installed in August 1995 at Lolodorf, Bipindi, Ebimimbang, Ebom, Melan, Minkan, Nyangong, Mvié and Akom II. All rainfall gauges were installed with their collecting surfaces at heights between 1.6 and 1.8 m. Daily rainfall totals collected by the 'Service Météorologique de Cameroun' at Kribi and Ebolowa have been used to provide additional information. An overview of the location of all rainfall stations and their elevations is given in Table 1.

*Table 1 Geographical locations and elevations of the rain gauges in the TCP area and of those in Kribi and Ebolowa*

| Location | Latitude N | Longitude E | Elevation (m a.s.l.) |
|---|---|---|---|
| Kribi | 2°57.11' | 9°54.53' | 10 |
| Ebolowa | 2°54.00' | 11°10.00' | 628 |
| Lolodorf | 3°14.17' | 10°43.55' | 480 |
| Bipindi | 3°04.64' | 10°24.65' | 70 |
| Ebimimbang | 3°02.67' | 10°28.25' | 100 |
| Ebom | 3°04.73' | 10°41.24' | 410 |
| Melan | 3°03.66' | 10°48.25' | 610 |
| Minkan | 2°59.12' | 10°39.68' | 400 |
| Nyangong | 2°58.11' | 10°45.18' | 550 |
| Mvié | 2°54.22' | 10°33.31' | 420 |
| Akom II | 2°48.88' | 10°33.04' | 400 |

Rainfall amounts and intensities have been measured from March 1996 onwards using six tipping bucket rainfall recorders (ARG 100, 0.2 mm resolution) connected to AgroResearch Instruments 1LX dataloggers. These rainfall recorders have been installed in pairs in each of the study catchments to cover the spatial variation in rainfall within each catchment.

Throughfall measurements were made in rain forest in the Biboo - Minwo catchment (from April 4, 1996, onwards), as well as in a cassava field (from April 10, 1996, onwards) near the village of Ebom. In the forest, 36 custom-made throughfall gauges (orifice 56 $cm^2$) were installed in a 25 x 25 m grid, whereas 24 gauges were placed in the cassava field. Rain gauges were located in sufficiently large gaps at both sites to measure the above-canopy rainfall. The rainfall and throughfall measurements were made on a daily basis during the week. Less regular measurements were made during the weekends due to lack of transport to the sites.

The electrical conductivity (EC) of river water was determined using an Eijkelkamp EC-meter capable of measuring ranges from 0-30 $\mu S\ cm^{-1}$ to 0-10,000 $\mu S\ cm^{-1}$ at a temperature of 25 °C.

Water level measurements were made at the outlets of the Songkwé, Biboo-Minwo and Nyangong catchments using Hydrotrack Well Sensor dataloggers with staff gauge references. The sensors in the Minwo and Songkwé rivers had a resolution of 1.8 cm (range 0-5 m), whereas that at Nyangong had a resolution of 1.0 cm (range 0-3 m). The water level data were collected at 30 minute intervals. As a backup, local observers have been employed to record the water levels twice daily from November 1995 onwards.

Stage - discharge relations at the three measurement sites were established from water level readings and corresponding discharge measurements using the salt dilution technique at low discharges ($Q < 0.5\ m^3\ s^{-1}$) and the velocity - area method (Qualimetrics model 6660 digital water current meter) at higher discharges (Appendices 1-3). Water samples were collected regularly at the discharge measurement sites in 1000 ml plastic containers. In addition, an automatic water sampler (ISCO) was installed in the Biboo - Minwo catchment to sample storm runoff automatically.

The location and width of roads, skid tracks and landings were mapped using a global positioning system in combination with a compass, topofil and tape measure. Four classes of disturbance to the forest and soil have been recognised. The main and permanent access roads to a logging site and the landings were defined as Class 1 of disturbance (severely compacted surfaces, sometimes gravelled, no vegetation). The degree of damage to the soil on skid tracks was assessed visually at the time of mapping and these soils were classified as being severely damaged (Class 2, A-horizon removed, B- or C-horizon exposed and severely compacted, no vegetation cover left) or moderately damaged (Class 3, A-horizon still present but compacted, some vegetation left). The fourth class of disturbance consisted of tracks where the vegetation had been damaged but the soil remained relatively undisturbed during the (single) passage of the skidder.

Measurements of the infiltration rates of water into the soil were made using an Eijkelkamp double-ring infiltrometer system with a diameter of the inner ring of 30 cm. The saturated permeability was determined from repeated measurements of the rate of descent of the water level in the inner ring until a constant value was obtained.

Soil cohesion was determined with a pocket tor vane with a blade width of 25 mm. The average of 20 measurements was used as the soil cohesion value of the sample area. An indication of the compaction of the soil at the soil surface was obtained using a pocket penetrometer. Measurements were made on forest soils, as well as on soils under shifting cultivation and on skid roads and tracks.

The soil roughness (or random roughness) was determined using a 1 m rod with 47 holes, spaced at a distance of 2 cm, through which the micro-relief of the soil could be determined using a pin and ruler. The standard deviation of the 47 measurements was taken to represent the soil roughness (Pers. comm. A.P.J. de Roo, 1995).

A micrometeorological set-up, which measures wind speed at 30.03 m (Vector A100M), wind direction at 30.36 m (Vector W200P), temperature and relative humidity at 29.87 m (Vaisala HMP35A), thermocouple temperature at 30.01 m (custom built), global radiation at 29.92 m (Kipp & Zn. CM6B), net radiation at 28.10 m (R.E.B.S. Q7), rainfall at 29.52 m (ARG 100) and soil temperatures (PB107 probes, at 2 and 10 cm depth) was installed in secondary forest on a former field in the Songkwé catchment. The height of the vegetation around the mast was about 22 m. All data were measured at 30-second intervals from June 28 onwards by a Campbell Scientific CR10 datalogger and averaged to provide half-hourly values. The thermocouple temperature is measured at 0.125-second intervals and averaged over 5-minute intervals. Rainfall totals are also measured at 5-minute intervals.

## 3.2 Laboratory procedures and methods

Water samples were analyzed for sediment concentrations using a Sartorius filter unit connected to a water-jet vacuum pump. Pre-weighted cellulose nitrate filters (Sartorius A.G., order no. 13906-50-ACN)) with a diameter of 50 mm and a pore diameter of 0.47 µm were used to collect sediment particles in a predetermined volume of water sample (0.5-1.0 l). The filters were subsequently dried at a temperature of 105 °C and reweighed on a Sartorius balance (model BP-110), capable of weighing to the nearest milligramme. The discharge - concentration data are presented in Appendices 4-6.

The pH of a selected number of samples was determined using an Aqualytic pH-17 pH meter (Ingold electrode), which was calibrated using buffer solutions of pH = 4.00 and pH = 7.00.

Soil aggregate stability was determined following the drop-test method of Low (1954) and Imeson and Vis (1984). The test involved counting the number of drops necessary to break down a moist soil aggregate with a diameter of 4.0-4.8 mm, such that it passed completely through a sieve with a maze width of 3.0 mm. The drops of water (weight 0.1 g) were supplied by a reservoir connected to a nozzle with PVC tubing, and were allowed to fall on the aggregates from a height of 1.0 m through a PVC pipe (15 cm diameter). The test was repeated on 20 aggregates and the median value was taken to represent the aggregate stability.

## 3.3 Modelling procedure

The LImburg Soil Erosion Model (LISEM) was selected to simulate the hydrological behaviour and erosion in the catchments for various land use scenarios. LISEM is a physically-based distributed-area model developed by the Department of Physical Geography from the University of Utrecht. It is completely incorporated in a raster geographical information system (PCRASTER). Detailed descriptions of the model equations, capabilities and data requirements have been presented by De Roo et al. (1994, 1995). Because the model has been developed and tested for agricultural land on löss soils in a temperate climate, rather than for tropical rain forest areas, some of the equations describing the hydrological processes may need to be modified (e.g. rainfall interception, flow transport capacity). Field data collected during the present study will be used to test the model and to develop new equations when necessary. In addition, these data will be used to calibrate the model with respect to the predicted water yield and runoff distribution, as well as with respect to the sediment yield.

Digital Elevation Models (DEMs) have already been developed for the Saa and Biboo - Minwo study catchments using digitized contour lines (40 m interval) from the 1 : 100,000 topographical map from the research area. The maps were digitized in vector format using ARC/INFO and subsequently rasterized. The SURFER program was then used to develop a DEM using a geostatistical interpolation method (kriging) to interpolate between data points. The resulting raster maps (cell size 25 x 25 m) were converted to the CSF file format for further processing with the PCRASTER geographical information system developed by the Department of Physical Geography of the University of Utrecht (Van Deursen and Wesseling, 1992). Maps of the soil characteristics, land use, areas covered by the various rain gauges, roads and tracks, streams etc. have been digitized for the same catchments and have also been converted to the CSF file format. As such complete sets of maps in digital form exist for these areas. Similar sets have yet to be produced for the Songkwé and Nyangong catchments.

When properly calibrated, the LISEM model will be run using extreme rainfall events as input because a very large proportion of the erosion takes place during these events (Bruijnzeel, 1990).

The hydrological information obtained from the forested Songkwé catchment will form the baseline against which the effects of land use changes on the hydrology, as evident in the Biboo - Minwo (selective logging) and Nyangong (shifting cultivation) basins, can be measured.

# 4 Hydrology

## 4.1 Regional rainfall distribution

To obtain information on the rainfall distribution within the TCP area, daily rainfall observations collected between September 1995 and August 1996 at the eleven rainfall stations were analyzed. The resulting isohyetic map is shown in Figure 6. The spatial variation of rainfall in the TCP area was considerable, with a difference of 586 mm between the minimum and maximum totals. Rainfall was highest at the coastal station of Kribi (2805 mm) and decreased to 1677 mm at Nyangong, before increasing again further east towards Ebolowa where a total of 2175 mm was measured. The isohyetic map indicates that there is a distinct spatial rainfall pattern. The lowland (Bipindi) and upland (Nyangong) areas received less rainfall (1723 mm and 1677 mm, respectively) than the lowland - upland transition zone along the SSW-NNE axis Lolodorf - Ebom - Minkan - Mvié - Akom II (1961-2264 mm). This suggest that orographic effects caused by the lowland-upland transition (Fig. 2) may contribute significantly to the rainfall in this zone. The rainfall data showed a clear seasonal trend with high rainfall during October - November and April - May, and much lower rainfall from December - March. The seasonal variation at Ebom is presented in Figure 7. Daily rainfall data may be used to calculate an antecedent precipitation index (*API*). This index can be considered as an indicator for the variation of the wetness of the soil in time and may be calculated from the equation given below using daily rainfall records (Van de Griend, 1979).

$$API=\sum_{t=1}^{n} P_t K^t \qquad (1)$$

where:
$P_t$ = precipitation on the day before the calculation date
$n$ = number of days used in the calculation
$K$ = a constant (range: 0.80-0.98)

*API* values have been calculated for Ebom and Lolodorf using a seven days time period and a constant of 0.8. The results are shown in Figure 8. Because soil moisture conditions affect the efficiency of the logging operation and the degree of damage afflicted to the soil, API values may be used to serve as indicators for the efficiency of the skidders in hauling logs from the forest under varying weather and soil moisture conditions (Pers. comm. G.J.R. van Leersum, 1996). Forestry research on this topic should indicate at which API level logging operations cease to be feasible in an economic way, as well as in an environmental way.

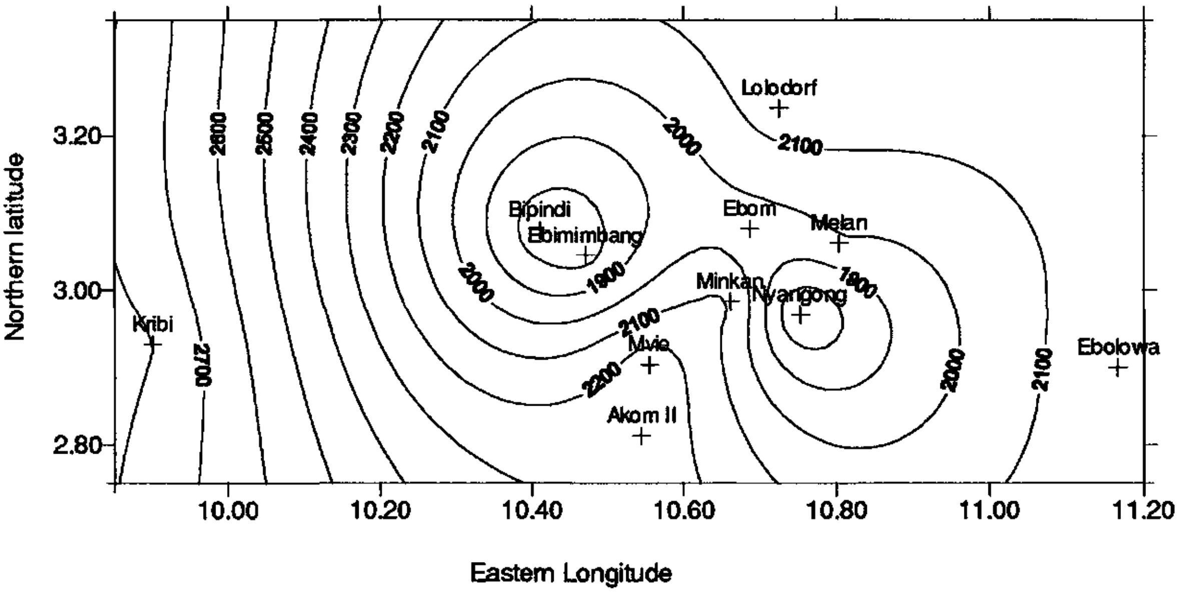



*Fig. 6 Isohyetic map (mm) of the Kribi-Ebolowa region in South Cameroon for the period September 1995 until August 1996*

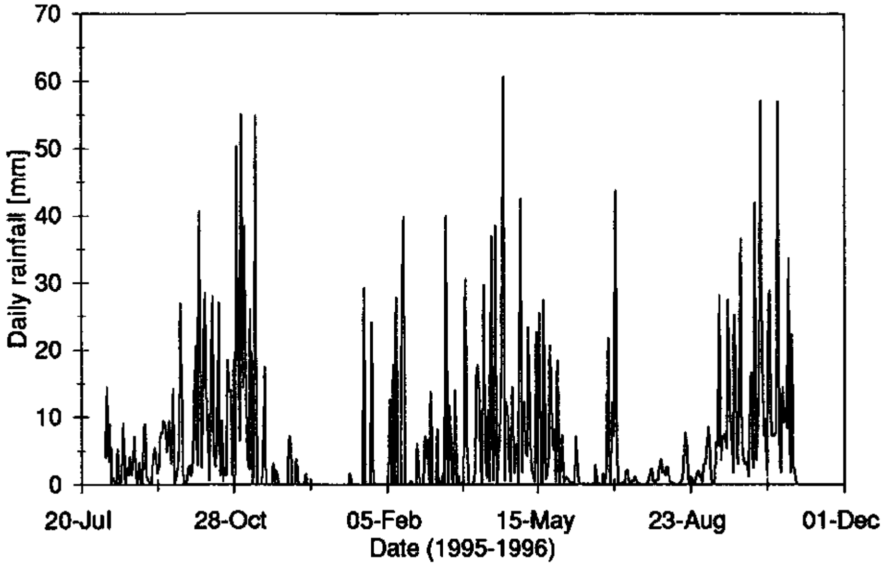



*Fig. 7 Variation in daily rainfall totals observed at Ebom over the period 5 August 1995 until 31 October 1996*

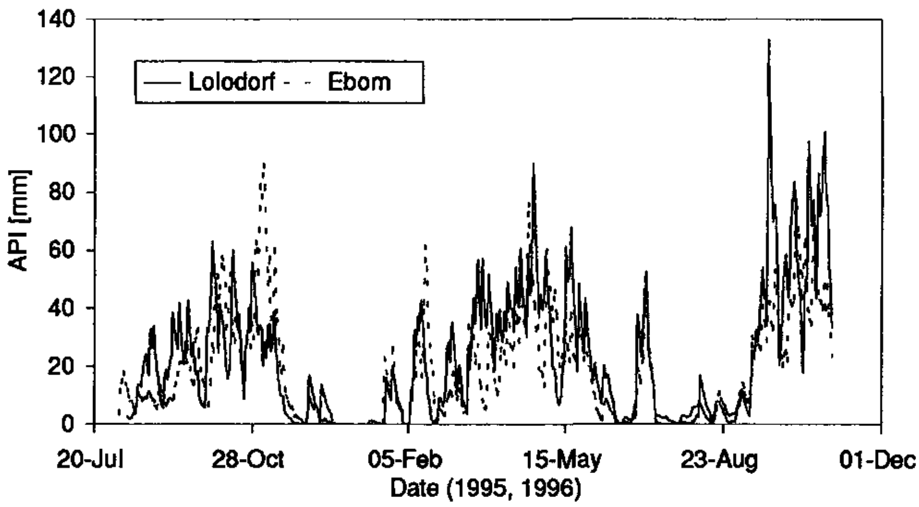



*Fig. 8 Antecedent precipitation indices calculated using daily rainfall totals observed at Ebom and Lolodorf*

## 4.2 Rainfall interception

Conversion of one vegetation type to another type with a different canopy structure usually results in changes in the amount of water reaching the soil surface due to changes in the interception loss in the canopy of the vegetation (Bonell and Balek, 1993). In South Cameroon, forest land is usually cleared for shifting cultivation and a study has been initiated to determine the effects of a conversion from primary rain forest to a cassava crop, which is the dominant crop type in the Ebom area. The effects of such a conversion on the interception of rainfall were determined by comparing rainfall and throughfall measurements made in primary forest in the Biboo - Minwo catchment with those made in a cassava field south of Ebom. The results of this study have been discussed in more detail by Ruppert (1996).

At the forest site, incident rainfall during the measurement period (April 11 until July 9, 1996) amounted to 683 mm (36 measurements), whereas the corresponding throughfall total was 436 mm. With an approximation for the stemflow during this period of 1.5% of the above-canopy rainfall (11 mm) the interception loss could be calculated at 238 mm, or 35% of incident rainfall. Rainfall and throughfall totals in the cassava field over the same period were somewhat lower at 498 mm and 413 mm, respectively.

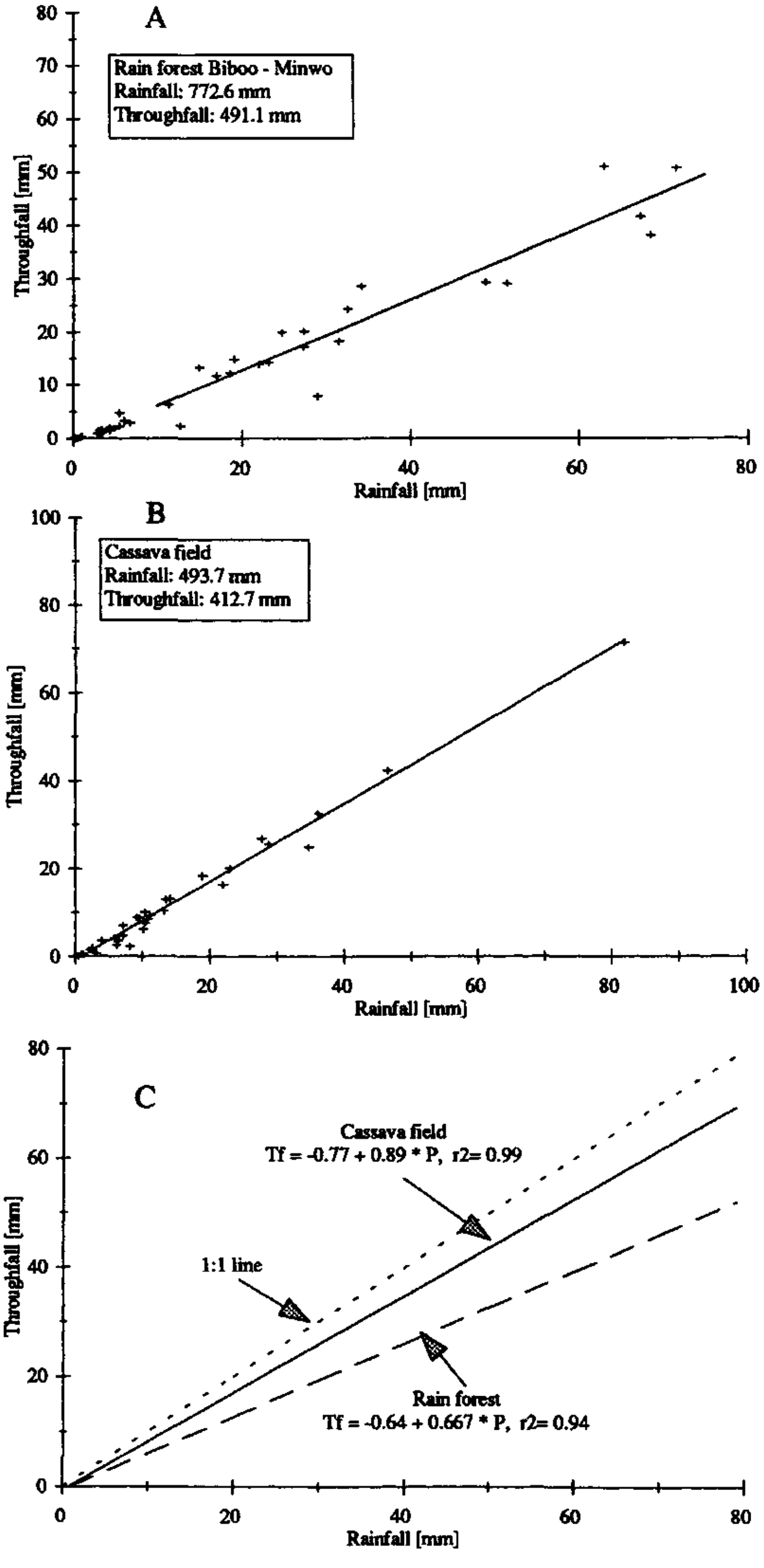



*Fig. 9 Plots of rainfall vs. throughfall at a primary forest site (a) and a cassava field (b). The difference in rainfall interception characteristics is illustrated in (c), where the regression lines for the two vegetation types are shown*

The interception loss for this crop was 76 mm, or 15% of incident rainfall (stemflow again set at 1.5% of total rainfall). Plots of rainfall vs. throughfall for the forest vegetation and for the cassava field are shown in Figure 9a and 9b, respectively. Regression lines were calculated for both rainfall - throughfall data sets and these lines are shown in Figure 9c, together with the regression equations. A comparison of the interception losses shows that a conversion from forest to crop types similar to cassava will result in an increase in the amount of water reaching the soil by some 20% of incident rainfall. When such a conversion is made on a large scale, the catchment water yield may be expected to change accordingly, as long as all other environmental factors (e.g. soil permeability) remain the same.

## 4.3 Electrical conductivity and pH of stream water

The chemical composition of water in small streams is strongly influenced by the chemical composition of the precipitation and the rate and intensity of the chemical processes in the soil (biological activity, buffering reactions, precipitation or dissolution of minerals, etc.) and rock (weathering of minerals) from which the water is derived (Duchaufour, 1982). The chemical composition of rainfall in the area is low, as indicated by the low EC-value of 5 $\mu S\ cm^{-1}$ (measured on two occasions at Kribi and Ebom), and may be considered fairly uniform over the area. As such differences in the chemical composition of stream water in the area will reflect differences in soil and rock, rather than variations in the chemical composition of the precipitation. Because the EC is a very good indicator of the sum of anions and cations up to EC-values of about 2000 $\mu S\ cm^{-1}$ (Appelo and Postma, 1993), measurements of the variation of the EC of stream water may be used as an indicator for the rate and intensity of these chemical processes.

During the present study EC measurements were taken from 30 streams, draining areas varying in size from less than 1 $km^2$ to over 3000 $km^2$ (Lokoundjé river at Bipindi). Regular measurements in the three research catchments indicated that the EC showed little variation in time (less than 5 $\mu S\ cm^{-1}$ variation over the period of a year). Measured EC values ranged from 14 $\mu S\ cm^{-1}$ in two catchments near Lolodorf and Nyangong, to 76 $\mu S\ cm^{-1}$ in the Saa catchment near Ebimimbang.

Based on the EC data, two types of river water may be distinguished. The first type is characterised by relatively high EC values (range: 40-80 $\mu S\ cm^{-1}$) and has only been observed in the area west of the line Bipindi - Ebimimbang -Mimfombo - Adjap - Mvié. The higher EC values encountered in this area support the findings of the soil scientist that the nutrient status of the soil (Ebimimbang soil type) in this area is higher than that in the soils in other parts of the TCP research area (Van Gemerden and Hazeu, 1997).

The second type of river water is characterised by low EC values (range: 14-35 $\mu S\ cm^{-1}$). This type is typical for most parts of the area, as well as for large areas upstream of the TCP research area as indicated by the EC values of 20 $\mu S\ cm^{-1}$ and 24 $\mu S\ cm^{-1}$ observed for the large Tchengué and Lokoundjé (at Lolodorf) river systems. The small range in EC for this type of water suggests that the intensity of chemical processes in the soil and rock is quite uniform throughout the area. The intensity of chemical processes in the soil and in the bedrock may be considered as very low because the EC value of this type of stream water is close to that of the rainfall (EC of about 5 µS $cm^{-1}$).

All study catchments were located in the area with the second type of surface water (EC range 17-25 µS $cm^{-1}$, n = 3) but detailed mapping of the landforms, soils and vegetation was also carried out in the Saa catchment near Ebimimbang where the EC at the basin outlet measured 75 µS $cm^{-1}$.

A decrease of the EC was observed with increasing discharge in all study catchments, which may be attributed to dilution of the baseflow with rain water with a lower EC. The steepest decrease was observed in the Songkwe catchment, as can be seen in Figure 10.

The pH of river water collected at the outlet points of the small-scale study catchments was measured on several occasions between 26 February and 4 April 1996. The water was slightly acidic with pH values of 5.53 ± 0.14 for the Nyangong river (n = 6), 5.55 ± 0.13 for the Songkwé river (n = 8) and at 5.60 ± 0.26 for the Biboo river (n = 6). The pH values for the three catchments were not significantly different.

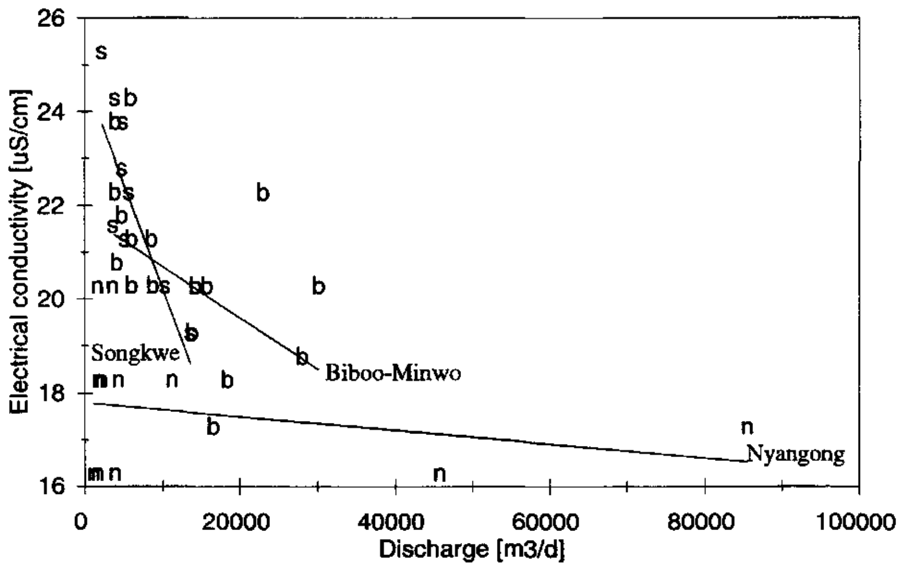



*Fig. 10 Plot of the EC vs. discharge for the Biboo-Minwo (b), Nyangong (n) and Songkwé (s) catchments.*

## 4.4 Soil hydrological characteristics

The LISEM model requires the spatial distribution of a number of soil parameters as input for the prediction of the hydrological behaviour and erosion patterns in an area. Measurements of such soil properties have been initiated in the Nyangong and Biboo-Minwo catchments and to a much lesser extent in the Saa catchment. Such measurements are yet to be initiated in the Songkwé catchment.

In the Nyangong catchment a survey has been carried out to see if differences existed in the cohesion and compaction of forest soils on the one hand, and of soils under shifting cultivation (fields, fallow areas) on the other hand. In the Biboo-Minwo catchment, the effects of logging on soil properties such as bulk density, compaction, cohesion and permeability were measured by comparing measurements made on various classes of skid tracks with those made in adjacent forest areas. The results of these studies have been discussed in more detail in Nangmo (1996), and only a short overview will be presented below.

### 4.4.1 Infiltration rate

Measurements of infiltration rates were made on undisturbed forest soils and on adjacent soils which were severely disturbed by the passage of skidders during timber harvesting. The infiltration rate in the forest soil was high, averaging 28 ± 23 m $d^{-1}$ (range: 8-84 m $d^{-1}$, n = 10). Much lower rates were observed on the skid tracks where the infiltration rates ranged from 0.1-8.4 m $d^{-1}$, with an average of 3.1 ± 3.3 m $d^{-1}$ (n = 7). The differences between the means of the undisturbed and disturbed soils were significant at a confidence level of 95% (student's t-test).

### 4.4.2 Soil cohesion and compaction

The cohesion of the top soil is one of the parameters in the LISEM model, which determines the detachment of sediment by overland flow (De Roo et al., 1995). This parameter has therefore been measured with a pocket tor vane in the Nyangong, Biboo - Minwo and Saa catchments. In the Nyangong catchment, measurements of soil cohesion were made in primary or old-secondary forests, in soils in young (5-20 years old) secondary forests, in agricultural fields and in swampy valleys.

The cohesion was highest in the old-secondary or primary forests (0.30 ± 0.08 kg $m^{-2}$, n = 59) due to the abundance of organic matter in the top soil (root mat). The cohesion of the soils in the agricultural fields was significantly lower (95% confidence level) at 0.17 ± 0.05 kg $cm^{-2}$ (n = 8), whereas intermediate values were observed for the young secondary forests (0.23 ± 0.06 kg $cm^{-2}$, n = 8). The lowest values were observed in the swampy valley bottoms where the average soil cohesion was 0.12 ± 0.01 kg $cm^{-2}$ (n = 3).

In the old-secondary or primary forests, the cohesion increased with slope steepness, ranging from 0.28 ± 0.09 kg $cm^{-2}$ on slopes of 0-20%, to 0.34 ± 0.08 kg $cm^{-2}$ on slopes steeper than 40%. Evidence of natural erosion (sheet wash) exposing a less well developed A-horizon, was observed for the latter type of soils.

The compaction of the soil at the surface was measured with a pocket penetrometer for various land use types and slope classes in the Nyangong catchment and showed a pattern similar to that of the soil cohesion. The compaction was highest for the forest soils at 0.41 ± 0.19 kg $cm^{-2}$ (n = 59), which could be due to the presence of a well-developed litter layer and root mat. The compaction of the forest soils showed an increase from 0.39 ± 0.20 kg $cm^{-2}$ (n = 25) for soils on slopes less than 20%, to 0.46 ± 0.21 kg $cm^{-2}$ (n = 17) for soils on slopes exceeding 40%.

The compaction of the soils in agricultural fields (root crops, peanuts, plantain, banana) where root mats were usually not observed, was significantly lower (95% confidence level) than that of the forest soils at 0.22 ± 0.14 kg $cm^{-2}$ (n = 8). This suggests that the conversion from forest to agriculture results in a lower cohesion and compaction of the soil due to decomposition of the soil organic matter.

Intermediate values (0.26 ± 0.16 kg $cm^{-2}$, n = 8) were again observed for young (5-20 years old) secondary regrowth on former agricultural fields, suggesting that a recovery of the soil cohesion and compaction occurs, although at a slow rate.

The cohesion of forest soil in the Minwo - Biboo catchment was similar to that of the forest soils in the Nyangong catchment with an average of 0.33 ± 0.05 kg $cm^{-2}$ (n = 5). Much higher cohesion values (0.53 ± 0.19 kg $cm^{-2}$, n = 6) were found in areas where the soil had severely been disturbed by skidders during log extraction.

The compaction at the soil surface under forest in the Biboo - Minwo catchment was 0.35 ± 0.23 kg $cm^{-2}$ (n = 5), which is not significantly different from the value observed for the forest soils in the Nyangong catchment. The disturbance of the soil as a result of the construction of skid tracks and roads resulted in a high compaction value of 0.95 ± 0.72 kg $m^{-2}$ (n = 6) for the areas affected.

The degree of soil cohesion and compaction depended on the number of passes made by the skidder and the highest values were observed on the main skid track (0.80 kg $cm^{-2}$ and 2.35 kg $m^{-2}$, respectively), whereas those of a soil disturbed by a single skidder pass were similar to the forest values at 0.23 kg $cm^{-2}$ and 0.29 kg $m^{-2}$, respectively.

### 4.4.3 Bulk density

The bulk densities of the surface horizons of forest soils in the Biboo - Minwo and Nyangong catchments were 975 ± 96 kg $m^{-3}$ (n = 4) and 1047 ± 66 kg $m^{-3}$ (n = 8), respectively. The bulk density of the top soil of skid tracks in the former catchment was significantly higher at 1297 ± 354 kg $m^{-3}$. In a separate study, Voeten (1997) observed an average bulk density of 968 ± 178 kg $m^{-3}$ (n = 31, range 627-1335 kg $m^{-3}$) for undisturbed forest soils in a different part of the Biboo - Minwo catchment and a significantly higher (99% confidence level) value of 1241 ± 271 kg $m^{-3}$ (n = 46) for skid tracks.

### 4.4.4 Aggregate stability

The stability of soil aggregates is an important parameter determining the rate of splash detachment in the LISEM erosion model (De Roo et al., 1995). Aggregates collected from the clayey A-horizon in the forests of the Nyangong and Biboo - Minwo catchments were very stable as they did not break upon the impact of over 200 drops of water. Soil aggregates collected on frequently used skid tracks in the Biboo - Minwo catchment were less stable with median values of 30 and 63 drops.

Lower values were also observed for the sandy soils under agriculture in the Ebimimbang area (Saa catchment), where the median values ranged between 20 and 118 drops (n = 7). The aggregate stability of soils under different land use types (e.g. shifting cultivation) in the Nyangong catchment has yet to be determined.

### 4.4.5 Soil roughness

The soil roughness, or random roughness, is a measure of the micro-relief and is used by the LISEM model to simulate surface storage of water in depressions (Onstad, 1984). At present, four measurements have been made on forest soils at the discharge gauging site in the Biboo - Minwo catchment. The roughness of these soils varied between 1.1 and 3.4 cm and averaged of 2.0 cm.

### 4.4.6 Litter layer biomass and moisture content

The biomass and moisture content of the litter layer (L+F layers) was determined from 0.25 $m^2$ samples collected between 20 June and 29 November 1996 in a primary rain forest plot in the Biboo - Minwo basin. The litter biomass over this period averaged 7602 ± 2352 kg $ha^{-1}$ (n = 92) and contained between 0.3 mm and 1.5 mm of moisture. Monthly averages of the litter biomass decreased from 7978 ± 2149 kg $ha^{-1}$ (n = 20) in July to 5932 ± 1553 kg $ha^{-1}$ (n = 17) during the dry season in August and increased again gradually during the wet season to 8584 ± 2632 kg $ha^{-1}$ (n = 19) in November.

## 4.5 Quantification of the water balance components

Long-term evaporation rates for a basin are usually obtained using the water balance method. The water balance equation reads:

$$E = P - Q - \Delta S - L \qquad (2)$$

where:

$E$ = evaporation (mm)
$P$ = mean areal precipitation (mm)
$Q$ = discharge (mm)
$\Delta S$ = change in soil moisture and ground water storage (mm)
$L$ = leakage into or out from the catchment (mm)

As the basement of the catchments consists of solid gneiss and the discharge measurement sites were located on bedrock, leakage through the river bedding and to regional ground water flows through faults is presumably negligible and has been ignored in the water balance calculations.

To quantify the components of the water balance and the runoff coefficients for the study catchments, rainfall and discharge data for the period 27 November 1995 until 26 November 1996 were used. Rainfall totals for the different catchments were estimated from observations made at Mvié and Adjap (Songkwé catchment), at three stations in the Nyangong catchment and at Ebom, Lolodorf and Minwo (Biboo - Minwo catchment). Daily rainfall totals are shown in Figures 12-14.

Water yields were calculated by converting water level readings ($H$, in cm) to discharge values ($Q$, in $m^3\ d^{-1}$) using discharge rating curves based on the data presented in Appendices 1-3. These rating curves are shown in Figure 11, together with the water level - discharge data points. The regression equations are given below.

Songkwé river ($H$ = 24-47 cm)
$Q = -10330(\pm 1396) + 557.6(\pm 61.2) * H$ $\qquad r^2 = 0.85$, n = 17

Biboo river ($H$ = 20-37 cm):
$Q = -2460(\pm 855) + 282.9(\pm 33.6) * H$ $\qquad r_2 = 0.80$, n = 20

Biboo river ($H$ = 37-60 cm):
$Q = 10^{2.634 \pm 0.099} * H^{4.173 \pm 0.380}$ $\qquad r^2 = 0.85$, n = 23

Nyangong river ($H$ = 15-60 cm)
$Q = 10^{-0.418 \pm 0.158} * H^{3.024 \pm 0.171}$ $\qquad r^2 = 0.93$, n = 25

Errors in the discharge totals calculated with the equations above may be considerable because of the extrapolation of the discharge rating curves beyond their range during high discharge events. In addition, storm flows were not recorded in sufficient detail due to malfunctioning of the water level recorders which resulted in less regular observations, particularly at the remote Biboo - Minwo site. The discharge patterns recorded during the study period are shown in Figures 12-14.

Changes in the soil moisture and ground water storages were neglected as the effects on the calculated evaporation totals may be considered small over the period of a year. The results of the water balance calculations are presented in Table 2.

Rainfall was highest in the Songkwé catchment and lowest in the Nyangong catchment, with a difference of 486 mm being observed for the period under consideration. The differences in water yield (591 mm between Songkwé and Nyangong) reflected differences in rainfall, rather than differences in evaporation (105 mm between Songkwé and Nyangong).

*Table 2 Quantification of the water balance components over the period 27-11-1995 until 26-11-1996 for the Songkwé (undisturbed forest), Biboo - Minwo (selectively logged forest) and Nyangong (forest - shifting cultivation) catchments*

| Site | Rainfall | Discharge | Evaporation | | Runoff |
|---|---|---|---|---|---|
| | (mm) | (mm) | (mm) | (mm $d^{-1}$) | Coeff. |
| Songkwé | 2219 | 1010 | 1209 | 3.30 | 0.46 |
| Nyangong | 1733 | 419 | 1314 | 3.59 | 0.24 |
| Biboo - Minwo | 2108 | 866 | 1241 | 3.39 | 0.41 |

The conversion from rain forest to selectively logged forest or to shifting cultivation generally causes a decrease in the evaporation due to decreases in the canopy interception loss and, to a lesser extent, in the transpiration rate (Bonell and Balek, 1993; Bruijnzeel, 1990). The values given in Table 2 indicate that the evaporation was lowest in the undisturbed forest and highest in the shifting cultivation area. However, the errors in these evaporation totals may be as large as 20% due to errors in the measured rainfall (about 10%) and discharge totals (about 15%) and errors introduced by neglecting changes in soil moisture and ground water storages and leakage (Lee, 1970). The impact of differences in land use on the catchment water yield and evaporation was not significant as it fell well within the range of the measurement errors.

The evaporation totals presented in Table 2 were similar to those given by Olivry (1986, Section 2.2) for much larger basins in South Cameroon and to those published by Seyler et al., 1993; 1115-1322 mm $yr^{-1}$) for the Ngoko River basin in Southeast Cameroon, where rainfall was somewhat lower (1460-1689 mm). The values are also well within the range published by Bruijnzeel (1990) for rain forests in the humid tropics (900-1400 mm $yr^{-1}$).

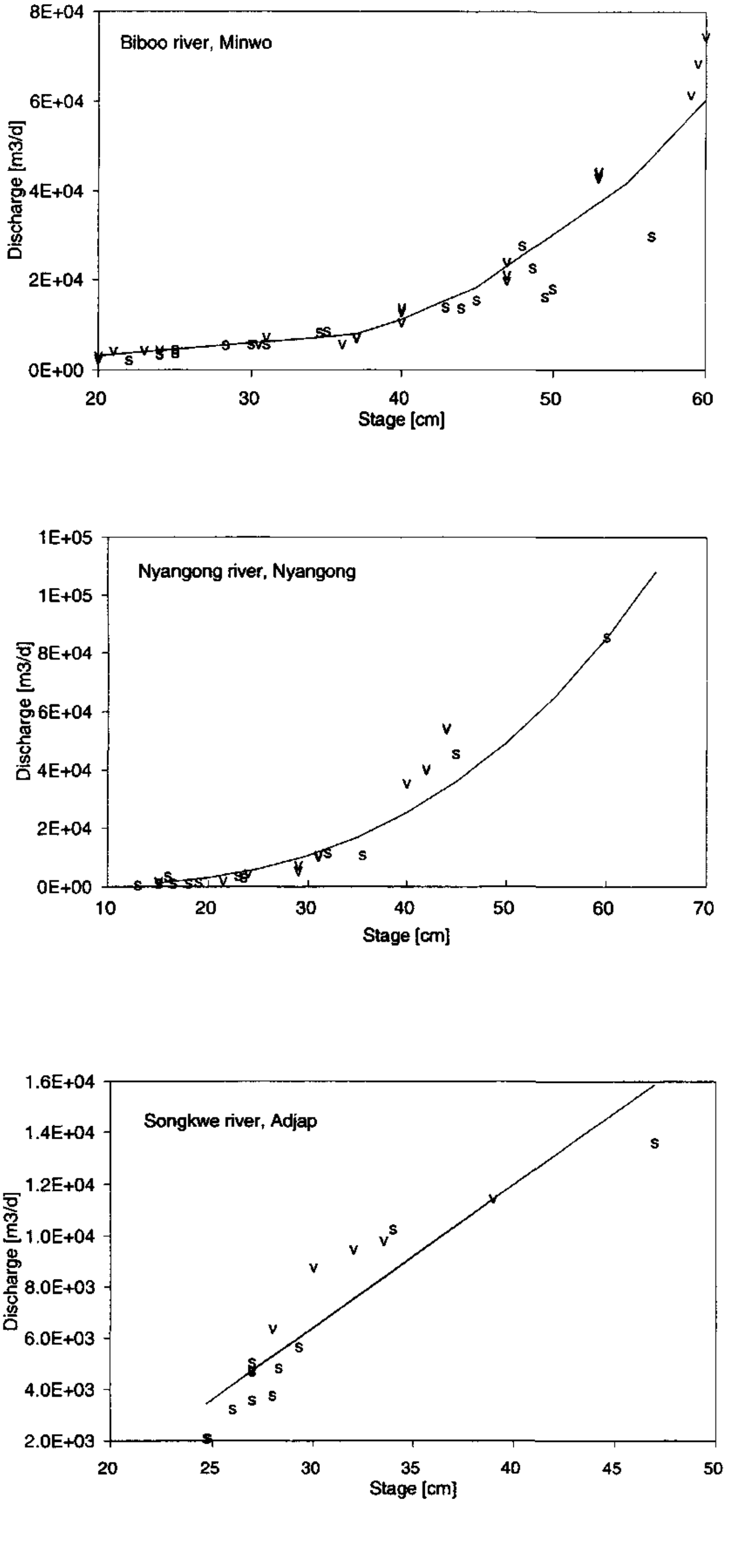



*Fig. 11 Discharge rating curves for the Biboo - Minwo, Nyangong and Songkwé catchments (v: velocity area method, s: salt dilution method)*

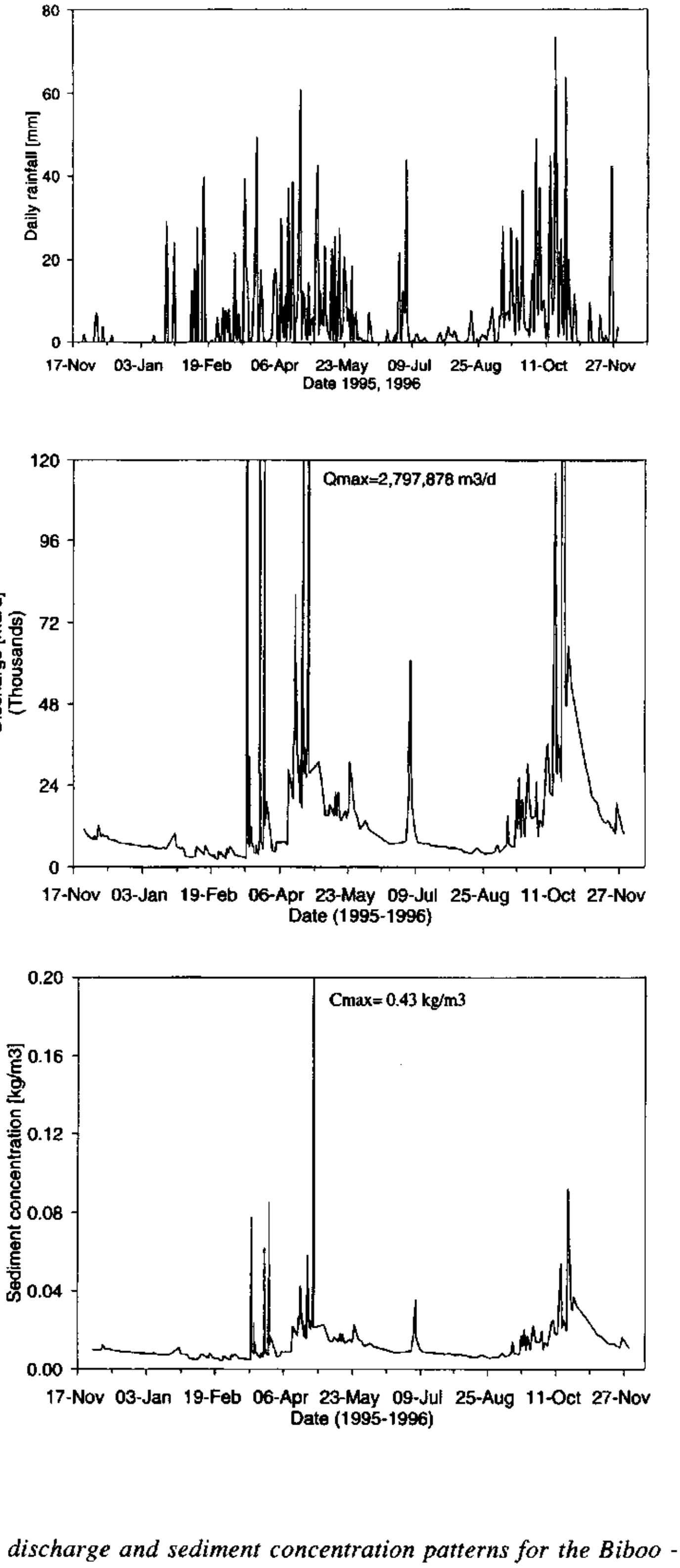



*Fig. 12 Rainfall, discharge and sediment concentration patterns for the Biboo - Minwo catchment*

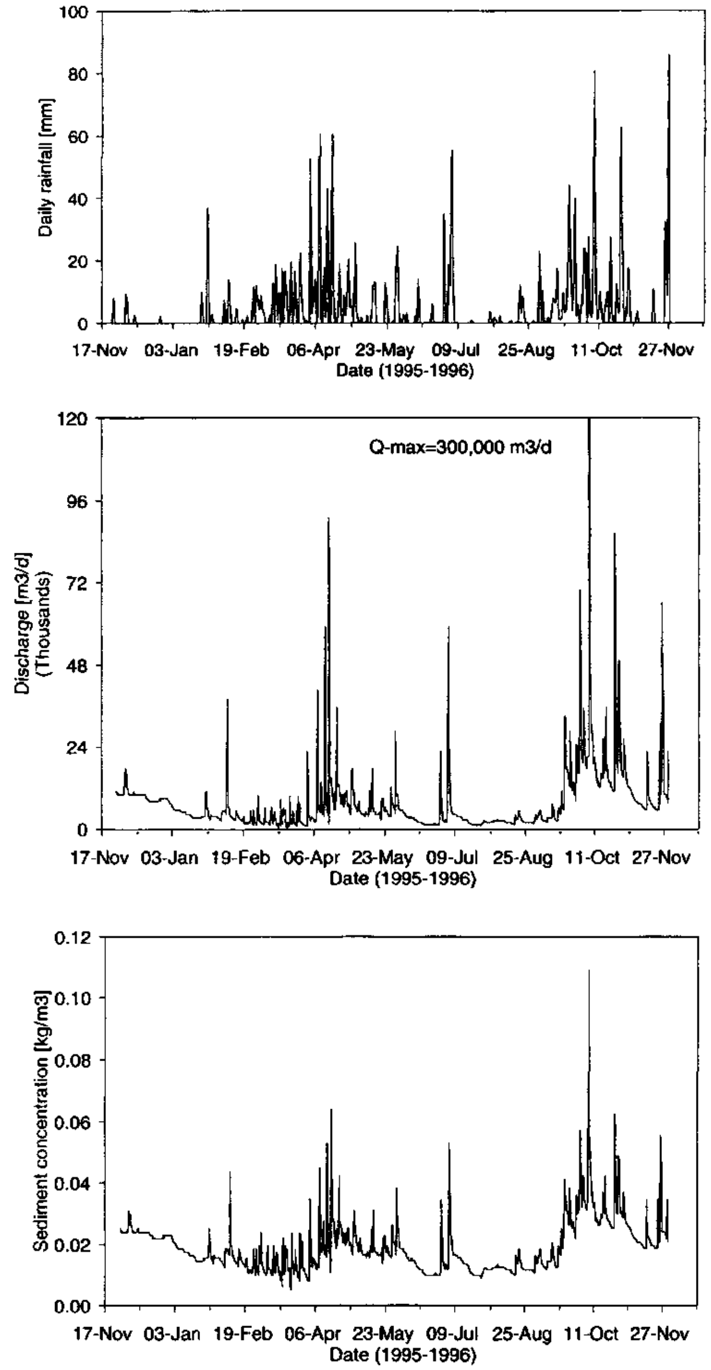



*Fig. 13 Rainfall, discharge and sediment concentration patterns for the Nyangong catchment*

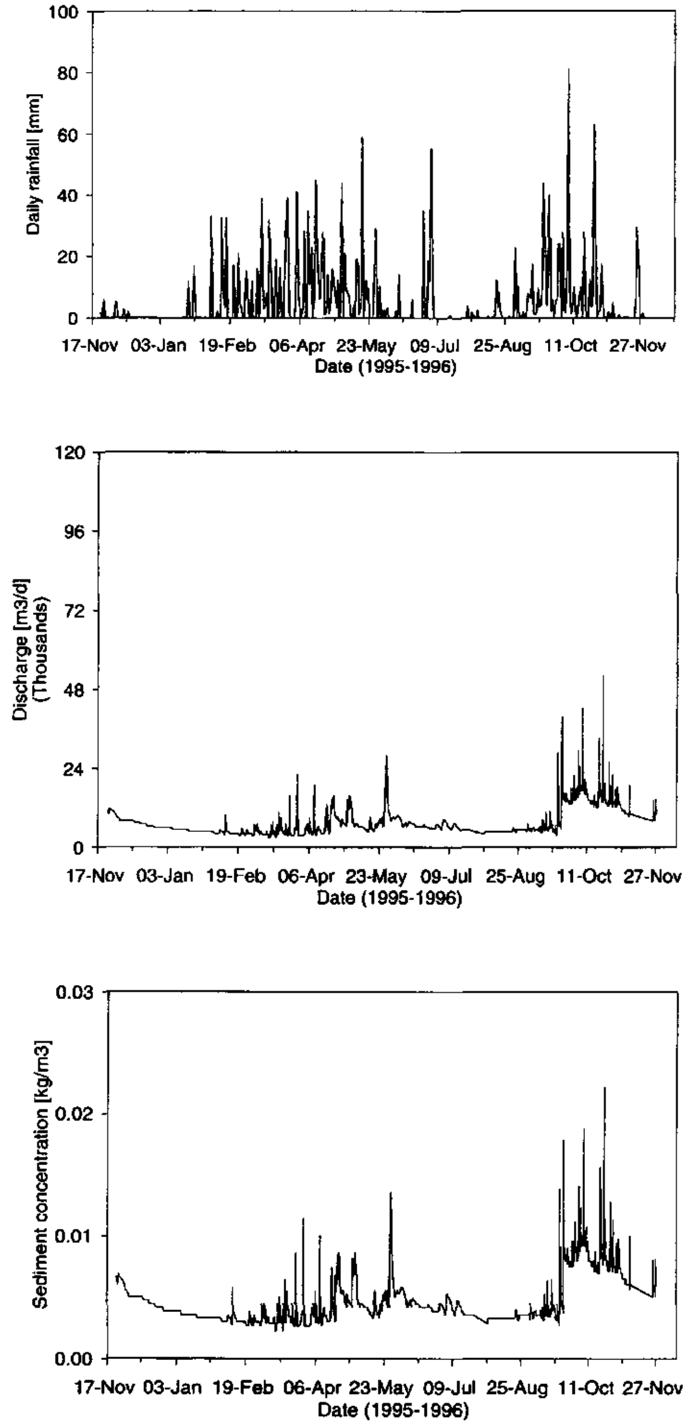



*Fig. 14 Rainfall, discharge and sediment concentration patterns for the Songkwé catchment*

## 4.6 Catchment sediment yield

Preliminary sediment rating curves were developed for each of the three basins, relating the sediment concentration, measured at the outlet of the basin ($C$, in kg $m^{-3}$), to the corresponding discharge ($Q$, in $m^3\ d^{-1}$) using linear regression analyses on the data presented in Appendices 4-6. The resulting sediment rating equations are presented below, whereas the rating curves are shown in Figure 15.

Songkwé river ($Q$ = 3,610-39,296 $m^3\ d^{-1}$)

$$C = 10^{-5.377(\pm 0.466)} * Q^{0.789(\pm 0.251)} \qquad r^2 = 0.18,\ n = 48$$

Biboo river ($Q$ = 2,632-258,034 $m^3\ d^{-1}$):

$$C = 10^{-4.574(\pm 0.227)} * Q^{0.635(\pm 0.055)} \qquad r^2 = 0.54,\ n = 116$$

Nyangong river ($Q$ = 701-299,885 $m^3\ d^{-1}$)

$$C = 10^{-3.404(\pm 0.304)} * Q^{0.446(\pm 0.058)} \qquad r^2 = 0.43,\ n = 80$$

The sediment load was calculated by multiplying the discharge with the corresponding sediment concentration and the total sediment yield was then determined for the length of the research period.

Sediment concentrations showed an exponential increase with discharge at all sites. The observed ranges are given in Table 3. The highest sediment concentrations were measured at Nyangong, which may be attributed to the agricultural activities along the main river channel, as well as to fishing activities in the river for which small earthen dams were constructed in the main channel. In addition, some of the sediment may have been derived from natural erosion of the steep slopes under the undisturbed rain forest vegetation. The range of sediment concentrations in the Biboo - Minwo catchment was much lower, in spite of the fact that the eastern part of the area had been logged in May 1995, whereas the western part was logged during the study period (February - March, 1996). Very low concentrations were measured at the undisturbed Songkwé catchment.

The annual sediment yields from the three catchments are presented in Table 3.

*Table 3 Sediment concentrations and sediment yields for the three study catchments during the period 27-11-1995 until 26-11-1996*

| Site | Concentration range (mg $l^{-1}$) | Sediment yield (kg $ha^{-1}\ yr^{-1}$) |
|---|---|---|
| Songkwé | 1-150 | 56 |
| Nyangong | 6-495 | 105 |
| Biboo - Minwo | 2-210 | 564 |

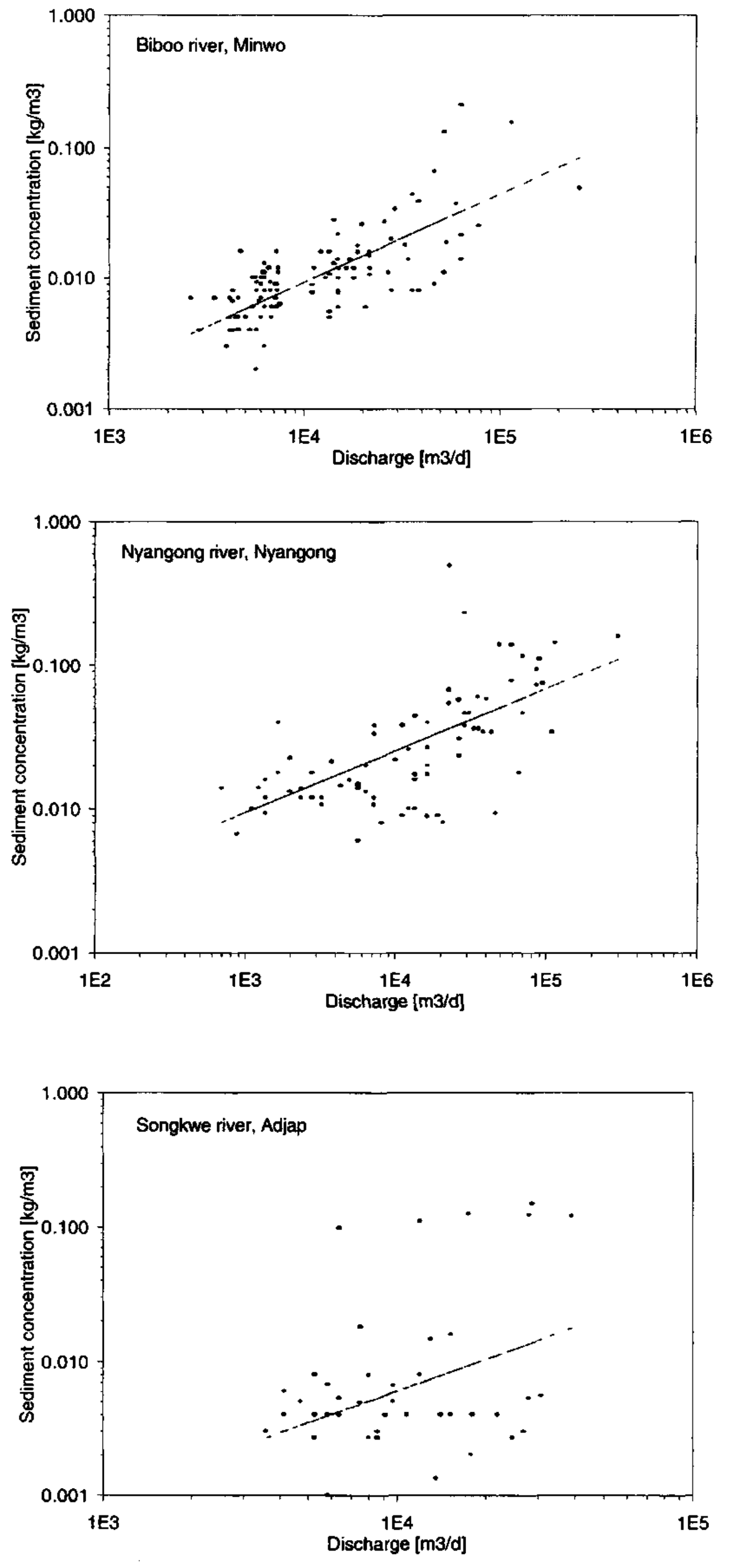



*Fig. 15 Sediment rating curves for the Biboo - Minwo, Nyangong and Songkwé catchments.*

The values indicate that the yield was highest in the Biboo - Minwo catchment, which may be attributed to a combination of a relatively high water yield and high sediment concentrations during wet periods as a result of the erosion of skid tracks, roads and landings. The sediment yield from the Nyangong catchment was much lower, in spite of the high sediment concentrations. This must be attributed to the low water yield caused by low rainfall inputs. Very low sediment yields were calculated for the Songkwé catchment, which is in line with the absence of human activity in the area.

Small-scale studies on catchment sediment yields have not been carried out earlier in the rain forests of South Cameroon. However, sediment yields from the large Ngoko River drainage system (67,000 $km^2$) have been determined between 1988 and 1992 at Moloundou, Southeast Cameroon. There, the sediment yield amounted to 86 kg $ha^{-1}$ in 1989-1990. In 1992, however, the yield had increased to 140 kg $ha^{-1}$, which was attributed to a 30% increase in logging activities and associated road construction, as well as to agricultural activity in the region (Seyler et al., 1993; ORSTOM, 1995).

Although the sediment yields from Biboo - Minwo and Nyangong catchments were influenced by logging and shifting cultivation, the values remained very low in comparison to those observed elsewhere in the humid tropics. Published values of surface erosion and sediment yield range from 30 to 6200 kg $ha^{-1}$ $yr^{-1}$ for natural forests in tectonically stable areas (Douglas, 1967; Wiersum, 1984) to up to 40,000 kg $ha^{-1}$ $yr^{-1}$ for forests in tectonically active zones during wet years (Dickinson et al., 1990).

# 5 Hydrological modelling

Discharge, sediment yield and erosion in the selectively logged Biboo - Minwo catchment have been simulated using a 48.1 mm storm (catchment average), which occurred in the afternoon of March 23, 1996. The simulations were made for two scenarios, i.e. for undisturbed forest and for selectively logged forest. The results were compared to the measured hydrograph and sediment yield. Detailed soil and vegetation maps are not yet available for this area and the model input was therefore estimated from the few and incomplete soil and vegetation data presented in the previous sections. Furthermore, the model has not yet been calibrated sufficiently and the results of these test-runs should therefore not be considered as final.

A digital elevation model (DEM) of the area was developed using topographical information obtained from the 1 : 100,000 map. This map is not very detailed as contour intervals are at a spacing of 40 m. Areal photographs were therefore used to provide additional information on the topography. The DEM was developed with a statistical interpolation program (kriging interpolation method). The result is shown in Figure 16.

A list of input maps, soil tables and the various settings used in the simulations are presented in Appendix 7. The SWATRE sub-model of LISEM was used to describe the infiltration process. This sub-model allows for the simulation of the effects of roads and skid tracks (Fig. 17) on the hydrology, erosion and sediment yield of the catchment area.

Rainfall intensities during the simulation period on March 23 are shown in Figure 18. Rainfall started at 13:21 h (t = 800 minutes) and ended at 17:45 h (t = 1065 minutes). The measured runoff for the 48.1 mm storm was 2.3 mm over the 495-minute simulation period. The measured peak flow amounted to 1.4 $m^3$ $s^{-1}$ and the time-to-peak was 292 minutes. The sediment yield, calculated from the discharge using the appropriate sediment rating curve (Section 4.6), amounted to 1137 kg or 1.4 kg $ha^{-1}$. The maximum sediment concentration was 0.11 g $l^{-1}$. The measured hydrograph and sediment concentrations are shown in Figure 19.

The simulated water yield for the selectively logged scenario amounted to 1.3 mm, which is somewhat lower than the measured water yield. The results of the simulations for the forested and selectively logged scenarios are shown in Figure 20. The shape of the simulated hydrograph for the selectively logged scenario, which shows a peak at 2.7 $m^3$ $s^{-1}$ and has a much shorter time-to-peak of 101 minutes, was distinctly different from that of the measured hydrograph for the selectively logged forest (Fig. 19), which was less pronounced. Furthermore, the simulated sediment yield was much to high at 30,600 kg, or 39 kg $ha^{-1}$, which may only partly be due to errors in the modelling of the runoff (peak flow much too high). The peak sediment concentration simulated by LISEM amounted to 5.1 g $l^{-1}$, which was 50 times higher than the actual peak sediment concentration.

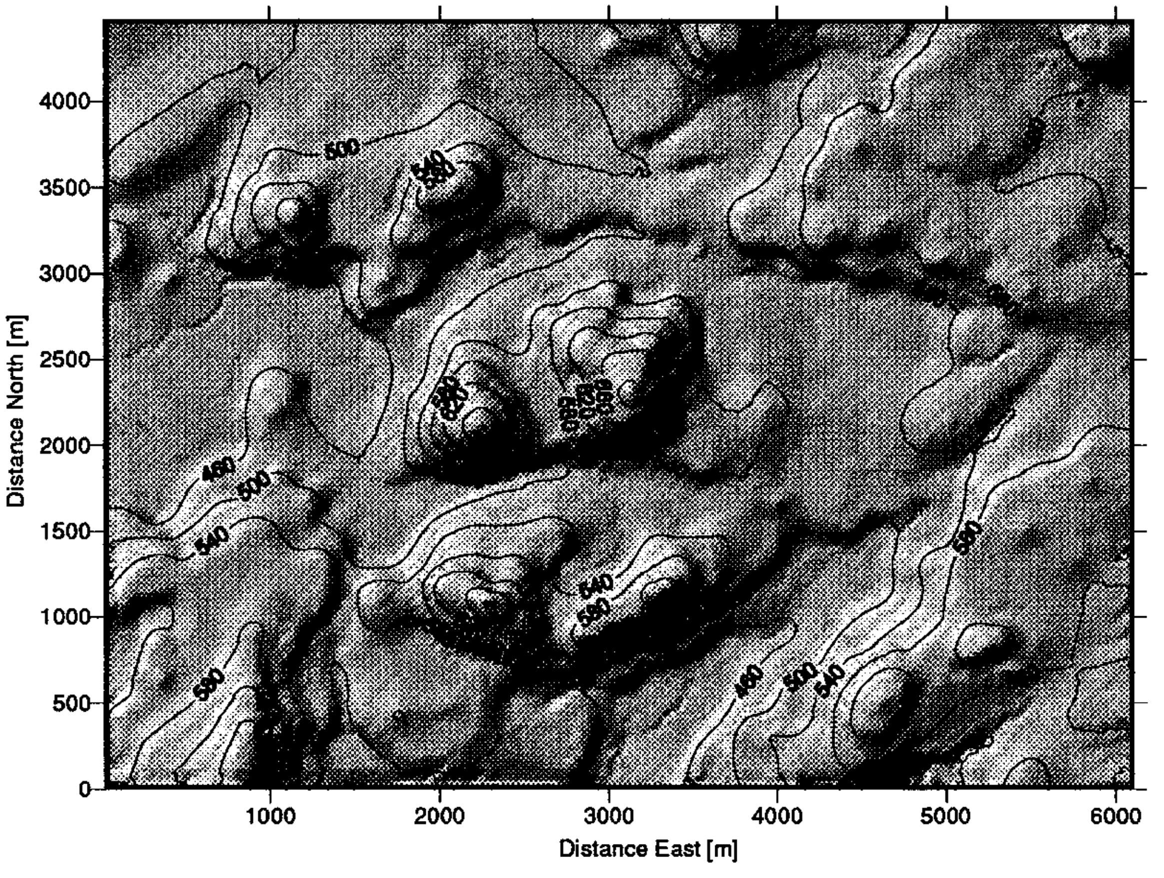



*Fig. 16 Digital elevation model of the Biboo - Minwo catchment area*

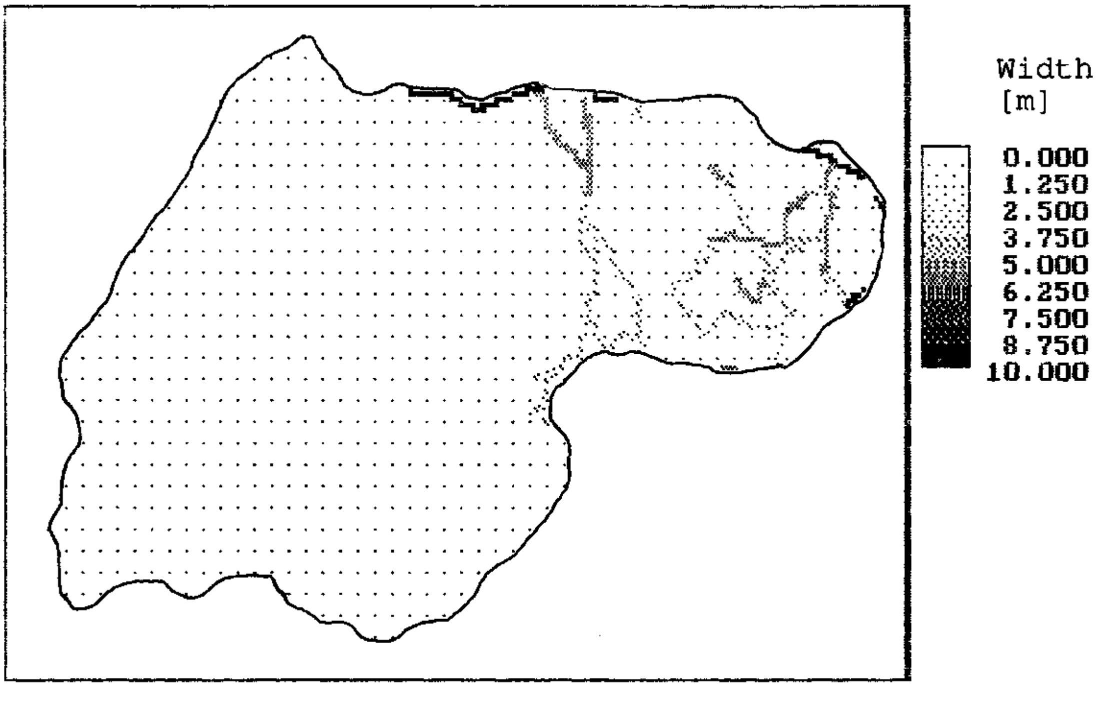



*Fig. 17 Map showing the location and width of roads and skid tracks in the Biboo - Minwo catchment*

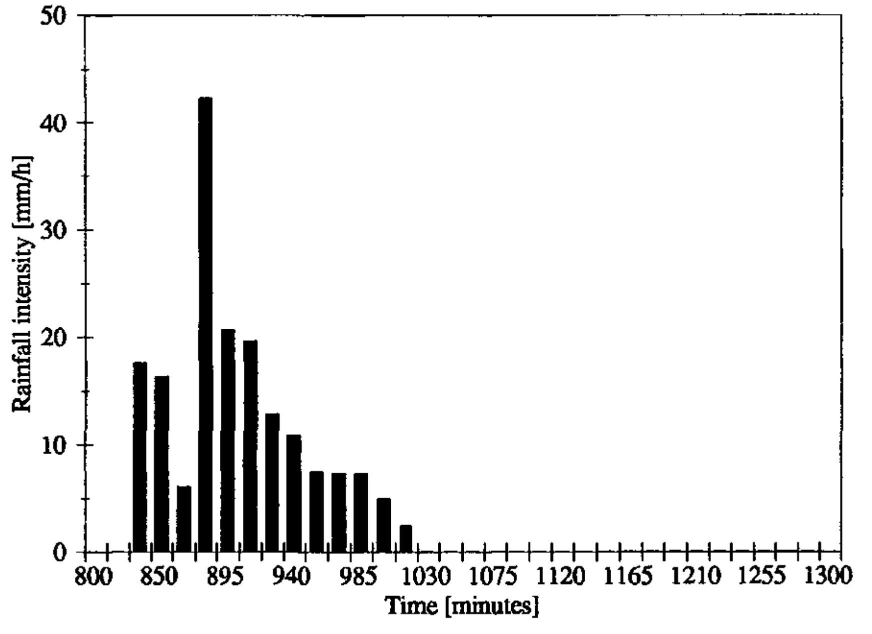



*Fig. 18 Average rainfall intensities during the simulation period on March 23, 1996 in the Biboo - Minwo catchment*

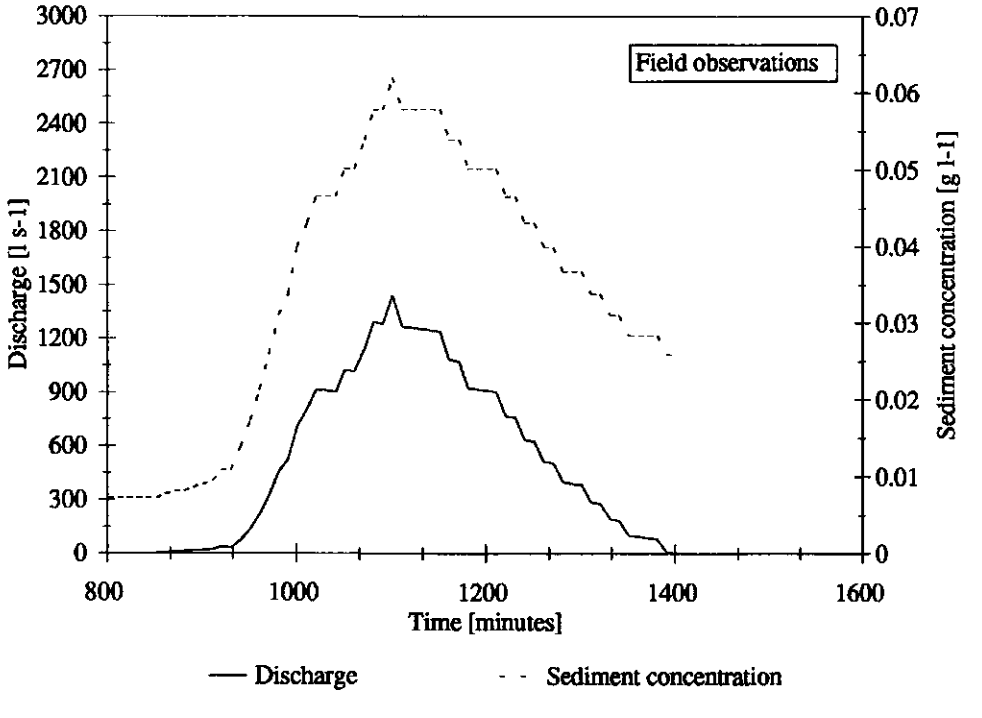
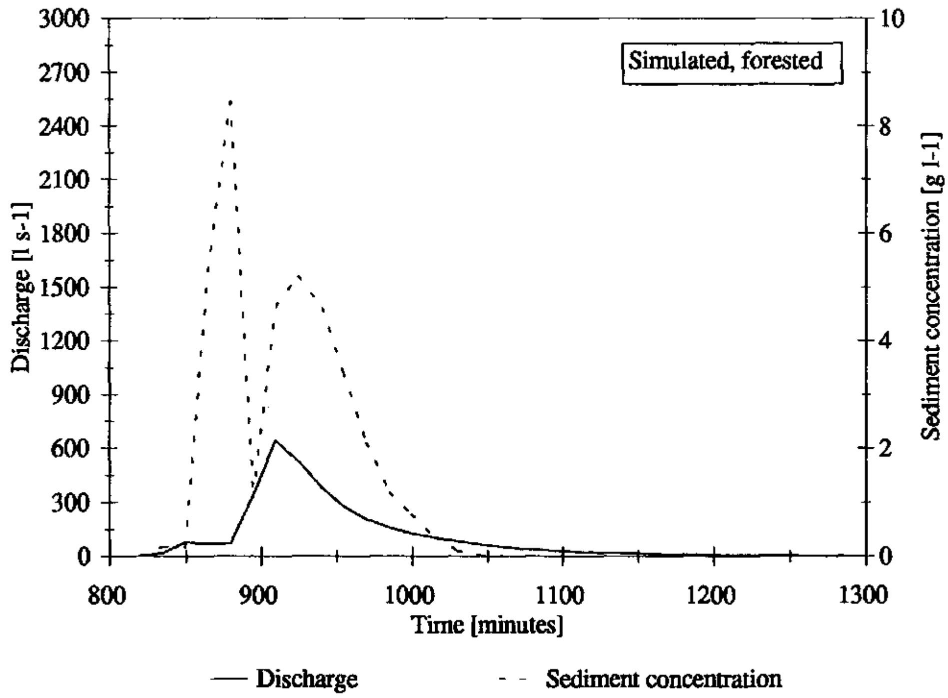



*Fig. 19 Measured hydrograph and sediment concentrations for selectively logged Biboo - Minwo catchment during a 48.1 mm rainfall event on March 23, 1996*



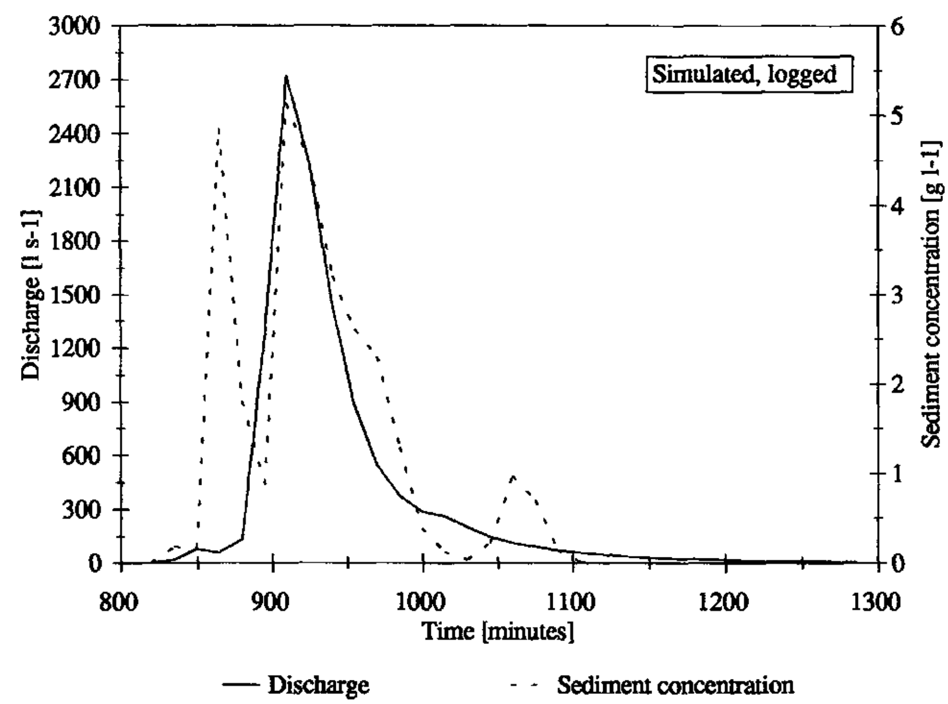




*Fig. 20 Simulated hydrographs and sediment concentrations for the forested and selectively logged Biboo - Minwo catchment during a 48.1 mm rainfall event on March 23, 1996*

The simulated water yield for the forested catchment scenario was 0.4 mm, which was much lower than that predicted for the selectively-logged forest scenario due to a higher total infiltration (43.8 mm vs. 43.0 mm) and a slightly higher interception loss (3.9 mm vs. 3.8 mm). The peak discharge was much lower at 0.7 $m^3$ $s^{-1}$ but the time to peak remained the same at 912 minutes. The predicted sediment yield was much lower than that predicted for the selectively logged scenario at 9500 kg or 12.3 kg $ha^{-1}$.

Erosion maps for the selectively logged and forested scenarios are given in Figures 21 and 22, respectively. Both maps show relatively high erosion values for the steep slopes in the catchment, which are not supported by field observations. However, increases in erosion were correctly predicted where skid tracks were constructed on such steep slopes in the northeastern part of the area, or where these tracks crossed a river channel. Figure 23 shows the location of 35 cells in the catchment where the erosion increased by more than 1000 kg $ha^{-1}$ after the construction of skid tracks. Of these 35 cells, 90% had a slope exceeding 7.5° and 77% had a slope between 10° and 17°. The highest increase in erosion (140,000 kg $ha^{-1}$) was observed for a skid track constructed on a slope of 17°. Erosion from the same skid track on an adjacent cell with a slope of 7.5° was only 7000 kg $ha^{-1}$ higher than in the forested situation. These roads and skid tracks must therefore be considered as a major source of sediment and soils on slopes steeper than 7.5°-10° seem to be particularly sensitive to erosion after disturbance by skidders.

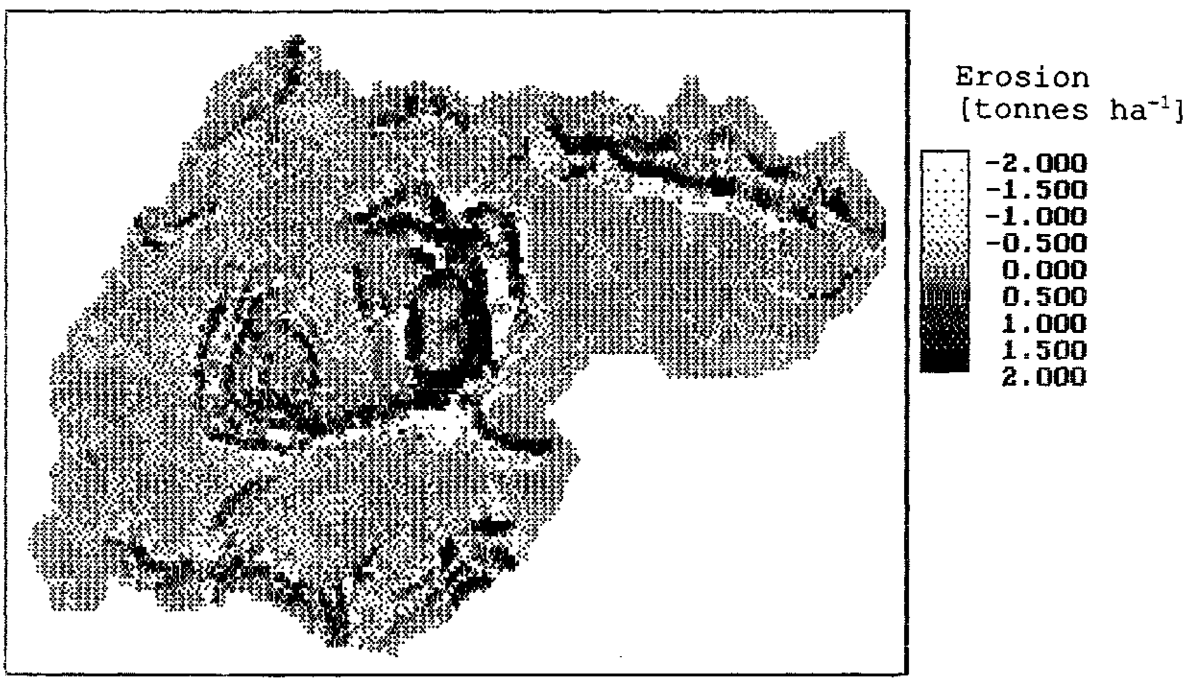



*Fig. 21 Erosion map of the selectively logged Biboo - Minwo catchment for a 48.1 mm rainfall event on March 23, 1996*

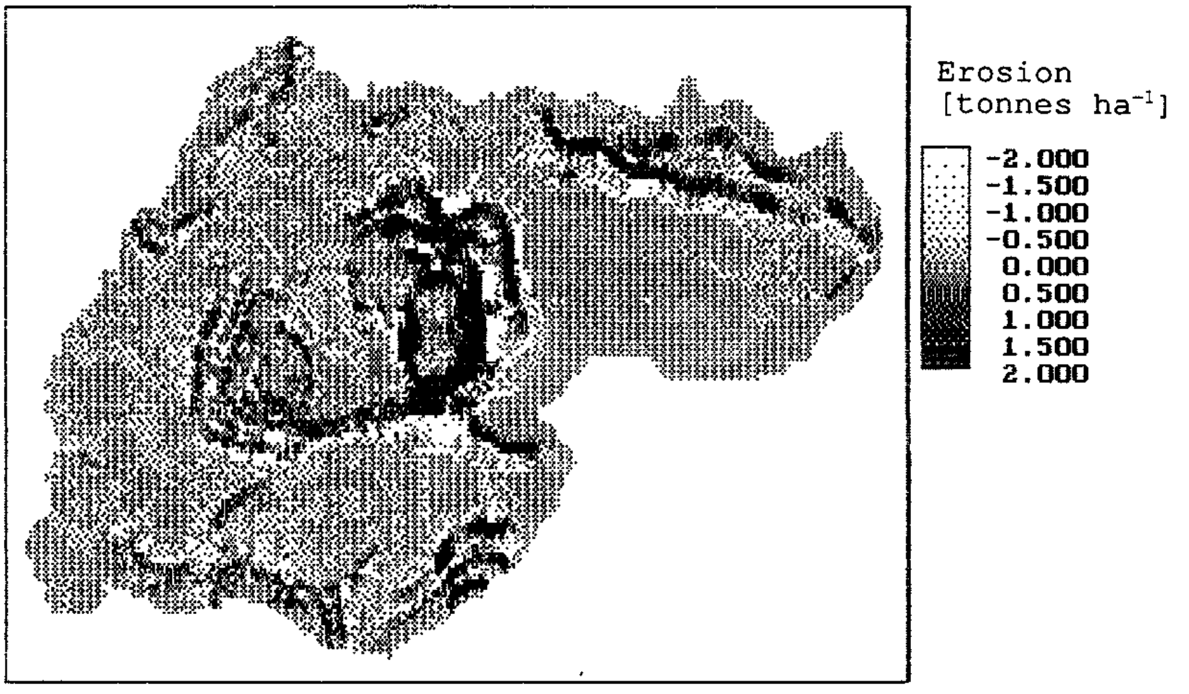



*Fig. 22 Erosion map of the forested Biboo - Minwo catchment for a 48.1 mm rainfall event on March 23, 1996*

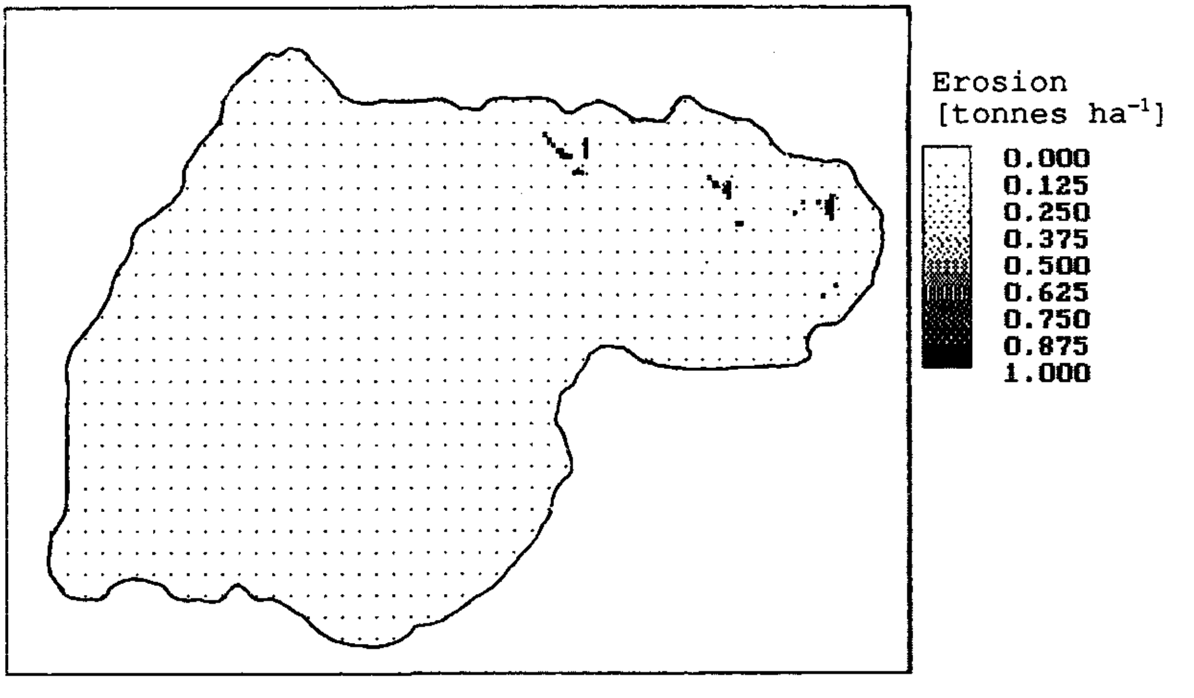



*Fig. 23 Map of the Biboo - Minwo catchment showing cells where the erosion increased by more than 1000 kg ha$^{-1}$ after the construction of skid tracks*

# 6 Meteorology

A micrometeorological set-up recording air temperature, relative humidity, global and net radiation, wind direction and soil temperatures has been functioning since July 1996 in the Songkwé catchment. Wind speed data have not yet been obtained as the anemometer became defective only two days after the installation. The thermocouple and soil temperature probes deteriorated during the study and had to be replaced in December 1996. Monthly averages of temperature ($T$-avg) and relative humidity ($RH$-avg) and monthly minimum ($T$-min) and maximum temperatures ($T$-max) are given in Table 4. The average temperature increased slightly during the study period, corresponding with an increase in the daily radiation totals, and reached a maximum in November. The monthly average relative humidity was high throughout the study period, but reached a maximum during the wet season (September - October) and decreased again at the beginning of the dry season.

*Table 4 Summary of micrometeorological data collected above a secondary rain forest near Adjap between August and November 1996. The values quoted for the global and net radiation ($R_g$ and $R_n$) are average daily totals*

| | August | September | October | November |
|---|---|---|---|---|
| $T$-avg (°C) | 22.7 | 22.7 | 23.0 | 24.4 |
| $T$-min (°C) | 19.7 | 20.0 | 19.5 | 20.1 |
| $T$-max (°C) | 29.6 | 30.4 | 30.0 | 31.0 |
| $RH$-avg (%) | 90.6 | 94.9 | 95.9 | 89.3 |
| $R_g$ (MJ m$^{-2}$ d$^{-1}$) | 10.1 | 11.5 | 12.1 | 12.3 |
| $R_n$ (MJ m$^{-2}$ d$^{-1}$) | 7.4 | 8.6 | 8.8 | 8.8 |

A frequency distribution of the wind direction over the four months is shown in Figure 24. The wind direction was predominantly southwest, with 35% of all half-hourly wind direction readings (n = 5815) falling within the range of N210°-240°E, and 66% falling within the range N180°-270°E. A much smaller peak was observed for the range of N60°-90°E, which consisted of 7% of all readings.

To allow for the calculation of net radiation from measured incoming shortwave radiation for forested areas elsewhere in South Cameroon, linear regression analysis was used to establish a relationship between half-hourly values of the global ($R_g$) and net radiation ($R_n$). The following equation was found:

$$R_n = -5.6(\pm 7.9) + 0.77(\pm 0.00) \cdot R_g \qquad r^2 = 1.00, \quad n = 5988 \qquad (3)$$

This equation is similar to that observed for tropical rainforest in Amazonia (Bastable et al., 1993).

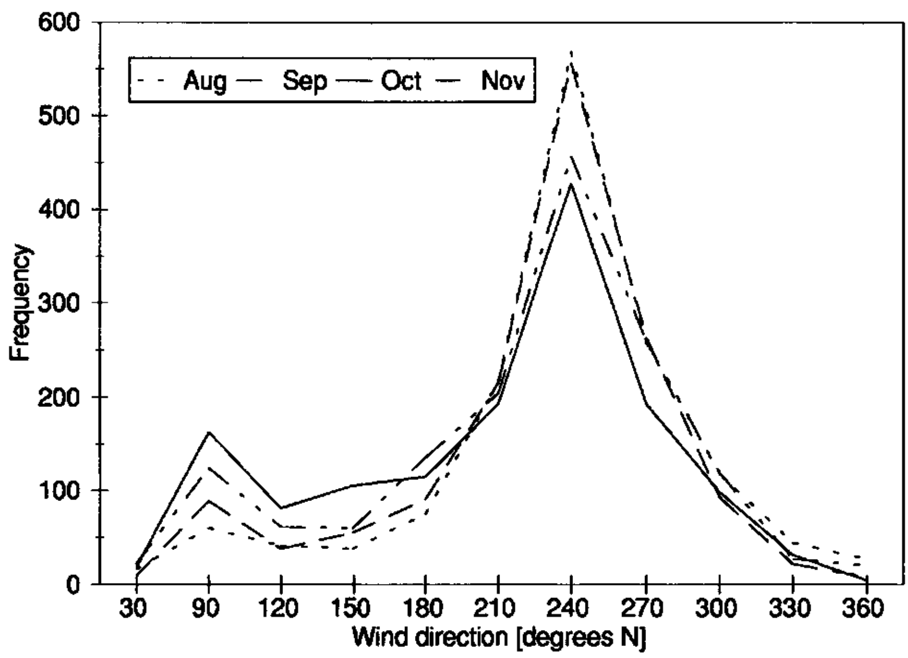



*Fig. 24 Monthly frequency distributions of the wind direction above secondary forest at Adjap*

The partitioning of the available solar energy (i.e. net radiation) over the sensible (H) and latent (LE) heat fluxes can be determined from the net radiation and thermocouple temperature and standard deviation data using the temperature fluctuation energy balance method (Tillman, 1972; Bruin et al., 1993; Waterloo, 1994). Under non-advective conditions the energy balance of a forest surface may be written as:

$$R_n - G - J - P_{veg} = H + \lambda E \qquad (4)$$

where $R_n$ is the net radiation, $G$ the soil heat flux, $J$ and $P_{veg}$ the physical and biochemical storages of energy in the vegetation, $H$ the sensible heat flux and $\lambda E$ the latent heat flux (all fluxes in W $m^{-2}$). Turbulent motions of the air are responsible for most of the vertical transfer of heat (Thom, 1975). The standard deviation of high-frequency temperature measurements may serve as a measure of the intensity of temperature fluctuations caused by turbulence, and Tillman (1972) obtained the following equation relating the temperature ($T$) and its standard deviation ($\sigma_T$) to the latent heat flux $H$.

$$H = h_\sigma \rho c_p \sqrt{(z-d)\frac{g}{T} \cdot \sigma_T^{1.5}} \qquad (5)$$

In this equation, the constant $h_\sigma$ is equal to 0.7 (Wijngaard and Cote, 1971), $\rho$ is the density of air (kg $m^{-3}$), $c_p$ the specific heat of air at constant pressure (J $kg^{-1}$ $K^{-1}$), $z$ the thermocouple height (m), $d$ the displacement length (m) and $g$ the acceleration due to gravity (m $s^{-2}$). The soil heat flux and the physical and biochemical storages of energy are usually much smaller than the other terms in the equation and may therefore safely be neglected. The sensible heat flux can then be evaluated by inserting the value of $H$, calculated with the temperature fluctuation method, in the simplified energy balance equation.

As an example, the partitioning of the available solar energy (net radiation) over the latent and sensible heat fluxes on August 7 (Julian day 220) is shown in Figure 25. The daytime evaporation on this day amounted to 2.9 mm, which is fairly close to the evaporation rate calculated with the water balance method in Section 4.5 for the Songkwé catchment (3.3 mm $d^{-1}$).

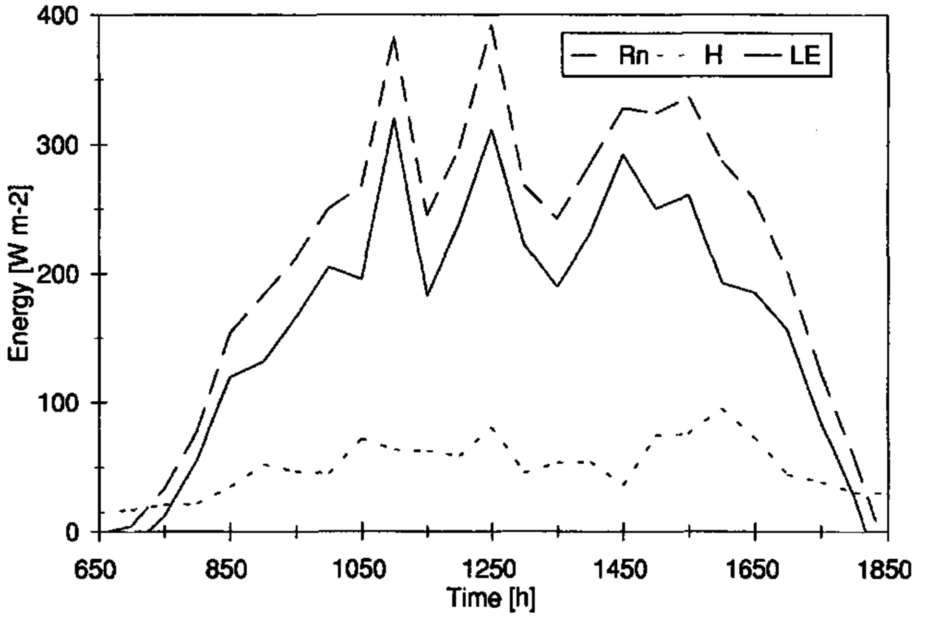



*Fig. 25 Partitioning of available energy over the latent and sensible heat fluxes on August 7, 1996 at Adjap*

# 7 Discussion and conclusions

The initialisation phase of the hydrological study (i.e. site selection, instrumentation, training and selection of a hydrological model) has been completed and the study has entered its second phase of data collection and data processing, which should be followed by the calibration and implementation of the LISEM erosion model. This phase is carried out by the CRH-IRGM under supervision of Dr. J.C. Ntonga, who works in collaboration with Dr. A.J. Dolman of SC-DLO.

The results presented in this report are based on hydrological and soil data collected between August 1995 and November 1996. The data collection period has been too short for an accurate quantification of the hydrological cycle and the conclusions given below should therefore be viewed as tentative until additional data have been collected to validate them. Furthermore, the modelling exercise has only just been initiated and the modelling results presented in Chapter 5 should therefore be viewed with caution.

The distribution of rainfall over the TCP area showed a clear pattern. Relatively low rainfall totals were observed in the lowland (1729 mm) and highland (1677 mm) areas, whereas distinctly higher rainfall totals (2115-2263 mm) were observed in the lowland - highland transition zone over a twelve-month study period. The rainfall distribution pattern may be related to the change in the topography, which favours orographic rainfall in the central zone of the area where the elevation changes from less than 200 m a.s.l. to up to 1000 m a.s.l over a distance of less than 20 km.

Rainfall interception by primary rain forest in the central part of the research area amounted to 35% of the incident rainfall (683 mm) during a 3-month study period. This is a rather high value as compared to those observed in other studies in tropical rain forest, where the interception loss generally varies between 15 and 30% of total rainfall (Bruijnzeel, 1990). Rainfall interception by the cassava crop was much lower than that by the forest vegetation at 15% of the incident rainfall (498 mm). As interception of rainfall by the vegetation canopy is one of the parameters affecting the total evaporation from a catchment, and therefore indirectly the catchment water yield, the large-scale conversion of rain forest to a cassava (or comparable) crop type will result in a higher water yield. In this case, the amount of water reaching the soil would have increased by 136 mm over the 3-month period. In South Cameroon, agricultural activities are presently limited to a small percentage of the total area. Effects of selective logging and shifting cultivation on rainfall interception may therefore be considered small on a regional scale.

The surface water in the TCP area could be classified on the basis of its electrical conductivity and two types of water have been be recognised. The first type had a relatively high EC (35-75 $\mu S\ cm^{-1}$) and was observed only in the western and south-western parts of the area where soils were known to be relatively nutrient-rich (Van Gemerden and Hazeu, 1997). The second type of water covered the central and eastern parts of the TCP area, as well as vast areas to the south and to the east of the TCP area. This type of surface water had a low to very low EC, ranging from 14 µS $cm^{-1}$ to 30 µS $cm^{-1}$. The differences in surface water conductivity may be caused by local differences in the mineralogical composition of the rock, or by differences in the chemical weathering processes in the soil and rock, which occur at a lower rate or intensity in the latter area than those in the former zone where EC values are higher. In spite of the observed (rather small) differences in the surface water conductivity, the TCP area may presumably be considered homogeneous with respect to the chemical composition of the surface water. To verify this, however, water samples for chemical analysis should be collected at several locations including both types of surface water (e.g. Saa catchment and Biboo - Minwo catchment).

Physical properties of the soil (permeability, soil cohesion, aggregate stability) were studied in the Nyangong (forest - shifting cultivation) and Biboo - Minwo (forest - selective logging) catchments. The properties of the soils under undisturbed rain forest were distinctly different from those of soils on skid tracks made in the process of selective logging, or from those of soils under agriculture. The permeability of the forest soils was high, but decreased sharply upon disturbance and compaction by skidders during log extraction. The soil cohesion and compaction was higher in forest soils than in soils under shifting cultivation due to the presence of a root mat in the former. The highest cohesion and compaction values, however, were observed in heavily disturbed soils on skidder tracks. The bulk density of forest soils was low due to the presence of organic material and large pores. Compaction of the soil by skidders resulted in a significant increase of the bulk density. Soil aggregate stability measurements showed that the clayey forest soils at Biboo - Minwo and Nyangong were very stable. The more sandy soil of the Saa catchment was less stable. The aggregate stability decreased after the soil had been disturbed by skidders in the Biboo - Minwo catchment.

The results of the soil studies suggest that the susceptibility of the soil to erosion increases when forest land is converted to another type of land use. Much more detailed information on the spatial distribution of soil properties (e.g. cohesion, aggregate stability, soil roughness, permeability and moisture retention) for the different land use types should be collected to confirm this. Furthermore, the changes in soil properties (cohesion, moisture retention, aggregate stability, soil roughness, permeability) upon conversion should be quantified such that the LISEM model may be used to predict the change in erosion patterns after conversion. These properties should be determined in a combined effort of the hydrology and soil science research teams.

Rainfall inputs for the three research catchments differed considerably (1733-2219 mm over a year) and this strongly affected the water yield, which ranged from 419 mm at Nyangong to 1010 mm at Songkwé. Evaporation rates were fairly constant, however, in spite of the differences in rainfall and land use, ranging from 1209 mm to 1314 mm $yr^{-1}$. As such the effect on the water yield of differences in precipitation was much more pronounced than that of differences in land use, which would primarily have affected the calculated evaporation rates. The effects of small-scale land use conversions on the catchment water yield may therefore be considered negligible (i.e. within the range of measurement errors) at the present intensity of logging or agriculture.

Sediment concentrations were highest in the Nyangong catchment where agriculture and fishing activities were common practice along the main river, and lowest in the forested Songkwé catchment (in spite of a peak value of 0.15 kg $m^3$ during a storm event). Sediment yields from all the study catchments were low, but seemed to show a response to agricultural and fishing activities (Nyangong) and to selective logging (Biboo - Minwo) as the values for the catchments where these land uses were practised had distinctly higher sediment yields (105 and 564 kg $ha^{-1}$, respectively) than that of the catchment under undisturbed forest (Songkwé, 56 kg $ha^{-1}$). Although the water quality is affected by changes in land use, the deterioration of the water quality at the present levels of intensity does not give rise to great concern.

The results presented in this report indicate that changes in land use do not have a large impact on the hydrology or water quality at the catchment scale (area > 3 $km^2$). The impacts of selective logging and shifting cultivation on the vegetation, soil and water quality are, however, clearly visible on a smaller scale (e.g. at a scale of several hectares). Improvements in the techniques of selective logging and in the method of timber extraction in particular (forestry projects, ecology project), and in the agricultural system (farming systems project) should make it possible to reduce the damage to the soil and vegetation to some extent, which will further minimize the impact of the land use activities on the hydrology. A first step should be the implementation of a logging code (e.g. Gilmour, 1977b) as part of the management plan, which should provide guidelines for the protection of the drainage system through improved road and track construction, river crossings, implementation of buffer zones around the rivers, etc. Special attention should be given to village water supply areas, where human activity (e.g. selective logging or agriculture) should be minimized or prohibited to guarantee a continuous supply of water of good quality. Mapping of the present village water supply areas should receive proper attention during the development phase of a management plan.

As the hydrological study is still in its data collection phase, physical data on which to calibrate the LISEM erosion model are not yet available. A first test-run on the Minwo - Biboo area for forested and selectively logged scenarios with rough estimates for the soil and vegetation parameters showed that the simulated hydrograph and sediment yield were very different from the measured hydrograph and sediment yield. The model did predict that roads and skid tracks constructed during timber extraction are the main sources of sediment in the Biboo - Minwo catchment and that severe erosion may be expected when these roads or skid tracks are constructed on slopes exceeding 7.5°-10°.

When more detailed field measurements of the soil and vegetation parameters become available, the LISEM model should be properly calibrated on several storms for each of the basins. During the calibration process it will also become clear whether the model equations describing the hydrology and erosion patterns should be adapted to the conditions in South Cameroon. When the model has been properly calibrated, the sensitivity of the area to erosion should be determined. This can be done by running the model on different scenarios (e.g. forested scenario and various scenarios with different scales and intensities of logging and agriculture) for each of the areas. By comparing the predictions for the baseline scenario (complete forest cover) with those for the various other land use conversion scenarios, the impact on the hydrology (total water yield and runoff pattern) and erosion may be determined. This should lead to the formulation of a threshold level below which the effects of land use conversions on the hydrology and erosion are 'acceptable' with respect to the constraint of sustainable land use. The results of the modelling for the study catchments should then be related to landforms, soils, vegetation and land use in these catchments to allow for extrapolation (using ARC/INFO) of the predicted sensitivity to erosion to the whole TCP area.

The meteorological set-up in the Songkwé catchment has provided half-hourly averages and standard deviations of global radiation, net radiation, wind direction, temperature, relative humidity measured at a height of 26-30 m, and those of soil temperatures at -2 and -10 cm. Wind speed data will be available in the near future. These data should be used to calculate daily evaporation rates, as well as for the modelling of the long-term hydrology. The data are also available to the other projects of the Tropenbos Cameroon Programme. Tentative calculations of the evaporation with the temperature fluctuation method provided reasonable results.

Hydrological field measurements should continue at least until November 1997 (to obtain a two-year data set) but preferably until November 1998 to account for the large temporal variation of the rainfall, evaporation and discharge in the equatorial climate of South Cameroon.

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## Annexes

## Annex 1 Stage - discharge data Songkwe river, Adjap

| Date | Time | H (cm) | Q ($m^3 day^{-1}$) | Method[1] |
|---|---|---|---|---|
| 23-Nov-95 | 13.60 | 39.0 | 11491 | v |
| 01-Dec-95 | 14.25 | 33.5 | 9850 | v |
| 15-Dec-95 | 11.75 | 32.0 | 9504 | v |
| 03-Jan-96 | 16.75 | 28.0 | 6394 | v |
| 31-Jan-96 | 14.90 | 27.0 | 4752 | v |
| 09-Feb-96 | 9.00 | 26.0 | 3283 | s |
| 21-Feb-96 | 15.75 | 24.8 | 2160 | s |
| 21-Feb-96 | 16.00 | 24.7 | 2160 | s |
| 01-Mar-96 | 13.60 | 28.3 | 4873 | s |
| 21-Mar-96 | 13.25 | 28.0 | 3819 | s |
| 16-Apr-96 | 17.30 | 29.3 | 5694 | s |
| 25-Apr-96 | 12.00 | 34.0 | 10316 | s |
| 20-Jun-96 | 14.60 | 30.0 | 8813 | v |
| 25-Jul-96 | 12.40 | 27.0 | 5098 | s |
| 01-Aug-96 | 14.75 | 27.0 | 4752 | s |
| 16-Aug-96 | 12.70 | 27.0 | 3629 | s |
| 02-Oct-96 | 9.75 | 47.0 | 13651 | s |

[1]v: velocity area method, s: Salt dilution method

## Annex 2 Stage - discharge data Biboo river, Minwo catchment

| Date | Time | H (cm) | Q ($m^3 day^{-1}$) | Method[1] |
|---|---|---|---|---|
| 24-Nov-95 | 9.45 | 40.0 | 10800 | v |
| 24-Nov-95 | 9.80 | 40.0 | 12960 | v |
| 15-Mar-96 | 8.75 | 56.5 | 30154 | s |
| 15-Mar-96 | 11.30 | 48.7 | 22956 | s |
| 17-Apr-96 | 12.10 | 60.0 | 74822 | v |
| 17-Apr-96 | 12.50 | 59.5 | 68774 | v |
| 17-Apr-96 | 13.60 | 59.0 | 61776 | v |
| 18-Apr-96 | 12.33 | 53.0 | 43200 | v |
| 18-Apr-96 | 12.60 | 53.0 | 44237 | v |
| 18-Apr-96 | 12.90 | 53.0 | 44582 | v |
| 18-Apr-96 | 13.05 | 53.0 | 43977 | v |
| 20-Apr-96 | 10.10 | 47.0 | 24278 | v |
| 20-Apr-96 | 10.50 | 47.0 | 19958 | v |
| 23-Apr-96 | 10.33 | 50.0 | 18403 | s |
| 24-Apr-96 | 9.85 | 48.0 | 27993 | s |
| 26-Apr-96 | 12.00 | 49.5 | 16589 | s |
| 10-May-96 | 8.70 | 45.0 | 15724 | s |
| 17-May-96 | 9.30 | 43.0 | 14256 | s |
| 27-May-96 | 9.84 | 44.0 | 13858 | s |
| 05-Oct-96 | 9.45 | 40.0 | 14083 | v |
| 05-Oct-96 | 10.00 | 40.0 | 13564 | v |
| 10-Oct-96 | 8.20 | 47.0 | 24192 | v |
| 10-Oct-96 | 10.30 | 47.0 | 21340 | v |
| 30-Nov-95 | 16.00 | 37.0 | 7344 | v |
| 30-Nov-95 | 16.15 | 37.0 | 7516 | v |
| 14-Dec-95 | 13.40 | 36.0 | 6048 | v |
| 05-Jan-96 | 10.80 | 30.5 | 5961 | v |
| 01-Feb-96 | 15.00 | 22.0 | 2505 | s |
| 01-Feb-96 | 15.40 | 21.0 | 4492 | v |
| 01-Feb-96 | 15.55 | 20.0 | 2764 | v |
| 08-Feb-96 | 9.00 | 20.0 | 3369 | v |
| 26-Feb-96 | 9.25 | 24.0 | 4665 | v |
| 26-Feb-96 | 9.80 | 23.0 | 4665 | v |
| 01-Mar-96 | 8.25 | 28.3 | 5892 | s |
| 22-Mar-96 | 9.25 | 24.0 | 3896 | s |
| 22-Mar-96 | 10.50 | 24.0 | 3810 | s |
| 03-Apr-96 | 13.00 | 25.0 | 4017 | s |
| 04-Apr-96 | 9.00 | 35.0 | 8804 | s |
| 04-Apr-96 | 10.00 | 34.5 | 8605 | s |
| 24-Jul-96 | 9.28 | 31.0 | 5961 | s |
| 24-Jul-96 | 9.75 | 31.0 | 7603 | v |
| 27-Jul-96 | 8.75 | 30.0 | 6048 | s |
| 06-Sep-96 | 11.75 | 25.0 | 4752 | s |

[1]v: velocity area method, s: Salt dilution method

## Annex 3 Stage - discharge data Nyangong river, Nyangong

| Date | Time | H (cm) | Q ($m^3 day^{-1}$) | Method[1] |
|---|---|---|---|---|
| 23-Nov-95 | 9.50 | 31.0 | 10541 | v |
| 23-Nov-95 | 10.00 | 31.0 | 11146 | v |
| 01-Dec-95 | 10.20 | 29.0 | 7690 | v |
| 14-Dec-95 | 16.70 | 29.0 | 5875 | v |
| 04-Jan-96 | 14.60 | 24.0 | 5098 | v |
| 01-Feb-96 | 9.50 | 21.5 | 2506 | v |
| 09-Feb-96 | 10.80 | 32.0 | 12096 | s |
| 20-Feb-96 | 10.00 | 16.5 | 1555 | s |
| 13-Mar-96 | 11.25 | 15.0 | 1572 | s |
| 16-Apr-96 | 11.50 | 16.0 | 3948 | s |
| 16-Apr-96 | 21.00 | 60.0 | 85908 | s |
| 17-Apr-96 | 7.40 | 45.0 | 45809 | s |
| 22-Apr-96 | 10.33 | 42.0 | 40262 | v |
| 22-Apr-96 | 10.40 | 42.0 | 40781 | v |
| 22-Apr-96 | 12.00 | 40.0 | 35597 | v |
| 14-May-96 | 8.10 | 23.5 | 3542 | s |
| 16-May-96 | 6.60 | 35.5 | 11232 | s |
| 21-Jun-96 | 10.00 | 15.0 | 2246 | v |
| 25-Jul-96 | 9.90 | 15.0 | 1642 | s |
| 26-Jul-96 | 16.75 | 13.0 | 1123 | s |
| 02-Aug-96 | 14.50 | 18.0 | 1728 | s |
| 20-Aug-96 | 17.50 | 19.0 | 2074 | s |
| 03-Sep-96 | 10.10 | 23.0 | 4234 | s |
| 09-Oct-96 | 7.00 | 44.0 | 54259 | v |
| 09-Oct-96 | 7.00 | 44.0 | 54605 | v |

[1]v: velocity area method, s: Salt dilution method

## Annex 4 Sediment concentrations Songkwé river, Adjap

| Date | Time | H (cm) | Q ($m^3 day^{-1}$) | Conc. ($kg\ m^{-3}$) |
|---|---|---|---|---|
| 09-Feb-96 | 17.90 | 26.0 | 4167 | 0.006 |
| 21-Feb-96 | 14.00 | 25.0 | 3610 | 0.003 |
| 01-Mar-96 | 14.84 | 28.0 | 5283 | 0.008 |
| 09-Mar-96 | 7.00 | 26.0 | 4168 | 0.004 |
| 11-Mar-96 | 6.44 | 26.0 | 4168 | 0.004 |
| 12-Mar-96 | 18.20 | 32.0 | 7513 | 0.018 |
| 13-Mar-96 | 21.20 | 30.0 | 6398 | 0.004 |
| 15-Mar-96 | 7.00 | 30.0 | 6398 | 0.005 |
| 21-Mar-96 | 7.45 | 29.0 | 5840 | 0.007 |
| 21-Mar-96 | 13.16 | 28.0 | 5282 | 0.004 |
| 17-Apr-96 | 7.20 | 42.0 | 13089 | 0.015 |
| 20-Apr-96 | 6.50 | 40.0 | 11974 | 0.008 |
| 21-Apr-96 | 6.40 | 46.0 | 15319 | 0.016 |
| 23-Apr-96 | 7.60 | 36.0 | 9743 | 0.007 |
| 24-Apr-96 | 6.90 | 34.0 | 8628 | 0.003 |
| 25-Apr-96 | 7.57 | 35.0 | 9186 | 0.004 |
| 26-Apr-96 | 6.33 | 33.0 | 8070 | 0.003 |
| 27-May-96 | 7.00 | 69.0 | 28144 | 0.124 |
| 28-May-96 | 18.33 | 50.0 | 17550 | 0.126 |
| 01-Jun-96 | 8.00 | 35.0 | 9186 | 0.004 |
| 02-Jun-96 | 8.00 | 34.0 | 8628 | 0.003 |
| 04-Jun-96 | 8.00 | 36.0 | 9743 | 0.005 |
| 05-Jun-96 | 7.00 | 35.0 | 9186 | 0.004 |
| 04-Jul-96 | 8.00 | 29.0 | 5840 | 0.004 |
| 08-Aug-96 | 7.20 | 27.0 | 4725 | 0.005 |
| 26-Aug-96 | 7.20 | 28.0 | 5282 | 0.004 |
| 04-Sep-96 | 13.55 | 29.0 | 5840 | 0.001 |
| 04-Sep-96 | 6.75 | 28.0 | 5282 | 0.003 |
| 06-Sep-96 | 6.90 | 28.0 | 5282 | 0.003 |
| 26-Sep-96 | 7.75 | 46.0 | 15319 | 0.004 |
| 27-Sep-96 | 7.20 | 44.0 | 14204 | 0.004 |
| 28-Sep-96 | 7.00 | 43.0 | 13646 | 0.001 |
| 05-Oct-96 | 16.35 | 58.0 | 22010 | 0.004 |
| 06-Oct-96 | 7.25 | 67.0 | 27029 | 0.003 |
| 06-Oct-96 | 17.52 | 63.0 | 24798 | 0.003 |
| 08-Oct-96 | 17.25 | 51.0 | 18107 | 0.004 |
| 12-Oct-96 | 7.33 | 44.0 | 14204 | 0.004 |
| 19-Oct-96 | 16.25 | 40.0 | 11974 | 0.111 |
| 19-Oct-96 | 16.75 | 70.0 | 28702 | 0.150 |
| 19-Oct-96 | 17.90 | 89.0 | 39296 | 0.120 |
| 19-Oct-96 | 19.05 | 74.0 | 30932 | 0.006 |
| 19-Oct-96 | 22.40 | 69.0 | 28144 | 0.005 |
| 20-Oct-96 | 6.90 | 50.5 | 17828 | 0.002 |
| 09-Nov-96 | 7.33 | 38.0 | 10859 | 0.004 |

Continued

| Date | Time | H (cm) | Q ($m^3 day^{-1}$) | Conc. ($kg\ m^{-3}$) |
|---|---|---|---|---|
| 12-Nov-96 | 7.25 | 35.0 | 9186 | 0.004 |
| 15-Nov-96 | 7.00 | 34.0 | 8628 | 0.001 |
| 19-Nov-96 | 7.67 | 33.0 | 8071 | 0.008 |
| 22-Nov-96 | 7.25 | 32.0 | 7513 | 0.005 |
| 12-Dec-96 | 17.00 | 57.0* | 4400* | 0.098 |

*Discharge rating curve changed from November 27 onwards due to changes in river channel as a result of road construction, discharge estimated.

**Annex 5 Sediment concentrations Biboo river, Minwo**

| Date | Time | H (cm) | Q ($m^3 day^{-1}$) | Conc. ($kg\ m^{-3}$) |
|---|---|---|---|---|
| 08-Feb-96 | 10.00 | 21.0 | 3481 | 0.007 |
| 17-Feb-96 | 8.66 | 24.5 | 4471 | 0.005 |
| 22-Feb-96 | 10.84 | 19.0 | 2915 | 0.004 |
| 26-Feb-96 | 9.00 | 25.0 | 4612 | 0.007 |
| 29-Feb-96 | 13.84 | 18.0 | 2632 | 0.007 |
| 01-Mar-96 | 7.87 | 28.5 | 5602 | 0.010 |
| 01-Mar-96 | 9.16 | 28.0 | 5461 | 0.010 |
| 02-Mar-96 | 10.04 | 23.5 | 4188 | 0.007 |
| 03-Mar-96 | 8.75 | 30.5 | 6168 | 0.011 |
| 18-Mar-96 | 8.00 | 35.0 | 7441 | 0.012 |
| 19-Mar-96 | 8.00 | 29.0 | 5744 | 0.009 |
| 22-Mar-96 | 9.00 | 24.0 | 4329 | 0.007 |
| 23-Mar-96 | 9.00 | 31.0 | 6309 | 0.013 |
| 26-Mar-96 | 8.00 | 29.5 | 5885 | 0.007 |
| 01-Apr-96 | 8.00 | 25.5 | 4753 | 0.016 |
| 04-Apr-96 | 8.65 | 35.0 | 74415 | 0.011 |
| 04-Apr-96 | 9.66 | 34.5 | 7300 | 0.016 |
| 10-Apr-96 | 8.00 | 35.0 | 7441 | 0.012 |
| 11-Apr-96 | 7.75 | 32.5 | 6734 | 0.009 |
| 20-Jun-96 | 9.00 | 33.0 | 6875 | 0.005 |
| 28-Jun-96 | 10.00 | 34.5 | 7300 | 0.008 |
| 02-Jul-96 | 9.59 | 35.5 | 7582 | 0.006 |
| 15-Jul-96 | 7.16 | 34.0 | 7158 | 0.007 |
| 16-Jul-96 | 7.55 | 34.5 | 7300 | 0.006 |
| 17-Jul-96 | 8.00 | 34.0 | 7158 | 0.006 |
| 18-Jul-96 | 8.00 | 34.0 | 7158 | 0.009 |
| 19-Jul-96 | 8.25 | 33.0 | 6875 | 0.006 |
| 22-Jul-96 | 9.50 | 31.0 | 6309 | 0.008 |
| 23-Jul-96 | 8.50 | 31.0 | 6309 | 0.003 |
| 24-Jul-96 | 8.30 | 31.0 | 6309 | 0.006 |
| 26-Jul-96 | 9.80 | 30.0 | 6027 | 0.009 |
| 27-Jul-96 | 8.16 | 30.0 | 6027 | 0.005 |
| 30-Jul-96 | 7.84 | 31.0 | 6309 | 0.010 |
| 31-Jul-96 | 7.80 | 29.0 | 5744 | 0.008 |
| 10-Aug-96 | 7.75 | 27.5 | 5319 | 0.004 |
| 12-Aug-96 | 8.50 | 25.0 | 4612 | 0.005 |
| 16-Aug-96 | 7.86 | 24.0 | 4329 | 0.008 |
| 17-Aug-96 | 7.33 | 24.0 | 4329 | 0.004 |
| 19-Aug-96 | 8.00 | 26.5 | 5036 | 0.005 |
| 20-Aug-96 | 9.45 | 29.0 | 5744 | 0.004 |
| 21-Aug-96 | 8.50 | 29.0 | 5744 | 0.002 |
| 23-Aug-96 | 8.30 | 25.0 | 4612 | 0.005 |
| 24-Aug-96 | 8.33 | 25.0 | 4612 | 0.004 |
| 26-Aug-96 | 7.86 | 23.0 | 4046 | 0.003 |

Continued

| Date | Time | H (cm) | Q ($m^3day^{-1}$) | Conc. ($kg\ m^{-3}$) |
|---|---|---|---|---|
| 27-Aug-96 | 7.90 | 23.0 | 4046 | 0.003 |
| 28-Aug-96 | 8.10 | 23.5 | 4188 | 0.004 |
| 30-Aug-96 | 8.00 | 23.5 | 4188 | 0.005 |
| 02-Sep-96 | 7.90 | 25.0 | 4612 | 0.004 |
| 03-Sep-96 | 8.33 | 30.0 | 6027 | 0.010 |
| 04-Sep-96 | 7.75 | 32.5 | 6734 | 0.008 |
| 05-Sep-96 | 10.90 | 28.0 | 5461 | 0.006 |
| 06-Sep-96 | 10.05 | 25.2 | 4669 | 0.004 |
| 10-Sep-96 | 8.90 | 32.0 | 6592 | 0.012 |
| 11-Sep-96 | 9.67 | 43.0 | 15050 | 0.022 |
| 12-Sep-96 | 7.90 | 34.5 | 7300 | 0.009 |
| 13-Sep-96 | 10.33 | 31.0 | 6309 | 0.011 |
| 16-Sep-96 | 8.35 | 30.0 | 6027 | 0.007 |
| 15-Mar-96 | 8.84 | 56.5 | 46993 | 0.066 |
| 15-Mar-96 | 9.84 | 53.0 | 35994 | 0.044 |
| 15-Mar-96 | 11.00 | 50.5 | 29425 | 0.034 |
| 27-Mar-96 | 8.75 | 41.0 | 12339 | 0.016 |
| 28-Mar-96 | 9.26 | 45.5 | 19050 | 0.016 |
| 12-Apr-96 | 8.65 | 50.0 | 28229 | 0.020 |
| 17-Apr-96 | 8.00 | 64.0 | 79026 | 0.025 |
| 17-Apr-96 | 11.56 | 61.0 | 64688 | 0.021 |
| 17-Apr-96 | 13.90 | 58.5 | 54330 | 0.019 |
| 18-Apr-96 | 10.00 | 54.0 | 38911 | 0.039 |
| 20-Apr-96 | 8.50 | 47.0 | 21809 | 0.011 |
| 23-Apr-96 | 10.55 | 50.0 | 28229 | 0.008 |
| 13-May-96 | 9.00 | 43.0 | 15050 | 0.008 |
| 14-May-96 | 9.00 | 43.0 | 15050 | 0.012 |
| 15-May-96 | 9.00 | 43.0 | 15050 | 0.014 |
| 16-May-96 | 9.00 | 47.0 | 21809 | 0.012 |
| 18-May-96 | 9.00 | 42.0 | 13644 | 0.016 |
| 21-May-96 | 9.00 | 44.0 | 16565 | 0.012 |
| 22-May-96 | 9.00 | 42.5 | 14334 | 0.028 |
| 23-May-96 | 9.00 | 44.5 | 17364 | 0.014 |
| 27-May-96 | 9.84 | 44.0 | 16565 | 0.012 |
| 29-May-96 | 9.00 | 43.0 | 15050 | 0.010 |
| 08-May-96 | 9.00 | 43.0 | 15050 | 0.006 |
| 03-Jul-96 | 10.00 | 42.5 | 14334 | 0.013 |
| 04-Jul-96 | 7.67 | 47.0 | 21809 | 0.015 |
| 05-Jul-96 | 11.50 | 60.0 | 60379 | 0.037 |
| 06-Jul-96 | 10.00 | 45.0 | 18193 | 0.012 |
| 17-Sep-96 | 8.50 | 46.0 | 19939 | 0.026 |
| 18-Sep-96 | 9.25 | 40.2 | 11366 | 0.012 |
| 19-Sep-96 | 8.25 | 49.0 | 25949 | 0.027 |
| 03-Oct-96 | 8.50 | 42.0 | 13644 | 0.005 |
| 08-Oct-96 | 8.00 | 52.5 | 34599 | 0.014 |

Continued

| Date | Time | H (cm) | Q ($m^3 day^{-1}$) | Conc. (kg $m^{-3}$) |
|---|---|---|---|---|
| 09-Oct-96 | 8.70 | 53.0 | 35994 | 0.008 |
| 10-Oct-96 | 8.00 | 47.0 | 21810 | 0.012 |
| 14-Oct-96 | 8.75 | 70.0 | 114831 | 0.156 |
| 15-Oct-96 | 8.25 | 49.5 | 27071 | 0.011 |
| 17-Oct-96 | 7.90 | 52.0 | 33246 | 0.018 |
| 19-Oct-96 | 10.05 | 85.0 | 258034 | 0.049 |
| 21-Oct-96 | 9.50 | 58.0 | 52420 | 0.011 |
| 22-Oct-96 | 9.75 | 56.5 | 46994 | 0.009 |
| 23-Oct-96 | 11.10 | 61.0 | 64688 | 0.014 |
| 25-Oct-96 | 9.33 | 58.0 | 52420 | 0.132 |
| 31-Oct-96 | 8.25 | 54.0 | 38912 | 0.008 |
| 08-Nov-96 | 8.00 | 46.5 | 20858 | 0.006 |
| 11-Nov-96 | 14.90 | 61.0 | 64688 | 0.210 |
| 12-Nov-96 | 7.75 | 45.0 | 18193 | 0.010 |
| 14-Nov-96 | 8.67 | 43.0 | 15051 | 0.008 |
| 16-Nov-96 | 8.10 | 42.0 | 13644 | 0.006 |
| 23-Nov-96 | 7.95 | 40.0 | 11132 | 0.009 |
| 25-Nov-96 | 10.00 | 45.5 | 19051 | 0.018 |
| 26-Nov-96 | 8.05 | 42.0 | 13644 | 0.011 |
| 27-Nov-96 | 8.35 | 47.0 | 21810 | 0.016 |
| 28-Nov-96 | 8.67 | 41.5 | 12980 | 0.010 |
| 29-Nov-96 | 8.90 | 40.0 | 11132 | 0.008 |
| 02-Dec-96 | 8.55 | 38.5 | 9492 | 0.008 |
| 04-Dec-96 | 8.95 | 37.8 | 8793 | 0.008 |
| 07-Dec-96 | 8.45 | 38.0 | 8989 | 0.005 |
| 10-Dec-96 | 8.48 | 36.0 | 7724 | 0.007 |
| 12-Dec-96 | 8.45 | 35.5 | 7583 | 0.007 |

## Annex 6 Sediment concentrations Nyangong river, Nyangong

| Date | Time | H (cm) | Q ($m^3 day^{-1}$) | Conc. ($kg\ m^{-3}$) |
|---|---|---|---|---|
| 09-Feb-96 | 10.00 | 32.0 | 13601 | 0.044 |
| 17-Feb-96 | 8.30 | 16.0 | 1672 | 0.018 |
| 08-Mar-96 | 8.25 | 15.0 | 1376 | 0.016 |
| 11-Mar-96 | 7.66 | 23.0 | 5010 | 0.016 |
| 12-Mar-96 | 8.20 | 18.0 | 2388 | 0.012 |
| 14-Mar-96 | 7.50 | 14.0 | 1117 | 0.010 |
| 15-Mar-96 | 6.90 | 26.0 | 7259 | 0.038 |
| 17-Mar-96 | 7.33 | 24.0 | 5698 | 0.014 |
| 18-Mar-96 | 8.34 | 20.0 | 3283 | 0.012 |
| 20-Mar-96 | 21.10 | 12.0 | 701 | 0.014 |
| 21-Mar-96 | 10.05 | 30.0 | 11190 | 0.038 |
| 26-Mar-96 | 10.00 | 16.0 | 1672 | 0.040 |
| 27-Mar-96 | 9.25 | 29.0 | 10099 | 0.022 |
| 27-Mar-96 | 18.50 | 21.0 | 3805 | 0.021 |
| 30-Mar-96 | 8.00 | 19.0 | 2812 | 0.012 |
| 02-Apr-96 | 13.50 | 14.5 | 1242 | 0.014 |
| 02-Apr-96 | 20.27 | 38.0 | 22870 | 0.495 |
| 09-Apr-96 | 7.00 | 46.0 | 40755 | 0.058 |
| 10-Apr-96 | 7.00 | 24.0 | 5698 | 0.015 |
| 14-Apr-96 | 7.00 | 52.0 | 59046 | 0.078 |
| 16-Apr-96 | 19.90 | 55.0 | 69961 | 0.116 |
| 16-Apr-96 | 21.00 | 60.0 | 91018 | 0.110 |
| 16-Apr-96 | 22.00 | 61.0 | 95684 | 0.074 |
| 17-Apr-96 | 6.33 | 47.0 | 43493 | 0.034 |
| 17-Apr-96 | 7.00 | 45.0 | 38134 | 0.034 |
| 17-Apr-96 | 18.35 | 32.0 | 13601 | 0.016 |
| 22-Apr-96 | 7.00 | 44.0 | 35629 | 0.036 |
| 24-Apr-96 | 18.25 | 26.0 | 7259 | 0.012 |
| 01-May-96 | 7.00 | 22.0 | 4380 | 0.015 |
| 04-May-96 | 7.40 | 25.0 | 6447 | 0.013 |
| 27-May-96 | 17.67 | 31.0 | 12356 | 0.026 |
| 30-May-96 | 17.50 | 41.0 | 28778 | 0.232 |
| 21-Jun-96 | 9.83 | 15.0 | 1376 | 0.009 |
| 05-Jul-96 | 8.00 | 52.0 | 59046 | 0.140 |
| 05-Jul-96 | 12.25 | 59.0 | 86508 | 0.072 |
| 07-Jul-96 | 7.10 | 24.0 | 5698 | 0.015 |
| 25-Jul-96 | 9.45 | 15.0 | 1376 | 0.012 |
| 26-Jul-96 | 16.10 | 13.0 | 892 | 0.007 |
| 01-Aug-96 | 18.33 | 17.0 | 2009 | 0.023 |
| 03-Sep-96 | 9.90 | 23.0 | 5010 | 0.016 |
| 06-Sep-96 | 7.10 | 19.0 | 2812 | 0.018 |
| 09-Sep-96 | 7.25 | 17.0 | 2009 | 0.013 |
| 09-Sep-96 | 18.50 | 20.0 | 3283 | 0.011 |
| 12-Sep-96 | 18.10 | 26.0 | 7259 | 0.033 |

Continued

| Date | Time | H (cm) | Q ($m^3 day^{-1}$) | Conc. (kg $m^{-3}$) |
|---|---|---|---|---|
| 15-Sep-96 | 7.50 | 18.0 | 2388 | 0.014 |
| 17-Sep-96 | 7.33 | 25.0 | 6447 | 0.020 |
| 20-Sep-96 | 18.20 | 38.0 | 22870 | 0.066 |
| 21-Sep-96 | 7.20 | 43.0 | 33236 | 0.036 |
| 24-Sep-96 | 16.25 | 41.0 | 28778 | 0.046 |
| 30-Sep-96 | 8.67 | 34.0 | 16338 | 0.017 |
| 01-Oct-96 | 18.25 | 55.0 | 69961 | 0.046 |
| 03-Oct-96 | 18.00 | 44.0 | 35629 | 0.060 |
| 05-Oct-96 | 9.00 | 37.0 | 21098 | 0.008 |
| 07-Oct-96 | 17.50 | 65.0 | 115944 | 0.144 |
| 07-Oct-96 | 19.33 | 89.0 | 299885 | 0.160 |
| 08-Oct-96 | 2.45 | 64.0 | 110634 | 0.034 |
| 08-Oct-96 | 6.50 | 54.0 | 66185 | 0.018 |
| 08-Oct-96 | 18.75 | 48.0 | 46353 | 0.009 |
| 11-Oct-96 | 10.10 | 36.0 | 19420 | 0.009 |
| 15-Oct-96 | 17.00 | 31.0 | 12356 | 0.010 |
| 17-Oct-96 | 13.90 | 32.0 | 13601 | 0.017 |
| 17-Oct-96 | 18.55 | 40.0 | 26707 | 0.031 |
| 18-Oct-96 | 19.20 | 34.0 | 16338 | 0.009 |
| 21-Oct-96 | 7.67 | 32.0 | 13601 | 0.010 |
| 24-Oct-96 | 15.00 | 30.0 | 11190 | 0.009 |
| 25-Oct-96 | 7.90 | 40.0 | 26707 | 0.057 |
| 25-Oct-96 | 8.30 | 34.0 | 16338 | 0.040 |
| 25-Oct-96 | 20.90 | 49.0 | 49335 | 0.140 |
| 25-Oct-96 | 22.67 | 59.0 | 86508 | 0.093 |
| 26-Oct-96 | 7.00 | 40.0 | 26707 | 0.023 |
| 27-Oct-96 | 17.50 | 34.0 | 16338 | 0.027 |
| 31-Oct-96 | 8.67 | 41.0 | 28778 | 0.038 |
| 08-Nov-96 | 7.18 | 27.0 | 8137 | 0.008 |
| 16-Nov-96 | 16.90 | 38.0 | 22870 | 0.068 |
| 24-Nov-96 | 19.05 | 24.0 | 5699 | 0.006 |
| 25-Nov-96 | 3.25 | 26.0 | 7259 | 0.012 |
| 25-Nov-96 | 5.59 | 38.0 | 22870 | 0.054 |
| 25-Nov-96 | 11.45 | 42.0 | 30953 | 0.046 |
| 25-Nov-96 | 19.33 | 34.0 | 16337 | 0.020 |
| 06-Dec-96 | 7.00 | 26.0 | 7259 | 0.022 |

## Annex 7 Data input for hydrological modelling with LISEM

### MAPS

| | |
|---|---|
| AREA.MAP | Map of the catchment area, calculated with the WATERSH program from the digital elevation model, contains 12,353 25 x 25 m cells. |
| ID.MAP | Map showing the areas allocated to each rain gauge. Two rain gauges were installed. |
| LDD.MAP | Map showing the local drain direction for each cell, calculated with the WATERSH program. |
| GRAD.MAP | Map of the slope gradient, calculated from the digital elevation model, values of zero changed to 0.001. |
| OUTLET.MAP | Map showing the outlet of the catchment. |
| ROADWIDT.MAP | Map showing the width of the roads in the catchment. The width of the main road was set at 10 m, those of the skid tracks at 6 m (Class 2) and 4 m (Class 3). This map is shown in Figure 17. No roads in the undisturbed forest scenario. |
| LAI.MAP | Map of the leaf area index, forest 7.0 $m^2$ $m^{-2}$, main road 0.3 $m^2$ $m^{-2}$ (Class 1), skid roads 3.0 $m^2$ $m^{-2}$ (Class 2) and 4.3 $m^2$ $m^{-2}$ (Class 3). Uniform LAI of 7.0 $m^2$ $m^{-2}$ used for the undisturbed forest scenario. |
| PER.MAP | Map of the soil coverage by vegetation. Undisturbed forest 0.98, main road 0.31, skid roads 0.58 (Class 2) and 0.71 (Class 3). |
| RR.MAP | Map of the random roughness. Set at 2.0 cm for the whole area. |
| CH.MAP | Map of the crop height. Set at 28.5 m over the whole area (maximum allowed = 30 m). |
| AGGRSTAB.MAP | Map of the soil aggregate stability. Set at 180 for the whole area. |
| COH.MAP | Map of the soil cohesion. Set at 4.1 KPa for the whole catchment. |
| COHADD.MAP | Map of the added cohesion of the soil by roots. Set at 4.0 for the forest and at 0.0 for road surfaces. |

| | |
|---|---|
| N.MAP | Map of the Mannings roughness coefficient. Set at 0.3 for the whole area. |
| D50.MAP | Map of the d50 particle size value of the soil. Set at 80 μm for the whole catchment. |
| STONEFRC.MAP | Map of the fraction of the soil covered by stones. Estimated range of 0.004 for flat areas to 0.169 for steep areas. |
| WHEELWID.MAP | Width of wheel tracks set at 1 m for the main road and 0.5 m for the skid tracks. |
| GRASSWIDT.MAP | Width of grassed waterways, not present, set at 0.0 for the whole area. |
| LDDCHAN.MAP | Local drain direction of channel cells, calculated with the WATERSH program. |
| CHANGRAD.MAP | Map of the channel gradient, calculated from grad.map. |
| CHANMAN.MAP | Mannings roughness value for the channel set at 0.04. |
| CHANCOH.MAP | Cohesion of channel bed set at 175. |
| CHANWIDT.MAP | Calculated from upstream elements map (WATERSH program). Width varies between 2.3 m and 4.1 m. |
| CHANSIDE.MAP | Calculated from upstream elements map (WATERSH program). Range 0.6-1.0. |
| PROFILE.MAP | Map showing the locations of the various soil profiles (3 types present: undisturbed forest, main road, skid roads). |
| PROFWLTR.MAP | Tractor wheels profile type. Not used, set at 0.0. |
| HEADOUT.MAP | Locations of detailed soil profile moisture output. |
| INITHEAD.001 | Initial pressure head for soil horizon 1, -70 cm used for the whole area. |
| INITHEAD.002,003 | Initial pressure heads for horizons/type 2 and 3, -200 cm used for the whole area. |

## TABLES

MAINROAD.TBL: Table with physical properties of main road soil, estimated values given below.

| Theta | Pressure head (cm) | Ksat (cm day$^{-1}$) |
|---|---|---|
| 0.050 | -1.00E+15 | 0.01E-15 |
| 0.258 | -3.16E+04 | 0.01E-13 |
| 0.263 | -1.00E+04 | 0.01E-12 |
| 0.272 | -3.16E+03 | 0.01E-11 |
| 0.288 | -1.00E+03 | 0.01E-10 |
| 0.315 | -3.16E+02 | 0.01E-08 |
| 0.360 | -1.00E+02 | 0.13E-06 |
| 0.432 | -3.16E+01 | 4.40E-04 |
| 0.523 | -1.00E+01 | 0.84E-03 |
| 0.585 | -3.16E+00 | 5.96E-02 |
| 0.600 | -1.00E+00 | 1.54E-01 |

SKIDROAD.TBL: Table with physical properties of skid road soil, estimated values given below.

| Theta | Pressure head (cm) | Ksat (cm day$^{-1}$) |
|---|---|---|
| 0.050 | -1.00E+15 | 0.01E-15 |
| 0.258 | -3.16E+04 | 0.01E-13 |
| 0.263 | -1.00E+04 | 0.01E-12 |
| 0.272 | -3.16E+03 | 0.01E-11 |
| 0.288 | -1.00E+03 | 0.01E-10 |
| 0.315 | -3.16E+02 | 0.01E-08 |
| 0.360 | -1.00E+02 | 0.13E-06 |
| 0.432 | -3.16E+01 | 4.40E-04 |
| 0.523 | -1.00E+01 | 0.84E-02 |
| 0.585 | -3.16E+00 | 5.96E+00 |
| 0.600 | -1.00E+00 | 1.54E+01 |

PERM.TBL: Table with physical properties of the forest topsoil, estimated values given below.

| Theta | Pressure head (cm) | Ksat (cm $day^{-1}$) |
|---|---|---|
| 0.271 | -3.16E+04 | 0.01E-08 |
| 0.282 | -1.00E+04 | 0.01E-06 |
| 0.299 | -3.16E+03 | 0.01E-05 |
| 0.325 | -1.00E+03 | 0.01E-03 |
| 0.365 | -3.16E+02 | 2.00E-03 |
| 0.426 | -1.00E+02 | 4.20E-02 |
| 0.515 | -3.16E+01 | 1.00E+00 |
| 0.623 | -1.00E+01 | 1.80E+01 |
| 0.707 | -3.16E+00 | 1.06E+02 |
| 0.739 | -1.00E+00 | 5.05E+02 |

UNPERM.TBL: Table with physical properties of the forest subsoil, estimated values given below.

| Theta | Pressure head (cm) | Ksat (cm $day^{-1}$) |
|---|---|---|
| 0.249 | -3.16E+04 | 0.01E-09 |
| 0.266 | -1.00E+04 | 0.01E-08 |
| 0.289 | -3.16E+03 | 0.01E-06 |
| 0.321 | -1.00E+03 | 0.01E-05 |
| 0.364 | -3.16E+02 | 0.01E-04 |
| 0.423 | -1.00E+02 | 0.15E-03 |
| 0.499 | -3.16E+01 | 0.30E-01 |
| 0.592 | -1.00E+01 | 0.51E+00 |
| 0.679 | -3.16E+00 | 5.40E+00 |
| 0.728 | -1.00E+00 | 2.64E+01 |

**RAINFALL INPUT: FILE P230396.MIN**

RUU CSF TIMESERIE INTENSITY NORMAL 2
station_1
station_2

| | | |
|---|---|---|
| 805 | 0.0 | 0.0 |
| 810 | 4.8 | 0.0 |
| 815 | 2.4 | 0.0 |
| 820 | 0.0 | 0.0 |
| 825 | 0.0 | 38.4 |
| 830 | 0.0 | 40.8 |
| 835 | 0.0 | 33.6 |
| 840 | 0.0 | 38.4 |
| 845 | 0.0 | 36.0 |
| 850 | 0.0 | 31.2 |
| 860 | 9.6 | 12.0 |
| 865 | 4.8 | 7.2 |
| 870 | 7.2 | 33.6 |
| 875 | 26.4 | 19.2 |
| 880 | 64.8 | 21.6 |
| 885 | 31.2 | 16.8 |
| 890 | 36.0 | 33.6 |
| 895 | 43.2 | 0.0 |
| 900 | 45.6 | 0.0 |
| 905 | 38.4 | 14.4 |
| 910 | 38.4 | 2.4 |
| 915 | 45.6 | 4.8 |
| 920 | 36.0 | 12.0 |
| 925 | 21.6 | 4.8 |
| 930 | 31.2 | 4.8 |
| 935 | 14.4 | 12.0 |
| 940 | 9.6 | 12.0 |
| 945 | 2.4 | 12.0 |
| 950 | 2.4 | 12.0 |
| 955 | 2.4 | 12.0 |
| 960 | 2.4 | 12.0 |
| 965 | 2.4 | 9.6 |
| 970 | 4.8 | 9.6 |
| 975 | 2.4 | 9.6 |
| 980 | 2.4 | 9.6 |
| 985 | 4.8 | 9.6 |
| 990 | 7.2 | 9.6 |
| 995 | 7.2 | 7.2 |
| 1000 | 2.4 | 7.2 |
| 1005 | 0.0 | 7.2 |
| 1010 | 0.0 | 7.2 |
| 1015 | 2.4 | 2.4 |
| 1010 | 0.0 | 0.0 |

| | | |
|---|---|---|
| 1015 | 0.0 | 0.0 |
| 1020 | 0.0 | 0.0 |
| 1025 | 0.0 | 0.0 |
| 1030 | 0.0 | 0.0 |
| 1035 | 0.0 | 2.4 |
| 1040 | 2.4 | 0.0 |
| 1045 | 0.0 | 0.0 |
| 1050 | 0.0 | 2.4 |
| 1055 | 0.0 | 0.0 |
| 1060 | 0.0 | 0.0 |
| 1065 | 0.0 | 2.4 |
| 1300 | 0.0 | 0.0 |

End of rainfall file. First column represents the time (in minutes), second and third columns are rainfall intenities (mm $h^{-1}$).

**OVERALL SETTINGS IN THE PRE.RUN FILE.**

| | |
|---|---|
| Map directory | c:\hydro\lisem\minwomap |
| Tables directory | c:\hydro\lisem\minwotbl |
| Output directory | c:\hydro\lisem\minwoout |
| Name of rainfall file | p230396.min |
| Start time (min) | 805.0 |
| End time (min) | 1300.0 |
| Simulation timested (sec) | 30 |
| Print option | 30 |
| Infiltration method (SWATRE) | 1 |
| Minimum sim. time SWATRE (days) | 0.0001 |
| Precision factor SWATRE | 1 |
| Settling velocity | 0.0005 |
| Critical unit stream power | 0.8 |
| Splash delivery ratio | 0.000001 |
| Mannings n for waterways | 0.600 |
| Expected rill width | 0.4 |
| Critical velocity for rills | 0.8 |
| Erosion map name | eroslog.map |
| Deposition map name | deposlog.map |
| Results file name | reslog.dat |
| Output file names | outlog.dat |
| | out_1log.dat |
| | out_2log.dat |
| Answer | n |
| Answer yes for runoff maps | y |
| Time of first runoff map | 810 |
| second map etc. | 900 |
| | 950 |
| | 1000 |
| | 1050 |
| | 1100 |
| | 1300 |
| End of runoff map generation | 0 |
| Prefix of runoff maps | LQ |