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Conrado Tobón Marin

The Tropenbos Foundation
Wageningen, the Netherlands
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The Tropenbos Series presents the results of studies and research activities related to the conservation and wise utilization of forest lands in the humid tropics. The series continues and integrates the former Tropenbos Scientific and Technical Series. The studies published in this series have been carried out within the international Tropenbos programme. Occasionally, this series may present the results of other studies which contribute to the objectives of the Tropenbos programme.

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To my mother, Ofelia
To the memory of my father, Carlos (R.I.P.)
To my wife, Lina Maria

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1. GENERAL INTRODUCTION

At the global scale, Amazonia has been conceived as the ecosystem containing almost half of the world's undisturbed tropical forest with a high biodiversity. Because of its size, the amount of fixed CO_2 in the vegetation, the water stored in these (Leopoldo *et al.,* 1987) and in other ecosystem compartments and the related Soil Vegetation Atmosphere Transfer processes (SVAT), changes in Amazonian vegetation such as large scale deforestation might well have a large impact on global climate and biogeochemical cycles at a global scale (Gash *et al.,* 1996; Shuttleworth, 1988). The special hydrological significance of this forest is particularly due to its high total evapotranspiration, resulting largely from the fact that, compared with other vegetation types, a substantial and large proportion of incident rainfall is evaporated after interception by the canopy. At the regional scale, too, the disappearance of the forest may have large impacts on the hydrology and climate, for instance, of the Andean Mountains, which border the Amazon basin. These mountains act as a barrier blocking most of the humidity coming from Amazonia, which results in high precipitation rates throughout the year. Thus a major part of the evaporated water from the basin condenses and returns to the area through the Andean rivers. The relation between the eastern Andean slopes and Amazonia has been described as a feedback relation (Leopoldo *et al.,* 1987), where precipitation in the Andes depends on the existence of the Amazonian forest with its large evapotranspiration and these mountains. At the local scale, large land-use changes can lead to changes in rainfall amounts and distribution. More important are the changes in water fluxes and catchment discharge, which in different ways affect the remaining forests and local population. Land degradation brought about by loss of nutrients, soil erosion and increases of runoff are the immediate consequences (Bosch and Hewlett, 1982; Armstrong *et al.,* 1980).

At international level, there is a general concern about the conservation of tropical rain forests and a need for scientific research to increase the knowledge and understanding of the functioning of these ecosystems. This has been translated into major research programmes and attempts to develop and stimulate alternative types of land use including sustainable forestry and agricultural types of land use. One of these initiatives is the Dutch Tropenbos Programme, which is being executed in a number of countries including Colombia. The Tropenbos Foundation was established in 1988, as a continuation of the Tropenbos programme, which was active since 1986. The programme is an initiative of the Dutch government to contribute to the conservation and promote the wise use of tropical rain forests and to support local institutes with the same objectives. By the time the research programme started in Colombian Amazonia (1987), there was almost no basic scientific information regarding biophysical aspects and functioning of ecosystems in that area. Therefore, a research programme was established in agreement with local institutes concerning the main aspects to be investigated and knowledge required for the understanding of the natural ecosystems, and to provide information for sustainable land use planning and forest management. Initially, the programme largely dealt with inventory studies, such as soil surveys (Abaunza and Tobón, 1994; Ordoñez, 1992; Alarcón, 1990), vegetation studies (Duivenvoorden and Lips, 1995; Alvarez, 1993; Londoño, 1993; Rodriguez, 1991; Urrego 1994) and ecological studies and mapping (Duivenvoorden and Lips, 1995; Duivenvoorden, 1993). In the early nineties, research turned to process oriented studies on ecosystem functioning and the current project was formulated, as part of a larger research project on the hydrological and nutrient cycling in representative forest ecosystems. Other aspects which received attention were root dynamics and below ground biomass (de Vente, 1999; Wassenaar, 1995), litter production and turnover (Overman *et al.*, 1994; Beijers, 1993) and forest recovery (Vester and Cleef, 1998; Vester, 1997; Saldarriaga, 1996).

Hydrological studies of the Amazonian rain forest are of broad relevance for scientists and local and global policy makers. Reasons range from the needs to predict the consequences of deforestation, to include the hydrological forest characteristics into global models (Lesack, 1993; Shukla *et al.*, 1990; Salati and Vose, 1984), to understand biogeochemical fluxes through the forest compartments and ecosystems (Vorosmarty *et al.*, 1989; this issue), and for local policy makers to define the appropriate sustainable land use and management and the conservation of tropical rain forests and its biodiversity. A hydrological and nutrient cycling study of mature forests in the Middle Caquetá is required to provide information on the initial conditions of undisturbed forests and of related processes, which contribute to the understanding of the ecosystem functioning. Understanding water fluxes, as the key factor in physical, chemical and biotic processes, is vital to understand nutrients dynamics in the ecosystem. Hydrological studies at compartment level allow for a detail study of nutrient fluxes, which contributes to the overall understanding of the nutrient dynamics in the studied ecosystems.

Most hydrological research in the Amazon basin has been and still is concentrated in central Amazonia (LBA, Nobre *et al.*, 1996; ABRACOS, Gash *et al.*, 1996; Lloyd *et al.*, 1988; Shuttleworth *et al.*, 1984), although some research has been carried out in coastal areas (Jetten, 1996; Poels, 1987). Reasons probably lie in factors such as the availability of basic information on and facilities in the area. They comply with the proposal by Bruijnzeel (1996), that 'research efforts should be concentrated on a relatively small number of well researched key locations, with long term records to be linked in a pan tropical network information'. However, the consequence is that very little attention has been paid to areas, in which conditions differ from those of central Amazonia with respect to rainfall amounts and distribution, forest types and soils. One of the areas concerning this lack of knowledge relates to the Northwest part of Amazonia, which represents the most humid region of Amazonia as a whole, in which there are very few studies on the hydrology and nutrient cycling. For the Colombian part of it, such studies are virtually non-existent.

Accordingly, a full scale study of forest hydrology in all its aspects was required to understand nutrient cycling dynamics in the forest ecosystems of the Middle Caquetá, Colombian Amazonia. Moreover, comprehensive and detailed studies of soils and vegetation of forest ecosystems in this area (Duivenvoorden and Lips, 1995; Alvarez, 1993; Londoño, 1993) pointed to the existence of major differences in soils and forest types between the physiographic units in this part of Amazonia. This heterogeneity of landforms and forest ecosystems might result in significant differences in water storage and fluxes through the ecosystem compartments and between ecosystems, which may affect the spatial and temporal patterns in evapotranspiration, soil moisture and drainage. Therefore, this study comprises four representative forest ecosystems (i.e. represented with most surface cover), located in four main physiographic units in the Middle Caquetá.

Instead of pursuing a water balance study where the ecosystem is considered as a unit (black box approach), a compartment approach was followed in which the upper and lower boundary conditions at each forest compartment and the internal processes were either measured or predicted through simulation models. Such a compartment approach allows to identify factors and parameters affecting the hydrological behaviour at this level and link these to the entire ecosystem. Moreover, it provides specific information on the water fluxes between and water stocks in each compartment, which is essential to understand the processes controlling nutrient cycling and allows to link site-specific conditions to ecosystem functioning.

The application of models in ecology is required if we want to understand the functioning of complex ecosystems as those of tropical rain forests. It is therefore not surprising that modelling is nowadays a widely used technique as a tool to assess and to understand the processes and properties of some ecosystems. An important aspect of a hydrological research is the link between field observations, as a case of study, and models in an effort to identify the system parameters influencing water fluxes and the dynamics of these fluxes. It is also relevant to assess the understanding of the modelled linkages of the processes within an ecosystem and among studied ecosystems. One of the objectives of modelling is to extrapolate this understanding and the applicability of the model to other sites and time at which water fluxes have not been studied, or to those where the land use and land cover have been changed. This study includes some modelling approach for a better understanding of functioning of ecosystems studied.

1.1 OBJECTIVES

The central objective of this research is the assessment of the water balance of four representative undisturbed forest ecosystems in Colombian Amazonia. This water balance was studied by describing and quantifying the temporal and spatial dynamics of hydrological fluxes through the forest compartments, namely forest canopy, forest floor and mineral soil. Results may serve as reference for undisturbed conditions, to characterise nutrient cycling in such areas and to evaluate the hydrological impacts of changes in land use.

The need for the characterisation of hydrological processes and fluxes, which can not be measured, led to the second objective: to apply existing hydrological models, to develop these if required and to identify the parameters controlling the fluxes and storage. These models can be used for the extrapolation of time series within the area studied and for scenarios to be used in the evaluation of changing conditions.

Characterisation of the climate of the study area is of obvious importance for hydrological studies. Therefore, the third objective of the research is multiple: to analyse collected long term and detailed data on meteorological variables, to characterise forest transpiration, to provide inputs for the models and to enable relating climatic factors to the hydrological functioning of the systems studied.

Dynamics in water moving from the forest canopy to the stream may result in spatial and temporal variation in water and connected nutrient fluxes, which can be related to specific conditions in each ecosystem. Hence, a fourth objective is to discuss the implications of the overall results for the nutrient cycling in undisturbed forest ecosystems and for forest management.

As described above, at the onset of this research, there was no information on hydrological fluxes in Colombian Amazonia. The fifth objective of the research, therefore, is to contribute in a more general way to the understanding of the hydrology of tropical rain forests in the Amazon basin, by providing relevant data on climate and hydrology of four forest types in Northwest Amazonia.

1.2 OUTLINE OF THE THESIS

In this thesis, the results from the hydrological research and the analysis of collected data are presented according to the top down water fluxes within a forest ecosystem, (Figure 1.1): inputs (gross rainfall), fluxes (throughfall, stemflow, litterflow and soil water fluxes) and outputs (evaporation, transpiration and underground drainage). This information is related to some measured forest and forest floor characteristics and to some soil properties, to define relationships.

The introduction to the research topic, the objectives and the research approach of monitoring and modelling is presented in chapter 1. The research sites with the biophysical aspects are presented in chapter 2. The soil description is presented as an appendix and the actual land use in the Middle Caquetá area is discussed. The climate of the area is characterised through meteorological data collected continuously during the period 1992 until 1997, on 20 minutes basis. Reference transpiration is calculated and presented separate from evaporation of intercepted rainfall by the forest canopy. Chapter 3 focuses on the analysis of data on gross rainfall, throughfall, stemflow and evaporation from the forest canopy, in the four forest ecosystems studied. Evaporation of intercepted water by the forest canopy is related to different climatic parameters (rainfall amounts and characteristics) as well as vegetation characteristics (e.g. forest cover). Static models are derived from the observed relationships.

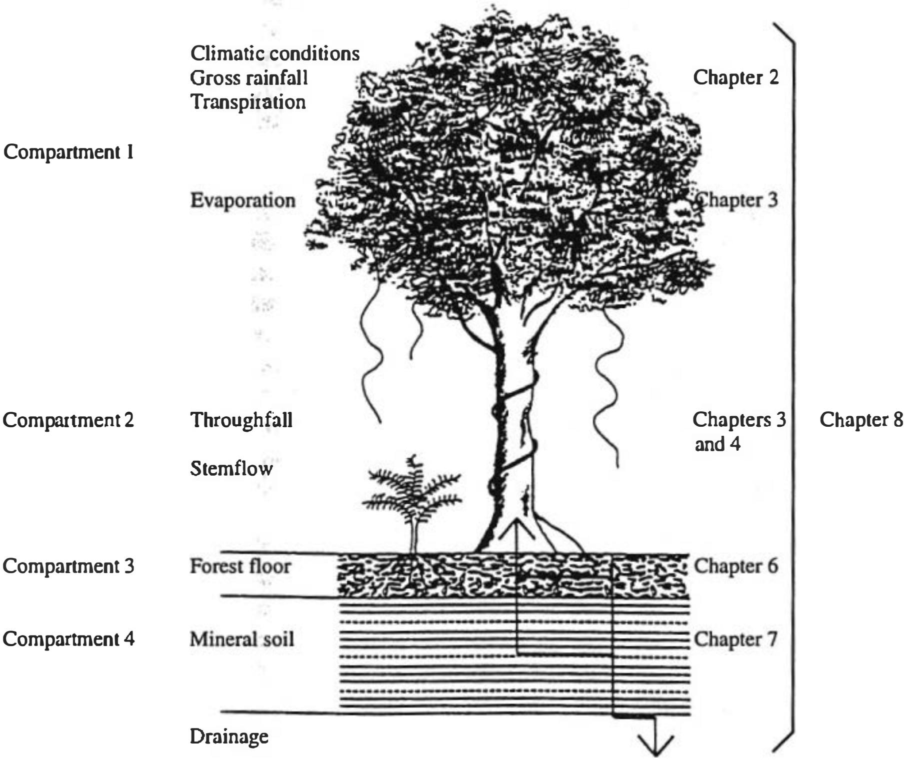

Figure 1.1 Schematic representation of the monitored and modelled hydrological fluxes through forest compartments (represented by a single tree) in Colombian Amazonia. The location of the information within this study regarding each compartment is indicated by the chapter number. Chapters 1, 5 and 9 correspond to the general introduction, calibration of water content measurements and conclusions respectively.

Modelling of rainfall interception is approached in chapter 4. This chapter provides an important insight into modelling of forest interception processes and contributes to define the relevant forest parameters affecting net rainfall and evaporation of intercepted rainfall. Both, static and dynamic models are evaluated in terms of their suitability to extrapolate the measurements to different periods for which they are calibrated and to different locations (ecosystems). For accurate determination of forest floor and soil water content and storage amounts, calibration of TDR water content measurements, in both the FF and mineral soil, was required. The values of calibrated parameters, for the FF and mineral soil separately, and the linear models are presented in chapter 5. Calibrated parameters are used for the determinations of the FF and soil volumetric water content from the TDR measurements. The presence of a thick litter layer, or forest floor (FF), and the abundance of fine roots in this layer, requires that the hydrological fluxes and processes in this compartment are studied separately. Chapter 6 presents the results of the analysis of collected information on FF water storage, water content and drainage (litterflow). Processes related to net rainfall partitioning in the FF, namely total drainage to the mineral soil, root water uptake and storage changes, could not be identified from the measurements since they often occur simultaneously. Therefore, a FF interception model was developed from the Rutter's concept of canopy rainfall interception. The dynamic model, calibrated values of model parameters and the identification and quantification of these processes are also presented in this chapter. Chapter 7 deals with the analysis of collected data on soil water content, soil pressure head and soil water storage at 8 different depths in the four physiographic units in the Middle Caquetá. Soil water uptake and soil water fluxes are simulated through the SWIF model, by using field data as input to the model, without calibration of parameters. This method has the advantage that a split of data, to assess the capability of the model to reproduce further measurements, is not required. Model results for each unit, the related statistics and the analysis are presented and compared. In chapter 8 the results from previous chapters are numerically integrated into a compartment-based overall hydrological water balance, pertaining to a period of four years. The components of the water balance are separately evaluated for each compartment, with evapotranspiration (evaporation and transpiration) being quantified separately. General conclusions are presented in chapter 9 together with the discussions related to the possible implications of overall results for nutrient cycling and forest management. Finally, the summary is presented.

2. GENERAL INFORMATION ON THE RESEARCH AREA: MIDDLE CAQUETA–COLOMBIAN AMAZONIA

2.1 INTRODUCTION

The research sites are located in the Middle Caquetá (Colombian Amazonia), which lies in the Northwest part of the Amazon basin. Through earlier projects by Tropenbos (1987-1995) and Proradam (1979) information is available in particular on the geology, geomorphology, soils and vegetation of this area, whereas information on aspects such as climate and hydrology remained extremely scarce. This Chapter therefore consists of two parts. The first part deals with the general characteristics of the area including its geology, geomorphology, drainage system, soils, vegetation and land use. It largely consists of a review of existing literature and data. The second part pertains to the climate of the area. Several parameters relevant for the later Chapters are extensively discussed. The data concerned were collected during the period 1992-1997 at a climatic station in the area of research.

2.2 GENERAL CHARACTERISTICS

2.2.1 Location

The Amazon basin covers an area of approximately 7.05 millions km^2 of which 6% corresponds to Colombian Amazonia (403.0000 km^2). The Middle Caquetá is located in the Southeast of Colombia or Northwest part of the Amazon basin, between 0° 37' and 1° 24' latitude S and 72° 23' and 70° 43' longitude W (see Figure 2.1). In this area four major types of landscape can be distinguished: 1) a large, level sedimentary plain of Late Tertiary age at an altitude of about 250-300m a.s.l.; 2) isolated sandstone plateaus standing over this plain; 3) the alluvial system of floodplains and terraces of Andean rivers, including the Caquetá river, between 200-250m a.s.l.; 4) the system of floodplains and terraces of Amazonian rivers.

The sites are located in the two main landscapes: Tertiary sedimentary plain (SP) and the alluvial system of the River Caquetá with the high (HT) and low terraces (LT) and rarely inundated flood plain (FP). These sites are within the research areas of the Tropenbos Foundation at Peña Roja and were selected as being representative areas for the ecosystems in the main landscapes (physiographic units) in this part of Amazonia.

2.2.2 Geology and geomorphology

In the Middle Caquetá area, four main geological units can be distinguished corresponding to the landscapes mentioned above: sandstones covering a basement of igneous and metamorphic rocks, which is locally exposed along the River Caquetá; a Tertiary sedimentary complex; sediments of the River Caquetá including high and low terraces and a floodplain; and sediments of Amazonian rivers.

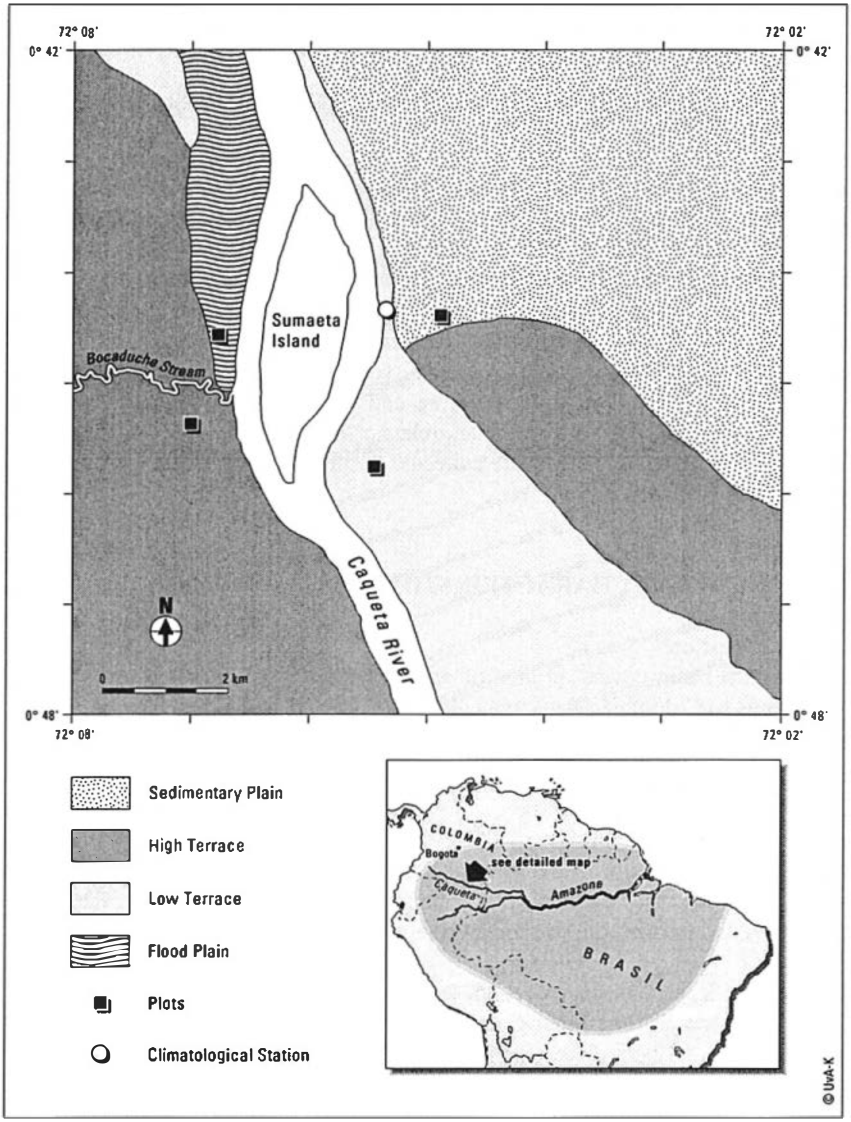

Figure 2.1 Location of the research area in the Middle Caquetá, Colombian Amazonia. The detail map (deduced from Duivenvoorden and Lips, 1993) shows the specific location of the climatological station (AWS) and the research sites in the four physiographic units: the Tertiary sedimentary plain (SP), high terrace (HT), low terrace (LT) and flood plain (FP) of the River Caquetá. The grey-toned area in the general map corresponds to the Amazon Basin area, according to Leopoldo et al. (1987).

Sandstone plateaus occur near Araracuara and near Santa Isabel, about 50 km downstream of Araracuara, in both areas forming elongated N-S running plateaus. According to van der Hammen (1954) the sandstones belong to the Palaeozoic Araracuara Formation and are highly quartzitic. The plateaus have a flat to slightly irregular topography, with a prominent system of deep fissures and associated angular drainage pattern.

During the Miocene, marine incursions reached the Amazon basin and mainly fluvio-lacustrine sediments started to be deposited, covering a rather level older erosional surface developed on the basement rocks. Initially, these sediments originated from the Guyana shield (Hoorn, 1993). Studies on the composition of the lower members along the River Caquetá showed that the sediments are composed of very stable minerals only, with tourmaline, zircon and rutile dominating the heavy mineral fractions. They were deposited by a low sinuosity fluvial system with an anastomosing character, and with backswamps, shallow lakes, channels and crevasse splays (Hoorn, 1993). Later, i.e. during the Middle Miocene, the provenance of the sediments changed as a result of the orogenesis of the Andes and connected changes in the direction of the rivers transporting sediments into the basin, becoming W-E. The higher members largely consist of quartzitic sands with some micas and ferruginous crusts, intercalated with sandy clay and clays.

The Tertiary sediments reach an altitude of between 40 and 70 m above the mean level of the River Caquetá and constitute a highly dissected plain (Hoorn, 1994; Botero, 1980). Hoorn (1994) distinguished three types of dissection in this unit. The first is characterised by a deep dissection of about 40 to 60 m and steep (25 to 35 degrees), straight slopes with V-shaped valleys and a dense dendritic pattern. The second type has a dissection depth of about 20 to 30 m and steep (20 to 30 degrees) straight slopes with U-shaped valleys and a dense dendritic drainage pattern. The third dissection type has V-shaped valleys with a variable depth of about 20 to 60 m, with slopes of 10 to 35 degrees, and a dendritic to sub-dendritic drainage pattern.

Locally, near the main rivers, thin fluvial deposits occur on top of the finer, distinctly Tertiary deposits. They are composed of very well rounded gravels and may date back to the Plio-Pleistocene (Hoorn, 1993; Proradam, 1979). In the eastern valley slope of the plot selected in the sedimentary plain (SP) such gravelly deposit is encountered.

The sediments of the Andean rivers can be divided into three different units: the high terraces, the low terraces and the flood plains. The high terraces lie at 25 to 40 m above mean river level and have a flat topography with slight to moderate fluvial dissection. Sediments are clayey with a low gravel content and are generally thin (2 to 3 metres), covering the Tertiary deposits. Organic sediments such as peaty backswamp deposits lack. The low terraces lie at about 10 to 15 m above mean river level, have a flat topography and are only slightly dissected. They are built up by deposits of Middle Pleniglacial age (van der Hammen *et al.*, 1992) and are sandy at the base, grading into finer textured, mostly clayey sediments. The sediments are often cemented by iron, forming ferruginous crusts. The flood plain of the River Caquetá consists of sediments from the Late-Glacial to Holocene (van der Hammen *et al.*, 1992), located at approximately 3 to 5 m above the mean level of the River Caquetá. It has a flat, non-dissected topography, with small, sandy textured bars running parallel to the river stream and with depressions, which are inundated during wet periods and have finer textured and organic sediments (peats). The floodplain can be subdivided into lower, frequently inundated areas, and slightly higher, rarely inundated areas (with lesser poorly drained depressions). The sediments of the River Caquetá, being an Andean river, contain relatively large amounts of weatherable primary minerals (Kroonenberg and Hoorn, 1990). However, in the high terraces weathering has been strong and weatherable minerals are virtually absent (Duivenvoorden and Lips, 1995).

The alluvial plain of the Amazonian rivers largely consists of floodplains, which are of Holocene age. The composition of the sediments differs according to the geology of the catchment, but on the whole sediments are low to very low in weatherable minerals. The floodplains have a flat topography with point bar systems, many cut-off meanders and swamp areas. Along some Amazonian rivers, narrow strips of upland terraces occur with rather flat and slightly dissected topography.

2.2.3 Drainage system

General descriptions of the drainage systems in the various units have already been presented in the description of the geomorphology of the Middle Caquetá area. Here attention is paid to the drainage system in the four plots studied. Two of the research plots, on the Sedimentary Plain (SP) and on the High Terrace (HT) respectively, are first order catchments, while in the other two plots (LT and FP) catchment boundaries cannot be defined and drainage is largely subsurface.

The SP plot consists of a deep V-shaped valley. The depth is about 38 m (between top level of Sedimentary Plain and lowest point). The catchment is drained by an intermittent creek. The size of the catchment is about 16 ha and the drainage basin relief ratio (Rh = H/L) is about 0.09. The creek drains to a second order small stream which runs into the River Caquetá. The HT plot comprises a small catchment, which is drained by a seasonal creek. This creek dries out at the end of the dry period, begins within the plot and extends into an adjacent flat area. Here it joins a slightly larger stream (Bocaduche), which is a tributary of the River Caquetá. Since most of the area is almost flat, the identification of the boundaries of the catchment is problematic. The size of the plot is approx. 10 ha and the size of the catchment is estimated at about 2 ha. The drainage basin relief ratio is about 0.12.

2.2.4 Soils

General trends in soil development and characteristics in the Middle Caquetá have been investigated by Lips (1995) and Proradam (1979), paying attention to both mineral soils and humus forms. They are summarised in Table 1. On the whole, with increasing age reserves of weatherable minerals, base saturation and soil reaction rapidly decline. Furthermore, soils have a textural contrast between topsoil and subsoil (argic B), which tends to become more prominent with increasing age. Litter decomposition becomes retarded and a distinct ectorganic horizon and superficial root layer develops.

Soils of the Tertiary sedimentary plain (SP) are developed in sediments, largely originating from the Precambrian Guyana shield, with highly weathered granites, gneisses and sedimentary rocks (Proradam, 1979). These soils have a very low chemical fertility (low pH and very low base saturation). They contain very low amounts of weatherable minerals, reflected in very low stocks of potassium, phosphorus, calcium and magnesium. The soil is largely composed of quartz and kaolinite, and only some iron (hydr)oxides. Soils in alluvial sediments of Andean rivers (e.g. River Caquetá) developed in mineralogically richer sediments, which consist of a mixture of Andean material and material derived from the Tertiary sediments. These soils have a somewhat higher base saturation and are higher in weatherable minerals such as feldspars, vermiculite and micas. However, they are also high in quartz and kaolinite, particularly in the high terraces. It is only in the low terrace and floodplain that weatherable minerals are encountered in significant amounts, but relative high values for base saturation and soil reaction are only observed where soils are regularly inundated.

Detailed soil surveys of the research plots were executed during the field campaign (see Appendix 1). Clear differences in soil types exist between the four plots studied, in accordance with the trends described above. Soils are relatively fertile in the floodplain of the River Caquetá, while the soils in the sedimentary plain are very poor in nutrients and have a very clayey texture (Abaunza and Tobón, 1994; Ordoñez, 1992). The main soil types in the research plots (according to USDA system 1990) are: typic Paleudults (SP and LT), typic Hapludults (SP and HT), typic Kandiudults (SP and HT), typic Tropofibrists (LT), aeric tropic Fluvaquents (LT and FP), typic and aquic fluventic Dystropepts (FP) and tropaquodic Quartzipsamments (FP). For descriptions of representative soils and some soil properties reference is made to (Appendix 1).

In the previous research, limited attention was paid to the physical properties of the soils in the Middle Caquetá area. Therefore during the current research relevant physical properties of the main soil types were investigated. These include soil texture, bulk density, porosity and water retention. To study these properties, samples were taken at eight different depths in accordance with the required input for modelling of soil water fluxes (see Chapter 6).

The most prominent feature of the soils, apart from the increase in clay content with depth (textural contrast, see above), is the abundance of macro and mesopores, mainly in the upper part of the soil profiles. This high porosity seems to be related to both a high faunal activity (ants, termites and worms) and massive root growth and decay. Dry bulk density was determined from core samples (100 cm^2) collected for the soil water retention analysis and from soil samples used for determination of volumetric water contents in connection with the calibration of TDR measurements. The bulk density in the topsoil ranges from 1121 kg m^{-3} to 1346 kg m^{-3}, while in the Bt horizon it ranges from 1330 kg m^{-3} to 1525 kg m^{-3} (Table 2.1). Profiles of soil porosity were deduced from the bulk density of the soil samples and the average density of the solid phase, taken as 2650 kg m^{-3} $(1 - {}^{b}\rho_{s}/\rho_{s})$ as most of the studied soils have very low organic matter content (Koorevaar *et al.*, 1983). The soils exhibit a decreasing porosity with depth with the highest value in the floodplain (Table 2.1).

Table 2.1 Estimated soil porosity, from dry bulk density and the average density of solids, at 8 different soil depths in four forest ecosystems in the Middle Caquetá, Colombian Amazonia.

Soil depth (cm)	SP	std	HT	std	Soil depth (cm)	LT	std	FP	std
10	0.49	0.03	0.52	0.02	10	0.58	0.04	0.59	0.02
15	0.49	0.03	0.50	0.02	15	0.56	0.01	0.57	0.02
20	0.48	0.03	0.50	0.02	20	0.55	0.01	0.55	0.02
30	0.46	0.03	0.49	0.02	30	0.50	0.02	0.54	0.02
50	0.47	0.03	0.44	0.04	40	0.46	0.03	0.52	0.02
80	0.45	0.03	0.43	0.05	60	0.44	0.02	0.50	0.03
120	0.45	0.04	0.42	0.02	80	0.41	0.01	0.49	0.02
160	0.43	0.03	0.43	0.05	100	0.42	0.02	0.47	0.01

Water retention characteristics (WRC) of the soil profiles were determined from undisturbed core samples (100 cm^3) collected at eight soil depths in each soil profile where soil water content was measured (TDR). Undisturbed soil samples were used for suctions lower than –100 cm. Small subsamples were used for the estimation of suction values between –1000 and –16000 cm. The soil water retention point data were fitted with a non-linear fitting algorithm (Freijer, 1990) through which the van Genuchten parameters can be also determined. Representative pF curves for the main soil types and at four different depths in each landscape unit are presented in Figure 2.2.

Though the litter layer or forest floor plays an important role in geomorphological and hydrological processes (e.g. interception of rainfall, evaporation, overland flow, control of erosion) and in nutrient supply to vegetation, limited attention has been paid to the forest floor under natural undisturbed forest in Amazonia. The study by Duivenvoorden and Lips (1995), on humus forms in the Middle Caquetá constitutes an exception and counts among the few publications on forest floors of Amazonian tropical forest ecosystems.

The forest floor consists of dead leaves and coarser debris such as twigs, bark, wood, fruits and seeds, and fine roots. The upper part (L-horizon) forms a discontinuous, loose layer, which largely consists of dead leaves and fine and coarse debris, with a low proportion of fine roots adhering to the surface of decomposing leaves and growing into the debris. The underlying layer (F-horizon) has a loose consistence and more decomposed materials, of which the structure can still be recognised (leaves and debris), with a considerable amount of fine roots adhering to the decomposing materials. The bottom layer (H-horizon), if occurring, is formed by a very thin layer of humified, highly decomposed organic matter. In most cases, this layer is discontinuous, filling pockets in the mineral soil.

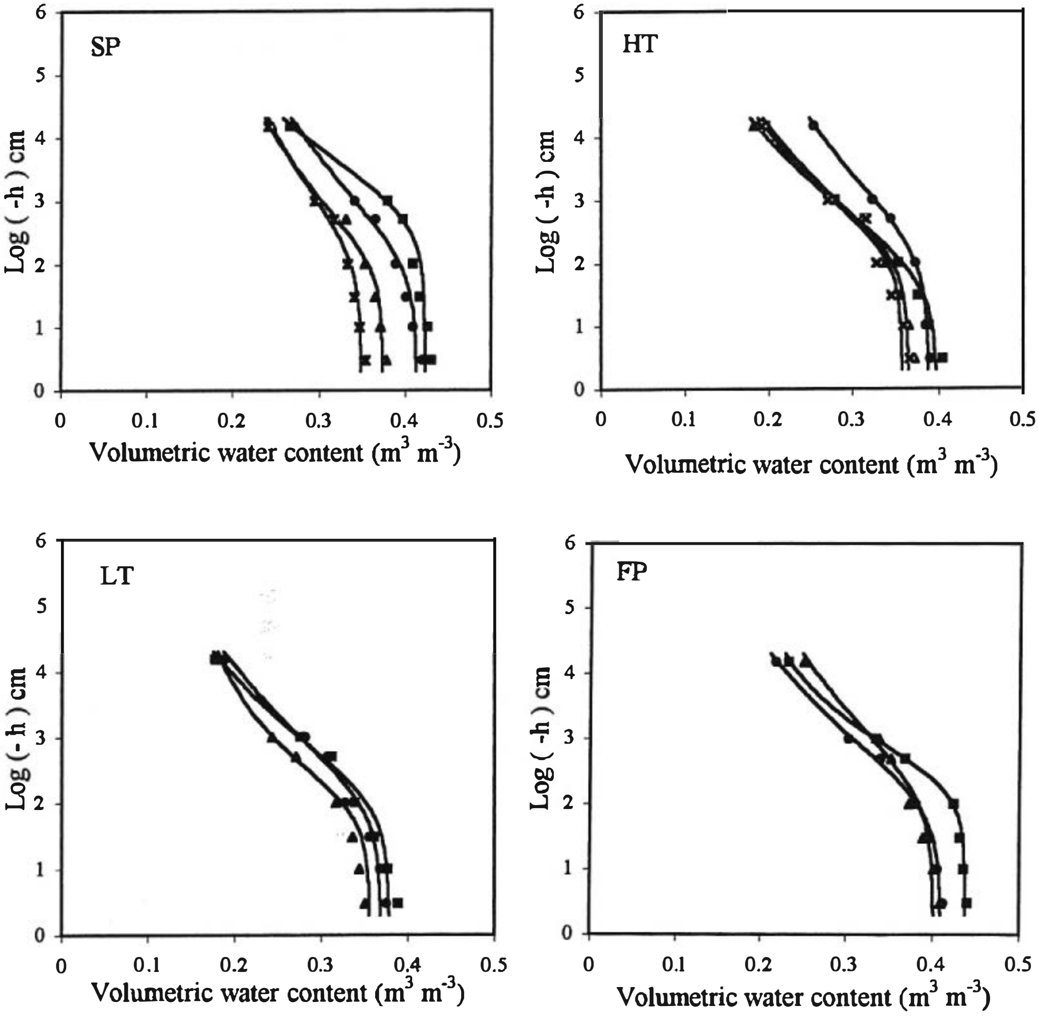

Figure 2.2 Soil water retention curves for various soil horizons in four physiographic units in Colombian Amazonia. Lines (–) represent the fitted curve (van Genuchten, 1980) and symbols represent the measured points (■ for 0.1m, ● for 0.5 m, ▲ for 1.0 m and x for 1.6 m).

Amounts of litter (ectorganic matter) in undisturbed forest in Colombian Amazonia vary considerably, ranging from 3 kg m^{-2} to 21 kg m^{-2}, with a total average of 8.4 (± 5.7) kg m^{-2}. Characteristic features of the forest floor are its considerable thickness in the SP (up to 35 cm) and sharp decline in thickness towards the floodplain, the presence of abundant fine roots mixed with decomposing material (up to 40% of total fine root content) in all humus forms, the low bulk density (generally lower than 100 kg m^{-3}) and the sharp boundary with the mineral soil. Average dry bulk density of the forest floors in studied ecosystems was 78.2 (± 22.0) in the SP, 85.6 (± 27.7) in the HT, 90.0 (± 22.4) in the LT and 92.9 (± 40.5) in the FP. In its lower part commonly a mixture of mineral soil is observed, mainly in the form of sandy material brought up by ants and termites. The main difference in forest floor characteristics among the systems studied is its thickness, which decreases from the SP to the FP, and the amounts of fine roots.

2.2.5 Vegetation

Natural vegetation in the form of undisturbed forest is by far the prevailing type of vegetation in the area of study. Classified according to the FAO system, it belongs to the group of ombrophilous tropical forest (Duivenvoorden, 1995). The area belongs to the life zone of humid tropical forest (Bh-T) of the Holdridge life zone system (Holdridge *et al.*, 1971). As part of the Tropenbos research programme, a series of sites has been investigated for its structure and floristic composition, a.o. demonstrating the very high species diversity of these mature forests in the western part of the Amazonia (Alvarez, 1993; Londoño, 1993; Duivenvoorden and Lips, 1993).

The canopy height varies considerably: canopy closure is around 25 to 30 in the SP and between 30 and 35 m in the FP, with some emergent trees reaching up to 40 m. The tree density is high with up to 850 trees per hectare (Londoño, 1993). There are three to four canopy layers with an almost closed upper canopy layer. The understorey is mainly composed of small palms and seedlings of trees reaching a height of 2 to 4 metres. Lianas and epiphytes are common in the research plots, but their abundance has not been established, while grasses and herbs on the forest floor are rare. Differences in vegetation between the various types of forest regard floristic composition (including species diversity) and tree density (e.g. 650 trees with diameter larger than 10 cm in the flood plain and 850 in the sedimentary plain) (Duivenvoorden, 1995; Alvarez, 1993; Londoño, 1993). Another important difference is the crown cover, which seems to be higher in the floodplain and lower in the sedimentary plain. A floristic study of the research plots showed that with regard to forest species the SP is the most diverse area with 706 species classified into 242 genera and 81 families (plot of 1.8 ha). Some vascular families are represented with significantly high number of species. In order of decreasing species richness can be referred to Leguminosae, Lauraceae, Sapotaceae, Melastomataceae and Rubiaceae (Londoño, 1993). The flood plain of the Caquetá river seems to be the least diverse unit with 511 vascular species and 7 epiphytes, classified into 242 genera and 85 families (plot of 1.8 ha). In order of decreasing species richness can be referred to Leguminosae, Rubiaceae, Annonaceae, Moraceae and Araceae. (Alvarez, 1993). The floristic composition of the HT and LT plots has not been separately investigated. In a study, comprising all units and carried out in a large area, 1200 vascular plant species were reported for plots of 0.1ha, distributed over 369 genera and 112 families (Duivenvoorden and Lips, 1995).

As to biomass, data on aboveground biomass are scarce, whereas more attention has been paid to belowground biomass. According to Overman *et al.* (1994), Alvarez (1993) and Rodriguez (1991) aboveground biomass in undisturbed forest ecosystems in the Middle Caquetá ranges from 256 ton/ha in the flood plain of the River Caquetá to 351 ton/ha in Venezuela (*terra firme*). Belowground biomass was 20 ton/ha in the flood plain in the Middle Caquetá, according to Alvarez, 1993.

Table 2.2 Fine root (Ø < 6 mm) distribution in the forest floor (FF) and throughout the mineral soil in the four physiographic units in the Middle Caquetá, Colombian Amazonia. Average values and standard deviation deduced from the root studies in the research sites (de Vente, 1999; Wassenaar, 1995).

Depth (cm)	**SP**		**HT**		**LT**		**FP**	
	%	**std**	**%**	**std**	**%**	**std**	**%**	**std**
FF	35.0	13.1	18.6	10.3	19.2	18.2	12.4	8.5
A/B	12.4	7.9	13.6	6.5				
10	15.0	11.2	28.2	12.0	38.5	17.3	40.6	19.4
20	14.0	9.7	21.6	13.1	18.8	6.2	14.0	10.5
30	7.0	4.2	6.8	2.1	9.6	3.0	8.2	6.2
40	4.0	2.6	4.6	2.6	4.0	2.6	8.4	7.1
50	3.0	2.2	2.1	1.8	2.3	1.6	5.1	4.1
60	3.0	3.3	1.2	1.4	2.0	1.0	4.2	5.9
70	2.2	1.7	1.6	1.7	1.8	2.0	2.6	2.5
80	1.0	0.6	0.8	1.0	1.6	1.1	1.4	1.4
90	1.3	0.4	0.5	0.9	1.2	1.1	1.5	1.6
100	1.0	0.2	0.4	0.9	1.2	1.3	1.2	1.3

Within the framework of the current research, a study of the fine root distribution and root content was carried out in the research plots. The distribution of fine roots (< 6 mm in diameter, Ø) in the forest floor and the mineral soil was determined by sampling each 10 cm up to 1 m depth where root content decreases to very low values. Samples were taken at 10 locations randomly distributed in each plot. Necromass (litter) was collected by using a frame and soil mass by core augering to 1 m depth. Roots collected from these samples were separated into 2 different size classes: fine roots (Ø < 6 mm) and coarse roots (Ø > 6 mm). Average fine root distribution with soil depth is presented in Table 2.2. In the SP, the average total fine root biomass was 0.95 (± 0.5) kg m^{-2} in the forest floor, which represents 33.6% of the total fine roots. The first twenty cm of the mineral soil and the forest floor hold 81% of the total fine roots, which is 2.27 (±

1.46) kg m^{-2}. As fine root content decreases considerably after 1 m depth, it is expected that root biomass will not increase significantly by sampling to greater depths. Spatial variation of fine root biomass in the SP is very high: as a general trend, the convex upper part of the valley slope has a higher root mass than the slope and bottom of the valley, of which the latter has the lowest root content.

In the HT, the average root biomass in the forest floor was 0.43 (± 0.14) kg m^{-2} which represents 18.6% of the total fine roots. The first twenty cm of the mineral soil and the forest floor contain 2.04 (± 1.28) kg m^{-2}. The variability between the sites in the HT is lower than in the SP. In the LT the average of fine roots in the forest floor is about 0.382 (± 0.124) kg m^{-2} which represents 19.2% of the total fine roots. In the first twenty cm of the mineral soil together with the forest floor, 82% of the total fine roots 1.63 (± 0.62) kg m^{-2} are concentrated. In the FP ecosystem, the forest floor has 0.193 (± 0.038) kg m^{-2} fine roots, which represents 12.4% of the total fine roots. The first twenty cm of the mineral soil and the forest floor contain 1.12 (± 0.22) kg m^{-2}, which is 72% of the total fine roots.

2.2.6 Land use systems

Rain forests in Amazonia have already been settled for centuries. In the Middle Caquetá area, in particular around Araracuara, population density seems to have been relatively high and higher than it is nowadays (Dominguez, 1985). In some areas (sandstone plateau), ancient cultures practising agriculture may date back to about 300 AD (Herrera *et al.*, 1992).

The main indigenous land use in the Middle Caquetá was and still is "shifting cultivation", where only small areas of native forest, mostly less than one hectare, are cut and used for crop plantations during two or three years, depending on the aggregated soil fertility (ashes from the burning litter). Several other types of land use can be distinguished, part of which are connected with colonisation and new techniques. Types of land use and their major characteristics are described below.

The first type of land use is the collection of products from the forests. The forest is used without any visible disturbance, delivering products such as proteins (hunting), wood, roof material, medicinal plants, fibres, oil, resins, salt and wild fruits. This use is mainly practised by indigenous tribes living in the area (van der Hammen, 1991). Recently, this land use has been intensified by both indigenous people and colonists, mainly through selective cut of hardwood trees in a fringe along the main rivers. The timber is used for local constructions and for export to the main population centres. This land use is nowadays extensively practised and mainly due to the low density of several hardwood trees, some species are probably more affected than others. Although the scale of selective logging of hardwood is small, this land use may cause major damage to certain species, mainly because of their low density.

A second type of land use is the indigenous slash and burn or "shifting cultivation". This is mainly practised on the low terraces (mainly on those of Andean origin) and the rarely inundated floodplain. In small areas, often smaller than 1 hectare, the forest is cut entirely at the start of the dry season, the debris is dried for a short period and subsequently burnt. Approximately one week after the burning, the stand is planted mainly with cassava (*Manihot* spp.) pineapple and banana; some slow growth fruit trees are also planted. After the first harvest, the stand is replanted with cassava and some fruits. Depending on the nutrient status of the plot, it may be used for the third year after which the plots are commonly partially abandoned. Plots are rapidly covered by successional forest (*rastrojo*), growing mixed with planted fruit trees, and thus turned into an agroforestry system, which is used for periods longer than 10 years. This land use system causes little disturbance, mainly because the land is used only to produce food for local consumption by indigenous communities and plots are small and rapidly abandoned to the secondary forest regeneration.

The third use of the land is less common in the area and it is mostly practised by colonists, being large scale crop plantation and small-scale cattle ranging. This land use causes a major forest disturbance for two reasons: the size of the land used is often larger than 5 ha and the areas are continuously used, followed by conversion of the plot into permanent pasture. These two processes together impede the natural forest to invade and regenerate the plot.

Although still rarely practised, a fourth type of land use can be mentioned here, which is a specific type of agroforestry without cattle and fertilisers, as practised by some inhabitants. After an initial clearing of the understorey, the site is planted with mainly maize, cassava, fruits and banana. Subsequently, the forest is selectively cut, with preservation of the tallest and hardwood trees, as well as those providing food for wild animals. The major characteristic of this land use is that burning is not practised and that the plot is used consecutively during at least about ten more years. Management includes cleaning the stand for undesired vegetation and sprouting re-growth. Although it has not yet been properly studied, this land use may cause very limited disturbance, mainly because of the specific characteristics of the land use and the small areas used.

Although the actual population in this part of Amazonia seems to be lower than in the past, recent studies suggest that deforestation has increased in the last years. This may indicate that recent land use does not fit with the prevailing conditions of Amazonian ecosystems. Therefore, it may present a menace to the existence of the forest. Losses of natural habitat for tree species and animals are the result of land pressure by man and may lead to a breakdown of indigenous cultures, land degradation and even effects on local and global climate (Bruijnzeel, 1996; Lean *et al.*, 1996; Nobre *et al.*, 1991).

In the Middle Caquetá, as in most of the Amazonian rivers, fishing along with hunting, has been a long standing tradition of river use as a source of food intake of the communities of people living along the river corridors. In the last decades commercial fisheries culture has grown as a result of the growing demand for fresh water fish, which includes the ornamental fishes. As such, every household is engaged in the fisheries activities during most of the year, as a man's activity within both the indigenous people and colonists. Fishing traditions, cultural controls and commercial fisheries in the River Caquetá have been studied by Rodriguez (1999).

2.3 CLIMATE

The climate of the Middle Caquetá is wet tropical, classified as Afi according to Köppen (1936). The average annual rainfall is approximately 3100 mm and the average annual temperature is 26 °C and mean relative humidity is 87%. Two main seasons can be distinguished: although a truly dry season is not common in the area, a relatively dry period occurs from the end of December till the end of February. The rainy season lasts from March until December with a relatively dry month in August, which can be related to the passage of the equatorial low pressure belt through the North.

At the onset of this research, only one climatological station was functioning in the entire area (IDEAM-Araracuara) providing data manually measured on daily basis. To provide the current research with local and reliable climatological data, an automatic weather station (AWS) was installed in an open area of about 20 ha near to the "Nonuya" indigenous community. The station was located on the bank of the River Caquetá (Figure 2.1), with short grass vegetation covering the soil surface (maximum height of 0.2 m). Parameters measured in the open were gross rainfall, air temperature, air humidity, incoming radiation, wind speed, wind direction and Class A pan evaporation. A CR10 datalogger was programmed to measure the instruments each 30 seconds and to register mean and total values each 20 minutes.

Gross rainfall in the open area was measured by means of a tipping bucket rain gauge with a resolution of 0.2 mm, giving information on the number and duration of showers and the total precipitation. The gauge was installed at 0.2 m height. It was also measured manually next to the tipping bucket, with a funnel (open area of 298.6 cm^2) connected to a collector. As the collector was measured twice daily (7:00 and 19:00 hours local time) it provided comparative data and information on rainfall amounts at the station for periods during which the automatic station was malfunctioning and data were lacking.

For some periods, gross rainfall in each plot was also measured in two ways: 1) automatic measurements with a tipping bucket installed in the top of an emergent tree crown, after clearing all branches, connected to a CR10 datalogger on the forest floor; 2) manual measurements with two rain gauges per subplot pending from cords attached to two emergent trees in gaps within the forest. Funnels for gross precipitation above the forest canopy had an orifice of 298.6 cm^2. Measurements were calibrated against standard rain gauges in the open.

Temperature and relative humidity were measured with a Rotronic air probe instrument installed at 3 m above the surface in the station. Solar radiation was measured with a Pyranometer probe (LI200), installed at 4 m above the surface. Wind speed was measured with an A-100R anemometer and wind direction was measured with a W-200P potentiometer (Vector instruments) both installed at 3 metres above the surface. All instruments were connected to a CR10 datalogger, which was programmed to register mean and total values each 20 minutes during the period from November 1992 until August 1997. Additionally, a NWS Class A pan evaporation tank was installed at the station and measured twice daily (7:00 and 19:00 local time). The A pan evaporation was measured from the fluctuations of the water level in the tank and corrected for inputs by rainfall. Mainly due to battery collapses or instrument malfunctioning some gaps occurred in the collected information. Therefore, some of the values presented were calculated from the available climatological data during the period, except for the rainfall that was filled with the manually collected data.

In the following sections, climatic conditions of the Middle Caquetá area (Colombian Amazonia) within the period between November 1992 and August 1997 are presented. Twenty minutes data are used to deduce monthly values for each climate parameter. Detailed data on the meteorological parameters are used as input data on parameters or variables, used to calculate the water balance for each compartment in the forest ecosystems, as well as for the calculation of reference transpiration (Monteith, 1965). Gross rainfall is related to net rainfall under the canopy, to the interception by four forest ecosystems, to forest floor interception and to forest floor and soil water content dynamics. During the measured periods, some gaps in data collection occurred due mainly to malfunctioning of battery and dataloggers. These gaps are: 1993 (between days 352 to 365), 1994 (from day 1 to 22 and from 336 to 349), 1995 (from day 23 to 41, from 287 to 302), 1996 (from day 185 to 224) and 1997 (from day 1 to 14). For these periods, monthly values of climatic parameters were calculated from the remaining days of the respective months and by extrapolation of values, as the case of reference transpiration (available data in those months with gaps were in general for more than 20 days). Gaps in rainfall values were filled by using average values from measurements in the plots and manual gauge readings from the station, except for the gap in 1996, for which data completely lack.

2.3.1 Rainfall

Rainfall may be considered as the only input of water in most Amazonian rain forests. However, flood plain forests and swamps may receive water from other sources than local precipitation in the form of floodwater and seepage, originating from adjacent areas or even completely different regions, such as the Andes in case of flooding.

Monthly amounts of rainfall in the research area are presented in Table 2.3.1. Monthly rainfall during the five-year period was evenly distributed with a slightly drier period around December to February. However, during 1997 an abnormally second dry period occurred during March, which lasted about 22 days. The distribution of rainfall in the area and the existence of a short relatively dry season (with rainfall higher than 100 mm per month) and two very wet periods (March to June and September to November) seems to be related to the displacement of the intertropical convergence belt, resulting in the passage of the equatorial low pressure zone to the north and its passage again towards the south from September to November. During the study period, January was the driest month with an average of 144 mm of rainfall and September was the wettest with an average of 353 mm. The mean annual rainfall was 3400 mm yr^{-1}, which slightly deviates from the long term rainfall average of the zone according to the long term rainfall observations at the station in Araracuara, situated at about 20 km to the north-west (Duivenvoorden and Lips, 1995). The annual average of days with rain was 197, with an effective time with rainfall of 616 hours per year.

2.3.2 Rainfall characteristics

During the measurement period (1992 to 1997) data on 1584 rainfall events were obtained, with storms ranging from 0.2 to 161.6 mm and with duration of 20 to 780 minutes. Most showers (63%) fell during the afternoon and at night. 37% of the incident rainfall fell in single showers with less than 2 mm, and 92% of these rainfalls contributed with less than 30 mm. Rainfall intensity averaged 5.5 mm h^{-1}, with a maximum of 78.2 mm h^{-1}. 56% of the storms fell in less than one hour and these represent only 21% of total rainfall. When comparing the five years data with that from longer period, the observed rainfall characteristics seem to comply with the long term average for the Middle Caquetá.

Table 2.3.1 Total monthly rainfall (mm) at the station in Peña Roja (Middle Caquetá). Number between brackets indicates the number of days per month with rainfall higher than 0.2 mm. * Due to temporary damages of the tipping bucket in the AWS, values were deduced from the average of measured rainfall in the plots.

	J	F	M	A	M	J	J	A	S	O	N	D
1992									392.2 *	308.2 *	365.6 (19)	269.4 (14)
1993	152.4 *	139.8 *	291.2 (21)	342.8 (21)	292.2 (22)	233.0 (21)	339.4 (20)	216.4 (16)	399.8 (21)	339.4 (19)	391.0 (21)	130.2 (15)
1994	110.6 (9)	254.2 (19)	282.2 (17)	405.8 (18)	410.8 (24)	395.0 (22)	280.4 (17)	321.6 (18)	305.2 (17)	234.8 (16)	369.2 (20)	255.4 *
1995	170.6 *	106.2 *	227.8 (13)	310.6 (20)	259.2 (19)	314.6 (21)	345.6 (14)	280.2 (14)	268.6 (21)	393.4 (19)	288.4 (16)	136.3 *
1996	194.8 (10)	299.2 (18)	349.8 (17)	254.3 (17)	297.0 (21)	387.0 (20)		253.6 (15)	397.0 (19)	303.2 (14)	308.6 (15)	193.0 (15)
1997	103.4 *	346.4 (23)	325.6 (16)	297.4 (20)	416.6 (22)	225.4 (18)	320.4 (20)	178.6 *				

The wettest year was 1994 followed by the driest, 1995, during the measured period. Registered mean rainfall in the Middle Caquetá during the five years period (Peña Roja) is similar to that at Araracuara station (IDEAM) over the period between 1979 - 1990 and higher than the annual rainfall average of 2485 mm yr^{-1} from 11 years data at Igarapé Açu, Brazil located about 1300 km to the south-east, according to Hölscher (1997) and the 25 five years rainfall average of 1911 mm yr^{-1} reported from Manaus station (Brazil), which is located to the south-east of the Peña Roja station. However the annual average is lower than the 12 years rainfall average of 3960 mm yr-1 reported from the station located in Villavicencio, about 250 km to the northwest of the Peña Roja station (International Station Meteorological Climate Summary, 1995). These data somehow confirm the existence of a trend towards increasing amounts of rainfall in the northwest direction through the Amazon basin. It should be remarked that rainfall amounts during February in 1994, 1996 are high and much higher than the mean value over the last 20 years, observed at the Araracuara station (IDEAM).

Table 2.3.2 Monthly average, maximum and minimum (20 min) air temperatures (°C) at Peña Roja station, Middle Caquetá – Colombian Amazonia.

		J	F	M	A	M	J	J	A	S	O	N	D
1992	Mean											24.2	24.3
	Max											32.5	32.1
	Min											20.5	20.6
1993	Mean	24.6	24.5	24.0	24.3	24.1	23.4	22.1	23.6	23.9	24.0	24.2	24.4
	Max	31.6	33.0	32.8	31.4	31.7	31.0	31.2	32.2	33.2	33.2	32.2	31.8
	Min	21.2	20.2	20.4	21.3	20.6	19.8	16.2	19.8	19.7	19.5	19.6	20.8
1994	Mean	24.6	25.2	24.2	24.2	24.1	23.1	22.6	23.3	23.9	24.4	24.2	24.7
	Max	32.4	33.8	32.6	32.3	30.6	31.3	30.8	32.4	33.6	33.6	32.2	32.5
	Min	21.2	21.4	20.4	20.4	20.8	15.6	17.6	18.4	20.0	20.4	20.2	20.8
1995	Mean	25.0	26.2	24.8	24.7	24.3	23.5	23.5	24.3	24.2	25.0	25.4	27.7
	Max	34.1	34.8	33.3	33.0	33.2	32.2	32.0	32.9	34.3	34.6	38.6	38.1
	Min	19.7	21.4	20.6	20.8	20.0	18.9	19.9	19.7	18.9	19.1	20.1	22.8
1996	Mean	26.8	27.0	24.9	24.5	24.4	22.9		24.2	24.5	24.7	25.1	24.2
	Max	37.7	38.8	33.0	34.2	31.2	31.2		33.5	34.8	35.9	33.3	34.2
	Min	19.7	22.2	21.3	20.6	21.0	15.0		19.7	20.1	20.1	21.2	20.4
1997	Mean	27.2	24.4	25.1	25.0	24.2	24.2	23.9	23.1				
	Max	34.3	34.8	34.0	36.9	33.2	33.9	33.6	33.9				
	Min	21.5	19.9	20.0	20.3	20.2	20.8	19.4	18.6				

Table 2.3.3 Monthly average, maximum and minimum (20 min) relative humidity at the Middle Caquetá – Colombian Amazonia.

		J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
1992	Mean											85.3	87.6
	Max											95.5	96.9
	Min											50.8	56.4
1993	Mean	87.2	87.4	89.4	91.6	93.0	93.9	92.9	92.3	93.2	93.6	94.4	94.9
	Max	97.9	98.7	99.4	99.3	99.2	99.3	99.3	99.4	99.5	99.6	99.3	99.6
	Min	53.2	46.5	52.2	58.8	60.4	62.3	58.6	57.2	53.3	55.2	61.3	61.4
1994	Mean	87.3	86.8	94.6	94.3	95.4	97.6	91.8	90.9	90.5	89.4	91.3	89.5
	Max	99.2	99.3	99.5	99.6	99.5	99.6	99.6	99.6	99.5	99.4	99.6	99.4
	Min	49.9	51.5	63.8	59.6	66.6	61.1	65.4	55.0	54.4	59.2	65.4	59.4
1995	Mean	79.7	82.5	90.2	91.4	92.8	95.2	93.8	89.9	90.0	87.4	85.7	85.8
	Max	99.6	99.0	99.4	99.6	99.5	99.6	99.6	99.5	99.4	99.4	99.5	99.4
	Min	39.4	47.2	59.4	62.7	66.1	65.9	65.5	60.3	54.5	55.4	47.8	45.8
1996	Mean	72.0	78.0	81.4	82.2	83.8	85.1		84.9	79.5	79.3	79.4	80.8
	Max	99.6	99.4	98.6	98.4	98.3	98.6		99.6	98.3	98.2	98.5	98.3
	Min	39.4	40.6	48.2	50.0	59.4	57.8		50.1	44.9	46.7	46.9	54.8
1997	Mean	77.4	80.6	76.2	79.3	83.3	82.4	81.6	83.6				
	Max	98.6	98.0	98.0	98.0	97.8	98.1	98.2	98.0				
	Min	39.2	40.5	38.9	34.8	52.9	53.7	49.6	48.4				

Table 2.3.4 Monthly average and maximum (20 min) measured global solar radiation (W m^{-2}) at the Middle Caquetá – Colombian Amazonia.

	J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
1992												
Mean											359	343
Max											889	841
1993												
Mean	362	280	271	263	246	242	257	292	287	307	280	277
Max	816	962	938	978	901	821	822	952	950	944	990	962
1994												
Mean	247	313	312	347	318	351	298	350	362	395	379	355
Max	948	1146	1096	1121	1062	1017	1015	1009	1065	1105	1182	1074
1995												
Mean	412	350	379	360	351	317	354	389	406	460	419	383
Max	1161	1045	1017	1004	967	934	961	986	1097	1016	1100	1011
1996												
Mean	443	394	359	355	340	308		390	402	400	384	378
Max	1071	1095	1134	1167	1137	1148		1041	1078	1152	1205	1210
1997												
Mean	415	331	377	358	311	334	329	372				
Max	1174	1203	1132	1167	1074	1177	1017	1006				

Table 2.3.5 Monthly average and maximum (20 min) wind velocity (m s^{-1}) measured at Peña Roja, Middle Caquetá – Colombian Amazonia.

		J	F	M	A	M	J	J	A	S	O	N	D
1992	Mean											1.02	0.98
	Max											3.84	3.40
1993	Mean	0.99	0.97	0.92	1.02	0.95	0.95	1.04	0.96	1.00	0.96	0.96	0.90
	Max	2.92	2.80	3.01	4.59	4.54	3.50	4.07	3.35	3.36	3.16	4.11	2.71
1994	Mean	0.92	0.98	0.98	0.91	0.76	0.86	0.84	0.94	0.94	0.95	0.90	0.92
	Max	2.84	3.45	3.30	4.35	3.45	3.20	3.14	3.46	4.40	3.42	3.24	2.52
1995	Mean	1.10	1.06	0.93	0.87	0.81	0.89	0.92	1.01	1.08	1.09	1.08	1.10
	Max	3.40	2.64	3.65	2.87	2.99	3.07	4.13	4.18	3.40	4.06	3.66	3.50
1996	Mean	1.16	1.08	1.04	0.95	0.94	1.00		1.00	1.05	1.00	1.07	0.97
	Max	3.40	3.67	4.76	3.66	3.68	4.10		4.18	3.71	3.91	4.20	4.27
1997	Mean	1.05	0.96	0.99	0.92	0.84	0.84	0.81	0.80				
	Max	3.50	3.91	3.56	3.51	3.52	3.21	2.78	2.23				

2.3.3 Temperature

Mean monthly temperature at Peña Roja station during the period 1992 - 1997 is presented in Table 2.3.2. Seasonal variation in air temperature was lower than the diurnal fluctuations and differences between day and night temperatures are larger during the dry season than during the wet season, except for short periods between June and August when temperature drops to markedly lower values due to the passage of cold fronts from the south of Brazil, which is further discussed in this Chapter. The general cyclic behaviour of the temperature in the Middle Caquetá is illustrated by Figure 2.3. The average variation between day and night temperatures is about 12°C. Maximum temperature recorded at Peña Roja station rarely exceeded 35°C, registered early in the afternoon (about 14:00 hours, local time) and generally two hours after the solar maximum. Minimum temperatures usually drop to about 19 °C, recorded early in the morning at around 4:00 hours local time. The average for the warmest and coldest month does not deviate more than 3°C. During rainfall events, temperature generally decreases and this decrease depends on the duration of the event. With storms at night-time no significant changes were observed in the temperature. Over the year, maximum temperatures were generally observed in January and February and the lowest was mostly registered in June.

Some of these low temperatures were related to the presence of cold air moving from the south of the continent across the Amazon basin, locally described by the indigenous as "friaje". This phenomenon has been widely reported, particularly for the south of Brazil, by Marengo *et al.* (1997) and Culf *et al.* (1996). Although it has been described in Brazilian territory (Ji-Parana and Manaus), no reports have been presented for northwest Amazonia.

Though the low temperatures do not have visible effects on the crops and fisheries in Colombian Amazonia, they merit to be mentioned as special phenomena occurring throughout the Amazon basin. Table 4 presents dates of "friajes" registered during the period 1993 to 1997, as well as the respective reported dates for the same events in Brazil (Marengo *et al*., 1997). It is interesting to note the differences between the dates when the phenomenon was observed in Brazilian territory and Colombian Amazonia: according to the available comparative information from Manaus station, the "friajes" in the Middle Caquetá area were nearly always registered one day after the cold front passed the station at Manaus, reducing temperature in the area for about 3 to 5 days.

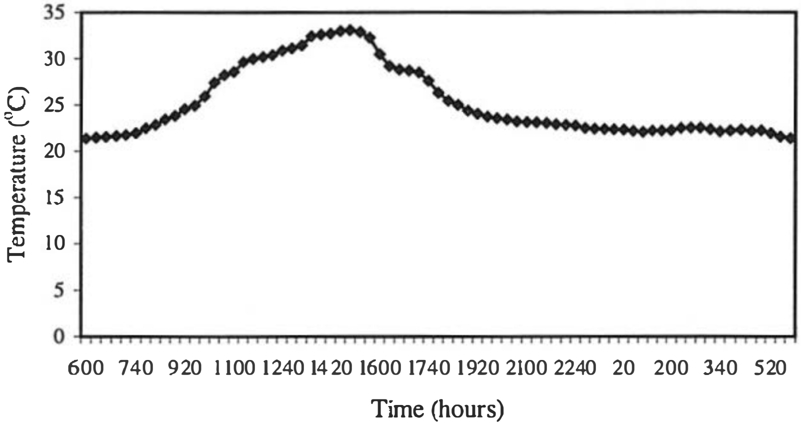

Figure 2.3 Characteristic daily dynamics of air temperature (°C) in the Middle Caquetá, Colombian Amazonia.

Similarly, as observed in Brazil, in Colombian Amazonia the cold air was often associated with relatively low humidities and high wind speeds (above 2 m s^{-1}). As most of the lowest temperatures were registered during the night, the side effect of decreasing the relative humidity is masked by the high night-time relative humidities. Nevertheless, during the day humidities were somewhat lower than average. Differences between the sites for registered temperature values and changes in related other variables clearly point to modification of the original cold air on its passage through the Amazon basin, temperatures in Colombian Amazonia being lower than at the station in Manaus, Brazil (data from Marengo *et al*., 1997). I cannot explain this, since a decrease of the intensity of the phenomenon is expected during its passage from the south to the northwest.

Table 2.4 Dates of registered low temperatures in the Middle Caquetá, related to the passage of a cold air front "friaje" moving from the south of Brazil through the Amazon basin, during the period studied. Data on related events reported in Brazil by Marengo *et al.* (1997) are also presented. (NI = no information for other sites)

Year	Dates	Duration (days)	Minimum temperature	Dates other sites
1993	June 12	3	18.7 °C (4:00 hours)	June 15
	July 14	4	17.0 °C (2:00 hours)	July 8
	July 31	5	16.2 °C (8:00 hours)	August 1
1994	June 27	4	15.6 °C (6:00 hours)	June 26 (Manaus)
	July 11	5	17.6 °C (4:00 hours)	July 10 (Manaus)
	August 12	3	18.4 °C (6:00 hours)	August 10
1995	June 21	4	18.9 °C (6:40 hours)	NI
1996	June 30	5	15.1 °C (6:40 hours)	NI
	July 1		15.2 °C (5:40 hours)	NI

2.3.4 Relative humidity

Monthly averages of relative humidity are presented in Table 2.3.3. The relative humidity in the Middle Caquetá increased rapidly after 18:00 to values above 95% and remained above this percentage in most nocturnal periods, while in the morning humidity dropped more gently. Minimum humidities were normally registered at about 14:00 to 15:00 hours, local time. The twenty minutes data showed that relative humidity started to decrease early in the morning at around 3:00 hours. It increased again around 5:00 hours just before sunrise, to decrease again around 7:00 hours. This behaviour can be the result of the early evaporation of dew, which accumulated in the vegetation during the night, or to a slight decline in temperature or both. Although the monthly average of relative humidity did not show clear differences over the year, the lowest humidity was generally observed in January and February, which corresponds with the dry season. The main changes in relative humidity occurred on daily basis (day and night time) rather than over the year. Figure 2.4 presents the daily tendencies of the relative humidity during a typical dry day.

2.3.5 Solar radiation

Although solar radiation was mostly registered between 6:00 and 18:00 hours (local time), during the dry seasons solar radiation was often registered to start after 5:40 and to last till 18:20 hours. Average values of solar radiation were calculated from all readings between the first hour in the morning with some solar radiation until the last hour with any value registered by the instrument. Monthly averages of solar radiation are presented in Table 2.3.4. During the first part of the wet season solar radiation was commonly somewhat lower, with clearly lower values early in the morning and late in the afternoon. With open sky conditions and during dry seasons, maximum solar radiation was generally observed around 12:00 to 13:00 hours, with values up to 1210 W m^{-2}. Hourly averages of solar radiation often exceeded 1000 W m^{-2}, mainly around noon, but average values from 800 to 900 W m^{-2} were more common.

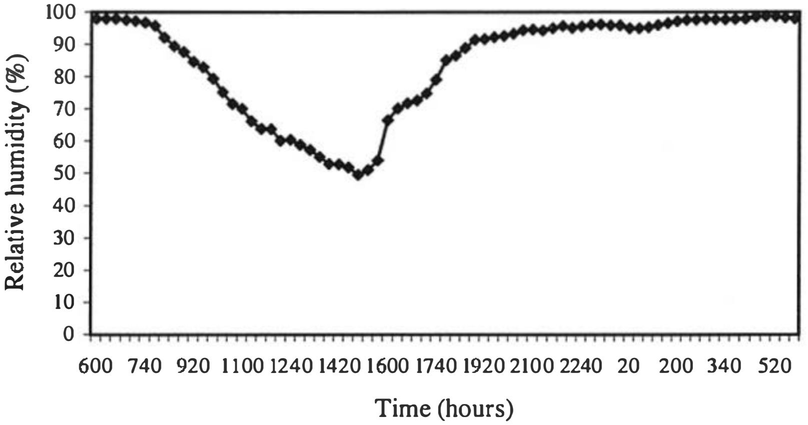

Figure 2.4 Typical behaviour of relative humidity during a dry day in the Middle Caquetá, Colombian Amazonia.

In general, there is a tendency of increasing solar radiation in January and around March and October. The high radiation in January is mainly due to the open sky during the dry season and the relatively high solar radiation around March and October is connected with the low solar declination in these months. During the measured period, 1993 was a year with a relatively low average solar radiation (271.8 W m^{-2}) followed by 1994, while 1995 had the largest total average solar radiation (358.8 W m^{-2}).

2.3.6 Wind speed and direction

In the studied area the wind speed is low (Table 2.3.5) and high wind speeds are uncommon, and most of the times related to rainstorms. Generally, wind speed was higher during the day and decreases at night (Figure 2.6) with exception of the time before and during rainstorms. The prevailing wind was SE to E. The position of the station on the riverbank (i.e. N-S oriented) may affect the wind direction.

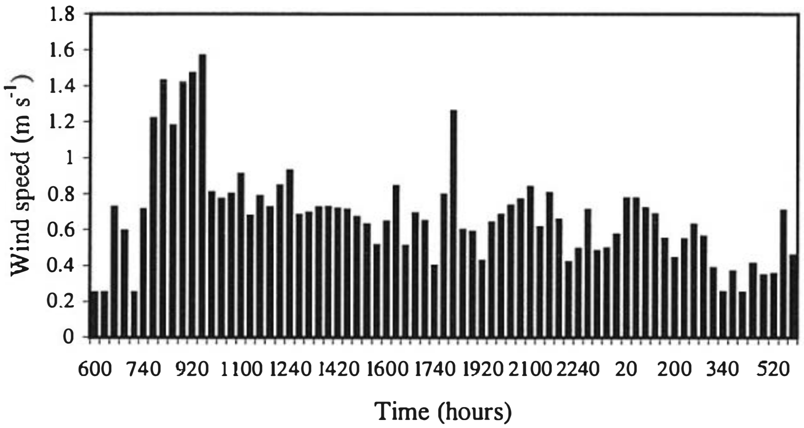

Figure 2.5 Typical wind speed dynamics during day and night time in the Middle Caquetá, Colombian Amazonia.

2.3.7 Reference transpiration

The combined processes of evaporation and transpiration constitute total evaporation, which is often referred to as evapotranspiration. In the last two decades, it has been generally concluded that one of the most relevant results of forest hydrological studies in the last years is that transpiration needs to be considered separately from evaporation of water, intercepted by vegetation (Shuttleworth *et al.*, 1984; Shuttleworth and Calder, 1979). This holds in particular for those ecosystems where a significant part of gross rainfall in intercepted by the forest canopy. The primary explanation for the higher evaporation rate from wet vegetation surfaces, and especially from wet forest canopies, relates to the relative importance of the two main resistances, imposed at the vegetation canopy (surface resistance or physiological resistance and the aerodynamic resistance) upon the flux of water vapour into the overlying atmosphere (Monteith, 1985). Transpiration is strongly controlled by the surface or stomatal resistance, while evaporation from the wet canopy is controlled, among others, by the aerodynamic resistance.

The terms evaporation and reference transpiration will be used throughout this thesis. For that reason they are defined and discussed in more detail. Evaporation refers to the amount of water that is intercepted by the forest canopy and subsequently evaporated. The term reference transpiration, refers to the Monteith equation (Monteith, 1965) as suggested by Cain *et al.* (1998), although a different value was used for the stomatal resistance.

$$\lambda E = \frac{\Delta R_n + \rho Cp(e_s - e_a)/r_a}{\Delta + \gamma(1 + r_s/r_a)} \tag{2.1}$$

Where,

λ = latent heat of vaporisation of water (J kg^{-1})
Δ = slope of saturated vapour pressure curve, (mbar K^{-1})
R_n = net radiation, (W m^{-2})
ρ = density of air, (kg m^{-3})
C_p = specific heat of air at constant pressure, (J kg^{-1} K^{-1})
e_s = saturated vapour pressure, (mbar)
e_a = actual vapour pressure, (mbar)
r_a = aerodynamic resistance (s m^{-1})
γ = psychometric constant, (mbar K^{-1})
r_s = stomatal resistance (s m^{-1})

The aerodynamic resistance (r_a) is calculated from the general equation for the wind profile, using a height, $z = h + 2$ (m).

$$r_a = \frac{\left[\ln\left(\frac{z-d}{z_0}\right)\right]^2}{k^2.u_z} \tag{2.2}$$

Where h (m) is the average height of the forest, k is the von Karman's constant (0.40), d (m) is the displacement height (0.67h), z_0 (m) is the roughness length, 0.1 h (Brutsaert, 1982). The average forest height is about 30 m, although some trees can reach up to 45 m.

The wind speed above the forest canopy was not measured, therefore the method by Rutter *et al.* (1975) was applied. The measured wind speed at the AWS (3 m) was extrapolated to a height above the outstanding largest trees (50 m), with the values of parameters from the station (d = 0.13 m and z_0 = 0.02 m) and using the logarithmic wind profile equation:

$$u_{50} = u_3 . \frac{\ln\left(\frac{50-d}{z_0}\right)}{\ln\left(\frac{3-d}{z_0}\right)} \tag{2.3}$$

To calculate the wind speed at 2 m above the forest canopy (z =h+2), calculated wind speed at 50 m was subsequently interpolated down to a height of 32 m, (2 m above the mean canopy height) using the forest stand values (d = 20 m and z_0 = 3 m), by:

$$u_{h+2} = u_{50} \cdot \frac{\ln\left(\frac{h+2-d}{z_0}\right)}{\ln\left(\frac{50-d}{z_0}\right)} \tag{2.4}$$

The 32 m wind speed (u_{h+2}) was used to calculate the aerodynamic resistance.

It is clear that accuracy of predictions of reference transpiration strongly depend, among others (e.g. solar radiation), on the accuracy of used parameter values, particularly for the stomatal or surface resistance. Surface resistance (r_s) depends on some environmental factors (solar radiation, vapour pressure deficit and soil moisture status) and leaf physiology such as the amount of stomata in the leaf surface. This value can be approximated, for instance, by determining the leaf area index (Dolman, 1987). In the Amazonia the surface resistance exhibits a strong diurnal variation with relative low values from 8:00 hours to about 16:00 hours and large increases during the night (Shuttleworth *et al.*, 1984). Therefore, the daily average values of surface resistance (r_s) found by Shuttleworth *et al.*, (1984) are used in this study, as these were deduced for similar forest type and climate conditions in Central Amazonia.

Net radiation was calculated from the standard empirical relationship which uses surface measurements of clear sky global solar radiation, air temperature and humidity (Stewart *et al.*, 1982). Parameters deduced by Brunt (1932) were used for the determination of the effective emissivity for cloudless skies (a_B = 0.52 and b_B = 0.065). The vapour pressure e_a, was calculated using Teten's equation (Murray, 1967). A value of 0.121 was used for the albedo as the mean value deduced for the Amazonian conditions (Culf *et al.*, 1995).

The climate factors recorded at the Peña Roja weather station (each twenty minutes) were used to calculate the reference transpiration (Monteith, 1965). As the equation merely estimates the transpiration, the forest interception is separately calculated from the recorded rainfall at different time scales in each forest ecosystem and presented separately in the Chapter 3 and 4 of this thesis.

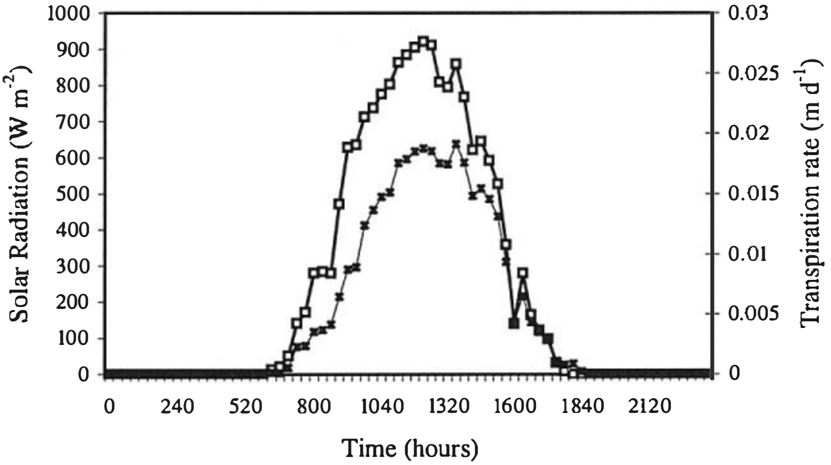

Figure 2.6 Dynamics of solar radiation (—□—) and calculated reference transpiration (Monteith, 1965), (-x-) for a typical dry day in the Middle Caquetá, Colombian Amazonia.

Monthly values of reference transpiration are presented in Table 2.5. Calculated total daily transpiration ranged from 0.8 mm to 9.8 mm with an overall average of 3.36 mm d^{-1}. As a general tendency, transpiration followed the solar radiation dynamics very close, with exception of those relatively windy days (above 2 m s^{-1}) when the wind speed partially controlled evaporation. Therefore, calculated transpiration values are mainly explained by solar radiation (see Figure 3.6). Accordingly, during the night transpiration was very low and probably controlled by wind speed. The annual average reference transpiration (5 years) was 1170 mm yr^{-1}. Transpiration in Amazonia, as in other sites, has been calculated in different ways and using different parameter values. Consequently, differences in daily and annual values are observed. However, differences between sites also obey to differences in measured radiation flux between sites and in time. In this study, transpiration is calculated separate from evaporation as two different components of evapotranspiration. Therefore, comparisons will be made in terms of evapotranspiration (see Chapter 8).

2.3.8 Class A pan evaporation

The pan evaporation in the research area follows solar radiation, temperature and relative humidity. During the day, pan evaporation was twice or three times higher than during the night. This low evaporation during the night can be explained by the high relative humidity, low wind speed and the low radiation flux. Class A pan evaporation was higher during January and February than in the other months. The monthly total values are presented in Table 2.6.

Table 2.5 Monthly values of calculated reference evaporation (Monteith, 1965) for the forests in the Middle Caquetá, Colombian Amazonia. * Missing information on climate.

	J	F	M	A	M	J	J	A	S	O	N	D
1992											85.7	84.9
1993	92.8	93.4	80.6	85.0	70.7	64.6	74.3	92.3	84.2	84.6	76.8	89.3
1994	104.6	79.9	89.6	92.9	86.5	80.8	81.5	94.4	93.2	106.5	100.3	113.6
1995	134.0	117.5	94.4	89.4	90.0	75.9	91.1	102.4	105.5	105.6	112.7	115.0
1996	152.2	118.9	104.9	102.3	94.4	79.9	*	104.9	117.6	118.6	113.2	104.5
1997	149.9	89.2	117.7	111.2	90.4	92.7	96.5					

Table 2.6 Monthly values of measured Class A Pan evaporation at Peña Roja station, in the Middle Caquetá, Colombian Amazonia. * Missing information for more than 15 days of the month.

	J	F	M	A	M	J	J	A	S	O	N	D
1993	119	105	109	117	108	99	107	112	123	111	104	101
1994	119	104	108	109	98	94	94	106	115	104	105	105
1995	124	126	112	116	98	93	111	129	129	127	111	*
1996	120	114	117	120	112	100	*	122	*	*	108	114
1997	128	113	137	128	118	123	117	*				

It is expected that the potential evaporation (Penman, 1948) is of similar magnitude as the open water evaporation (Class A pan evaporation multiplied by a pan coefficient). As the pan coefficient varies with climate and sites (Jones, 1997), observed values of pan evaporation were multiplied by a factor of 0.8, as the average of values suggested by Doorenbos and Pruit, (1977) for vegetated surfaces with low speed wind and for moist climate. The open water evaporation thus found for the Middle Caquetá was lower than the calculated PET. Results from the Middle Caquetá agree with those found by Poels (1987) in Suriname. A possible explanation for this difference is that in Penman equation (Penman, 1948) it is assumed that there is an immediate equilibrium of energy with solar radiation changes. Contrary in the pan some of the incoming energy is used to heat the pan, which may cause a delay in the response to the incoming radiation.

3. GROSS RAINFALL AND ITS PARTITIONING INTO THROUGHFALL, STEMFLOW AND EVAPORATION IN FOUR FOREST ECOSYSTEMS IN NORTHWEST AMAZONIA

3.1 ABSTRACT

The partitioning of gross rainfall into throughfall, stemflow and evaporation of intercepted rainfall was studied in four forest ecosystems in the Middle Caquetá, Colombian Amazonia. Hourly, daily and weekly water fluxes were measured automatically and manually for four years. Throughfall, stemflow and evaporation in each ecosystem were checked for correlations with gross rainfall characteristics, canopy gap fraction, tree crown area and bark texture. Canopy gap fraction was different between ecosystems ranging from 9% in the flood plain to 17% in the Tertiary sedimentary plain. Rainfall is rather evenly distributed over the year, with one dry period from December to February. 92% of the rain fell in single showers of less than 30 mm and most of the storms (56%) fell in less than one hour during the afternoon or early night. Percentage of throughfall ranges from 82 to 87% of gross rainfall in the studied ecosystems and varies with rainfall size in all ecosystems. The differences in throughfall percentages among ecosystems indicate that throughfall depends on both gross rainfall and forest structure. Stemflow contributes little to net precipitation (1.1% of gross rainfall on average in all ecosystems) and shows a power relation with gross rainfall. Correlations between stemflow per tree and projected crown area and bark texture are very poor as indicated by the low coefficient of determination. Evaporation during rainfall events exhibits a linear relation with rainfall duration and the ratio of evaporation over gross rainfall increases with forest cover (1- gap fraction) in the ecosystems. The structure of the ecosystems seems to vary considerably and given its influence on rainfall partitioning it may explain both differences and similarities between results from this study and those from most other studies within Amazonia.

3.2 INTRODUCTION

The Amazonian rain forest plays an important role in the regulation of regional and global climate (Salati and Vose, 1984). Recent concern about tropical rain forest deforestation has therefore concentrated on the impact on global climate change (e.g. The Anglo Brazilian Amazonia Climate observation study ABRACOS, Gash *et al.*, 1996; the Large Scale Biosphere-Atmosphere experiment in Amazonia, Nobre *et al.*, 1996). Consequently, research is focussed on global circulation models (Nobre *et al.*, 1991) and on the measurements of those parameters and fluxes that play a role in the global climate (e.g. Gash *et al.*, 1996). Local scale hydrological studies on undisturbed mature forests provide base level information on initial conditions that allow evaluation of the influence of the disappearance of tropical rain forest on local and global climate.

Differences in soil nutrient status may influence forest species composition and structure (Balslev *et al.,* 1987). In the Middle Caquetá (Colombian Amazonia), forest structure and tree species composition indeed vary considerably between the ecosystems in the different landscape units (Duivenvoorden and Lips, 1995). The structure of the tree canopy and patterns of lower layers play a decisive role in the partitioning of gross rainfall into throughfall, stemflow and evaporated water (Longman and Jenik, 1990). Epiphytes, climbers and aerial roots make the precise mechanisms of this partitioning more complicated in tropical than in temperate forests. Throughfall and stemflow are important parameters not only for water balance studies but also for nutrient cycling, as they transport nutrients through the forest compartments. On the other hand, evaporation from the forest canopy, especially during and immediately after rain events, may account for an important part of the water balance (i.e. the water not entering the ecosystem). Additionally, water on the forest canopy is an important ecological factor which influences chemical, physical and biological processes which take place on leaf and trunk surfaces (Longman and Jenik, 1990).

Most of the water balance studies in the Amazon basin have been concentrated in central Amazonia (Ubarana, 1996; Leopoldo *et al.*, 1995; Lesack, 1993; Shuttleworth, 1988) although some have been carried out in eastern Amazonia (Hölscher *et al.*, 1997; Jetten, 1996; Wright *et al.,* 1992). However, little attention has been paid to the forest hydrology of ecosystem types in northwest Amazonia and the effects of forest structure on water dynamics.

This paper describes a study designed to address this lack of knowledge by measuring rainfall and its partitioning after entering the canopy in four undisturbed rain forest ecosystems in the Middle Caquetá, Colombian Amazonia. It focuses on the analysis of long term hydrological measurements of rainfall, throughfall, stemflow, the resultant evaporation and the related forest structure of the ecosystems.

3.3 THE STUDY AREA

The study area is part of the undisturbed forest plots used as research sites by the Tropenbos Foundation and located in Peña Roja (Nonuya Indian community) near Araracuara, Middle Caquetá Colombia, (0° 37' and 1° 24' S, 72° 23' and 70° 43' W). The climate is classified as equatorial superhumid Afi (Köppen, 1936). The research sites lie approximately 200 to 250 metres above sea level in a sequence from the lower terrace of the River Caquetá to the Tertiary sedimentary plain. From the manually operated meteorological station in Araracuara (IDEAM), the average annual rainfall in the area is about 3100, April being the wettest month and January the driest.

Colombian Amazonia comprises 403,000 km^2 and the major part of this area is covered by mature rain forests classified by the FAO as belonging to the group of ombrophilous tropical forest (Duivenvoorden, 1995). The research plots are located in the four main landscapes units in the area: the Tertiary sedimentary plain, the upland terraces of the River Caquetá (high and low terraces) and the flood plain. The vegetation is very rich in species (Alvarez, 1993; Londoño, 1993; Duivenvoorden and Lips, 1995) and is typical of mature forest in the western part of the Amazon basin. The canopy reaches to about 25 to 30 metres above the forest floor with some emergent trees reaching up to 45 metres in the rarely inundated flood plain. There are three to four canopy layers, but the bulk of the vegetation is in the form of large tree crowns in the upper canopy. A smaller contribution to the forest cover is made by the lower canopies. Small palms reaching a height of 2 to 4 metres constitute the lowest storey. There are differences in the total standing biomass, species diversity and tree density between the landscape units. Other important differences between plots pertain to the structure of the forest canopy (canopy cover) and the contribution of epiphytes, climbers and aerial roots. A more detailed description and vegetation classification of the research sites is given by Duivenvoorden and Lips (1995), Alvarez (1993) and Londoño (1993).

3.4 MATERIALS AND METHODS

The areas for the present study were selected as being representative for the natural vegetation in the main physiographical units from this part of the Amazon basin. Three subplots were selected in the Tertiary sedimentary plain (SP) and two subplots in the high terrace (HT), the low terrace (LT) and flood plain (FP), to measure gross rainfall above the forest canopy, throughfall and stemflow. Approximately 3 kilometres from the plots, in an open area of about 20 hectare (within an Indian community village), an Automatic Weather Station (AWS) was installed in 1992 to measure gross rainfall, temperature, air humidity, incoming radiation, wind speed, wind direction and Class A pan evaporation. A datalogger (CR10 Campbell Scientific Instruments) measured the parameters each 30 seconds and recorded means or totals every 20 minutes.

Rainfall in the open area was measured by tipping bucket raingauge with a resolution of 0.2 mm providing information on the number and duration of showers and total rainfall. Gross rainfall in each plot was measured in two ways: 1- automatic measurements with a tipping bucket installed in the top of an emergent tree crown, after clearing all branches, 2- manual measurements with two raingauges per subplot suspended from cords attached to two emergent trees in gaps within the forest. Throughfall was measured by 20 collectors randomly located in each subplot of 50 by 20 metres (1000 m^2). Evaporation from the collectors was avoided by using an internal plastic tube running from the funnels to the bottom of the collectors. Funnels for gross rainfall above the forest canopy and for throughfall had an orifice of 298.6 cm^2. Throughfall and forest rainfall collectors were calibrated against standard raingauges in the open. Because of the large variability in throughfall due to the forest structure (Jetten, 1996; Ford and Deans, 1978), many readings are needed to study forest interception. Besides, when using average values, moving the collectors has a positive effect in reducing the standard error of estimations (Lloyd and Marques, 1988). Therefore, collectors from all subplots were randomly relocated each month (after 5 measurements) during total measured period. Natural large gaps in the forests due to death and fall of trees were avoided since they represent open areas rather than forest.

Stemflow was measured on 15 randomly selected trees in each subplot. Collars, constructed from 8 mm thick black polyethylene plastic, were sealed to the stems in an upward spiral pattern and the water diverted into bottle gauges on the forest floor. The opening of each collar extended only about two to three cm from the trunk to avoid drips from the branches or leaves being collected by the collars. The amount of water, which drops in a diffuse pattern around rough-barked trees rather than adhering to and flowing down the trunks, was considered throughfall. Only trees with crowns in the upper canopy and some with crowns protruding above the general canopy level were selected for stemflow. When palm trees were present at the measured subplots, depending in their presence, one or two of them were randomly selected to measure stemflow. In the SP and HT two palms were selected, in the LT four palms in total were selected and in the FP three palms were selected.

Manual measurements of rainfall, throughfall and stemflow were carried out on a weekly basis from December 1994 until February 1996, and daily measurements were performed from February to August 1997. Readings were made early in the morning (around 08:00 local time) or after the storm event whenever possible.

Horizontally or downwards inclined branches of trees may not direct intercepted rainfall to the centre of the tree as stemflow. Therefore, tree crown dimensions were mapped by means of vertical projections from the edge of outstanding upward branches to the forest floor. At least six projection lines were drawn for each tree and the crown area was found by integrating measured areas of each triangle. The periphery of the trunks or surface area was determined by measuring the tree trunk circumference at breast height and the height of the tree trunk to the first set of divergent branches. Trunk area was determined by considering the tree trunk as being rectangular and applying a correction factor to the conical form of tree trunks (Alvarez 1993, personal communication). Bark texture was classified according to the roughness of the bark in a range from smooth to very fibrous. Hemispherical photographs were taken to estimate the gap fraction of the forest canopy in the subplots where throughfall collectors were installed. A photographic camera was installed horizontally at the same height as the throughfall collectors, and 40 horizontal photographs per plot were taken of the tree crowns. The black and white photographs were digitised with a scanner and analysed with a Hemiphot program (ter Steege, 1994). This program calculates the gap fraction of a forest and roughly estimates the LAI from the forest cover. Although photographs were taken under covered sky with diffuse sun light, they were corrected for the reflected light from leaves, branches and trunks. It is assumed that the mean fraction of the white pixels in the photographs gives the best estimate of the gap fraction.

Total evaporation (E), which is take here as the total amount of water intercepted and evaporated from the forest canopy, hereafter referred to evaporation, is calculated from the difference between gross rainfall (P_g) and net rainfall (throughfall P_t plus stemflow P_s) of the single rainfall events. Evaporation during the rainfall events (E_w) is calculated from the difference between gross rainfall and net precipitation, plus the water stored on the forest canopy after rainfall ceased (inferred from the constant of the estimated evaporation versus gross rainfall).

$$E_w = P_g - (P_t + P_s + S) \tag{3.1}$$

Statistical analyses were made for the entire collected data. However, for the determination of rainfall sizes, measurements of single rainfall events are required. Therefore, throughfall percentage relative to gross rainfall and evaporation were calculated from these measurements. Moreover, for a further cross validation of static models, they have been deduced using the first half of the daily dataset.

3.5 RESULTS

3.5.1 Forest structure

The average crown area of the trees used for measuring stemflow was for each ecosystem as follows: in the SP was 9.5 (± 7.3) m^2, in the HT was 17.8 (±14.0) m^2, in the LT 9.8 (± 7.2) m^2 and in the FP 12.1 (± 8.3) m^2. The largest mapped crown area was 62.2 m^2 and the smallest 2.4 m^2, both in the HT ecosystem. The average stem or trunk surface area, applying a correction factor of 0.5 (for trees with diameter larger than 0.2 m), was 7.2 (± 4.6) m^2 in the SP, 8.2 (± 5.2) m^2 in the HT, 8.4 (± 5.4) m^2 in the LT and 5.4 (± 4.6) m^2 in the FP ecosystem. The results of the estimated gap fraction of the canopy show that there are considerably differences between ecosystems in the average size of the canopy cover. The average gap fraction found for the ecosystem in the SP was 16.8% (± 2.4), in the HT was 15.4%(±3.4), in the LT was 11.7% (± 1.5) and in the FP 8.2% (± 1.5).

3.5.2 Rainfall characteristics

Gross rainfall above the forest canopy does not vary considerably within one plot. On average the differences between subplots in the amounts of gross rainfall in the SP were 5.5% (± 5.6), for n = 3, whereas in the HT these were 3.7% (± 3.5), in the LT gauges differ on average by 3.7% (± 3.0) and in the FP by 3.1% (± 2.7) for n = 2. Rainfall distribution differs between plots when examining separate storms, although annual totals are rather similar. During the measurement period (1992 to 1997) the mean annual rainfall at the AWS was about 3400 mm yr^{-1} and the annual average of the total time with rainfall was 616 hours per year. In total 1584 rainfall events were recorded at the AWS in Peña Roja, with storms ranging from 0.2 to 161.6 mm and with durations of 20 minutes to 13 hours. During the total period, 37% of the incident rain fell in single showers with less than 2 mm and 92.3% of these showers contributed with less than 30 mm. Rainfall intensity over the total period with some rainfall averaged 5.46 mm h^{-1}

with a maximum of 78.16 mm h^{-1} (Figure 3.1a). Most showers (63%) fell during the afternoon and at night (Figure 3.1b) and 56% of these storms fell in less than one hour (Figure 3.1c). Monthly rainfall distribution during the five-year period shows that there is a slightly drier period around December to February (Figure 3.1d). Comparing our data on five years rainfall with data from earlier years in the Middle Caquetá, (Duivenvoorden and Lips, 1995) rainfall characteristics are similar to the long-term average in the studied area.

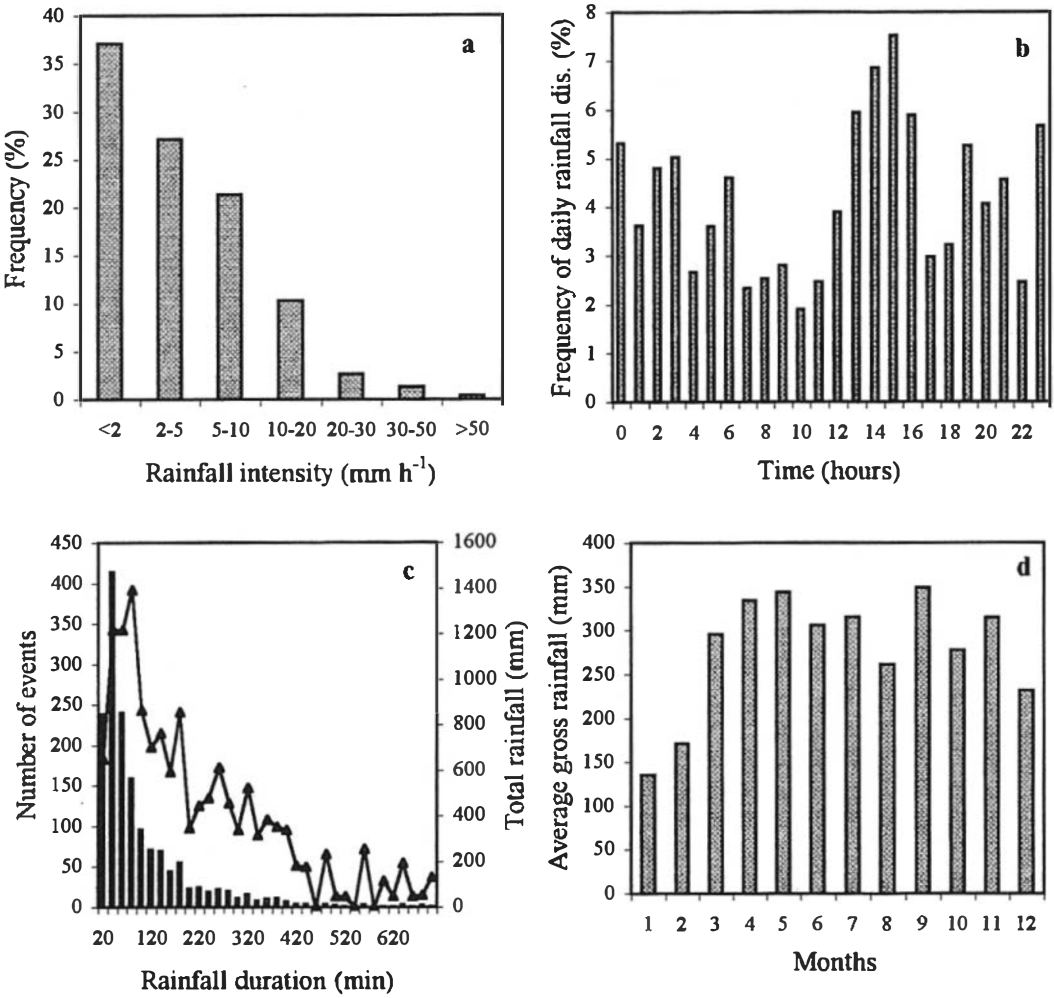

Figure 3.1 Patterns of rainfall distribution at the research site in the Middle Caquetá, Colombian Amazonia (August 1992 – August 1997).

3.5.3 Throughfall and stemflow

The variability of throughfall within a subplot was large, with the smallest variation in the FP ecosystem, although differences between subplots were small. The average coefficient of variation (CV) of individual gauges in each plot was 0.285 (± 0.10) in the SP; 0.306 (± 0.07) in the HT; 0.279 (± 0.09) in the LT and 0.225 (± 0.08) in the FP. The CV of the mean throughfall in each subplot was 0.062 (± 0.058) in the SP, 0.043 (± 0.05) in the HT, 0.046 (± 0.04) in the LT and 0.047 (± 0.04) in the FP. As a general trend in all ecosystems, the ratio of the std of throughfall (expressed as a percentage of mean throughfall) over the gross rainfall showed larger variability with small rainfall events than with major events. On the other hand, some individual throughfall gauges showed more than gross rainfall (e.g. 29% of total individual gauge measurements of throughfall in the SP were larger than respective gross rainfall, whereas in the HT it was 30%, in the LT was 27% and in the FP 21%), but the average (of 60 and 40 gauges) did never exceed gross rainfall.

Table 3.1 Throughfall percentage relative to gross rainfall for 5 storm classes in four forest ecosystems in the Middle Caquetá (Colombian Amazonia). Sedimentary plain (SP), high terrace (HT), low terrace (LT) and flood plain (FP).

Rainfall ranges (mm)	**Throughfall %**											
	SP	std	n	HT	std	n	LT	std	n	FP	std	n
< 5	58.7	11.4	41	56.2	12.1	34	52.3	9.6	32	47.4	13.2	27
5 – 20	81.4	6.3	78	80.5	5.6	68	79.8	6.8	71	74.5	6.9	57
20 – 40	88.9	2.8	39	87.9	2.6	36	87.7	3.4	41	83.0	2.5	32
40 – 80	90.6	2.1	19	90.0	1.9	19	88.8	2.5	17	84.6	3.1	19
> 80	92.8		1	92.2	0.8	3	92.4	1.0	2	88.5	1.2	5
Total	87.2	2.4	178	86.7	2.4	160	85.8	1.2	163	81.9	1.0	140

Throughfall was calculated as the percentage of gross rainfall for five different rainfall sizes and from the totals of measured daily gross rainfall and throughfall during the study. Throughfall percentage ranges from zero, with events below 2 mm, to 95% in storms larger than 100 mm, but mean throughfall varies from 50% to 93% depending on gross rainfall amounts and the type of forest ecosystem (Table 3.1). Calculated total throughfall percentage of total gross rainfall ranges from 82 to 87% in the four ecosystems.

Although empirical regression equations provide only specific site information, they may indicate a trend, especially if explained variance is high. Therefore, regressions of throughfall versus gross rainfall were computed separately for the four forest ecosystems from the single storms (Table 3.2). Average throughfall per plot was highly correlated with gross rainfall in all ecosystems (Figure 3.2). ANOVA analysis shows that the ratio of mean throughfall and gross rainfall in the FP is significantly different from the other ecosystems (significant at 0.05 level).

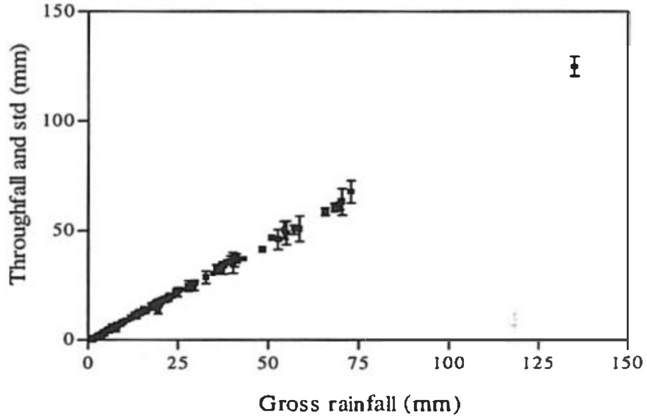

Figure 3.2 Trends of average throughfall amounts and the standard deviation (std) against gross rainfall in a forest ecosystem (SP, as an example) in the Middle Caquetá, Colombian Amazonia.

Table 3.2 Regression parameters of throughfall versus gross rainfall in four different forest ecosystems in Stemflow. The equation for linear form is T = a + bP, where T is throughfall amount and P is gross rainfall (mm). R^2 is the explained variance and n the number of observations.

Landscape unit	**a**	**b**	**se**	**R^2**	**n**
Sedimentary plain	-1.02	0.926	0.003	0.99	102
High terrace	-1.02	0.918	0.003	0.99	97
Low terrace	-1.07	0.906	0.004	0.99	97
Floodplain	-1.48	0.887	0.003	0.99	84

There were large differences in the amount of stemflow of each tree and among plots. In general, however, the contribution of stemflow to the net rainfall is very low. The average CV in each plot was 0.295 (± 0.12) in the SP, 0.207 (± 0.12) in the HT, 0.323 (± 0.20) in the LT and 0.303 (0.26) in the FP ecosystem. The percentage of stemflow in all plots varied from 0.2 to 3.2% of gross rainfall. Total average percentage of stemflow relative to gross rainfall was 0.85% (± 0.46) in the SP, 0.94 (± 0.51) in the HT, 1.45 (± 0.88) in the LT and 1.12 (± 0.56) in the FP. Differences are mainly due to the higher contribution of tree palms to the total stemflow per plot. In subplots with palms, high capacity collectors (more than 35 litres) were required to measure the incoming water. In these subplots, palms produced about 43% of total stemflow.

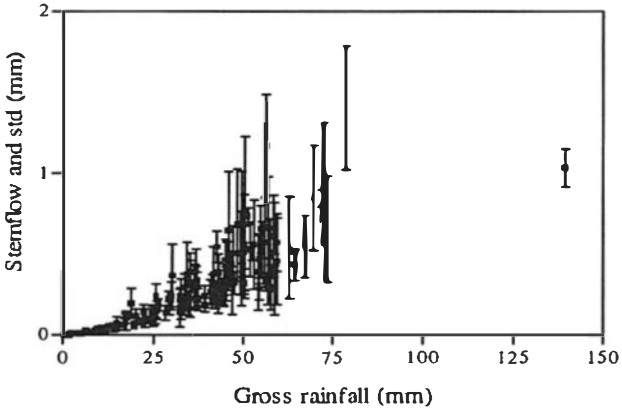

Figure 3.3 Average and standard deviation (std) of stemflow against mean gross rainfall in a forest ecosystem (SP) in the Middle Caquetá, Colombian Amazonia.

Stemflow amounts in all ecosystems rise very smoothly until a threshold of about 25 mm of gross rainfall is reached, (Figure 3.3) but tend to scatter with increasing rainfall. The relationship between measured stemflow and gross rainfall could be described with a power function (Table 3.3). Some rainfall events smaller than 3 mm did not produce stemflow in most of the plots, which explains the lower number of events (n) reported for stemflow regressions.

Table 3.3 Summary statistics for regressions of daily stemflow against gross rainfall in four forest ecosystems in the Middle Caquetá (Colombian Amazonia).). R^2 is the explained variance and n the number of observations.

Landscape unit	**Regression coefficient** c	d	**se**	**R^2**	**n**
Sedimentary plain	0.0015	1.530	0.049	0.92	86
High terrace	0.0020	1.467	0.038	0.94	92
Low terrace	0.0029	1.423	0.035	0.95	87
Flood plain	0.0031	1.325	0.050	0.91	73

For rainfall events with intensity greater than 5 mm h^{-1} stemflow showed no clear relationship with tree trunk area or bark texture. Nevertheless, there seems to be an inverse relationship between crown area and the amount of collected stemflow in each tree ($R^2 = 0.3$). It was also observed that the lower parts of trunks of trees with fibrous bark texture were slowly wetted during long storm events, which points to the high water storage.

3.5.4 Evaporation

Evaporation of intercepted water by the forest canopy is calculated by subtracting daily measured throughfall and stemflow from gross rainfall. Furthermore, it is related to gross rainfall characteristics and system parameters. Following net throughfall trends, the percentage of evaporation relative to gross rainfall varies from 6 to 100% in all ecosystems, depending on rainfall size. Total average of evaporation percentage of total gross rainfall also differs between ecosystems: 11.84 (± 2.4) in the SP, 12.24 (± 1.2) in the HT, 12.92 (± 1.1) in the LT and 17.15 (± 0.96) in the FP. For small storms (less than 2 mm) values of evaporation are very close to those of gross rainfall. For heavy showers, however, the relative value of evaporation becomes smaller (Figure 3.4).

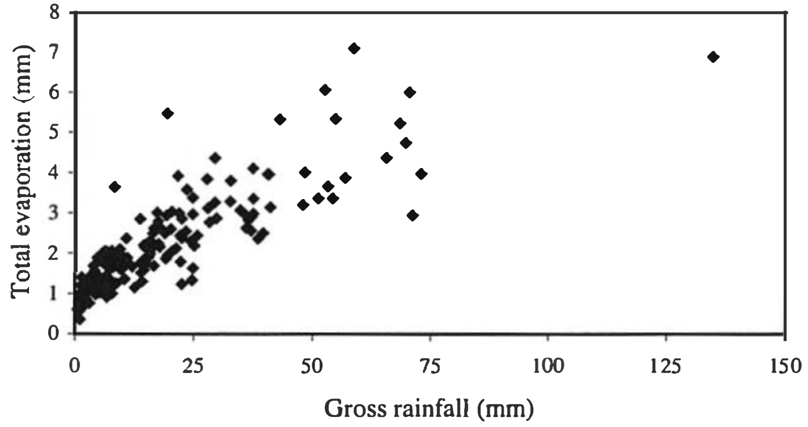

Figure 3.4 Total evaporation by Amazonian rain forest ecosystem (SP) as a function of gross rainfall. Middle Caquetá, Colombian Amazonia.

An assessment of the evaporation during rainfall (E_w) was calculated with equation 1 for the single rainfall events in each forest ecosystem. Additionally, E_w was related to rainfall duration. As canopy water storage capacity of the forest ecosystems is the only unknown parameter, it was derived from the intercept of the regressions of evaporation and gross rainfall measurements in each ecosystem. The evaporation rate during the rainfall varies from 0.34 to 0.68 mm h^{-1} among forest ecosystems (Table 3.4) and E_w exhibits a linear function with rainfall duration for all ecosystems (Figure 3.5). Negative values correspond to rainfall events of short duration and low intensity, indicating that the forest canopy did not reach saturated conditions during some events.

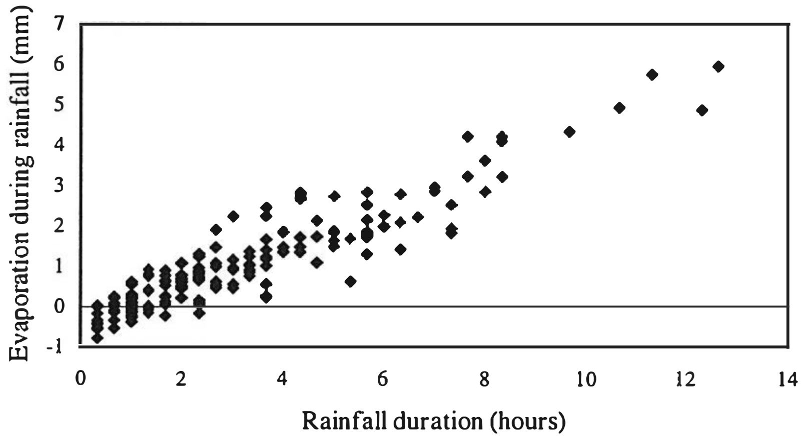

Figure 3.5 The variation in evaporation from wet forest canopy (E_w) in the SP forest ecosystem in relation to rainfall duration.

Table 3.4 Statistics of evaporation from wet forest canopy in single rainfall events in four forest ecosystems in the Middle Caquetá (Colombian Amazonia). Equations are of the form Ew = e + ft. e (mm) and f (mm h^{-1}).). R^2 is the explained variance and n the number of observations.

Forest	**Total rainfall (mm)**	**Total through. (mm)**	**Total stemf. (mm)**	**time (hour)**	**Evap. During rainfall (E_w) mm**	**Storage capacity (C) mm**	**Evap.rate from wet canopy mm h^{-1}**	**E_w versus rainfall duration. Reg. Coef. e**	**f**	**R^2**	**n**
SP	3274	2854	32.4	557.0	190.1	1.16	0.342	-0.424	0.46	0.86	178
HT	3293	2855	36.2	464.2	207.4	1.28	0.447	-0.263	0.52	0.75	160
LT	3158	2712	38.6	487.8	201.1	1.32	0.412	-0.351	0.52	0.82	163
FP	3121	2555	30.5	472.3	320.0	1.55	0.677	-0.366	0.78	0.88	140

When comparing similar rainfall events in the studied ecosystems, which have similar climate conditions, there still is a clear difference in amounts of evaporation. This implies that amounts of evaporation from the wet forest canopy are not only dependent upon gross rainfall and climate conditions. Differences in evaporation between close-by forests may be related to differences in their structure. Thus, the fraction of evaporation from each ecosystem, as the ratio between total evaporation and total gross rainfall (Table 3.4), was plotted against the mean forest cover (1 – gap fraction) found for each ecosystem. Figure 3.6 indicates that there is an increase of evaporation from the wet forest canopy with increasing canopy cover.

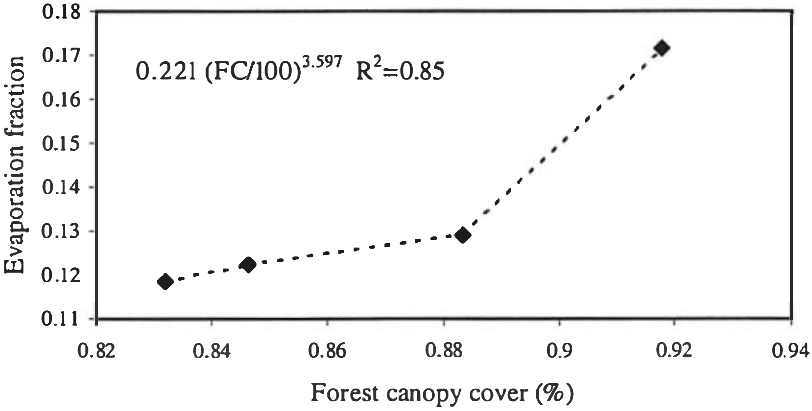

Figure 3.6 Fraction of evaporation from gross rainfall as a function of forest cover fraction, FC (1-gap fraction) in the four forest ecosystems. Middle Caquetá, Colombian Amazonia.

3.6 DISCUSSION

Results for throughfall and stemflow percentages of gross rainfall show that the studied range of forest ecosystems in this study comprises and explains most of the differences in results for rainfall partitioning reported in earlier studies from other sites within Amazonian rain forests (Table 3.5). Probably due to the large dataset, the allocated percentages of the coefficient of determination for the regressions in this study are significantly higher than most of those presented in the literature. Percentages of rainfall indicate that fractions of partitioning depend, among others, on the rainfall size. Moreover, it is clear from the analysis of throughfall and storm size (Table 3.1) that the high CV of throughfall is the result of the large variability in rainfall classes.

To define the total error (te) of the mean throughfall as a percentage of gross rainfall associated with forest structure and to allow comparisons, we applied the proposed formula of random relocation of n gauges by Lloyd and Marques (1988), although larger diameter funnels were used in the current study.

$$te = s.e.\left(1+\sqrt{N/n.m}\right) \qquad (3.2)$$

Where, s.e. is the standard error resulting from the random relocations of collectors, expressed as the best estimate of the standard error of mean throughfall in each, under the assumption that the specific canopy structure is properly described by N number of grid points and m the relocation of collectors. According to the results by Lloyd and Marques (1988), it appears that using the arrangement of 60 funnels with 23 relocations in the SP, the total error in measured throughfall is 3.5% of gross rainfall, whereas in the other ecosystems with 40 gauges and 23 relocations the error is 3.8% of gross rainfall due to variation in canopy structure. These figures are lower than those found by other authors, which can be explained by the continuous relocation of collectors. Nevertheless, te value from the present study is larger than that found by Lloyd and Marques (1988).

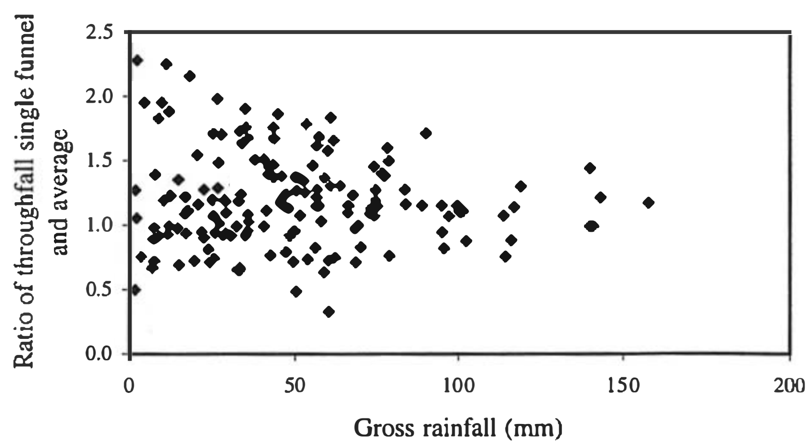

Figure 3.7 Variability of the weekly throughfall ratio (single gauge and the average of 20 gauges) of individual gauges as a function of gross rainfall.

The dependency of throughfall percentage on storm size remained to be established, as clearly stated by Lloyd and Marques (1988). Accordingly, we investigated the effect of storm size on throughfall percentage variability by using 20 months of weekly data of throughfall and gross rainfall from the same plots, which were collected by using the same methodologies but with the exception that gauges were not relocated. Figure 3.7, given as an example, shows that the variation in the ratio of throughfall from a single funnel to gross rainfall tends to decrease as storm size increases. This is an observed trend for most of the non-moving collectors but also from the relocated collectors, as stated earlier in this paper, which suggests that storm size also affects throughfall variability in the studied ecosystems. Although the relative proportion of the effect of the storm size on throughfall percentage is not determined, from the results here it can be concluded that for an appropriate determination of the percentage of throughfall relative to gross rainfall in mature Amazonian rain forests, when using the method of relocation of collectors, this relocation should be done, for instance, after a wide range of storms sizes have been sampled in a given position, in order to assess the combined effect of site forest structure and rainfall characteristics on throughfall percentage.

Variability of stemflow in undisturbed Amazonian rain forest ecosystems has been attributed to the high species diversity (Hutjes *et al.*, 1990; Hertwitz, 1985), which in the present study renders the estimation of stemflow difficult to assess on an areal basis. Thus, this parameter was estimated for different tree species with different diameter. Stemflow amounts from this study range from 0.9 to 1.5% of gross rainfall, which is in the range of values observed in other studies in similar forest types (Table 3.5). Although the percentage of contribution of stemflow to the net rainfall is very low, it probably represents an important input of solutes, to the forest floor concentrated around the base of the tree. Results suggest that little water is stored in excess of the storage capacity of the stem elements, as indicated by the very small stemflow quantities collected once rainfall has ceased or during small storms. This can be explained by the presence of some tree trunks with hydrophobic bark (personal observations 1992 - 1997) and of bark with fibrous texture. Tree species with these characteristics exhibit a clear flux of stemflow, even without being completely wet. However, once rainfall stops, there is a sharp decline in stemflow.

Table 3.5 Partitioning of gross rainfall (percentages) in Amazonian rain forests.

Location	**Forest type**	**Throughfall %**	**Stemflow %**	**Evaporative loss %**	**Reference**
Venezuela	Catinga	91	0.8 -14	--	Henera (1979)
Brazil	Tropical rain forest	80.2	--	19.8	Franken *et al.* (1992)
Brazil	Tropical rain forest	87 - 91	1.8	8.9 (± 3.6)	Lloyd and Marques (1988)
Brazil	Tropical rain forest	86 - 87	0.8 - 1.4	11.6 -12.9 (± 5.9)	Ubarana (1996)
Colombia	Tropical rain forest	82 - 87	0.9 - 1.5	12 - 17	This study

Static models seem to be capable of describing rainfall partitioning for the studied forest ecosystems. Although the applicability of these models is most probably restricted to the area and measurements conditions and the relationships may contribute little to the explanation of the hydrological processes at canopy level, they clearly indicate the magnitude of the dependence on the related parameters. While linear functions produce better fits for correlations between throughfall and gross rainfall, power functions produce better fits for such correlations with stemflow, in terms of the significance levels and standard deviation of residuals. The linear regression equations of throughfall versus gross rainfall fits most points and produce a high coefficient of determination in all ecosystems. Nevertheless, their application in very small storms (lower than 2 mm) result in negative values of throughfall and they slightly underestimate throughfall for very high rainfall events, which illustrates the limitation of regressions which fit a curve to a set of data.

The evaporation values found for the studied ecosystems comprise most of the values of interception reported in other studies within the Amazon basin. Some of the values found in the current study are higher than the value reported by Franken *et al.* (1992) in a study on a "terra firme" forest in Brazil (Table 3.5). Although differences seem to be large, when compared with the found evaporation value from the SP, which is a comparable ecosystem to those called in other studies as "terra firme" Franken *et al.* (1992) did not consider the contribution of stemflow to net rainfall and do not present the standard deviation of the calculated values. Moreover, the relative proportion of evaporation from the forest ecosystems in this study is also higher as gross rainfall is higher, at least when compared with the mean annual value of 2500 mm reported from central Amazonia (Leopoldo *et al.*, 1987).

Evaporation during rainfall (E_w) from the studied ecosystems strongly depends on rainfall duration. A distinct relationship also seems to exist between evaporation and forest cover (Figure 3.6). Although it should be realised that the number of forest ecosystems studied is small and the relationship is rather uncertain, it may serve for the estimation of evaporation by a forest where measurements are not available. Such estimations mainly rely upon an adequate estimation of the gap fraction or LAI.

3.7 CONCLUSIONS

Of the gross rainfall of about 3400 mm yr^{-1}, most fell in small showers during the afternoon and at night and were of short duration. The overall average rainfall intensity was about 5 mm h^{-1}. The rainfall characteristics mainly explain the partitioning of rainfall into throughfall, stemflow and ensuing evaporation in the studied ecosystems.

Water fluxes in the forest canopy in four ecosystems in the western Amazonia have been quantified as a percentage of gross rainfall. Amounts of net precipitation to the forest floor and evaporation from the wet forest canopy were different for the studied ecosystems: the SP ecosystem has the highest percentage of throughfall relative to gross rainfall and the FP the lowest of the studied forests. The observed differences in throughfall, stemflow and evaporation between ecosystems can partly be attributed to differences in forest structure (gap fraction). The range of these differences is similar to the overall range in these parameters as published in earlier studies from the Amazon basin, implying that the latter variability may be connected with differences in forest structure.

Results from the ecosystems studied provide some insight into the rates of evaporation from wet forest canopy and strengthen the understanding of the contribution of forests to atmospheric moisture. The mean evaporation rate from wet forest canopy during rainfall events in the Middle Caquetá, (Colombian Amazonia) was 0.47 mm h^{-1} and it increased with increasing percentage of the forest cover. Moreover, this study of throughfall, stemflow and evaporation in different forest ecosystems demonstrates the relevance of forest structure for the evaporation of rainfall intercepted by the forest canopy and the net precipitation reaching the forest floor. The results show that within the scope of this research the forest structure can be adequately characterised by the gap fraction and LAI. These structural characteristics together with the rainfall amount and rainfall duration are the main parameters determining rainfall partitioning in the western Amazonian rain forests.

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4. MODELLING NET RAINFALL IN NORTHWEST AMAZONIAN FORESTS WITH A PHYSICAL BASED INTERCEPTION MODEL

4.1 ABSTRACT

The Rutter's forest interception model (Rutter *et al.*, 1971), modified by Bouten *et al.* (1996), is calibrated for four forest ecosystems in the Middle Caquetá, Colombian Amazonia, to provide a tool for quantification of the temporal dynamics of net rainfall. Six months of hourly meteorological measurements, daily gross rainfall in the open and daily data on throughfall and stemflow (net rainfall) in the forest ecosystems are used to calibrate the model. The performance of the calibrated model was tested against daily and weekly measurements of net rainfall from another period than that used for calibration. To compare measurements and predicted values, two main statistical indicators were used: the normalised root mean square error (NRMSE) between measured daily net rainfall and simulated amounts and the explained variance (R^2). Although not focussed on predicting evaporation dynamics, the predicted evaporation dynamics were compared against values deduced from measurements. Model performance was improved after the calibration of the storage capacity parameter. Values of calibrated storage capacity differ from measured values and from published values for other sites in the Amazon basin. Yet, values increased from the SP to the FP, which agrees with the measured trend. The calibrated values of storage capacity have a linear relation with the values of LAI in ecosystems studied. In these ecosystems, the ratio between values of storage capacity and LAI is similar, pointing to a standard water holding capacity per unit leaf area in the ecosystems studied. The calibrated model is capable of predicting daily and weekly measurements of net rainfall with a NRMSE below 0.08 and R^2 above 0.99 for the ecosystems studied. Dynamics of predicted net rainfall by the physical based model differ from those predicted by the static model presented in Chapter 3. Because of the accuracy of the model predictions (daily and weekly) and the physical plausibility of predicted net rainfall dynamics in all ecosystems, the dynamic model is used for such in the current study.

4.2 INTRODUCTION

A number of simulation models, describing interception processes, can be used to predict net rainfall and evaporation of intercepted rainfall. These models range from static simple regression models (This issue, Chapter 3; Gash, 1979; Jackson, 1975; Zinke, 1967) to more elaborate dynamic models (Jetten, 1996; Bouten *et al.*, 1996; Bruijnzeel and Wiersum, 1987; Calder, 1986; Massman, 1980; Rutter *et al.*, 1977; Rutter *et al.*, 1971). While static models are simple and easy to use, they do not always give satisfactory results at short time scales, and provide no information on physical processes and parameters involved. Dynamic models minimise the hazards of empiricism by relying upon more fundamental physical reasoning (Massman, 1983). Additionally, a dynamic simulation model will help to identify ecosystem processes and parameters controlling interception, and thus to establish for which parameters input data are required for model predictions. Furthermore, such model will also help to explain observed spatial and temporal variability in net precipitation and evaporation of intercepted rainfall.

Rutter *et al.* (1971) developed a physically based single-layer model to calculate the interception of water by a Corsican pine forest plantation in U.K. The model estimates net precipitation and evaporation from input data on gross rainfall and climate, and has been applied to different forest types (Valente *et al.*, 1997; Jetten, 1996; Bouten *et al.*, 1996; Lloyd *et al.*, 1988; Gash and Morton, 1978). The main disadvantage when applying Rutter's model is that hourly meteorological data are required (Gash, 1979; Rutter *et al.*, 1971). It has been stated that the description of the wetting of the canopy in the Rutter's model yields an underestimation of evaporative loss when applied to tropical rain forest (Calder *et al.*, 1997; Calder *et al.*, 1986), and for such forest alternative approaches have been suggested (Hall *et al.*, 1996; Calder *et al.*, 1996; Calder, 1986). However, the model has also been used for tropical forest with satisfactory results (Ubarana, 1996).

The aim of this paper is to simulate the temporal dynamics and amounts of net rainfall with a calibrated dynamic model, which is based on physical principles. It is known that temporal dynamics of net rainfall do not only depend on rainfall characteristics but also on storage and evaporation dynamics and amounts. By using a dynamic model, after its calibration for the research sites, we expect to obtain better results than through static models. These results can be used as input for the forest floor model and for the water balance of the ecosystems studied (see Chapter 8).

4.3 METHODOLOGY

4.3.1 The dynamic model

A physically based single-layer model developed by Rutter *et al.* (1971) and modified by Bouten *et al.* (1996) was used to describe the net rainfall dynamics in four forest ecosystems in Colombian Amazonia. The resulting model is a numerical multi-layer interception model with four model parameters per layer. In the present study, for simplicity, the forest is considered to be composed of a single leaf layer. The model calculates the canopy water balance based on rainfall, drainage and evaporation rates. Since the theoretical framework of the model has been described by many authors (Bouten *et al.*, 1996; Jetten, 1996; Lloyd *et al.*, 1988; Gash and Morton, 1978; Rutter *et al.*, 1971), only general characteristics are presented here, including the modifications by Bouten *et al.* (1996) and its application for a single leaf layer instead of a multilayer forest.

The Rutter's interception Model (Bouten *et al.*, 1996), is of the form:

$$\frac{\Delta S}{\Delta t} = I - D - E \tag{4.1}$$

$$I = a\,(P) \tag{4.2}$$

Where S (mm) is the water storage in the canopy, t (day) the time, D (mmd^{-1}) is the drainage rate, I (mmd^{-1}) evaporation of rainfall interception by the forest canopy, E (mmd^{-1}) the evaporation rate, P (mm) gross rainfall and a (mm) the interception efficiency parameter

A linear function (Calder, 1977) is used in the model to describe the drainage rate:

$$D = b\,(S-C) \qquad \text{for } S \geq C \tag{4.3}$$

$$D = 0 \qquad \text{for } S < C \tag{4.4}$$

Where b (day) is the drainage parameter and C (mm) the water storage capacity by the forest canopy.

Throughfall and net rainfall are given by:

$$T = D + p \tag{4.5}$$

$$P_n = T + St \tag{4.6}$$

T (mm) is throughfall, P_n (mm) the net rainfall, p (mm) free throughfall to the forest floor and St (mm) is the stemflow.

In the model the reference evaporation for wet surface (Monteith, 1965) is calculated according to:

$$E_0 = \frac{\Delta R_n + \rho Cp(VPD)/e(r_a)}{\lambda(\Delta + \gamma)} \tag{4.7}$$

Where E_0 is wet surface evaporation, Δ (mbar K^{-1}) the rate of change of saturated specific humidity with temperature, R_n (W m^{-2}) net radiation, ρ (kg m^{-3}) density of air, C_p (J kg^{-1} K^{-1}) is the specific heat of air at constant pressure, VPD (mbar) vapour pressure deficit, e is the aerodynamic resistance parameter, r_a (s m^{-1}) aerodynamic resistance, λ (J kg^{-1}) latent heat of vaporisation of water and γ (mbar K^{-1}) the psychometric constant.

The evaporation rate from the canopy is calculated from:

$$E = f\,(E_0\,S/C) \tag{4.8}$$

Where f (mm) is the evaporation efficiency parameter. The aerodynamic resistance is calculated from the wind profile, according to:

$$r_a = \frac{\left[Ln\left(\frac{z-d}{z_0}\right)\right]^2}{K^2.u_z} = \frac{u_{zf}}{u_{*f}} \tag{4.9}$$

Assuming neutral conditions:

$$u_* = \frac{K.u_z}{Ln\left(\frac{z-d}{z_0}\right)} \tag{4.10}$$

Where d (m) is the surface roughness (0.67h), h (m) is the height of vegetation, K the van Karman's constant (0,40) u_* (m s^{-1}) the friction velocity, u_z (m s^{-1}) the wind speed and z_0 (m) the zero plane displacement (0.1h).

4.3.2 Model inputs

The areas for the present study were selected as being representative for the major physiographic units in this part of the Amazon basin cover with natural vegetation. The plots are located in the Tertiary sedimentary plain (SP) and the alluvial plain of the River Caquetá: high (HT) and low terrace (LT) and rarely inundated flood plain of the River Caquetá (FP). A number of plots were selected to measure gross precipitation above the forest and throughfall and stemflow: in the Tertiary sedimentary plain three plots and in the others ecosystems two plots were chosen. A more detailed description of the research sites and climate conditions is presented in Chapter 2.

In an open area, an automatic weather station (AWS) was installed from 1992 until 1997 to register each 20 minutes gross rainfall amount and mean values of temperature, relative humidity, solar radiation, wind speed and wind direction. Measurements were carried out at three meters above the surface in the open. Gross rainfall in the plots was measured automatically by using a rain gauge tipping bucket with a 0.2 mm resolution. Manual measurements were carried out with two rain gauges in each plot, installed above the forest canopy. Throughfall was measured with 20 collectors per subplot, randomly distributed within an area of 50x20 m. Both, gross rainfall and throughfall collectors were connected to plastic funnels with a surface of 298.6 cm^2. Stemflow was measured on 15 protruding trees in each subplot. Manual measurements were carried out every 5 days, from August 1992 to February 1996; and daily measurements were executed from February to August 1997. Each month, throughfall collectors were randomly relocated within the plots. A more detailed description of measurements, disposition of collectors and rotations can be found in Chapter 3. Evaporation of intercepted water by the forest canopy was calculated from the difference between daily gross rainfall and net rainfall in each plot.

To estimate the gap fraction (a) of the forest canopy, 40 hemispherical black and white photographs were taken horizontally to the tree crowns in each plot. The photographs were digitised with a scanner and analysed with the Hemiphot programme (ter Steege, 1994). This programme calculates de gap fraction of the forest from the white pixels and roughly estimates the LAI from the forest cover. Photographs were corrected for the reflected light and the mean fraction of the white pixels in the photographs is taken as the best estimate of the gap fraction (see Chapter 3).

The water storage capacity of the forest canopy (C) is derived from the constant of the regression of calculated evaporation against gross rainfall measurements. Most methods for the determination of C, which have been presented sofar, mainly differ in the way of accounting for the proportion of the drainage before the forest is completely saturated and the gradual saturation of forest layers with continuously proceeding evaporation. In the present study, only single and high-intensity rainfall events of short duration (less than one hour) were used. Late afternoon and night rainfalls were preferred representing rainfalls under low deficit of moisture conditions. In total, 30 to 40 events were selected for each ecosystem.

Free throughfall may be taken as the gap fraction of the forest (a). This parameter was estimated for each ecosystem from the digitised and scanned black and white photographs (ps) and from the regression coefficient of throughfall versus gross rainfall (pt) for small storms, which were insufficient to saturate the forest canopy (Gash and Morton, 1978). About 10 to 14 storms selected from each ecosystem were used to determine the value of pt. Values of estimated gap fraction of the forest types, storage capacity and free throughfall for each plot are presented in table 4.1 (first set).

4.3.3 Model calibration

First, the model performance was tested with parameter values that were determined from independent measurements. Therefore, observed values for the storage capacity in each ecosystem were used as input to the model and results were evaluated. To define the set of parameters to be optimised and the possible parameter dependence, the sensitivity of the model to each parameter and to the parameter combination were separately tested for their influence on the model results. Sensitivity analysis showed that the model is most sensitive to the storage capacity (C) and considerably less sensitive to evaporation efficiency (e) and aerodynamic resistance (f) parameters and almost not sensitive to the drainage parameter (b). Therefore, the e and f parameters were set to 1 and b was set to the value found by Bouten *et al.* (1995). The C parameter was optimised to test whether the performance of the model improves and if so, to what extent. A multivariable optimisation routine within the Matlab programme was used for the optimisation, on the basis of the Normalise Root Mean Square Error (NRMSE) between measured daily net rainfall and simulated amounts, without setting the value to any limits. Six months of daily data on net rainfall and twenty minutes data on climate and gross rainfall (1997) were used for the calibration of the model parameters. The calibration procedure consists here in finding the values of the model parameters producing the best fit with net rainfall measurements. Values of C parameter are also evaluated in terms of its physical plausibility.

The gap fraction parameter (a) is not optimised for two main reasons: first, it was estimated from the dataset as well from the set of black and white hemispherical photographs. The derived mean value from the white pixels in each ecosystem was used as input for the dynamic model. The second is that within the model it inversely interacts with the LAI, therefore any increase in LAI will produce a decrease in the value of this parameter.

The optimum values of the parameters obtained from the measurements and calibration procedure were used to evaluate the accuracy of the model to reproduce new data on daily and weekly net rainfall measurements. The performance of the calibrated model is also tested against weekly data. Additionally, the capability of the calibrated model to predict evaporation of intercepted gross rainfall in the forests studied is tested. Hourly data on climate, six months data of daily gross rainfall and two years of weekly data on gross rainfall are used as input to the model. Daily and weekly data on net rainfall from these periods are used to test the performance of the calibrated model. Two statistical indicators were used: the Normalised Root Mean Square Error (NRMSE), which renders a sort of coefficient of variation of the difference between predicted and measured values around the measured mean and the explained variance (R^2), which is a straightforward indicator of the agreement between predicted and measured values.

4.4 RESULTS AND DISCUSSION

4.4.1 Results of model calibration and parameter values

Parameter values directly calculated from the measurements are presented in Table 4.1, first set. The measured value of the storage capacity of the forests increases from the SP to the FP ecosystems, which reflects the differences in forest structure between these ecosystems. The highest value for the storage capacity is consistent with the lowest rate of net rainfall and higher rates of evaporation. The calculated pt values, based on the selected small storms, agree with the values found by Waterloo (1994) and Jetten (1996), but clearly differ from those derived from the scanned photographs (ps). Moreover, their application resulted in an overestimation of net rainfall in all ecosystems. The fact that small showers producing throughfall are required to determine pt, affects the accuracy of its estimation, since the frequency of such events is very low. Estimated values therefore are prone to a large error. Contrary, analyses of photographs of the forest canopy under non-direct sunlight, especially if large number of photographs have been taken and analysed, are likely to produce reliable estimates of ps.

Model results show that after applying measured parameter values, the explained variances between predicted and measured net rainfall are above 0.99 for all forest ecosystems (Table 4.1, first set). At this stage, results indicate that the accuracy of the dynamic model to predict net rainfall is similar to that of the static models with two calibrated parameters.

Table 4.1 Calculated and optimised parameter values for the four forest ecosystems in the Middle Caquetá, Colombian Amazonia. (ps = free throughfall estimated from white pixels and pt from the regression analysis, Pn is the net rainfall and E the evaporation of intercepted gross rainfall by the forests. Values in the fifth column correspond to the statistics from the test of the model performance with a data set independent from that used during the calibration.

	Parameter/statistical indicator	**1st Set**	**2nd. Set**	**Test of model performance**	
				Daily data	**Weekly data**
SP	ps (a)	0.168	0.168		
	Pt	0.59			
	C	1.16	1.61		
	NRMSE	0.084	0.074	0.045	0.089
	R^2	0.99 Pn	0.99 Pn	0.99 Pn	0.99 Pn
		0.22 E	0.49 E	0.53 E	0.38 E
HT	ps (a)	0.154	0.154		
	Pt	0.52			
	C	1.28	1.66		
	NRMSE	0.089	0.079	0.037	0.103
	R^2	0.99 Pn	0.99 Pn	0.99 Pn	0.99 Pn
		0.38 E	0.65 E	0.71 E	0.56 E
LT	ps (a)	0.117	0.117		
	Pt	0.49			
	C	1.32	1.75		
	NRMSE	0.125	0.114	0.044	0.077
	R^2	0.99 Pn	0.99Pn	0.99 Pn	0.99 Pn
		0.28 E	0.54 E	0.62 E	0.46
FP	ps (a)	0.09	0.09		
	Pt	0.27			
	C	1.55	2.23		
	NRMSE	0.16	0.131	0.062	0.097
	R^2	0.99 Pn	0.99 Pn	0.99 Pn	0.99 Pn
		0.30E	0.50 E	0.52 E	0.43

Results after the calibration of parameter C are presented in Table 4.1, second set. The contribution of the optimised C parameter to the model performance is very low. However, the NRMSE between measured and predicted net rainfall is lower in all ecosystems. There are some discrepancies between the estimated storage capacity parameter, derived from the dataset on evaporation and gross rainfall and that from the optimisation procedure. Moreover, the estimates for the canopy storage capacity from the optimisation routines for all ecosystems range from 1.6 mm to 2.2 mm. These values are larger than most values reported from other areas in Amazonia. (Ubarana, 1996; Jetten, 1996; Hutjes *et al.*, 1990; Lloyd *et al.*, 1988). These discrepancies can be explained by the fact that, when determining this parameter by regression of evaporation (or throughfall) and gross rainfall, evaporation during the events concerned is neglected. Additionally, most studies on rainfall interception which have been executed in Amazonian rain forest were in the so called "terra firme" forest (non-flooded ecosystem). As we studied a broader range of ecosystem types, the differences in parameter values mentioned here might be also ascribed to differences in forest structure.

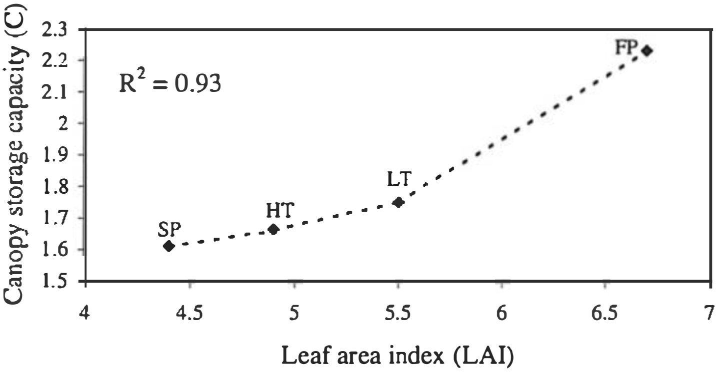


Figure 4.1 Calibrated values for the storage capacity of the forest canopy as a function of the leaf area index (LAI) in Colombian Amazonia. Tertiary sedimentary plain (SP) and the high terrace (HT), low terrace (LT) and flood plain (FP) of the River Caquetá.

Calibrated values for the C parameter were plotted against the values of LAI in the studied ecosystems. A linear function fitted these values with a high explained variance (Figure 4.1), in agreement with the tendencies presented in Chapter 3 with the forest cover and evaporation. This implies that values of forest parameter which present some difficulties to assess, as the identification of storage capacity (C), can be extended to forest characteristics, which can be measured and quantified (e.g. LAI). The ratio between calibrated values of the C and calculated LAI of the forest ecosystems can be interpreted as the water holding capacity per unit leaf area. Results from the calibration of C parameter in the ecosystems studied indicate that such water layer in the forest canopy is similar between ecosystems, with a value of about 0.33 mm. Comparisons with other ecosystems within the Amazon basin was not possible since there seems to be no data on the water holding capacity of the forest canopy for other sites.

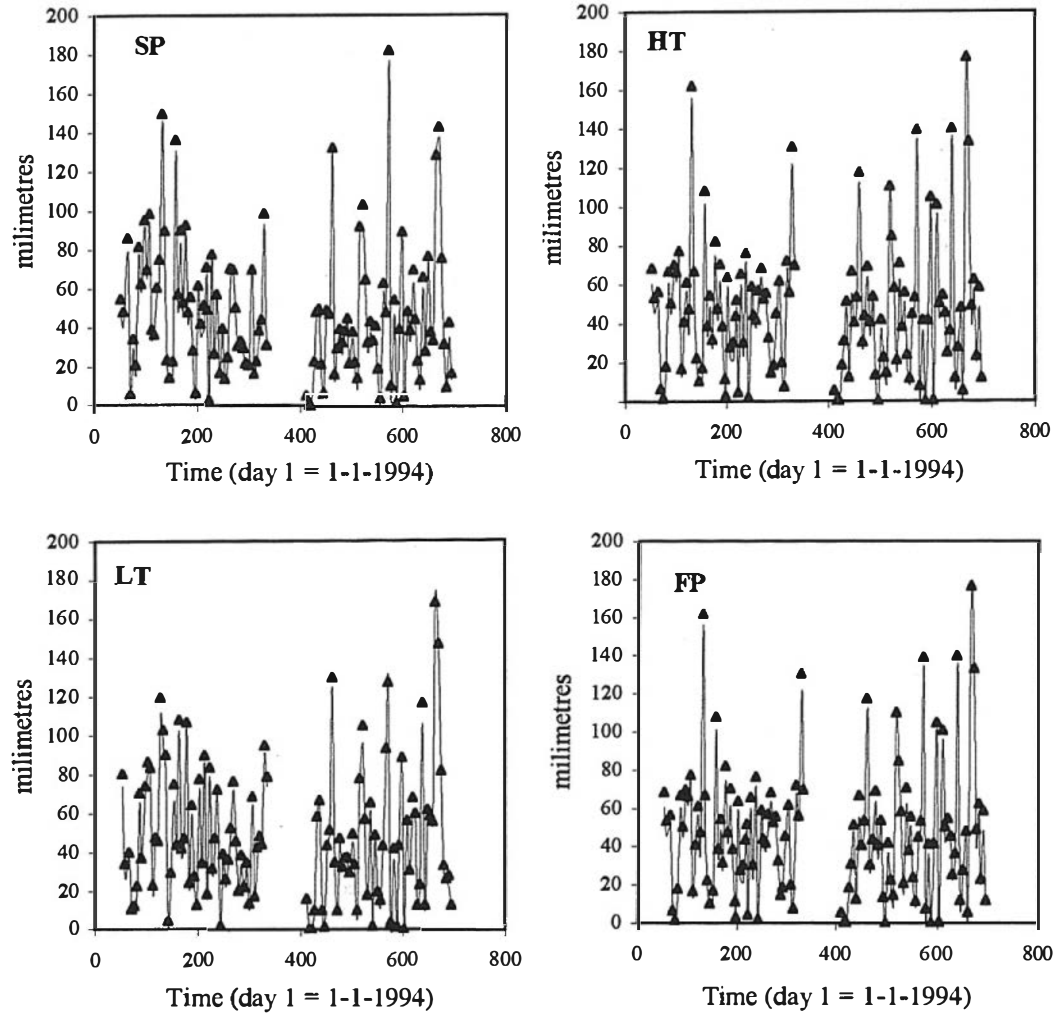


Figure 4.2 Temporal dynamics of measured (▲) and predicted (—) weekly net rainfall in four forest ecosystems in Colombian Amazonia. Tertiary sedimentary plain (SP) and high terrace (HT), low terrace (LT) and flood plain (FP) of the River Caquetá.

4.4.2 Predictions by the calibrated model

Results from the calibrated dynamic model show that the fit of the simulated and measured amounts of net rainfall during the validation period is as good as for the calibration period in all ecosystems. In order to illustrate the model predictions we tested these statistically within the 95% confidence regions. Analyses indicate that predictions for all ecosystems are above 99% and the NRMSE decreased from the values during the calibration, being lower than 0.062 for daily measurements and lower than 0.103 for weekly measurements (Table 4.1). Predicted weekly values and measurements from the four ecosystems are presented in Figure 4.2. Net rainfall was slightly underestimated, but the model was capable of explaining weekly net rainfall, amounts and dynamics also with 99% accuracy. The dynamics of net rainfall, as predicted by the dynamic model, clearly differ from those predictions by the static model (Figure 4.3). There is plausibility in the physical description of net rainfall dynamics as predicted by the dynamic model. The percentage of net rainfall is lower at the start of the rainfall event and increases as gross rainfall increases, to become almost equal to gross rainfall at the end of the event. Rather, the static model predictions, as expected, are a constant percentage of gross rainfall.

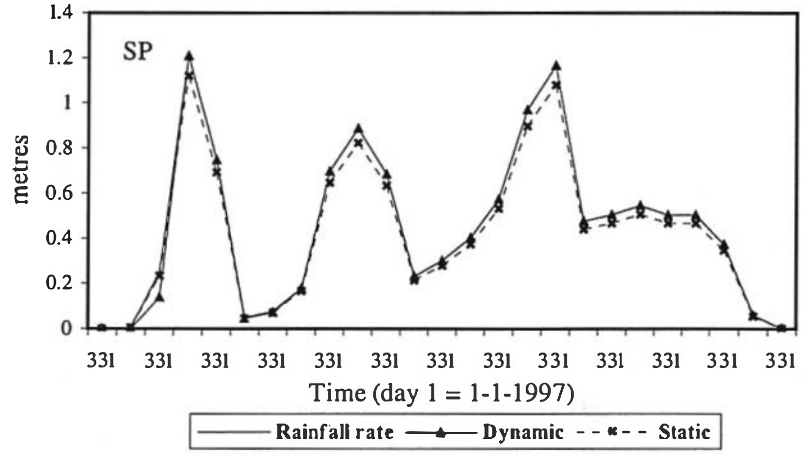


Figure4.3 Comparison of the dynamics of net rainfall rate as predicted by the physical based model and the static model in the Tertiary sedimentary plain (SP), as an example. Gross rainfall rate is also presented.

The calibration of the dynamic model is not focussed on predicting amounts of evaporation of intercepted rainfall by the forests. However, insight into processes occurring in wetting and drying canopies are important for describing the canopy water balance. The accuracy of the calibrated model for estimating evaporation is tested by using calculated values of evaporation from the measurements as comparative data.

Results indicate that although evaporation is somewhat less accurately predicted by the model, the accuracy of predictions increased after calibration of the C parameter and when using a different data set to test the performance of the calibrated model (Table 4.1), except for the weekly measurements when the NRMSE increased. Predicted dynamics show that saturation of the forest canopy is reached relatively fast after the rainfall starts, which agrees with the observations by Ubarana (1996) in Brazil. It is also clear that some events with a very high intensity do not saturate the forest canopy, which may be related to the high intensity and the short duration of rainfall events.

Considering the uncertainties in the measurements of net rainfall, the observed relation between predicted and measured evaporation dynamics, though not optimal, is still quite satisfactory. Moreover, it is clear that when using the calibrated model to predict evaporation dynamics of intercepted rainfall values will not be as accurate as when it is used to predict net rainfall. Evidently, studies focussed on modelling of evaporation dynamics need more detailed data on net rainfall in order to calibrate and compare the performance of the models concerned.

4.5 CONCLUSIONS

The modified Rutter's model by Bouten *et al.* (1996) has been calibrated for the forest ecosystems studied, in which the storage capacity appeared to be the most relevant parameter. After calibration, the model is capable of predicting measured daily and weekly net rainfall and temporal dynamics with high accuracy for the ecosystems studied. Calibrated values of storage capacity of forests are highly correlated to the LAI of these ecosystems. The ratio between calibrated values of water storage capacity and LAI is similar in all ecosystems, pointing to a standard water holding capacity per unit leaf area for the ecosystems concerned. This implies that the calibrated parameter is physically interpretable and generates confidence in the predicted dynamics of net rainfall.

For the study of the forest floor hydrology and overall water balance, input data for net rainfall are required. Some gaps in measurements exist, leading to gaps in these input data. Based on results here, the mentioned gaps will be filled with data generated by the calibrated physically based model, using net rainfall and canopy parameters as input.

5. CALIBRATION OF TDR WATER CONTENT MEASUREMENTS IN THE FOREST FLOOR AND CLAY SOILS IN NORTHWEST AMAZONIAN FORESTS

5.1 ABSTRACT

Time Domain Reflectometry (TDR) was used to investigate the water dynamics in the forest floor and mineral soils in four forest ecosystems in the Middle Caquetá, Colombian Amazonia. Undisturbed samples for gravimetric determination of water content and bulk density were collected from the same sites where TDR measurements were carried out. Volumetric water content of the samples (forest floor and mineral soil) was fitted with linear functions against the refraction index calculated from the TDR travel time measurements. These linear regressions, with an explained variances of 0.94 and 0.88, were compared with results from existing calibration models, indicating that existing calibration parameters either underestimate or overestimate measured water content from the samples. In an attempt to improve the accuracy of the function for the mineral soil, measured bulk densities from the soil samples were used following the procedure indicated by Malicki *et al.* (1996). Although the results were in close agreement with Malicki's function, interpretation of parameters with the available data on bulk density rendered a very low explained variance. Therefore, deduced regression parameters of measured water content and the refraction index (forest floor and mineral soil) can be used to translate TDR travel time measurements into volumetric water content.

5.2 INTRODUCTION

Time Domain Reflectometry (TDR) is a well-known and non-destructive method to measure water content in different soil types (Weitz, 1997; Heimovaara *et al.*, 1993; Topp *et al.*, 1980) and in the forest floor (FF) (Schaap *et al.*, 1995). TDR is based on the measurement of the propagation velocity of an electromagnetic pulse along parallel lines. This propagation velocity depends on the soil dielectric permittivity. According to Topp *et al.* (1980), the dielectric constant (K_a) strongly depends on the volumetric water content of the soil and it is almost independent of soil texture, density and electrical conductivity of the soil solution. Topp *et al.* (1980) also found that the apparent dielectric permittivity of clay soils differs from that of sandy soils.

One of the most common calibrations models relates the apparent dielectric permittivity (K_a) to the volumetric soil water content (Topp *et al.*, 1980). This third order function was derived from soils with water content ranging from 0.1 to 0.5 $m^3.m^{-3}$ and bulk densities between 1.3 to 1.4 $Mg.m^{-3}$. Although suitable for sandy soils with low bulk densities (Heimovaara and Bouten, 1990; Gardner *et al.*, 1990; Topp and Davis, 1984), it has been stated that the function may be inappropriate for the estimation of water content of soil with a high organic matter content (Herkelrath *et al.*, 1991; Topp *et al.*, 1980) or for clay soils with high bulk density (Vielhaber, 1995; Dirksen and Dasberg, 1993). Furthermore, when using a TDR system to measure FF water content, measurements need to be calibrated (Schaap, 1996). Calibration functions have been presented for clay soils (Dasberg and Hopmans, 1992), FF materials (Schaap *et al.*, 1995) and volcanic soils with low bulk densities (Weitz *et al.*, 1997). Lastly, Malicki *et al.* (1996) published a function relating volumetric water content to the refraction index and bulk density.

All functions seem to apply only for the measured range of water content and bulk densities, and to be rather site and soil specific. Extrapolation to other sites and outside the measured ranges may result in an inaccurate estimation of water content, which is for example the case when straightforward applying Topp's function. Furthermore, calibrations of FF water content usually pertain to disturbed litter samples packed in cylinders of 10 by 5 cm, in which laboratory measurements of TDR travel time and gravimetric water content are carried out simultaneously (Schaap *et al.*, 1995). Conditions in these cylinders may strongly deviate from natural conditions, particularly in thick litter layers, and results therefore may be biased.

Accurate determinations of FF and soil water content are essential in hydrological research such as the current, which aims at monitoring and modelling of the water balance of forest ecosystems where FF and soil water content play an important role. As water content of the FF and clayey soils was estimated through TDR measurements, proper calibration lines for the forest floors and mineral soils studied are required.

This paper focuses on the calibration of TDR measurements in the FF and mineral soil in four representative forest ecosystems in Colombian Amazonia, within the scope of a Tropenbos project on water and nutrient cycling in these ecosystems. Calibration is achieved by relating the refraction index calculated from the travel time measurements (TDR) to the volumetric water content of the FF and soil samples collected at the same time and sites, at which TDR measurements were carried out. Furthermore, refraction index of the mineral soil is related to both the volumetric water content and the bulk density of the soil samples. The functions and related calibration curves obtained for the FF and clayey mineral soils are compared with several of the above mentioned functions and related curves with regard to their accuracy in reproducing the estimated volumetric water content of the samples in this study.

5.3 MATERIALS AND METHODS

5.3.1 Site description

This study concerns the FF's and mineral soils from humid tropical forest ecosystems in four major physiographic units in the Middle Caquetá, Colombian

Amazonia. These comprise a Tertiary sedimentary plain (SP) and the high terrace (HT), the low terrace (LT) and flood plain (FP) of the River Caquetá. A detail description of the research sites and climate conditions are presented in Chapter 2 of this thesis.

The thickness of the FF in the research sites ranges from a few centimetres (5 cm) to over 30 cm. This FF consists mainly of dead leaves and coarse plant debris, and in its lower part commonly contains some mineral material as a result of bioturbation. Fine roots abound and, particularly in thicker FF's, dense root mats occur. Soil texture on the FP is mostly clay loam, while on the others landforms (SP, HT and LT) it tends to be clay loam over clay. Soils are kaolinitic and are low to very low in weatherable minerals. They range from typic Tropaquept and typic Dystropept on the LT and FP, to typic Kandiudult, typic Paleudult and typic Hapludult on the SP and HT. For a more extensive description of the FF's and soils, reference is made to Chapter 2 and Appendix 1.

5.3.2 TDR measurements

The TDR consisted of a Tektronix 1502B-cable tester connected to a portable computer. Measurements were made with three-wire probes of 0.5 m and with a cable length of 6 m. TDR probes were horizontally installed at two or three depths in the FF, depending on the FF thickness, and at 8 depths in the mineral soil. In total 9 subplots were instrumented. TDR data and waveforms were manually collected in the field and stored for subsequent analysis. Waveforms were interpreted, using the TDR software developed by Heimovaara and Bouten (1990). For a detailed description of equipment used and installation procedure reference is made to Chapters 6 and 7.

5.3.3 Forest floor and soil sampling

Undisturbed FF samples were taken by cutting a section of this layer with a surface of 10x10 cm, immediately after TDR measurements and adjacent to the TDR probes. The thickness of this section depended on the thickness of the FF. Moisture content was determined by drying at 64 °C during 48 hours. Dry bulk density of forest floor was established from the undisturbed volumetric samples. In total, 132 samples were collected and field measurements were carried out during the different dry and wet seasons.

Mineral soils were sampled in pits in which the TDR probes were installed, using a core sampler of 100 cm^3. During the monitoring period, samples were taken from the side of the pits and at the same depth of the TDR probes. When probes were relocated to new holes, samples were also collected from the same sites (along the wire probe holes) immediately after TDR measurements had been performed and probes had been removed. At the end of the monitoring period, duplicated samples were collected from each site along the small holes left by the probe wires. Soil samples were oven dried at 105 °C during 24 hours. Dry bulk density was calculated for each soil sample. In total 482 samples were collected between January 1996 and

August 1997, sampling being in such a way that a wide range in soil water conditions was covered.

5.3.4 TDR calibration

The polynomial function of Topp *et al.* (1980) relates the volumetric soil water content with the apparent dielectric constant (K_a) of the soil.

$$\theta = -0.053 + 0.0292\, K_a - 0.00055\, K_a^2 + 0.0000043\, K_a^3 \qquad (5.1)$$

K_a is calculated from the travel time of the electromagnetic pulse through a transmission line in the forest floor or in the mineral soil (Nadler *et al.*, 1991).

$$K_a = \left(\frac{ct_s}{2L}\right)^2 \qquad (5.2)$$

In which c is the velocity of light in free space (3.108 $m.s^{-1}$), t_s is the travel time (s) and L is the length (m) of the sensor. Schaap *et al.* (1995), Heimovaara (1993) and Herkelrath *et al.* (1991) all used a linear equation to relate the volumetric water content of the soil and forest to the refraction index (n_a).

$$\theta = a + bn_a \qquad (5.3)$$

In which,

$$n_a = \frac{ct_s}{2L} \qquad (5.4)$$

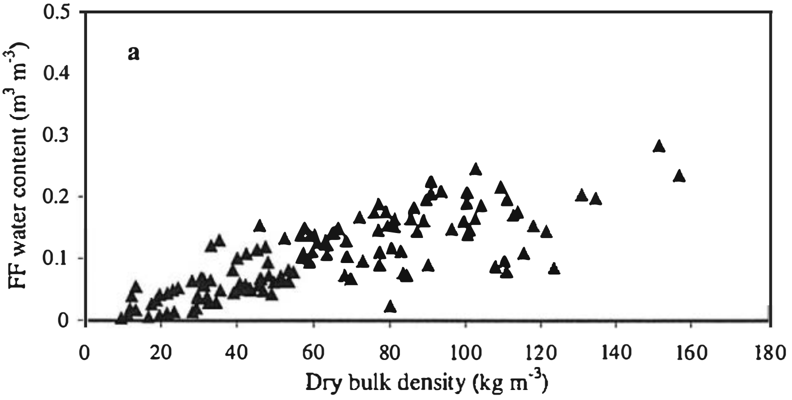
And a and b are site specific calibration parameters. The water content (θ) has been also related to the refraction index and to soil bulk density (${}^b\rho_s$) by Malicki *et al.* (1996)

$$\theta = \frac{n_a - 0.819 - 0.168\,{}^b\rho_s - 0.159\,{}^b\rho_s^{\,2}}{7.17 + 1.18\,{}^b\rho_s} \qquad (5.5)$$

Equation 5.4 will be used to determine the refraction index from the travel time measurements. Parameters in equation 5.3 will be calibrated for both the FF and the mineral soil, using the relationship between the volumetric water and the refraction index. The applicability of the equation 5.5 to the research conditions will be investigated using the available data on the volumetric water content of the soil samples, their dry bulk density (${}^{b}\rho_s$) and the refraction index (n_a), according to the procedure followed by Malicki *et al.*, 1996. Malicki's method consisted in the derivation of normalised conversion functions through triplets of data on refraction index, water content and bulk density of samples. In total 18 subsets of triplets were created according to ranges of bulk densities (e.g. ${}^{b}\rho_s$= 0.1, 0.2, 0.3...1.7 kgm^{-3}). For each subset there was a regression of water content and the refraction index. The resulting a and b parameters of these regressions were plotted against the respective bulk density (Malicki *et al.*, 1996). The explained variance (R^2) is used to evaluate the accuracy of the regression equations.

5.4 RESULTS AND DISCUSSION

The measured refraction index in the FF during the total period (2 years) and in all plots (9) ranges from 1.2 to 3.8 while in the mineral soil it ranges from 3.1 to 5.8. This points to clear differences in soil moisture dynamics in these two types of material. Additionally, the relationship between measured water content and dry bulk density of the FF and of the mineral soil exhibits different trends. In the FF, water content increased with increasing bulk density, whereas in the mineral soil it decreased when bulk density increased (Figure 5.1). Consequently, parameters for the equation 4 are separately investigated for the FF and the mineral soil.



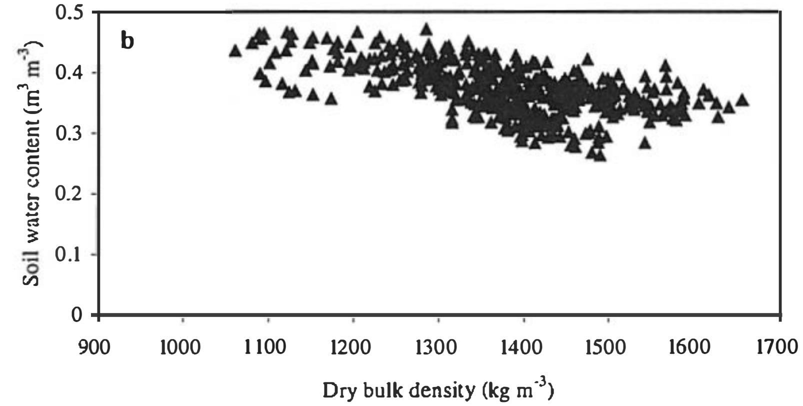


Figure 5.1 Relation between gravimetrically measured forest floor (a) and clayey soils (b) water content and the dry bulk density of samples from the Middle Caquetá, Colombian Amazonia.

Figure 5.2 shows the relation between measured FF volumetric water content and the refraction index for the FF samples. This relation can be well described by a linear regression ($R^2 = 0.94$).

$$\theta = 0.115\ (\pm 0.003) n_a - 0.154\ (\pm 0.015) \tag{5.6}$$

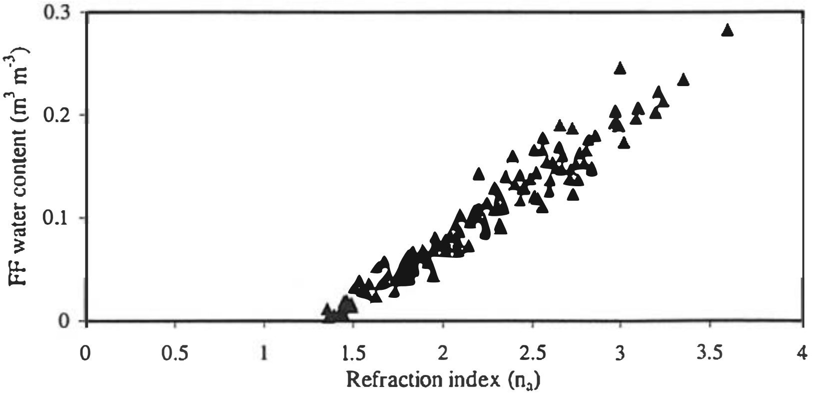


Figure 5.2 Gravimetrically measured forest floor water content versus the refraction index from the TDR measurements.

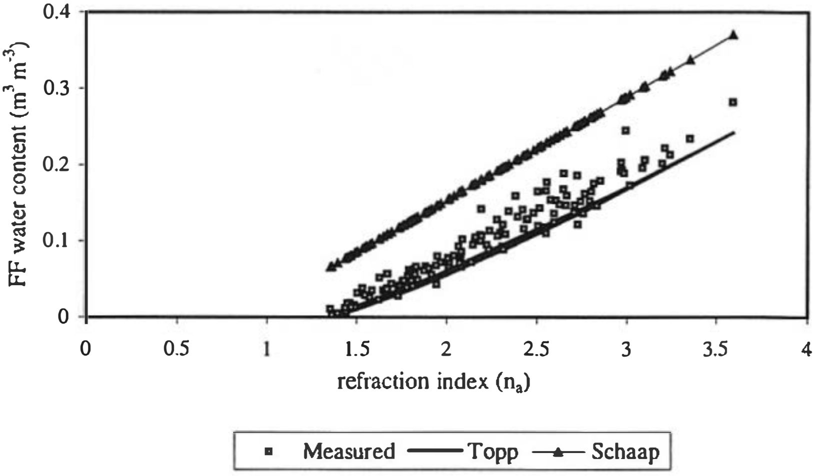


Figure 5.3 Comparison of calibrated water content for the forest floor in the Colombian Amazonia to the deduced values from two empirical models (Schaap *et al.*, 1995 and Topp *et al.*, 1980).

As shown by Figure 5.3, there is a considerable difference between the water content in the FF as based on the calibrated equation 5.6 and that based on the functions of Topp *et al.* (1980) and Schaap *et al.* (1995). Topp's function underestimates the water content of the FF by an average of 0.0208 (± 0.0149) m^3 m^{-3} and differences between the calibrated volumetric water content and that by Topp's function tend to increase with increasing n_a values (Figure 5.3). Application of the parameter values from Schaap *et al.* (1995), which were established for the FF in temperate forests in the Netherlands, leads to an overestimation of the water content in the FF by a mean value of 0.0806 (± 0.018) m^3 m^{-3}. Results from this study agree with that concluded by Topp *et al.* (1980) who stated that there is a shift in the calibration parameters when used for organic soils.

The measured water content of the mineral soil samples exhibits a linear relationship with the refraction index, as derived from the TDR measurements in these clayey soils (Figure 5.4a). This linear function has an explained variance (R^2) of 0.88 .

$$\theta = 0.102\,(\pm 0.0017)\, n_a - 0.0925\,(\pm 0.014) \qquad (5.7)$$

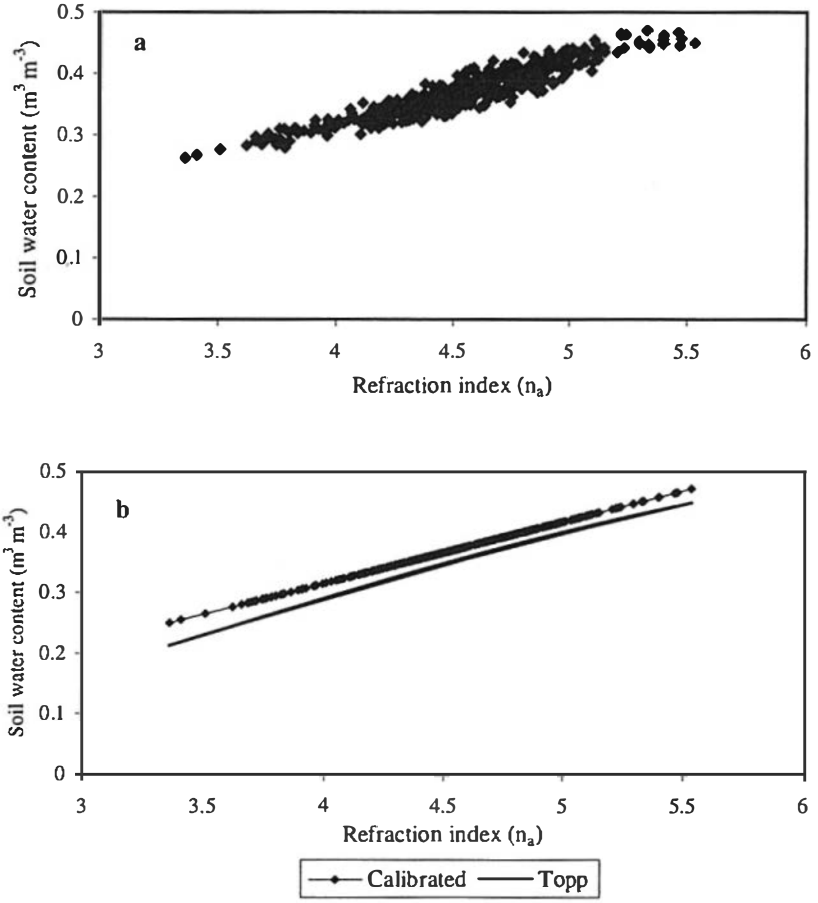


Figure5.4 Gravimetrically measured water content from clayey soil samples and the refraction index from the TDR measurements (a) and comparison of calibrated data from the clayey soils in the Colombian Amazonia to the empirical model by Topp *et al.*, 1980 (b).

For these soils, Topp's function yields a water content, which on average is 0.0195 (± 0.0127) m^3 m^{-3} lower than the value based on equation 5.7 (Figure 5.4b). Furthermore, the difference between the two functions seems to decrease when values of n_a are between 4.3 and 5.3. This behaviour could be attributed to the effect of different fitting curves.

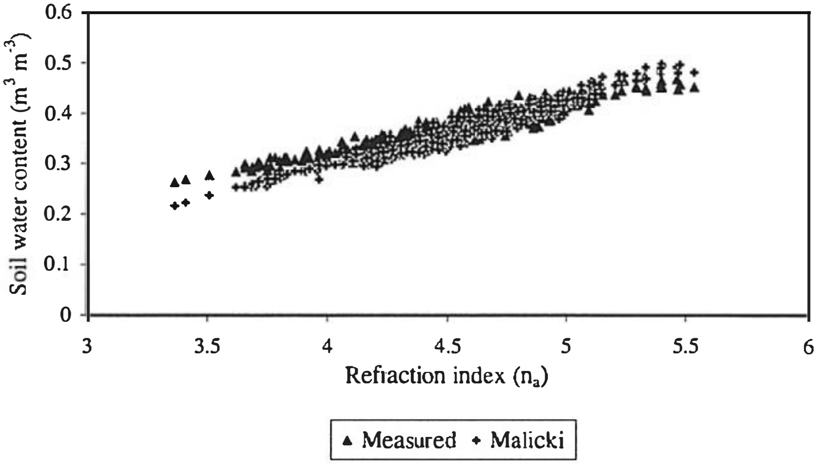


Figure 5.5 Comparison of gravimetrically measured water content from clayey soil samples to that derived using the Malicki's function. Data of dry bulk density from the soil samples were used to derive the values according to the equation 5.5 (Malicki *et al.*, 1996).

Although ranges of n_a for the Amazonian forest soils are within the range of Topp's and Schaap's data sets, the latter functions are clearly inadequate for the soils studied. To find out whether the explained variance of the calibration line for the mineral soil can be further improved, the procedure by Malicki *et al.* (1996) was followed, since Malicki's includes the bulk density and might be more adequate. Volumetric water content from the soil samples, based on the calibrated function in this study, and values deduced with Malicki's function (equation 5.5) were plotted against the refraction index (see Figure 5.5). Though there is no significant difference between Malicki's function and the calibrated function, and values for refraction index (between 4.3 and 5.3) are similar, Malicki's function underestimates the water content at lower n_a values and overestimates it at higher values. In other words, the slope of the calibration function differs from Malicki's function. Therefore, the a and b parameters of this calibration function were plotted against the average bulk density of subsets according to that described above (Figures 5.6a and 5.6b). Though a large data set was used to determine the subsets, there is no clear tendency in the plotted data and correspondingly regressions functions have very low coefficients of determination ($R^2 = 0.097$ for a and $R^2 = 0.012$ for b).

The poor relationship may be due to the relatively small range of the bulk density of the soil samples. Enlarging the range by adding FF samples provided no solution, since this was found to lead to an even large scatter of points. This can be attributed to the specific relation between the water content and bulk density in FF material, which differs from that in the mineral soil (see above). Consequently, it was impossible to properly establish the parameter values related to dry bulk density with the Malicki's function from the measured range in this study.

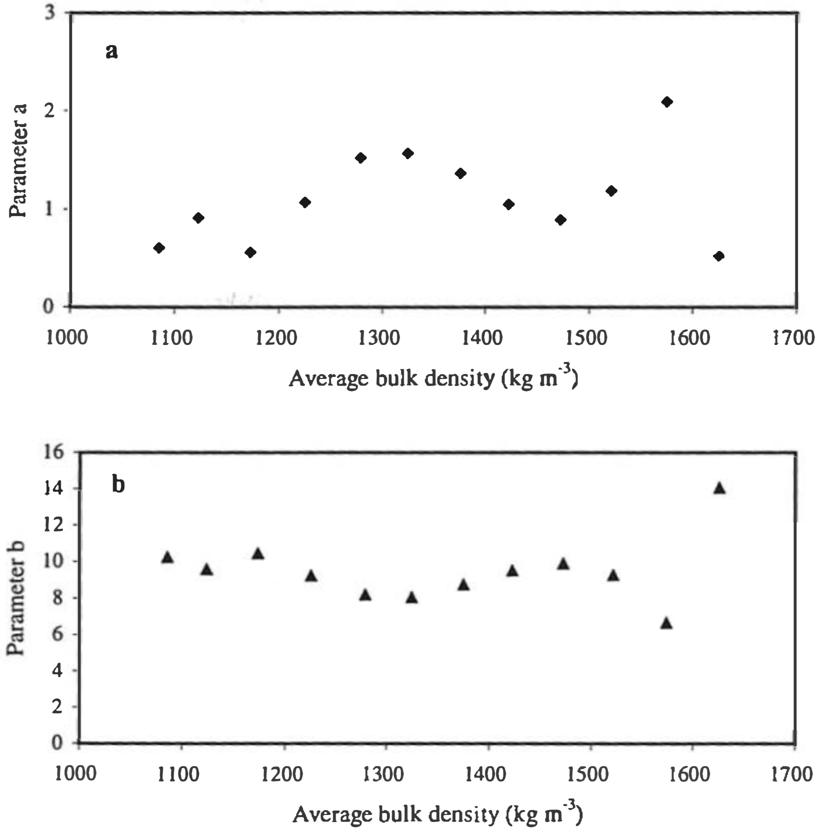


Figure 5.6 Deduced values of parameters a and b from the regressions of measured soil water content and the refraction index according to Malicki *et al.*, 1996, versus ranges of the average dry bulk density of soil samples.

5.5 CONCLUSIONS

Although published empirical models include the range in refraction index and bulk density encountered in the soils studied, their application produces inaccurate results, confirming that the parameters used are rather site and soil specific. Using Topp's function the water content is underestimated by 0,0208 m^3 m^{-3} (± 0.0149) in the FF and by 0.0195 m^3 m^{-3} (± 0.0127) in the mineral soil. When applying Schaap's function for the FF, the water content of this soil material is overestimated by 0.0806 m^3 m^{-3} (± 0.018). Malicki's function, based on the refraction index and bulk density, approximates measured water content relatively well. However, for low and very high values of the refraction index results are rather poor. Moreover, for the measured range of dry bulk density no clear relationship between the parameters and respective subsets of bulk densities were found, and correspondingly calibration of these parameters for the soils studied was impossible.

Empirical functions, obtained through linear regression of the measured volumetric contents and refraction index of the FF and mineral soils from the studied humid tropical forests, perform well, with an explained variance of 0.94 for the FF and 0.88 for the mineral soil. As compared to the calibration parameters of the FF material, those of the clayey mineral soils are of a different magnitude, evidencing the clear differences in behaviour between these materials, which have also been observed in other studies. Therefore it was decided to use the linear regressions of measured water content and the refraction index in both the forest floor and mineral soil to translate TDR measurements into volumetric water content for the current study.

6. FOREST FLOOR WATER DYNAMICS AND ROOT WATER UPTAKE IN FOUR FOREST ECOSYSTEMS IN NORTHWEST AMAZONIA

6.1 ABSTRACT

A common feature in the undisturbed forest ecosystems in the Middle Caquetá (Colombian Amazonia) is the presence of a thick litter layer with abundant fine roots over mineral soils which are highly weathered and very low in available nutrients. In these situations, the forest floor (FF) may play an important role in the forest water balance, controlling water fluxes and nutrient cycling. We investigated the forest floor water dynamics in four representative forest ecosystems in the Middle Caquetá ecosystems (sedimentary plain SP, high terrace HT, low terrace LT and the flood plain FP). Meteorological conditions, TDR water content in the FF and litterflow were measured daily over a two years period. A dynamic model was developed to simulate FF water storage, root water uptake and drainage to the mineral soil. The four-parameter model was calibrated applying a step-wise procedure. Analysis of collected data showed that FF water content was generally lower in the SP than in the other ecosystems, whereas FF water storage was the highest due to a high FF mass. The average storage capacity per unit area of the studied FF's was 1.23 mm cm^{-1}. The sensitivity analysis and calibration of model parameters highlighted the relevance of storage capacity as the most sensitive parameter for the FF water dynamics. For the validation period, there is a good agreement between predicted and measured FF water storage and especially between predicted total drainage from the forest floor and measured litterflow. Model predictions indicate that water uptake from the FF's during the validation period (190 days) differed between ecosystems, ranging from 15% to about 28% of the reference transpiration. This seems to be related to the fraction of fine roots in the FF in each ecosystem and to the water availability. On the other hand, total drainage to the mineral soil was very similar among ecosystems, except for the SP where total drainage was the lowest with about 87% of incoming throughfall.

6.2 INTRODUCTION

Amazonian soils are highly weathered and leached. In such weathering environments, soils generally consist of a mixture of quartz and secondary minerals, such as kaolinite, gibbsite and hematite. This leads to a very low cation exchange capacity and most of this capacity is located in the litter layer covering the mineral soil. In these impoverished ecosystems, the litter layer, here referred to as the forest floor, is the main soil compartment with respect to nutrient stocks and nutrient cycling (Tiessen *et al.*, 1994; Salati *et al.*, 1979). Apparently related to the concentration of available nutrients in the forest floor, fine roots of trees often concentrate in this compartment to form a "root mat" (Jordan, 1989; Cuevas and Medina, 1988; Golley, 1983). It should be stated, however, that shallow rooting is only prominent when soil fertility is very low and that particularly small feeding roots are concentrated in the forest floor and topsoil. (Longman and Jeník, 1990; Lawson *et al.*, 1970). Such root mat plus mycorrhizal mycelia are assumed to be capable of capturing released nutrients and even extracting these directly from the litter (Stark and Jordan, 1978). Consequently, in these ecosystems, uptake of nutrients takes place almost exclusively in the forest floor and in the top of the mineral soil, thus leading to a very tight nutrient cycling (Burnham, 1989; Jordan, 1989).

In these specific Amazonian ecosystems, the forest floor (FF) will also play an important role in the forest water balance and related water fluxes due to the high proportion of fine roots in this compartment. The FF intercepts part of the throughfall, affects runoff amounts, protects soil from erosion and contributes to the stability of soil characteristics (e.g. infiltration and soil storage capacity). According to Duivenvoorden and Lips (1995) and this study, the amounts of litter in the FF's and fine root content vary considerably, depending on soil nutrient status. Consequently, the FF water dynamics, including root water uptake and drainage to the mineral soil, are likely to vary considerably and this will give rise to differences in site conditions affecting germination and growth of seedlings (Longman and Jeník, 1990) and microbial activity. In spite of the important ecological role of the FF, in particular for water and nutrient supply to plants, there has been little progress in the study of the water dynamics of this compartment. In most forest hydrological studies, the FF is neglected or treated as part of the mineral soil for which van Genuchten parameters (van Genuchten, 1980) have been estimated. Only a few studies deal with the determination of the water storage capacity and temporal variability of water retention by the FF and these mainly pertain to coniferous and other temperate forests (Schaap, 1996; Puthuena *et al.*, 1996; Walsh and Voigt, 1977; Golding and Stanton, 1972; Helvey and Patric, 1965). The storage capacity, water content and fluxes in the FF of Amazonian rain forest ecosystems have not yet been investigated.

This Chapter deals with the FF water content dynamics and the contribution of FF moisture to forest transpiration in four representative forest ecosystems in Colombian Amazonia. To that purpose, data collected over a two years period on FF water content and drainage are analysed. Further issues of this study are to model the water uptake from the FF and total litterflow to the mineral soil, to identify the most important parameters influencing FF water fluxes and to establish the hydrological differences or similarities between FF' s of the ecosystems studied.

In Chapters 3 and 4, the canopy water balance was described and modelled. Throughfall to the FF is used as the upper boundary condition for the FF water balance study and free drainage to the mineral soil as the lower boundary condition. Water content of the FF was established by the Time Domain Reflectometry (TDR) technique. Travel time measurements were transformed into volumetric water content by applying a calibrated linear regression equation, based on TDR measurements and measured gravimetric water content of a large set of FF samples (Chapter 5). FF storage dynamics were assessed from the calibrated TDR water content measurements at different depths and FF thickness. Drainage was measured through flux plates installed under the FF.

6.3 SITE DESCRIPTION

The area of study is located within an Indian community territory near Araracuara, Middle Caquetá, Colombia (0° 37' and 1° 24' S, 72° 23' and 70° 43' W). It forms part of the Amazon basin and comprises a large dissected Tertiary sedimentary plain (SP) at about 250 a.s.l. and the alluvial system of the River Caquetá, including a high (HT) and low terrace (LT), and the rarely inundated flood plain (FP). Soil types vary, ranging from well drained (SP and HT) to hydromorphic (LT and FP, with predominantly clayey textured subsoil and topsoil with a texture of clay loam to sandy clay loam. They are very poor to relatively poor in nutrients, except for the flood plain soils, which regularly receive fresh, nutrient rich sediments from the River Caquetá. The vegetation is very rich in species and typical for mature forest in the western part of the Amazonian rain forest. The bulk of the vegetation is in the form of large tree crowns in the upper canopy, about 30 metres above the forest floor and some emergent trees reaching up to 40 metres. The lower canopies with small palms and shoots are relatively unimportant in terms of forest cover. The most important differences in vegetation among the landscape units pertain to total standing biomass, species diversity, tree density and the structure of the forest canopy, as defined by the canopy cover. A more detailed description and vegetation classification of the research sites is presented by Duivenvoorden and Lips (1995), Alvarez (1993) and Londoño (1993). The climate of the area is classified as equatorial superhumid Afi (Köppen, 1936). Annual average gross rainfall in the area is about 3400 mmyr^{-1} and daily mean temperature is 26°C with day-time air humidity generally above 75%. Detailed descriptions of the research sites and climate conditions are presented in Chapter 2.

6.3.1 Forest floor description

Duivenvoorden and Lips (1995) defined eight types of terrestrial humus in the Middle Caquetá area, with associated differences in amounts and distribution of fine roots and in structure. They also indicated that upland (non-flooded) ecosystems commonly have a thicker organic horizon with high root content and root density. They concluded that the amount of fine organic matter and fine root content of the forest floor generally increase with decreasing nutrient concentration in the mineral soil, i.e. from the FP, through LT and HT, to the SP.

A forest floor survey in the research plots showed that the thickness of the FF in the studied forest ecosystems ranged from 5 cm to 30 cm and even thicker, especially in the SP. The FF consisted mainly of dead leaves and debris (twigs, bark, wood material, fruits and seeds). The lower part generally contained mineral material brought up by termites, worms and ants. "Root mat" consisted of a dense network of mostly medium and fine roots in a matrix of decomposing organic matter, evidencing high macro faunal activity. This has been also found by Cuevas and Medina (1988) for the Upper Rio Negro (Venezuelan Amazonia) and by Duivenvoorden and Lips (1995) for Colombian Amazonia.

Table 6.1 FF characteristics and mean litter content in the four forest ecosystems in the Middle Caquetá, Colombian Amazonia. Data was collected from FF samples of 1 m^2. (std = the standard deviation and n the number of samples).

Ecosystem	**Mean FF thickness**		**Total dry mass**		**Fine roots dry mass**		**n**
	cm	**std**	**Kg m^{-2}**	**std**	**Kg m^{-2}**	**std**	
SP	16.36	4.22	9.81	4.41	2.12	1.03	31
HT	6.21	2.00	6.11	1.46	1.16	0.34	17
LT	5.25	2.51	4.28	2.04	0.69	0.31	14
FP	3.96	2.04	3.27	1.39	0.32	0.16	16

The forest floor (FF) varied in thickness both within and between ecosystems, but clearly increased with decreasing soil fertility (Table 6.1). In the SP, thickest FF's occurred on the crests. In the other units, the FF was lesser variable with the thinnest layer in the FP ecosystem. Concerning fine root distribution, a detailed study in the research sites showed that the average percentage of fine roots in the FF, relative to the total amount of roots over a depth of 1 m, was 34% for the SP, 19% for the HT, 19% in the LT and 12% in the FP. Results within the framework of the current research agree with results from Duivenvoorden and Lips (1995) who observed that the proportion of fine roots in the forest floor can be higher than in the mineral soil.

6.4 METHODOLOGY

To study the water dynamics in the FF and the water balance, three subplots were selected in the SP and two subplots in the HT, the LT and the FP, in which a number of parameters were monitored: gross rainfall above the forest, net rainfall (throughfall and stemflow), litterflow, FF water content and soil water content. Meteorological data were collected in an open area of about 20 hectare with an automatic weather station (AWS) equipped with a CR10 datalogger (Campbell Scientific Instruments). Parameters measured included gross rainfall, temperature, air humidity, incoming solar radiation, wind speed and wind direction. Average and total values were recorded every 20 minutes. In the plots, gross rainfall was measured (automatically and manually) with a tipping bucket calibrated to 0.2 mm per tip and with collectors installed above the forest.

To determine the water storage capacity of the FF's and to obtain field data that can be compared with the calibrated values from the model, the amount of water retained by the FF's after free drainage had ceased was investigated. To that purpose, we selected plots of 1 m^2 at random within the research areas. After cutting the roots (to avoid water uptake), selected FF layers were in-situ saturated during three consecutive days and covered with a plastic sheet (to avoid evaporation). Subsequently, after 24 hours total FF samples were collected and immediately weighed for wet weight. Samples were air dried until constant weight and finally weighed (dry weight). In total 78 samples were collected during four samples periods. The thickness of the layer was measured at different points within the square metre and the mean value was used as the best estimate. FF thickness ranged from 3.6 to 28.9 cm.

To evaluate the FF drainage or litterflow and to provide comparative data for the validation of the FF hydrological model, flux plates were used to measure the proportion of throughfall that passes through the FF and enters the mineral soil. Plates with an open area of 683.5 cm^2 and 5 cm depth were installed horizontally in the contact zone between the FF and mineral soil. To avoid disturbance of the FF layer, plates were installed at the same level as the mineral soil surface. Plates were connected with a tube to a container of 20 litres, installed in a soil pit. To avoid any solid material to enter the plate and funnel, a fine net was attached to the upper part of the plate and to the bottom of the funnel. In the SP plot, 45 plates were installed in three subplots (i.e. 15 per subplot) and in the HT plot, 30 plates in two subplots. Collectors were measured manually on daily and weekly basis, as were gross rainfall, throughfall and stemflow (Chapters 3 and 4). Weekly measurements were carried out from September 1995 until August 1996 and daily measurements, whenever rainfall occurred, were performed from August 1996 until August 1997.

For the characterisation of the FF water content and the spatial and temporal FF storage dynamics, Time Domain Reflectometry (TDR) measurements were performed at two or three different depths, depending on the thickness of the FF. In total, 31 three wire TDR sensors (50 cm length) were installed horizontally in the FF of soil profiles where soil water content was also monitored. FF water content in the SP was measured at six locations. In the other ecosystems, it was measured at four locations. Measurements were carried out every day, from August 1996 until August 1997. TDR travel time measurements were translated into volumetric water content using a calibrated regression equation for the specific FF based on litter samples collected at the same time and same sites where TDR measurements were executed (Chapter 5). Daily total FF water storage is calculated from the calibrated water content and the total FF depth.

6.4.1 FF water balance model

The concept of Rutter's forest interception (Rutter *et al.*, 1971) was used to derive a dynamic FF interception model, which describes the FF water fluxes and, more specifically, serves to determine the relative contribution of the FF to forest transpiration and the total litterflow or FF drainage to the mineral soil. The FF is considered as composed of a single continuous layer with a specific storage capacity, which intercepts and redistributes net rainfall. The input to the model is throughfall, either as measured or as calculated with the calibrated dynamic forest interception model (Chapter 4) and the reference transpiration (Monteith, 1965). FF evaporation can be neglected because the air within the forest remains almost saturated, the radiation flux is low and patchy and the wind speed near the soil surface is nil (Roberts *et al.*, 1980; Shuttleworth, 1979; Odum and Pigeon, 1970). The outputs from the model are the FF water uptake and total drainage to the mineral soil, which is assumed to occur whenever storage capacity is exceeded and in that case will continue during and after rainfall events until storage becomes equal or lower than storage capacity.

The FF dynamic water balance model is a single layer model with four parameters (Figure 6.1).

$$\frac{\Delta S_{FF}}{\Delta t} = P_n - U_{FF} - D_{FF} \qquad (6.1)$$

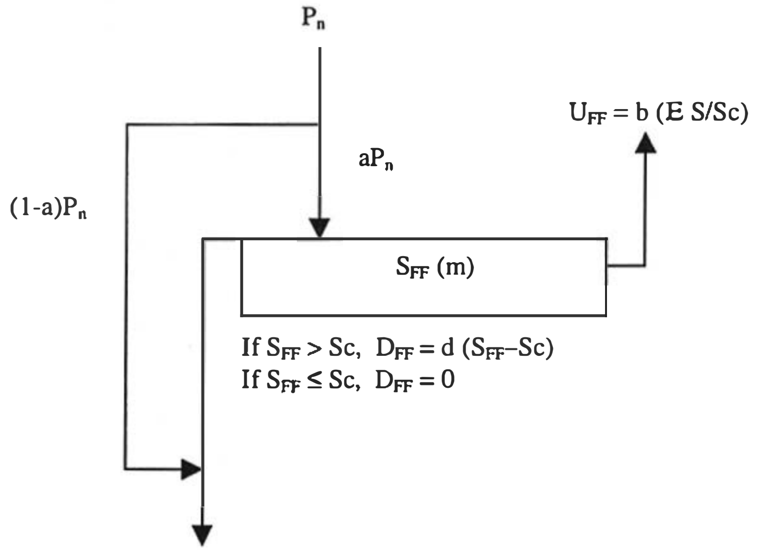


Figure 6.1 Schematic representation of a single layer forest floor interception model and model formulation.

Where S_{FF} (m) is the water storage of the FF, t (day) is the time, Pn (m d^{-1}) is net rainfall rate to the forest floor, here taken as the throughfall rate, U_{FF} (m d^{-1}) is the rate of water uptake from the FF, E (m d^{-1}) the reference transpiration rate (Monteith, 1965) and D_{FF} (m d^{-1}) is the drainage rate to the mineral soil. The model parameters are: a is the dimensionless interception efficiency parameter, b is the water uptake efficiency parameter, d (d^{-1}) stands for the drainage parameter and Sc (m) is the storage capacity of the FF. Total litterflow to the mineral soil includes the preferential flow and drainage from the FF.

Reference transpiration is calculated using the Penman-Monteith equation (Monteith, 1965) and collected data on climatological parameters. Parameters for the Monteith formula were deduced from literature and from the specific studies carried out within the Amazon basin (e.g. Culf *et al.*, 1995; Shuttleworth *et al.*, 1984). A more detailed description of the procedure used to estimate reference transpiration from the research sites and monthly values are presented in Chapter 2.

The FF water balance model was programmed in Matlab. A reference run of FF water dynamics on 20 minutes basis was used to evaluate the sensitivity of the model to each parameter. First, large numbers of simulations are run with different parameter sets, randomly selected from pre-set parameter ranges. Then, a parameter set is accepted if its corresponding simulation fits a specific point of the reference run within the confidence interval of the measuring technique. Each point in time thus reduces the range of one or more parameters. We can now define the measurement's information content with respect to a model parameter, as the proportional decrease of the standard deviation of that parameter in the accepted sets. The information content is then used to split the total set of measurements into independent subsets which each contain information on a specific parameter. Thereupon, each subset is used to identify its corresponding parameter. To evaluate the model results and to assess the goodness of fit between predicted and measured values, two objective functions were used: the normalised root mean square error (NRMSE) between predicted and measured FF water storage and FF drainage and the explained variance (R^2).

Specific sets of measured TDR water content in the FF were used for the calibration of the model parameters, according to the results from the sensitivity analysis. Six months daily data on FF water storage and FF drainage were used for the validation of the model.

6.5 RESULTS AND DISCUSSION

6.5.1 Forest floor storage capacity

Mean water storage capacity and dry bulk density of the FF's are presented in Table 6.2. The differences between ecosystems in water storage capacity can be explained by the differences in amounts of FF mass (see Table 6.1), since a clear linear relationship exists between FF water storage capacity and FF dry mass ($R^2 = 0.93$). The bulk density of the forest floor is very low, with the lowest value for the SP.

The average storage capacity of FF's in the ecosystems studied was 10.5 (± 7.5) mm or 1.51 (± 0.30) mmkg^{-1}, when expressed as the weighted mean storage capacity per unit dry mass. The FF in the SP had the lowest storage per unit FF thickness (0.99 mm cm^{-1}), which may be explained by the loose structure of this FF (low density) and its composition, i.e. only a thin layer of fresh litter and many very fine and fine roots. The FF in the other ecosystems is rather compact and has far less fine roots.

Table 6.2 Water storage capacity of forest floor in four ecosystems in the Middle Caquetá. Means are at 95.0% of the confidence level (std = the standard deviation and n the number of samples).

Forest ecosystem	**Mean storage capacity (mm)**	**std**	**Dry bulk density (kg m^{-3})**	**std**	**n**
SP	16.29	8.17	78.17	22.04	31
HT	7.62	3.10	85.61	27.72	17
LT	8.12	4.57	90.94	22.39	14
FP	4.57	2.33	92.90	40.54	16

When comparing the storage capacity of the FF of Amazonian ecosystems with that of FF's in temperate regions (Coniferous, Douglas fir and Bracken forests), it appears that the value found is lower than 4.83 mm kg^{-1} reported by Pitman (1989) for Bracken forest, and slightly higher than the 1.30 mm (±0.32) found by Pradham (1973) and 0.97 mm found by Putuhena (1996) for a Eucalyptus plantation in the U.K. It has to be stated that the amount of FF dry mass per unit area in the ecosystems studied is higher than most values reported by Pitman (1989) and Perkins *et al.* (1978) for temperate forests.

6.5.2 Measured FF water drainage

The coefficient of variation (CV) of litterflow from individual flux plates against the average per subplot was 0.626 (± 0.219) in the SP and 0.649 (± 0.290) in the HT. Comparing the average values between subplots in each ecosystem, the CV was 0.22 (± 0.16) in the SP and 0.15 (± 0.16) in the HT. The daily average percentage of litterflow ranged from 25% to 93% of the throughfall, depending on rainfall amounts and characteristics. Although litterflow was not observed for most gross rainfall events lower than 5 millimetres, incidentally some litterflow was collected upon small throughfall values (about 2 mm). This behaviour can be explained by the high canopy interception during small events as described in Chapter 3. In agreement with the lower FF storage capacity, interception by the FF in Amazonian ecosystems seems to be lower than that by Eucalypt and Pine forest in Australia (Pitman, 1989), where the FF retained 47% of the simulated rain.

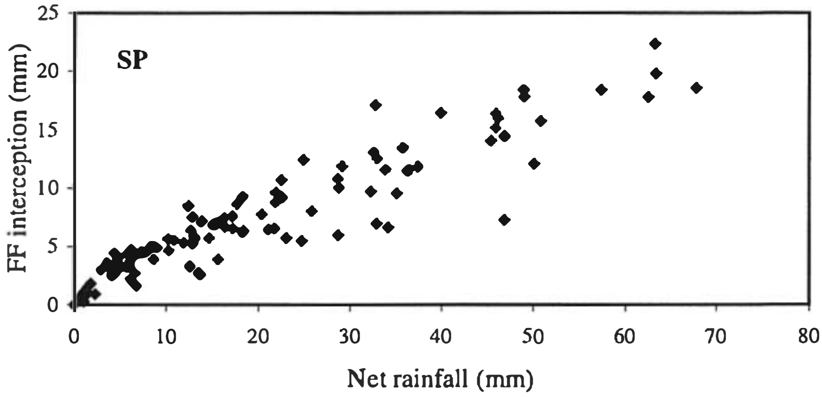


Figure 6.2 Forest floor (FF) interception, as calculated from the difference between daily measurements of net rainfall and litterflow, versus net rainfall in a forest ecosystem (SP) in the Colombian Amazonia.

The arithmetic means of daily litter interception in the SP and HT were separately plotted against measured throughfall in each plot. The trend points to a logarithmic relation between throughfall and its interception by the FF's for small rainfall events and a linear relation for larger events (Figure 6.2). This tendency in rates of litter interception is related to the asymptotic nature of the wetness curve: FF's retain higher percentages of throughfall during the earliest stage of the rainfall event. If the event lasts long enough, the FF storage capacity reaches its maximum value and total drainage and uptake rate become equal to the throughfall rate.

6.5.3 FF water content and storage dynamics

Figure 6.3 shows the measured FF water content in the four forest ecosystems. The FF in the SP exhibited the lowest water content over the whole period while in the LT and FP water contents were highest. Furthermore, the FF in the SP and HT dried out to lower values than in the FP and LT. As a general tendency, the dynamics of the FF water content in the different forest ecosystems showed a clear response to rainfall events: increases in water content in the FF were only observed after rainfall events. This behaviour and the decreasing FF water content during droughts suggest that upward (capillary) fluxes of water from the mineral soil to the FF either did not exist or amounts were that small that they are masked by water uptake from the FF.

Time series of total water storage by the FF's show that storage differs among forest ecosystems and that these differences were mainly due to the difference in litter mass (FF thickness). During the period of measurements, FF water storage ranged from 7.0 mm to 23.1 mm in the SP, 3.9 to 12.4 mm in the HT, 3.8 to 11.4 mm in the LT and 2.7 to 8.1 mm in the FP. Although some measurements were carried out a few hours after rainfall, the maximum measured values also showed a trend of storage capacity decreasing from the SP to the FP, which agrees with the results from the field experiments.

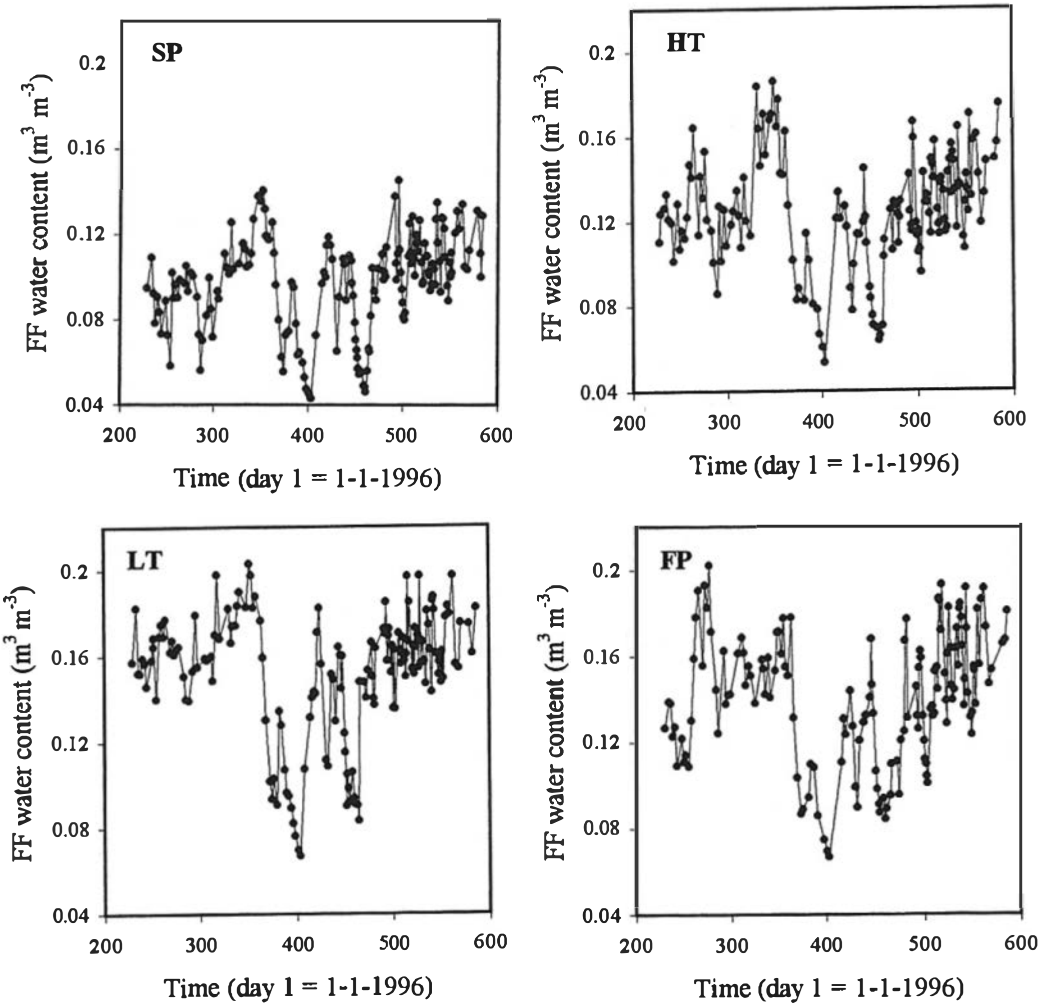


Figure 6.3 Temporal dynamics of measured forest floor (FF) water content (TDR) in four forest ecosystems in the Colombian Amazonia.

Assuming that no evaporation takes place from the FF, the free water in the FF layer can either be taken up by roots or drain to the mineral soil. Water depletion from the FF's was analysed during the two dry periods (from day 384 to 403 and from day

445 until 461), when drainage was zero since water storage in the FF's remained below the measured storage capacity. Therefore, uptake was assumed to be the only hydrological process active during these periods.

In all ecosystems the water content decreased, implying that the forests took up a certain amount of water from the FF. This uptake differs between forest ecosystems and between periods. Depletion rates during the dry periods were 0.51 and 0.61 mm d^{-1} in the SP, 0.20 and 0.34 mm d^{-1} in the HT, 0.21 and 0.40 mm d^{-1} in the LT and 0.19 and 0.24 mm d^{-1} in the FP. The relatively high uptake rate in the SP can be related to the relative high proportion of fine roots in the FF of this ecosystem.

6.5.4 Model results

Sensitivity analysis
Distributed sensitivity analysis showed that parameters are not interdependent and that they differ in their sensitivity to moisture conditions in the FF. Figure 6.4 shows the relative reduction of the standard deviations of the accepted model parameters. From Figure 6.4 it is evident that the standard deviation (std) of the Sc parameter is reduced during the droughts, reaching the lowest value at the lowest FF water content. This indicates that the information about the FF storage capacity is optimal at the end of wet periods, followed by a long dry period. This parameter appeared to be the most relevant parameter for which the model is most sensitive. The water uptake efficiency (b) seems to be the second important parameter. Its standard deviation is lowest at the end of long dry periods. This parameter mainly controls the water dynamics during the drying phase, which can be expected since available water in the FF decreases as a result of uptake by roots. The interception efficiency parameter (a) seems to be less sensitive to the FF wetting conditions. A reduction of its standard deviation was observed with increasing amounts of rainfall immediately after the long dry periods. The drainage parameter (d) is the least sensitive in the model and its standard deviation is only slightly reduced during heavy rainfall events.

Calibration
The result of the sensitivity analysis was used to split the total set of TDR measurements, used for model calibration, into four independent subsets, which contain information on a specific parameter. The value for the Sc parameter was set first, using data from the dry periods and applying an iterative procedure until the standard deviation does not decrease. Afterwards the value for the b parameter was identified following the same iterative procedure. Using specific data from the wettest period of measurements, the values for the a and d parameters were identified. Moreover, the calibration procedure indicated that the accuracy of the other parameters depends on the accuracy at which Sc can be identified. The values of the different parameters found through the calibration procedure and their corresponding standard deviation are shown in Table 6.3. The Sc parameter was easily identified for all ecosystems during the drying curve in the FF, as available measured data contained information for two significantly dry periods. The values of the calibrated Sc parameter decreased from the

SP to the FP, which is consistent with the results from the field experiments and with the measured FF storage capacity.

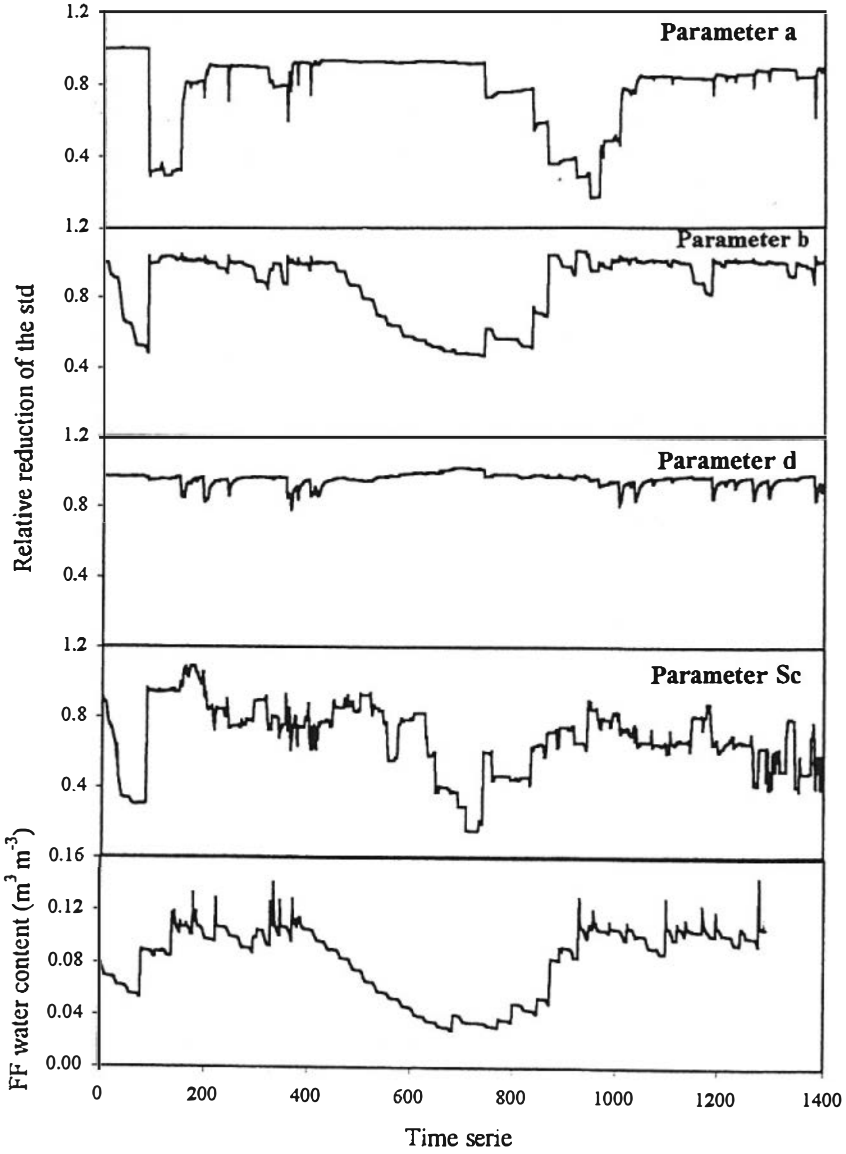


Figure 6.4 Sensitivity analysis of parameters of the forest floor (FF) dynamic model. Relative reduction of the standard deviation (std) according to specific parameter information in the calibration data.

Although the b parameter showed a high standard deviation, except for the SP ecosystem, the values indicated that the FF's differed in their contribution to forest transpiration in each ecosystem. The reason why this parameter value was better identified in the SP, lies in the fact that the FF in the SP dried out at a higher rate than in the other ecosystems, as indicated by the analysis of the water content dynamics. Therefore, data from the SP provided better information for parameter identification during those periods than that from the other ecosystems. The interception efficiency (a) and drainage (d) parameters were less accurately identified (high standard deviation), because of the low information contained in the calibration data and due to the lack of high resolution in temporal measurements of FF water content during such periods, data being only available on a daily basis. Low values of drainage and the dominance of preferential flow in the total litterflow may explain the uncertainties in the definition of the d parameter during the calibration period. Looking back, the calibration procedure showed that the model and the calibration method could have been used for a more optimal planning of the specific time for field sampling.

Table 6.3 Calibrated parameter set for the different FF's, with the standard deviation and objective functions for comparisons of measured and simulated values.

Parameter	**SP**		**HT**		**LT**		**FP**	
	Value	std	value	std	value	std	value	std
a	0.357	0.210	0.249	0.218	0.190	0.182	0.152	0.141
b	0.387	0.062	0.316	0.148	0.320	0.186	0.169	0.156
d (d^{-1})	63.3	25.6	67.8	24.6	65.3	22.2	72.5	21.5
Sc (m)	0.0192	0.0021	0.0094	0.0039	0.0096	0.0026	0.0069	0.0025
FF water storage								
NRMSE	0.101		0.168		0.186		0.130	
R^2	0.85		0.80		0.82		0.80	
FF Litterflow								
NRMSE	0.28		0.22					
R^2	0.94		0.98					

The sensitivity of the FF model to the parameters and the relative importance of these parameters in the model performance are clearly related: the storage capacity of the FF controls the amount of water that drains to the mineral soil and FF interception, and it partially controls the water uptake. Parameters values can also be evaluated in terms of their physical plausibility. The calibrated values of storage capacity are close to those found through the measurements (see Table 6.2). The evaporation efficiency parameter showed to be related to the amount of fine roots in the FF's and the resemblance between values of interception efficiency among ecosystems is consistent with the tendency as observed in litterflow measurements.

Model predictions and measured data

Calibrated parameter values were used to predict FF water uptake, storage and drainage to the mineral soil in the studied ecosystems for another period than that used for the calibration of parameters. As an example, predicted and measured FF water storage in the SP is presented in Figure 6.5. Although parameters exhibit a large standard deviation, the overall agreement is good with a NRMSE below 0.186 and explained variance higher than 0.80 (Table 6.3). This good fit between predicted and measured FF water storage and its dynamics is partly explained by the accurate estimation of the Sc parameter. This agrees with the statement by Heuvelink (1993) that improvement of model predictions is achieved most efficiently by improved identification of parameters for which the model is most sensitive. The largest differences between predicted and measured FF water storage generally occurred during the droughts when predicted storage decreased more than measured values. Apparently, the linear function applied for the water uptake is not valid at low water content of the FF.

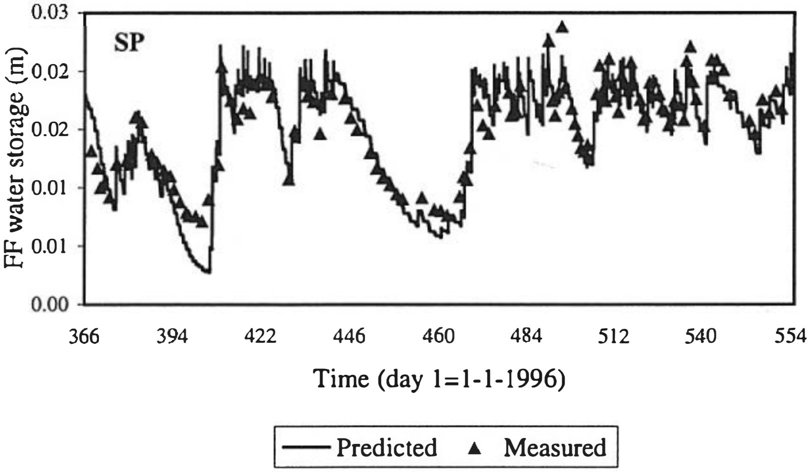


Figure 6.5 Comparison of predicted and measured forest floor (FF) water storage in a forest ecosystem (SP), as an example, in the Colombian Amazonia.

Measured litterflow in the SP and HT was used to validate the calibrated model with a dataset independent of that used for the calibration. Figure 6.6 presents the litterflow predicted by the calibrated model accumulated on event basis, and the measured FF litterflow. In both ecosystems, the model yields a high explained variance of the observed FF drainage (R^2 above 0.94). In spite of the uncertainty in the identification of parameters a and d, differences between predicted and simulated litterflow from the FF are very low and the largest differences are observed at high rainfall events, when predicted values are higher than measured.

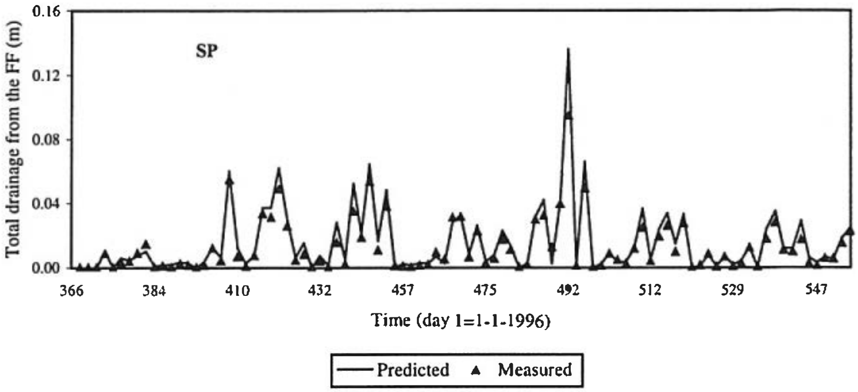


Figure 6.6 Comparison of predicted and measured total drainage from the forest floor (FF) in a forest ecosystem (SP), as an example, in the Colombian Amazonia.

It is clear that the model is well capable of predicting the FF water storage dynamics and amounts in all ecosystems, while it predicts total drainage with high accuracy. Therefore, the calibrated model was used to predict the water uptake from the FF's as the partial contribution to the total transpiration in each ecosystem for the period between January and August 1997. In the SP, the amount of water uptake from the FF represented 28.3% of the reference transpiration and the average uptake rate was 1.04 mm d^{-1}. In the HT, the FF water uptake corresponded to 20.2% of the reference transpiration with an average uptake rate of 0.74 mm d^{-1}. In the LT, the predicted water uptake was 19.2% and the uptake rate was 0.71 mm d^{-1}, whereas in the FP ecosystem, this FF uptake was 15.4% of the reference transpiration with an uptake rate of 0.57 mm d^{-1}. Predicted temporal dynamics of water uptake in the ecosystems studied showed that uptake from the FF's was strongly reduced during the droughts, with the largest reduction from the FF in the SP.

Predicted amounts and dynamics of total drainage and throughfall in the SP, as an example, are presented in Figure 6.7. There was an immediate response of the FF to rainfall, to produce litterflow even with small rainfall events. This behaviour is similar for all ecosystems studied. As has been described earlier in this paper, this is caused by the dominance of preferential litterflow in the FF. This indicates that preferential flow within the FF occurs even when the storage has not yet exceeded the storage capacity, in clear agreement with field observations: litterflow was collected a short time after rainfall started while the FF was still partly dry. Results also indicate that depending on the antecedent FF moisture content and on rainfall amounts, drainage from the FF may continue during the event and until approximately three hours after rainfall has ceased.

Predicted percentages of total litterflow relative to total throughfall between January and August 1997 are as follows: in the SP 87.2% of throughfall passed through the litter layer as total drainage to the mineral soil; 91.8% in the HT; 92.0% in the LT and 93.2% in the FP.

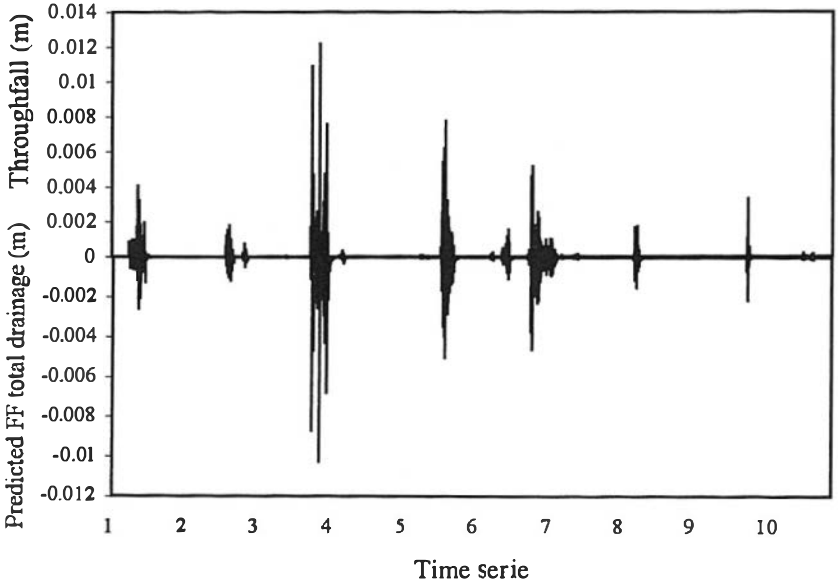


Figure 6.7 Dynamics and amounts of forest floor (FF) drainage as predicted by the dynamic model and measured throughfall in a forest ecosystem (SP), as an example, in the Colombian Amazonia.

6.6 CONCLUSIONS

Forest floors of the ecosystems studied show similar drainage dynamics, but amounts of water retained are different for each ecosystem: the FF in the SP consistently had the lowest water content and dried out stronger than the other ecosystems. In terms of water storage, the SP showed the highest values during the studied period while the FP showed the lowest. Differences between ecosystems in FF water storage amounts are mainly the result of differences in the FF thickness and to a lesser extent of their moisture conditions.

Our results indicate that it is appropriate to use the Rutter's interception approach to model FF water dynamics and uptake for the studied conditions, considering the FF as a continuous layer, which intercepts and redistributes net rainfall. The results from the calibration show the sensitivity of the model to parameters and the requirements for a proper identification of the parameter values. The identifiability of the FF model parameter's values is determined by the temporal dynamics of rainfall, the frequency of the FF water content measurements during specific periods and the sensitivity of each parameter. The sensitivity analysis and calibration procedure highlighted the importance of an accurate determination of the storage capacity parameter. Moreover, reasonable values for parameters and a high accuracy in predictions were found with a minimum of calibration and measurements, but improvements in the identification of parameters may be achieved with higher resolution of these measurements.

The calibrated model provides accurate estimates of FF water storage amounts and dynamics in the ecosystems studied. Although small discrepancies exist between measured and predicted FF water storage during the droughts, linear functions can be used to describe FF water uptake and total litterflow. From the model predictions it is concluded that water uptake from the studied FF's, expressed as percentage of total forest transpiration, differs between ecosystems and ranges from 15% to 28% over the period of study. The percentage of throughfall that passes through the FF as litterflow to the mineral soil is almost similar for the studied ecosystems (93%), except for the SP where total litterflow was lowest (87%).

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7. MONITORING AND MODELLING SOIL WATER DYNAMICS AND ROOT WATER UPTAKE IN FOUR FOREST ECOSYSTEMS IN NORTHWEST AMAZONIA

7.1 ABSTRACT

As a part of hydrological research in undisturbed forest ecosystems in Colombian Amazonia, soil water content dynamics were studied to assess the water fluxes in the ecosystems to support nutrient cycling studies. This was achieved by monitoring water content dynamics at various soil depths and by simulating water uptake by roots and vertical water fluxes in the mineral soil. The dynamics in soil water content in undisturbed conditions were monitored in four physiographic units in the Middle Caquetá (Colombian Amazonia), over two years. Soil water content was measured with TDR at eight different depths, while soil pressure was measured with tensiometers at the same depths. Measurements were performed every two days and every day whenever possible. The contribution of the soil layers to root water uptake and the vertical water fluxes were simulated with the dynamic model SWIF (Soil Water dynamics In Forested ecosystems), using measured boundary conditions and measured system characteristics as input, without any calibration of model parameters. Combined field and laboratory measurements indicated that due to a high water retention at wilting point soil water availability is low, especially in the SP, but water storage is high during most of the studied period. Fluctuations in water content are largest in the upper horizon, caused by the combined effect of rainfall frequency, high drainage fluxes in macro and mesopores, and the concentration of fine root in the upper soil layers in all ecosystems. Calculated water storage per soil layer (0.5 m) varied little between soil depths and between the subplots within one ecosystem. An exception is formed by the soils of the SP, with clear differences between crest, slope and valley bottom. These are probably related to differences in soil texture and slope position. Predicted water contents in all ecosystems and for all soil depths were highly correlated with field measurements. The simulated water uptake from the mineral soil and reference transpiration values were very similar during most of the simulated period, except for the short dry periods when actual transpiration decreased to almost one third of the reference value. Total water uptake from the mineral soil differs between ecosystems: during the simulation period, the total percentage of water uptake from the SP was 65% of the reference transpiration, 71% in the HT, 74% in the LT and 83% in the FP. Differences among ecosystems in their soil water dynamics and in the amounts of water uptake and drainage are caused by the differences between the studied soil types in storing and conducting water, in root distribution and the proportional contribution of the forest floor to total uptake in each ecosystem.

7.2 INTRODUCTION

Amazonian rain forests are assumed to have a tight internal cycle of nutrients (Brinkman, 1985) with low contributions through atmospheric deposition (Tobón, 1997; Brouwer, 1996). Nutrient losses from these ecosystems seem to decrease as soil fertility decreases (Bruijnzeel, 1991) which can be interpreted as plant strategies aiming at conservation of scarce nutrients. In such ecosystems, knowledge of the internal nutrient cycling is important to understand the most important processes contributing to forest productivity or to evaluate the effects of land use changes. As nutrients are transported by water, the understanding and quantification of water fluxes and storage dynamics in the forest compartments are essential for the characterisation of solute fluxes.

The characterisation of the soil hydrological conditions and properties provides an important insight into the factors and processes affecting water dynamics in the unsaturated zone. Such studies and the role of soil water in forest transpiration and drainage are poorly known features of forest ecosystems in northwest Amazonia. Moreover, for large forest areas, such as the Amazon basin, monitoring of soil moisture conditions throughout is a difficult task. Therefore, models can be used for better understanding of Amazonia functioning. These models required that long-term and large-scale soil moisture data are available for their calibration and validation, but such is extremely scarce. Additionally, this data can serve for the application of coupled atmosphere-soil-water transport models. According to Hodnet *et al.* (1996), the only published nine-month data on soil water content in eastern Amazonia was that by Nepstad *et al.* (1994). For central Amazonia, Hodnet *et al.* (1996) presented a long term soil storage data for paired forest and pasture ecosystems.

This Chapter has two main objectives. The first is to present and compare long-term data of soil water content dynamics in four undisturbed forest ecosystems in Colombian Amazonia. The second objective is to simulate the water uptake from the mineral soil and vertical water fluxes, and to compare these fluxes among ecosystems. Results are discussed in terms of differences the between ecosystems and are related to the most relevant hydrological properties of the soils.

Soil water content can be measured by a number of methods (i.e. gravimetric, neutron probes). Time Domain Reflectometry (TDR) is nowadays the most accepted method to measure soil water content under undisturbed conditions, which can provide accurate and rapid in-situ determinations of soil moisture conditions. In the present study, soil water content and water potential were measured by using a Time Domain Reflectometry (TDR) technique and tensiometers. Root water uptake can not be measured directly, but generally, it is calculated with a simulation model. A large number of soil water balance and soil plant atmosphere transfer models have been published (Bouten *et al.*, 1996; Bouten, 1995; Bouten, 1992; Lafolie *et al.*, 1991; Feddes *et al.*, 1988; Wagenet and Hutson, 1987; Belmans *et al.*, 1983; Feddes *et al.*, 1978). The model Soil Water In Forest ecosystems "SWIF" has shown to be capable of simulating the soil water dynamics in different forest types in the Netherlands (Bouten, 1992). We used this SWIF model to simulate soil water processes and to quantify the water uptake by roots and the unsaturated soil water fluxes. This one-dimensional finite difference model for unsaturated soil water fluxes simulates soil water uptake and vertical soil water fluxes. The model is linked to the forest interception model, which was calibrated and validated for the research sites. Different from most studies where model parameters were calibrated, in this study measured boundary conditions of soil hydraulic properties and fine root distribution are used as input, without calibration of parameters.

7.3 THE STUDY AREA

The study was carried out in the undisturbed forest plots used as research sites by the Tropenbos Foundation in Colombian Amazonia. They are located in Peña Roja (Nonuya Indian community) near Araracuara, Middle Caquetá Colombia (0° 37' - 1° 24' S and 72° 23' - 70° 43' W). The climate is classified as equatorial superhumid Afi (Köppen, 1936). Average annual rainfall is about 3400 mm (see Chapter 2). April and May are the wettest months and January the driest. Comparison with the long term climatic data from the Araracuara climatic station showed that during the period of study, climatic conditions registered at the Peña Roja station on the whole did not differ from the long term average. The only significant difference with previous years was the rainfall distribution during 1997, with an exceptional dry period in March.

Colombian Amazonia covers 403.000 km^2. The major part of this area consists of a dissected Tertiary sedimentary plain with unconsolidated, mostly fluvial to lacustrine sediments. The plot in this unit is a first order catchment at about 60 m above the mean level of River Caquetá with dominantly clayey sediments. The upland terraces from the River Caquetá, which is an Andean white water river, comprise a low terrace at about 10 to 15 m above mean level of River Caquetá and a high terrace at 25 to 40 m. The floodplain of the River Caquetá, of which the higher parts are only incidentally flooded, consists of sandy levee and finer textured basin deposits. The plot on the high terrace also represents a first order catchment with mostly clayey sediments. In the two other units, first order catchments could not be delineated. Plots in the latter units therefore were selected to include all major soil types. The plots in the Tertiary sedimentary plain (SP), high terrace (HT), low terrace (LT) and flood plain (FP) are representative for the major physiographic units in the northwest part of the Amazon basin.

The physiographic units strongly differ with respect to their soils (see Table 7.1 and Appendix 1). Soils on the floodplain, with lower regularly and higher rarely inundated parts, have a flat and hardly dissected topography, are more or less hydromorphic and are relatively poor in nutrients. Regularly or incidentally, they receive fresh nutrientrich sediments. They have a topsoil with a texture of sandy loam to silt loam and an increasing clay content with depth. Soils of the low terrace are similar, but do not receive fresh sediments and therefore are poorer in nutrients. Soils of the high terraces and the sedimentary plain also called "Terra firme", are well drained, have a very low total nutrient status and a texture of clay to heavy clayey, often with a less clayey topsoil. Except for the regularly flooded floodplain, soils have a litter layer of which the thickness is largest in the SP (up to 35 cm) and decreases to a few centimetres, descending to the low terrace (see also Chapter 5). Profile descriptions of the main soil types in the four units are presented in Appendix 1. Some soil properties of the main soil horizons are summarised in Table 7.1.

Table 7.1 Physical properties of main soil types in the various physiographic units in the Middle Caquetá, Colombian Amazonia. Fine root values are presented as the percentage of the amount of fine roots in the respective layer relative to the total fine roots in the forest floor and mineral soil up to 1 m depth. Bulk density values are the average of bulk densities of thinner layers and a variable number of soil samples in each horizon.

Soils	SP	HT	HT	FP
Classification				
USDA	typic Kandiudult	typic Hapludult	typic Paleudult	typic Tropaquept
FAO	xanthic Ferralsol	haplic Acrisol	haplic Acrisol	dystric Cambisol
Horizon	Ah	Ah	A/B	A
Thickness (cm)	12	30	45	10
Texture	sandy clay loam	sandy loam to sandy clay loam	silt loam	silty clay loam
Dry bulk density (kg m^{-3})	1346 (± 108)	1298 (± 49)	1210 (± 126)	1121 (± 58)
Percentage of fine roots	27	70	72	41
Horizon	Bt_1	Bt_1	Bt_1	Bw_1
Thickness (cm)	38	40	30	50
Texture	clay	clay	silty clay	silty clay loam
Dry bulk density (kg m^{-3})	1415 (± 109)	1390 (± 95)	1340 (± 109)	1224 (± 66)
Percentage of fine roots	28	10	6	40
Horizon	Bt_2	Bt_2	Bt_2	Bw_2
Thickness (cm)	110	60	50	40
Texture	clay	clay	clay	clay loam
Dry bulk density (kg m^{-3})	1510 (± 77)	1524 (± 98)	1525 (±73)	1330 (± 57)
Percentage of fine roots	9	2	3	7

In the research plots, fine root distribution seems to be related to soil nutrient availability: in nutrient poor conditions (SP) fine roots concentrates in the forest floor and in the top of the mineral soil. Contrary, in the FP, which probably is the most nutrient-rich soil in Colombian Amazonia, fine roots are more homogeneously distributed in the upper part of the mineral soil. Fine root distribution in the mineral soil exhibits a decreasing trend with depth, very low values being reached at about 1.0 m depth. Extensive data on fine root distribution are presented in Chapter 2.

7.4 MATERIALS AND METHODS

In each of the four ecosystems, within small plots a series of physical parameters were monitored. These include soil water content, soil water potential and forest floor water dynamics, as well as gross rainfall above the forest canopy, throughfall and stemflow. In the SP plot, three subplots were selected, located on respectively crest, midslope and valley bottom. In the other units, two subplots were randomly selected.

TDR was used to monitor soil water contents. The equipment consisted of a Tektronix 1502B-cable and three wire probes of 0.5 m with a cable length of 6m. Waveforms were interpreted using the TDR software developed by Heimovaara and Bouten (1990). TDR probes were horizontally installed in the upsweep of the pits (2.0x1.5x1.5 m). In total 8 sensors were installed in each plot at different soil depths. In the sedimentary plain and high terrace, probes were installed at 0.1, 0.15, 0.2, 0.3, 0.5, 0.8, 1.2 and 1.6 m depth. In the low terrace and floodplain, probes were installed at slightly different depths - 0.1, 0.15, 0.2, 0.3, 0.4, 0.6, 0.8 and 1 m - because of the decrease in fine root content at greater depth and the potential presence of a water Table at such depth. To avoid any external influence of outside factors, the probes were horizontally installed in holes, which were dug into the face of the pit to a distance from this face equal to its depth. After installing the TDR probes, profile faces and the pits themselves were covered with black polyethylene plastic. Next to the TDR pits, 8 tensiometers were vertically installed at the same depths as the TDR probes. Plots were randomly chosen and after one year of continuous measurements, the TDR sensors and tensiometers were relocated.

Both TDR probe and tensiometer readings were taken manually every two days and daily during some periods. Measurements were carried out early in the morning from August 1995 until August 1997 but for two gaps of twenty days, which were due to failure of the field portable computer. TDR travel time measurements were translated into volumetric water content applying a calibrated regression equation for the specific soils, based on soil samples collected at the same time, sites and depths where TDR measurements were carried out (see Chapter 5).

Water storage (W_S) of a soil layer was calculated from the calibrated TDR water content (θ) and weighed layer thickness (z). Total soil water storage is calculated for each research site as the integration of water storage in the soils layers, according to:

$$W_s = \sum_i \theta_i \Delta z_i \tag{7.1}$$

7.4.1 SWIF model

The SWIF model forms part of the FORHYD (FORest HYDrology) package (Bouten, 1995) which focuses on the hydrology of the mineral soil. Tiktak and Bouten, (1992) presented a full description of SWIF. The model is based on the numerical solution of the Richard's equation:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}[K(h).(\frac{\partial h}{\partial z}+1)] - S^*(h) - D_r(h) \tag{7.2}$$

Where the volume of water uptake by roots in a given time per unit of volume of soil is represented by a sink term S^*(m^3 m^{-3} d^{-1}). C (m^{-1}) is the differential water capacity, t the time (d), z the height (m), h (m) the soil pressure head and K(h) the unsaturated hydraulic conductivity (m d^{-1}). D_r is also a sink term, which represents the volume of water laterally drained in a given time from a certain volume of soil (m^3 m^{-3} d^{-1}).

As SWIF is used to simulate the root water uptake, the way in which this is approached within the model is presented here. The model is designed to distribute the reference plant transpiration over the entire soil and forest floor layers, according to the effective root distribution ($R_{eff,z}$). This is calculated from the root density (R_z) and the ratio between actual and saturated water content, included for the simulation of preferential water uptake from relatively wet soil layers.

$$R_{eff,z} = R_z \frac{\theta_z}{\theta_{s,z}} \tag{7.3}$$

Thereupon, the amount of water uptake at a certain depth is calculated from the reference plant transpiration (E^*_{pl}) by applying a reduction function (RED(h)) related to the pressure head (Belmans *et al.*, 1983). The actual transpiration, as the total water uptake, is calculated by the integral of the sink term over the total root zone.

$$S^*_i = E^*_{pl} \sum_{i=1}^{N} RED(h) \frac{R_{eff,i}}{R_{eff,tot}} \tag{7.4}$$

7.4.2 Input data

The upper boundary conditions for the model are total drainage from the FF and the difference between reference transpiration (Monteith, 1965) and the water uptake from the FF in each ecosystem, since part of the incoming energy used for plant transpiration was expended in the uptake from the FF. Water uptake and drainage from the FF were calculated with the dynamic FF interception model calibrated for each research site (Chapter 4). Evaporation from the soil surface is neglected, mainly because of the prevailing climatic conditions inside the forests, which are a high air humidity, low solar radiation (patchy) and very low wind speed. The lower boundary condition has been taken as constant pressure head at three meters for all studied soils.

Reference transpiration was calculated from meteorological data collected from the automatic weather station in Peña Roja (Middle Caquetá), using the Monteith equation (Monteith, 1965). The aerodynamic resistance parameter (r_a) is calculated from the wind profile extrapolated above the forest canopy (see Chapter 2). The value for the stomatal or surface resistance is taken according to the results by Shuttleworth *et al.* (1984) in a study in central Amazonia. Parameters to calculate the net radiation (e.g. albedo) were deduced from the specific studies carried out within the Amazon basin (Culf *et al.*, 1996; Shuttleworth *et al.*, 1984) and from Brunt (1932).

In most studies dealing with modelling, the calibration of parameters is focussed on the goodness-of-fit between simulated and measured variables. Rather than pursuing a modelling approach aiming at a best fit, we followed the approach of modelling based on a sound physical understanding, by using field and laboratory data as input to the model, to explore the capability of the model to predict soil water dynamics in the studied ecosystems. Consequently, paired measurements of soil water content and pressure head at the various soil depths and sites were used as in-situ input data for the water retention characteristics (WRC) and hydraulic conductivity, from the laboratory determinations. As field data only cover the range between –2 to –85 kPa, field WRC values were extended to a wider range by laboratory analysis of samples (Figure 7.1, for two soil depths, as an example).

The WRC of each soil layer from the four forest ecosystems was determined with sand box apparatus (Stakman *et al.*, 1969) using undisturbed core soil samples of 100 cm^3 and, for pressures up to 22000 kPa, with pressure plates using subsamples. For the laboratory and field measurements of WRC analytical functions by van Genuchten (1980) were fitted with a Simplex Algorithm programme (Freijer, 1990).

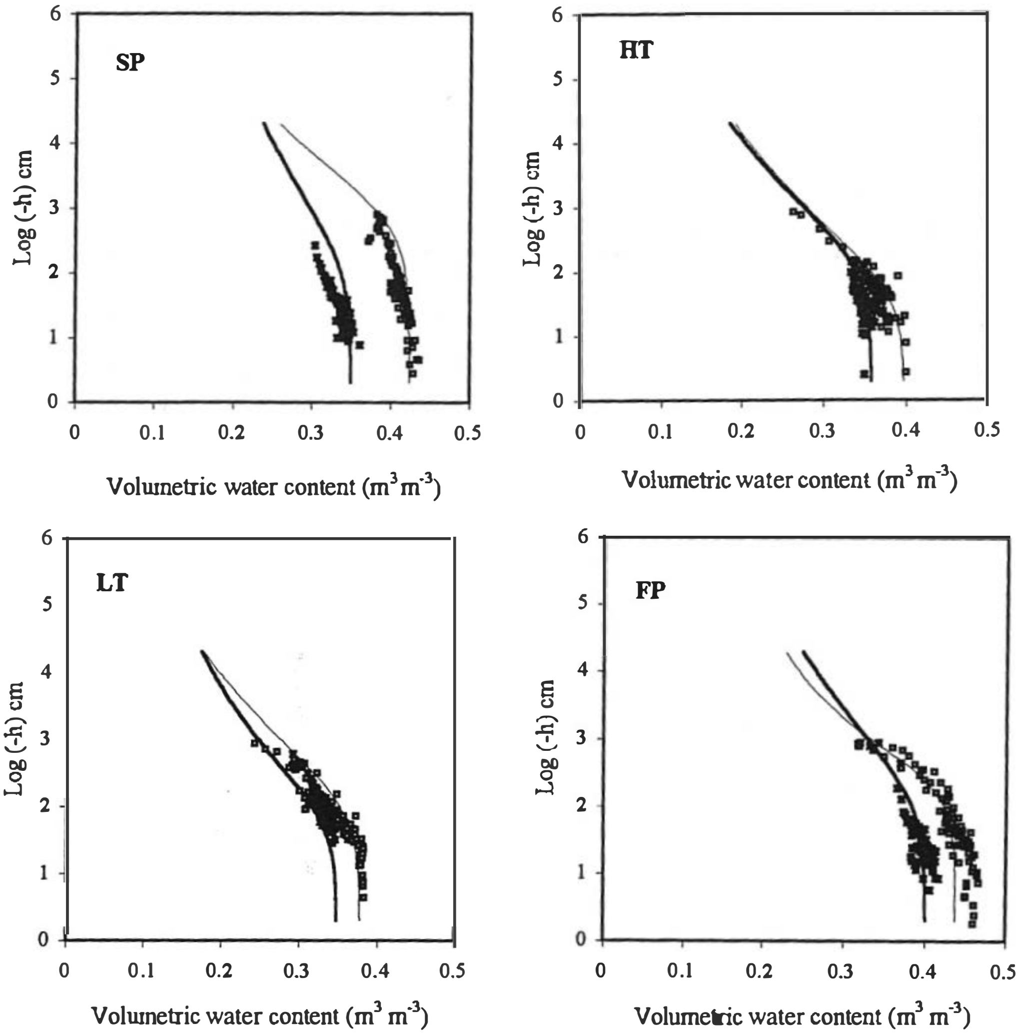


Figure 7.1 In situ derived water release curves from the monitoring of soil water content and soil pressure head and the fitted retention curve (van Genuchten, 1980) for two soil depths (—□— for 0.1 and —x— for 1.0 m) in four forest ecosystems in Colombian Amazonia.

The unsaturated hydraulic conductivity of soil layers was measured with the stationary flux-head or sprinkling infiltrometer method (Stolte *et al.*, 1994). Undisturbed soil samples from each soil horizon in the ecosystems studied were taken in perplex cylinders of 0.2 m high and 0.12 m diameter. Measurements of pressure head and flux density were used to calculate the unsaturated hydraulic conductivity characteristic [K(h)]. The soil survey and the analysis of the measurements of water content pointed to the existence of large amounts of macro and mesopores, mainly in the upper part of the soil profiles. As samples were too small to evaluate effects of macroporosity on hydraulic conductivity, the values of [K(h)] at high matric potentials were increased to be able to drain water excess.

Some of the uptake and drainage parameters were not measured and some of them can not even be directly assessed. Besides, comparative data on drainage and on uptake were not available for parameter calibration. Therefore, the values of these parameters were obtained from existing information in literature (Bouten, 1992). Data on fine root distribution were obtained from undisturbed soil samples collected in 1 m^2 soil pits. Samples were taken each 0.1 m down to 1.0 m depth (de Vente, 1999; Wassenaar, 1995). Deeper sampling was not relevant since fine root concentration declines to very low values at about 1.0 m.

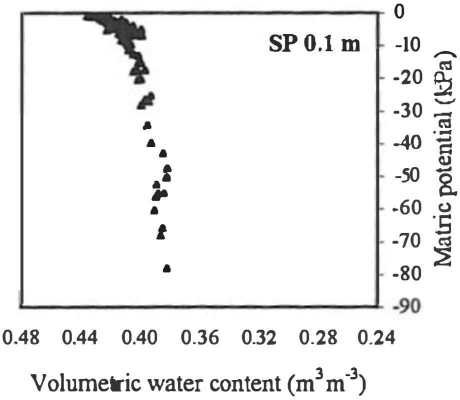
To evaluate the model results and to highlight the differences and the accuracy of predicted values, two different error functions were used: the normalised root mean square error (NRMSE) between predicted and measured soil water content and the correlation between them (R^2). The first renders a sort of coefficient of variation of the discrepancies between predicted and measured water content, around the measured average; the second indicates the explained variance.

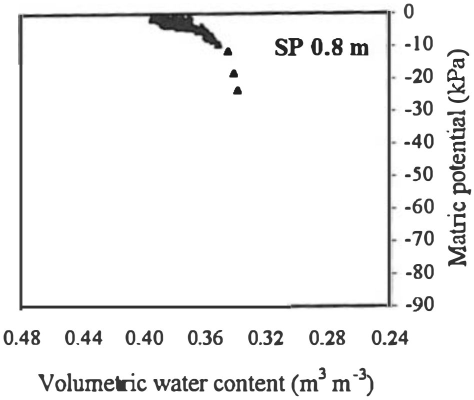
7.5 RESULTS AND DISCUSSION

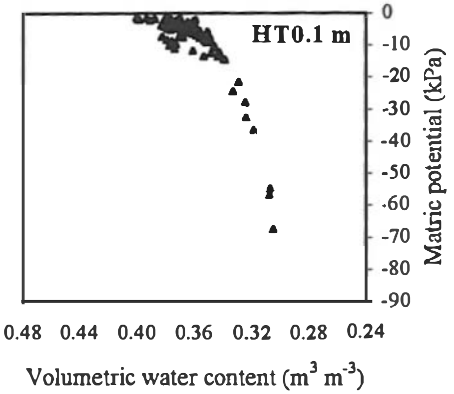
7.5.1 Soil water retention and water content dynamics

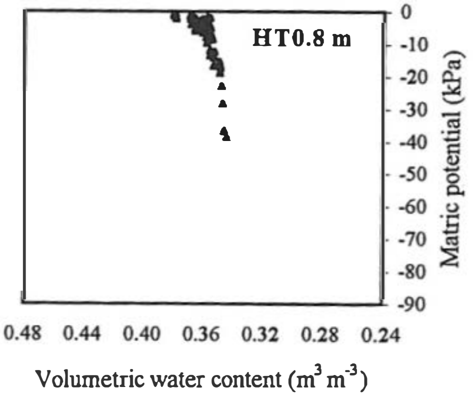
The water retention characteristics of some of the studied soils, deduced from field measurements of soil water content and pressure head at the various soil depths, are presented in Figure 7.2. In general, the upper part of the soil profile showed a wider range in soil water during the measured period (from –1.0 to –80 kPa) than the soil layers below 0.8 m, where the range was considerable smaller and lowest measured matric potentials were around –20 kPa. Figure 1 shows that a high proportion of soil water (0.05 to 0.09 m^3m^{-3}) is released at matric potential between –1.0 and -15 kPa, in the upper part of the soil profiles, while in the lower part this value decreases considerably. The ecosystems studied differ with respect to the amounts of water released at high suctions and to the depth at which these amounts decrease: in the SP decreases were clear at lesser depths than 0.8 m while in the other ecosystems decreases became noticeable below a depth of 0.5 m. These results agree with the field observations (Appendix 1) which indicate that macro and mesoporosity slightly decrease up to 0.5 m and strongly decrease below 0.8 m depth in all ecosystems.

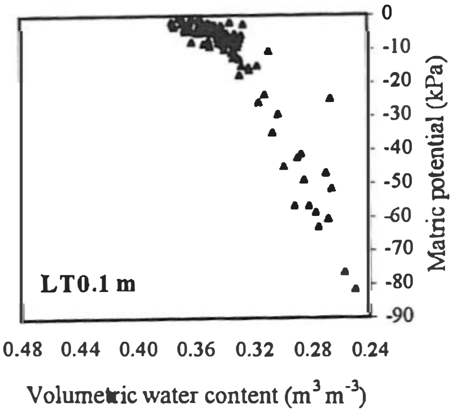
Notwithstanding the prevailing wet conditions in the area with high rainfall amounts and measurements taken immediately after the rainfall event, the dynamics of soil water content showed no saturated conditions during the studied period in any of the research sites up to 1.6 m soil depth. Because of macroporosity, it can be expected that part of the water in macropores had drained already at the time that the measurements were taken. Therefore, the saturation value for the studied soils was set somewhat higher than the maximum measured water content, mainly in the upper part of the soil profiles.

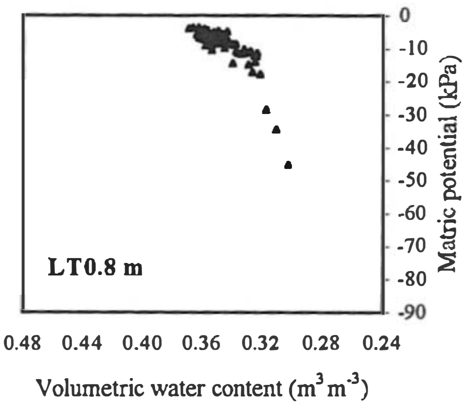












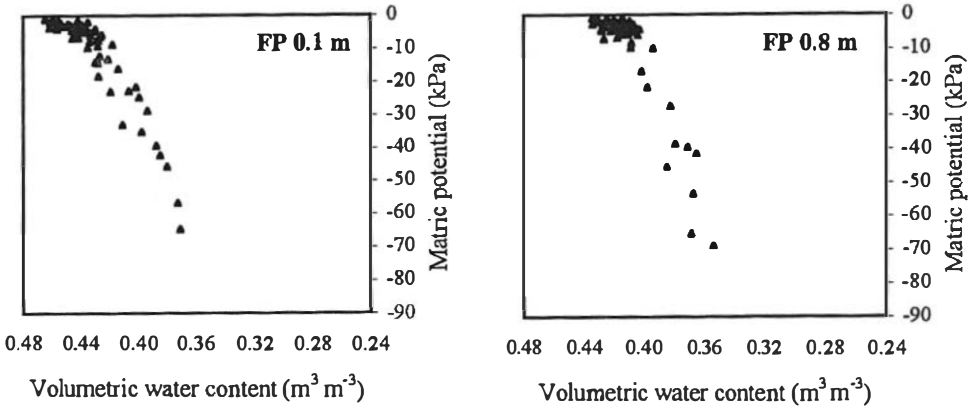


Figure 7.2 Water release curves from field measurements of soil water content and soil pressure head at two soil depths (0.1 and 0.8 m) in four forest ecosystems in Colombian Amazonia.

Since measured water contents decreased beyond the range covered by the tensiometers, fitted field measurements (van Genuchten, 1980) were combined with laboratory results on water retention curve (Figure 7.1). The high water contents at wilting point, especially in the SP, are remarkable. Results compare with those found by Chauvel *et al.*, 1991 and Hodnet *et al.*, (1994) in "terra firme" soils in Brazilian Amazonia who described the low water availability of these soils and a very high water content at wilting point (-1500 kPa). According to Proradam, (1979), this behaviour can be explained by the high clay content of soils (above 65%) and strongly developed structure of the soils, even under shifting cultivation. Further explanations for such behaviour of clay soils, which act as coarser textured soil at low tensions and as a true clay soil at high tensions, were put forward by Sanchez (1976) for Oxisols soils in Brazilian Amazonia. These include the abundance of medium and coarse decaying roots and a high faunal activity, mainly in the upper part of the soil profile.

Profiles of the maximum and minimum measured water content are presented in Figure 7.3. The water content dynamics in the SP clearly differ from those in the other ecosystems with smaller changes in water content and smaller differences with soil depth. The field observations and laboratory data indicate that these differences can be ascribed to the textural change (increasing clay content) in the soil profiles and to differences in water availability and root distribution in each ecosystem. Overall results clearly indicate that alluvial soils of the River Caquetá have a higher available water capacity than the soils of the Tertiary sedimentary plain.

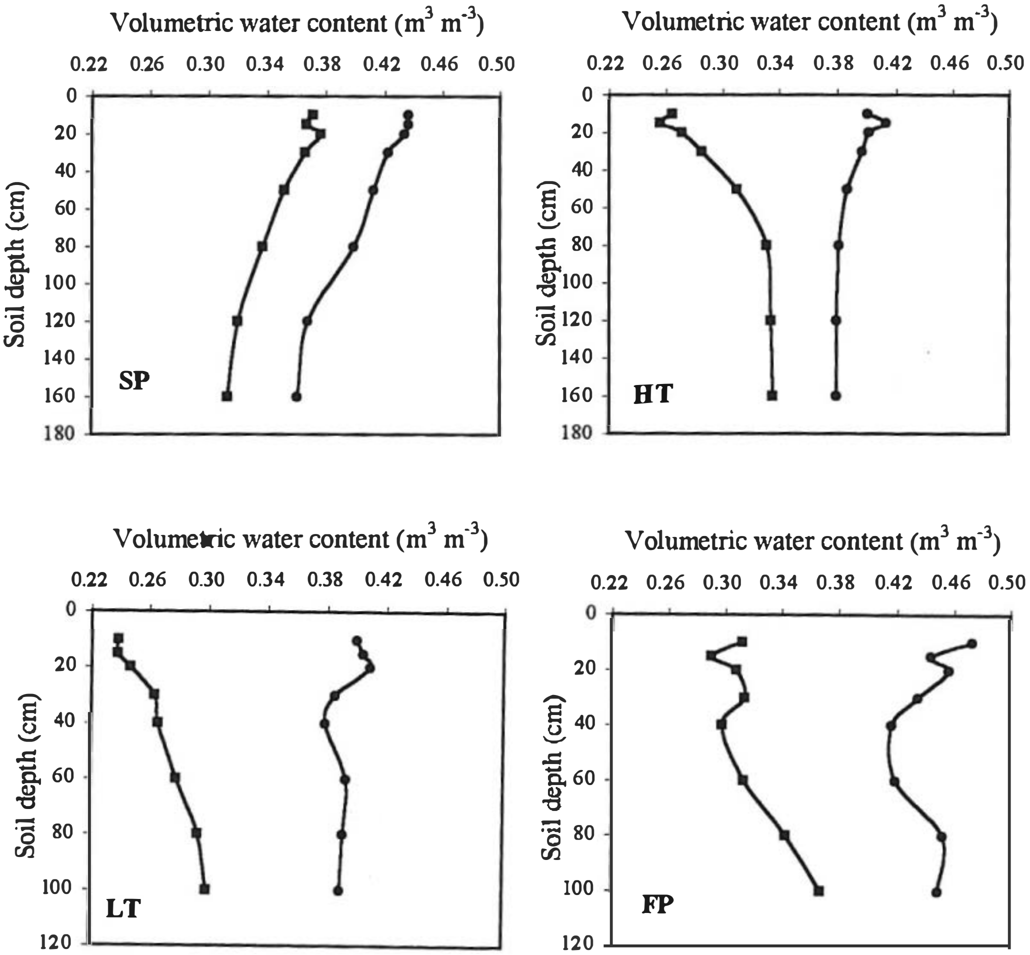


Figure 7.3 Profiles of maximum (—●—) and minimum (—■—) measured soil water content during the two years monitoring period (1996-1997) in four forest ecosystems in Colombian Amazonia.

7.5.2 Soil water storage and temporal dynamics

The eight depths at which water content was measured allow the integration of water volume over depth. As an example Figure 7.4 shows the daily FF total drainage and dynamics in water storage of the soil profile (1.6 m) in the SP. Storage amounts during the wet periods were almost similar for all ecosystems with a slightly higher storage in the FP. However, during dry periods, storage in the SP was higher than in the other ecosystems, which is consistent with the property of these soils to retain high amounts of water at low matric potential. Changes in water storage among ecosystems also differ. During the two dry periods (day number 384 to 403 and from day number 445 until 461) the highest water depletion was observed in the FP with 54.1 and 65.4 mm in each period.

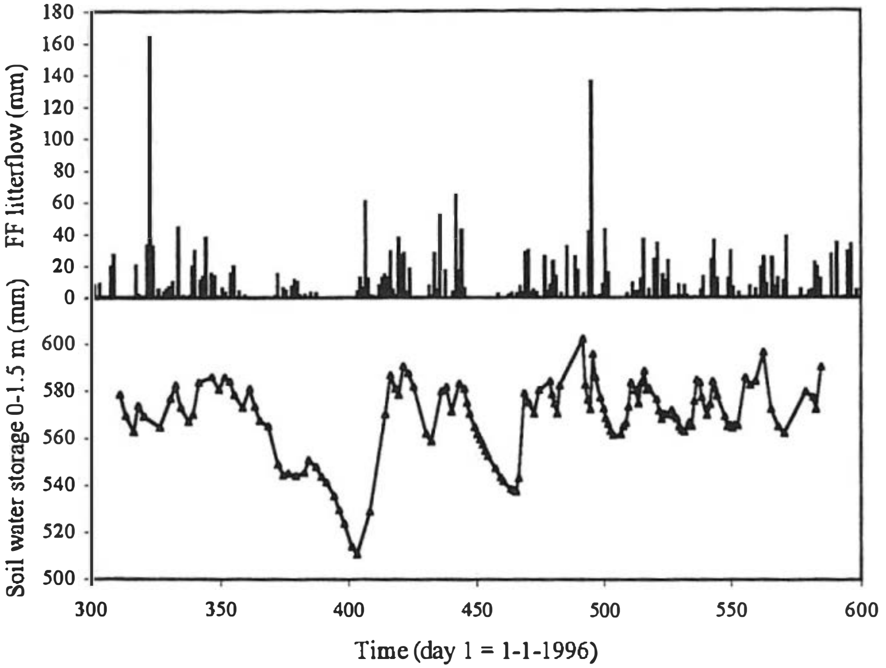


Figure 7.4 Temporal dynamics of measured soil water storage in the Tertiary sedimentary plain ecosystem (SP) and forest floor drainage (FF) to the mineral soil.

Water storage was also calculated for soil layers of 0.5 m up to 1.5 m. As an example, Figure 7.5 presents the temporal dynamics in water storage for three soil layers in the SP and HT. Main differences in water storage between depths were observed in the SP whereas in the other ecosystems (HT, LT and FP). Differences between soil depths and among sites within the same ecosystem were small. However, main differences in water storage between soil layers within the same plot were observed during the dry periods when the upper part of the soil profiles dried out differently in each ecosystem. In the SP ecosystem, the upper 0.5 m of the crest profile showed the highest storage and that in the valley bottom the lowest. Contrary, storage at 1.0 to 1.5 m was higher on the slope and bottom profile than on the crest. From the soil survey and texture analysis, it is likely that differences are due to different topography and differences in the soil texture.

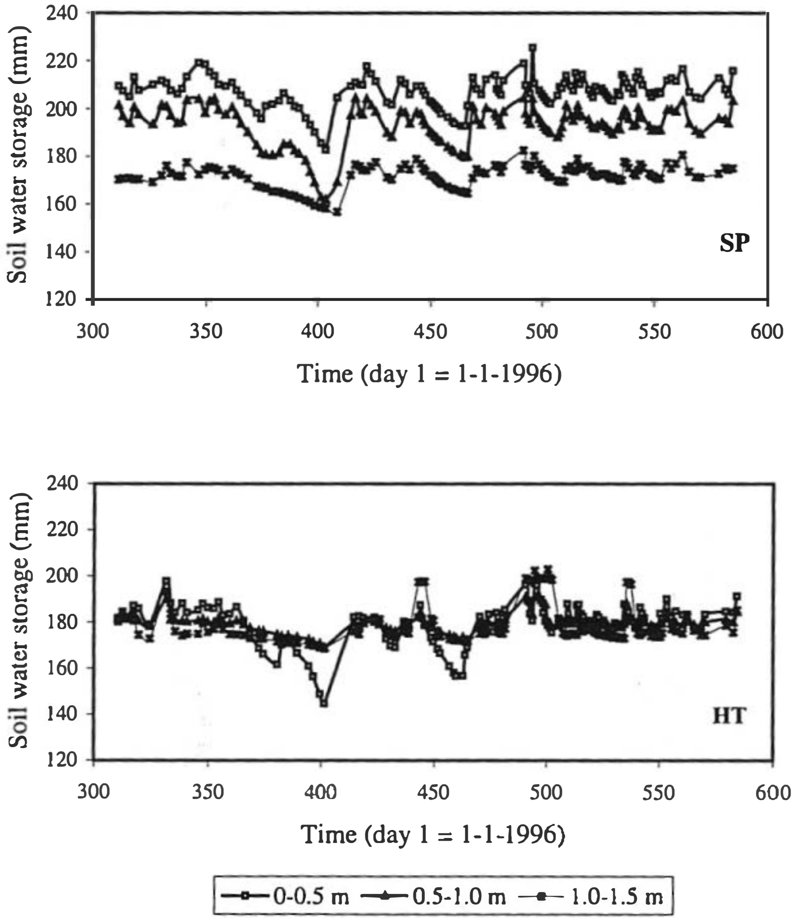


Figure 7.5 Soil water storage profiles by soil layers of 0.5 m at three different depths in two forest ecosystems (Tertiary sedimentary plain, SP and high terrace, HT) in Colombian Amazonia.

7.5.3 Model results

The SWIF model was applied to one of the soil profiles in each ecosystem. The period concerned was from November 1996 until August 1997, which corresponds to the period during which data was collected from the same soil profile in each ecosystem, after relocation of TDR probes and tensiometers.

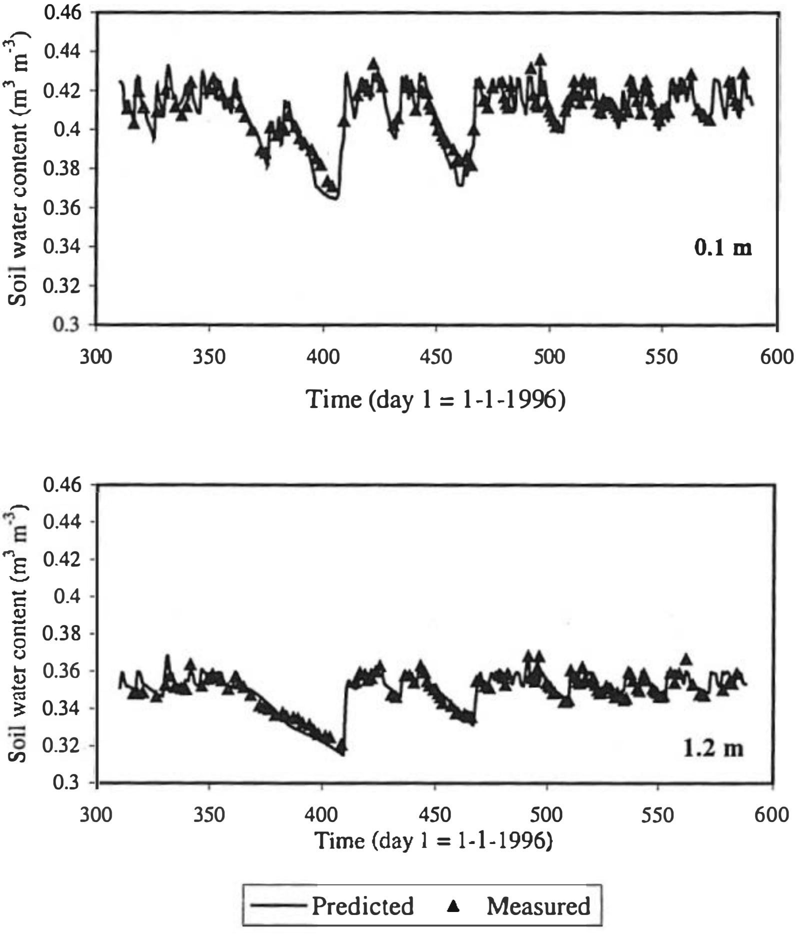


Figure 7.6 Comparison between measured soil water content at two soil depths (0.1 and 1.2 m) in a forest ecosystem (SP) and predicted values by the dynamic model using measured boundary conditions as inputs.

As an example, predicted and measured soil water content at two different soil depths in the SP ecosystems is presented in Figure 7.6. Measured water content dynamics in the studied soils were accurately predicted by the simulation model. The accuracy at which the model is capable of predicting measured values ranges from 71% to 96%, in all ecosystems and for all soil depths (Table 7.2). There is no systematic over or underestimation of measured water content. However, the model slightly underestimates water content at the end of the two dry periods, particularly in the SP and HT ecosystems. These results imply that the extrapolation of the K(h) curve at high matric potential has no negative side effect, which could be expected as saturation conditions in the studied soils are unlikely to occur.

Table 7.2 Statistics of predicted and measured soil water content at eight soil depths in four undisturbed forest ecosystems in the Middle Caquetá, Colombian Amazonia.

Depth (cm)	**SP**			**HT**			**Depth (cm)**	**LT**			**FP**		
	NRMSE	R^2	n	NRMSE	R^2	n		NRMSE	R^2	n	NRMSE	R^2	n
10	0.018	0.92	134	0.031	0.90	115	10	0.037	0.84	121	0.036	0.86	103
15	0.020	0.87	135	0.026	0.84	116	15	0.048	0.80	121	0.037	0.87	105
20	0.017	0.89	133	0.025	0.89	116	20	0.053	0.78	122	0.026	0.87	104
30	0.017	0.91	133	0.029	0.89	114	30	0.040	0.94	122	0.023	0.89	103
50	0.012	0.96	134	0.015	0.85	117	40	0.041	0.89	121	0.021	0.94	105
80	0.021	0.90	134	0.022	0.79	106	60	0.034	0.82	121	0.019	0.87	105
120	0.014	0.87	131	0.018	0.72	94	80	0.033	0.82	121	0.014	0.82	100
160	0.022	0.78	134	0.013	0.71	93	100	0.024	0.73	122	0.028	0.74	95

The accuracy of the model on predicting soil water content at the different depths may imply that other processes as soil water uptake and soil vertical fluxes are accurately simulated as well. Vertical soil water fluxes were clearly simulated by the model as a response of rainfall events. Generally, fluxes related to rainfall events smaller than 10 mm were noticeable up to 0.15 m deep, while only large rainfall events (larger than 25 mm) produced fluxes throughout the soil profile. Nevertheless, small storms during wet seasons induced vertical water fluxes through the profile. As an example, Figure 7.7 presents the total FF drainage and predicted daily soil water fluxes for four soil depths in the SP ecosystem. In general, high fluxes were predicted from the upper soil layers in all ecosystems, with the highest value in the SP, which agrees with the observed high macroporosity in these soils. In general, the high rate of percolation, as predicted high vertical water fluxes, agree with the nature of the soils which exhibit a well structure. Decreasing water fluxes were similarly predicted for all ecosystems in soils layers deeper than 0.5 m, decreasing to a very low values at 3.0 m. Low upward fluxes (up to 0.002 m d^{-1}) were predicted for the soil layers between 0.1 m and 0.5 m in all ecosystems, except for the dry periods when considerable amounts of upward fluxes were observed up to 0.8 m. This shows the role of deep soil layers, supplying water as the topsoil becomes dry. Upward fluxes are negligible at lower depths than 0.9 m.

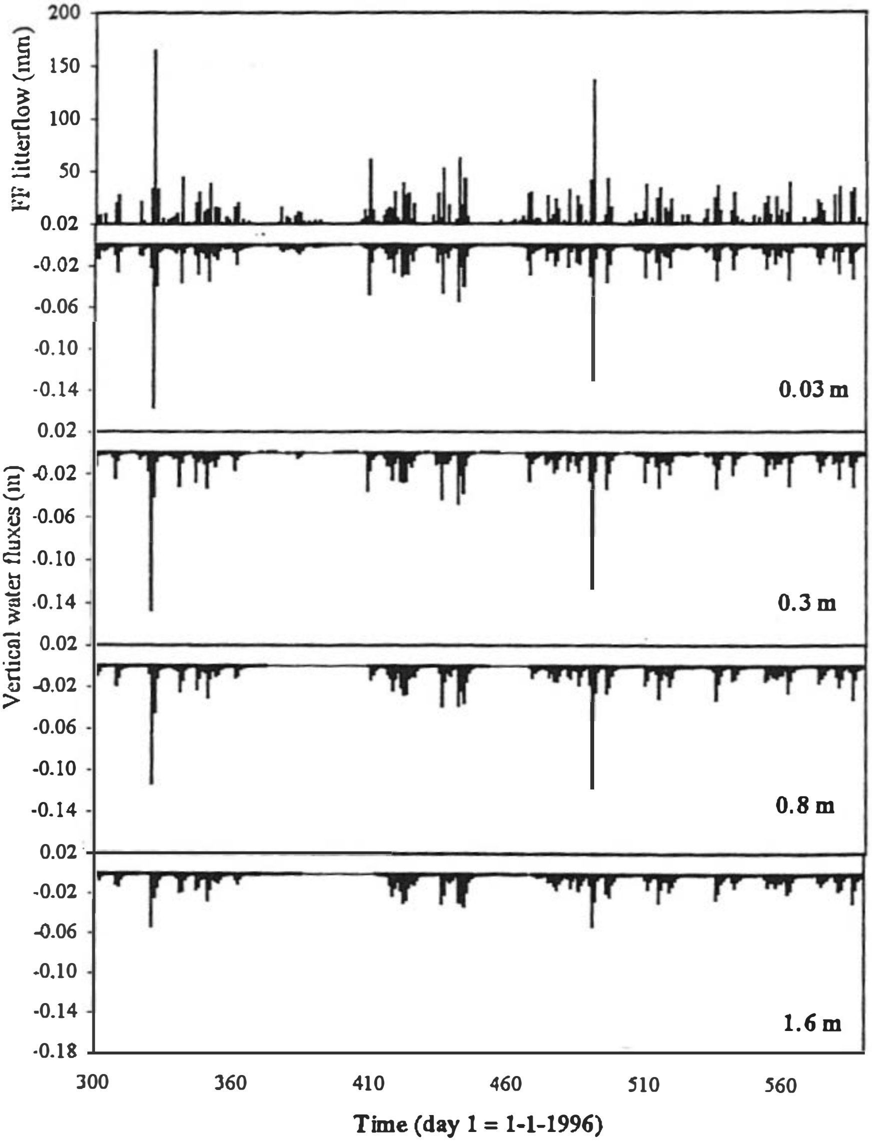


Figure 7.7 Soil water fluxes at four different depths (0.03, 0.3, 0.8 and 1.6 m) as predicted by the dynamic model for the tertiary sedimentary plain (SP) and forest floor (FF) drainage as the upper boundary condition for the mineral soil.

Calculated actual forest transpiration was of similar magnitude as reference transpiration during most of the simulation period, which implies that there is no significant reduction on transpiration in the studied forest ecosystems. However, a considerable reduction of the actual transpiration occurs in all ecosystems during the short dry periods, up to 60% (Figure 7.8). Although the soils showed to have low water availability, results indicate that the forest is supplied with sufficient water during most of the year.

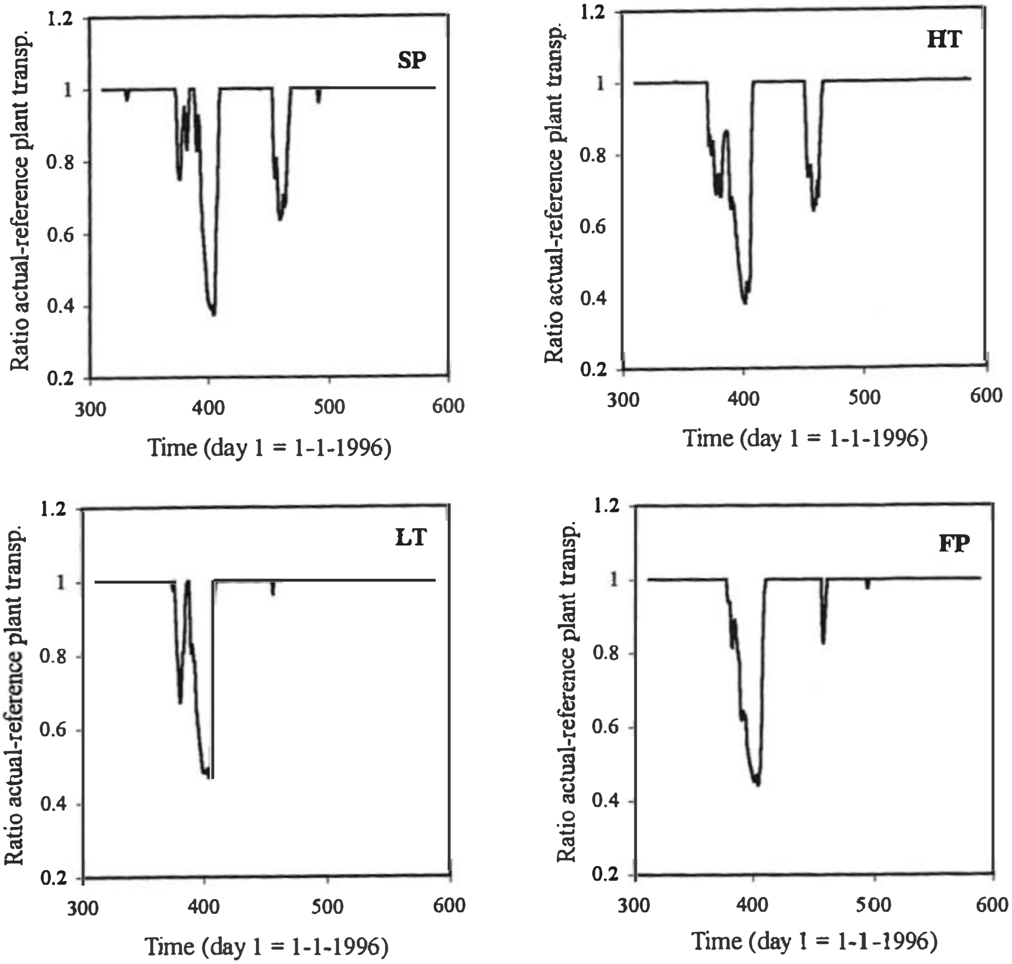


Figure 7.8 Temporal dynamics of the ratio between soil water uptake or actual plant transpiration and the reference transpiration (Monteith, 1965) in four forest ecosystems in Colombian Amazonia.

Figure 7.9 shows the vertical distribution of predicted total water uptake during the simulation period in the four ecosystems. During most of the simulated period, the soil layers in all ecosystems presented a relative constant contribution of water uptake, which was higher from the first 0.5 m of the soil profiles than from the deep soil layers, in agreement with the root distribution. This indicates that water uptake during the wet periods strongly depended on root distribution through the soil profile. Main changes were observed during the dry periods when the fraction of water uptake from deep soil layers increases, but immediately after the first rainfall, following a dry period, the uptake fraction from upper layers peaks considerably, while it decreases at lower layers. This suggests that at start of the dry periods the forest uptake available water from the FF (see Chapter 6) and from the upper part of the soil profile. Subsequently, when the storage of the upper part of the soil profile decreases beyond a certain limit, increases of water uptake from the lower layers occur, as the preferential water uptake.

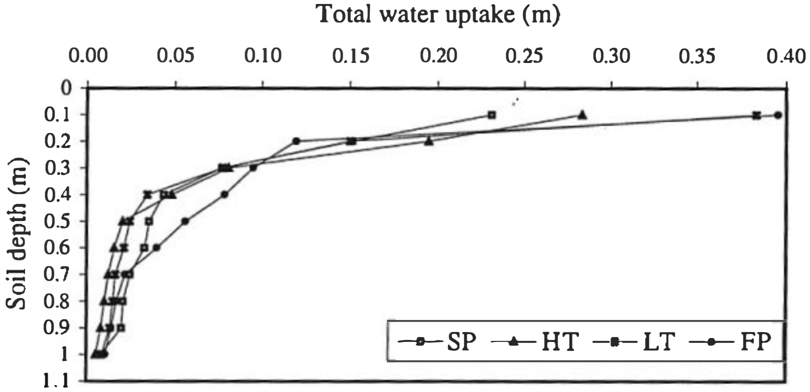


Figure 7.9 Vertical variation of total water uptake by the forest ecosystems (Tertiary sedimentary plain, SP; high terrace, HT; low terrace, LT and flood plain, FP) as predicted by the dynamic model during the period between November 1996 and August 1997.

During the simulation period, the relative contribution of water uptake from the mineral soils to forest transpiration was 64.8% of the reference transpiration in the SP, 70.6% in the HT, 74.2% in the LT and 82.7% in the FP. In all ecosystems, these percentages increased during the droughts and decreased immediately after the first rain storm following a dry period. These results agree with those from the analysis of water storage dynamics, which showed a higher storage in the SP during the droughts and the strongest depletion in the FP. Moreover, in a study of the FF water dynamics and uptake in the same research sites (in Chapter 6) water uptake from the FF in the SP was found to be the highest of the four ecosystems studied, totalling about 28% of the reference transpiration. This also explains why the uptake from the mineral soil is highest in the FP: in this ecosystem the FF is very thin and therefore can hardly contribute to forest transpiration.

Our results thus point to a reduction in forest transpiration during the dry periods, while available water capacity seems to be low, mainly in the SP. However, there are no clear indications for any significant physiological effects caused by water deficits such as leaf shedding, probably due to the short duration of these dry periods. Since climatic conditions during the studied period fell within the long-term range, this implies that in the systems studied large soil water deficits are unlikely to occur.

When comparing our results with those from the rare similar studies in Amazonia, we have to come to the conclusion that results clearly differ but that climatic conditions are also quite different. Nepstad *et al.* (1994) and Chauvel *et al.* (1992), both studied undisturbed forest to the north of Manaus (Brazilian Amazonia) and concluded that during dry periods significant amounts of water were taken up from deep soil layers, in contrast to our observations. The differences can be attributed to the lower mean annual rainfall at the Manaus site (2400 mm) and longer dry period (about 3 months versus about 3 weeks), according to the data presented by Nepstad *et al.* (1994). According to Longman and Jeník (1990), in such much harsher conditions the natural vegetation generally develops adaptive strategies including the extension of roots to great depths. Though we lack detailed information on rooting in deeper soil layers, our observations do not point to such strategy to play a role in the systems studied.

7.6 CONCLUSIONS

Results from monitoring and modelling soil water content dynamics provided relevant information for the ecosystem water balance and to understand the soil water processes and subsurface flow under natural undisturbed conditions in the representative research sites, as comparative and initial conditions data for assessing the nutrient cycling and the Hydrological impact of land use changes.

Field observations and the analysis of the soil water dynamics pointed to the existence of high macroporosity, mainly in the upper part of the soil profiles, in all ecosystems. Soils developed from the SP present lower water availability and higher water content throughout the study period than soils from the alluvial system of the River Caquetá, except for those in the FP, which have the highest water content. There are no considerably differences in water storage between same depths among sites within the same ecosystem, with exception of the SP, which exhibit large differences, between both sites and depths. Differences were explained by the differences in soil texture and position of plots on the slope.

Although model parameters were not calibrated, measured vertical and temporal soil water content dynamics in all ecosystems were accurately predicted by the model. The accuracy suggests that soil water processes were well simulated. Predictions indicate that there are high vertical water fluxes from the upper part of the soil profiles, with the highest in the SP. The contribution of the mineral soil to the total forest transpiration during the study period differed between ecosystems, ranging from 63% to 79% of the reference transpiration. Differences are explained by the differences in the root distribution between ecosystems and the respective contribution of the forest floor to transpiration. Though the model predicted a reduction in total transpiration during dry periods, there was no long shortage of water for the vegetation.

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8. INTEGRATED WATER BALANCE OF FOUR FOREST ECOSYSTEMS IN NORTHWEST AMAZONIA THROUGH A COMPARTMENT APPROACH

8.1 ABSTRACT

Using a compartment approach, water balances were established for four forest ecosystems in the Middle Caquetá, Colombian Amazonia. Results presented are based on field measurements and predictions of calibrated models in previous chapters and pertain to a four years period. Following a top-down approach, water balance calculations were carried out for each forest compartment: forest canopy, forest floor and mineral soil. The upper boundary conditions are the gross rainfall measured in each plot, reference transpiration and predicted drainage at 1 m soil depth. The fraction of evaporation of intercepted gross rainfall was relatively constant over the period of study. The ecosystems differ in their net evaporation with the highest value in the FP. Absolute amounts of evaporation of intercepted rainfall by forests in the research area are higher than those reported for the central Amazonian forests. Transpiration was relatively constant over the years and similar between ecosystems, and only appeared to be limited during 1997. Mean annual ET ranged from 1560 to 1725 mm yr^{-1} and differences among ecosystems are mainly caused by differences in forest evaporation. ET also appeared to be higher than most values reported for other sites within the Amazon basin, except for those reported by Franken and Leopoldo (1984). FF and soil water storage did not change considerably and appeared not to play an important role on determining actual transpiration. The fraction of drainage ranged from 52% to 58% of gross rainfall and were higher than most values in literature, for the Amazon basin. It is concluded that the compartment approach allows to assess the role of individual compartments in the overall water balance, notably in evapotranspiration and drainage, and the causes for the differences in this balance between the ecosystems studied.

8.2 INTRODUCTION

Studies on the hydrology and water balance of forest ecosystems may serve several purposes: to understand the Soil Vegetation Atmosphere Transfer (SVAT) processes and to assess the possible effect of deforestation on the global climate (Shukla *et al.*, 1990; Richey *et al.*, 1989b; Leopoldo *et al.*, 1987; Salati *et al.*, 1984), to provide information required for global hydrological and climate models (Vorosmarty *et al.*, 1989), to evaluate the effects of deforestation on forest hydrology and nutrient fluxes (Jetten, 1996) and to support studies on biogeochemical fluxes (Lesack, 1993). In some of these studies estimates of evapotranspiration, as deduced from input-output water balance measurements, differ from model predictions based on meteorological data (Lesack, 1993). A compartment water balance will add to a deeper understanding and quantification of the various fluxes determining the water balance and the factors involved. It is such compartment approach, which has been used in this study of four representative forest ecosystems in the Middle Caquetá, Colombian Amazonia.

A water balance, by quantifying top-down fluxes and stocks per compartment, explains and quantifies, for instance, the partial contribution of the forest floor and mineral soil to forest transpiration and drainage. Moreover, these contributions can be linked to physical forest floor and soil parameters, and to climatic conditions. This is particularly relevant for northwest Amazonia, since for this area long-term water balance studies do not exist and results of such compartment approach can be used to predict water balances as a function of climate, vegetation and soils. Lastly, this approach will contribute to explain changes in water fluxes and solutes if pathways change, for instance due to the elimination of part of the canopy or forest floor.

In previous chapters, a top-down approach has been used, treating water dynamics and related hydrological processes in each individual compartment. The latter comprised the forest canopy, the forest floor and the mineral soil. They are linked through top-down water fluxes, in which outputs from one compartment are inputs for the next. This chapter, as a concluding chapter, presents a numerical integration of the top-down water fluxes through the forest compartments into annual water balances of the four forest ecosystems. It focuses on the quantification of water balance components per compartment, namely gross rainfall, evaporation of intercepted rainfall, net rainfall, forest floor and soil water uptake and drainage. Differences in the water balance between compartments and among ecosystems are presented and discussed.

Generally, water balance studies are carried out to determine an unknown parameter in the water balance equation, which in most cases is the evapotranspiration term (Blackie, 1993; Lesack, 1993). In this study, the various water balance components were all quantified either by collected field data (e.g. gross rainfall, throughfall) or by a modelling approach (e.g. water uptake, drainage). Our water balance calculations serve other aims, which are to quantify the long term contribution of each compartment to the overall water balance and to highlight the differences between the ecosystems studied and the specific compartment which generates these differences.

8.3 METHODOLOGY

The water balance of the forest ecosystems is approached through the equation:

$$P_g = E + T + \Delta S + Dr \qquad (8.1)$$

Where P_g is the gross rainfall above the forest, E is the amount of water intercepted and evaporated from the forest canopy, T is the forest transpiration, ΔS is the soil moisture change and Dr is the drainage. Basic methods for the calculation of a water balance on a catchment basis require accurate measurements of rainfall and runoff. Surface runoff was not observed and data analysis and model results pointed to a high infiltration rate in the soils studied. Therefore, surface runoff is neglected and drainage is calculated as the water flux below the root zone, as predicted by the model.

For the compartment approach of the water balance, at the canopy level the water balance equation becomes:

$$P_g = E + P_n \tag{8.2}$$

Where P_n comprises the throughfall and stemflow, as net rainfall into the forest floor. Changes in canopy water storage on annual basis, if any, are of infinitely low magnitude. Therefore, they can be neglected. Equation 8.2 is used to determine the evaporation of intercepted water by the forest canopy.

For the forest floor (FF), equation 1 is transformed into equation 3 and used to split incoming net rainfall into FF water uptake and drainage to the mineral soil.

$$P_n = U_{FF} + D_{FF} + \Delta S_{FF} \tag{8.3}$$

Where U_{FF} is the water uptake from the FF used for transpiration, D_{FF} is the total drainage to the mineral soil or FF net rainfall and ΔS_{FF} is the FF water storage changes.

For the mineral soil, the water balance equation becomes:

$$D_{FF} = U_s + Dr + \Delta S_s \tag{8.4}$$

Where U_s is the total water uptake from the mineral soil, ΔS_s represents the annual net change in soil water storage (root zone). The water fluxes below the root zone, which is set at 1 m depth in all ecosystems, and water drained laterally from the first meter of the soil profiles are considered here as total drainage (Dr). The soil water balance is used to calculate the proportional contribution of the mineral soil to the forest transpiration (actual transpiration) in the four ecosystems. Forest transpiration is given by the sum of the FF water uptake (U_{FF}) and soil water uptake (U_s). All fluxes are integrated over one year and expressed as equivalent depths of water in mm.

The water balance is calculated for each compartment in the four forest ecosystems on annual basis for the period between 1994 and 1997 (1997 until August). Calibrated models are used either to predict those components of the water balance, which were not measured (e.g. FF and soil water fluxes) or to fill short gaps in the measurements (e.g. net rainfall to the forest floor). Terms of equation 8.2, namely gross rainfall, throughfall and stemflow were evaluated directly from the daily and weekly field measurements in each ecosystem. For the period between February and October 1996, measurements in the plots lack. Therefore, gaps in net rainfall measurements were filled by interpolation using the dynamic calibrated forest interception model for each ecosystem (see Chapter 4). Daily data on gross rainfall from the Automatic Weather Station (AWS) during this period was used as a standard input for all ecosystems, but as the AWS data had a gap for about a month (July 1996) the water balance during 1996 corresponds to an 11 months water balance. Therefore, results from 1996 and 1997 were transformed to yearly values by direct extrapolation to 365 days.

Terms of equations 8.3 and 8.4 were evaluated through the calibrated FF and soil water fluxes models. Net rainfall and calculated reference transpiration (Monteith, 1965) were used as the upper boundary condition for the FF water balance. FF total drainage and the difference between reference transpiration and FF water uptake were used as the upper boundary conditions for the mineral soil (see Chapter 7). Changes in FF and soil water storage in the first meter of the mineral soil were calculated on annual basis by the difference between soil water storage at day 1 of the year and that at day 365, as predicted by the models. The evapotranspiration (ET) components, namely evaporation of water intercepted by the forest canopy and transpiration, were evaluated separately.

8.4 RESULTS AND DISCUSSION

8.4.1 Evaporation of intercepted water

Results of the quantification of the water balance for each compartment are presented in Table 8.1. Comparison of these water balances shows the differences, both between compartments and among ecosystems, in their water evaporation, uptake and drainage. When considering results of each individual ecosystem, the first observation is that the percentage of evaporation relative to gross rainfall was relatively constant over years, although net values of evaporation differ. An exception is the year 1997 when this percentage increased in all ecosystems. As to the forest canopy compartment, Table 8.2 shows that although the storage depth of this canopy is low, in terms of intercepting incoming rainfall on, the net annual interception is considerably high and differs between ecosystems. Annual average evaporation of intercepted water was 366 mm in the SP, 361 mm in the HT, 405 mm in the LT and 508 mm in the FP, in agreement with the tendencies discussed in Chapter 3.

Table 8.1 Summary of the water balance data for four forest ecosystems in the Middle Caquetá, Colombian Amazonia. All units are expressed as a depth of water in mm yr^{-1}. ET is calculated as the sum of evaporation and actual transpiration. Values between brackets correspond to extrapolations of results to annual values.

Ecosystem	Year	Gross rainfall	Throughfall	Evaporation	Reference transpiration	ΔS_{FF}	FF water uptake	FF drainage	ΔS	Soil water uptake	Transpiration	Total drainage at 1 m	Evapotranspiration
SP	1994	3645	3303	343	1124	-8	399	2911	-23	725	1124	2209	1466
	1995	3157	2888	269	1234	-5	403	2489	-9	758	1161	1740	1431
	1996	3308	3008	300 (327)	1211 (1321)	-10	392	2626	-12	785	1177 (1284)	1854	1477 (1611)
	1997	2300	1981	319 (524)	776 (1276)	-2	236	1746	-5	496	732 (1203)	1255	1052 (1727)
HT	1994	3551	3265	286	1124	-4	302	2967	-17	810	1113	2172	1398
	1995	3307	3084	223	1236	-4	300	2787	-8	888	1188	1907	1411
	1996	3466	3081	385 (420)	1211 (1321)	-4	307	2778	-15	897	1204 (1313)	1896	1589 (1733)
	1997	2341	2029	312 (513)	776 (1276)	-4	175	1858	-4	541	716 (1177)	1319	1029 (1690)
LT	1994	3540	3213	327	1124	-2	302	2913	-26	822	1124	2116	1451
	1995	3235	2929	306	1234	-2	294	2635	-42	932	1226	1745	1532
	1996	3404	3022	382 (417)	1211 (1321)	-3	282	2742	-13	903	1185 (1293)	1850	1568 (1710)
	1997	2393	2046	347 (570)	776 (1276)	-1	168	1879	-5	569	737 (1212)	1314	1084 (1782)
FP	1994	3498	2992	506	1124	-1	168	2825	-22	956	1124	1892	1629
	1995	3235	2857	378	1234	0	168	2688	-18	1052	1220	1653	1599
	1996	3418	2965	453 (494)	1211 (1321)	-2	162	2804	-14	1030	1192 (1300)	1789	1645 (1794)
	1997	2289	1892	397 (652)	776 (1276)	0	95	1798	-3	650	745 (1225)	1151	1141 (1876)

As to forest interception, the relative proportion of gross rainfall interception appeared to be similar to those by forests in central Amazonia (Chapter 3). Nevertheless, when comparing absolute amounts, the evaporation of intercepted water in the studied area is higher than most of those values reported or deduced from other studies (Ubarana, 1996; Lesack, 1993; Lloyd and Marques, 1988; Franken and Leopoldo, 1984), which can be attributed to the higher total rainfall in the studied area.

Table 8.2 Summary of data on water balance components from some of the previous research within the Amazon basin. * Results summarised by Leopoldo *et al.*, 1987.

Rainfall	**Transpiration**	**Evapotranspiration**	**Changes in soil water storage**	**Drainage**	**Reference**
3664*	1722	1905		1759	Jordan *et al.*, 1981
2089*	1014	1542		541	Leopoldo and Franken, 1982
2075*	1287	1675		400	Leopoldo and Franken, 1982
2510*	1172	1642		869	Franken and Leopoldo, 1984
2870		1120	57	1692	Lesack, 1993

8.4.2 Transpiration

Transpiration was quite constant through the water balance period in all ecosystems. This is not surprising since rainfall is well distribute and FF and soil water storage showed to be a sufficient reservoir to meet forest transpiration demands during most of the studied period. Although meteorological factors dominate the rate of forest transpiration in ecosystems, which are exposed to the same weather conditions, actual transpiration slightly differs between ecosystems. This actual transpiration appeared to be larger in the FP than in the other ecosystems, while in the SP it was lowest. We should bear in mind that an uniform reference transpiration was used as input for all ecosystems. Moreover, in the FP a lower canopy resistance can be expected than in the other ecosystems, due to the higher nutrient availability, which influences forest dynamics and therefore transpiration.

During the four years, prolonged deficits in FF and soil moisture did not occur in any of the ecosystems studied, which can be expected since in most months rainfall exceeded reference transpiration values. Small differences between reference and actual transpiration, and connected small deficits, were only observed during dry periods. They were most prominent during 1997, due to the occurrence of two dry periods instead of the normal one. The actual deficit and connected moisture conditions in the FF and mineral soil vary in relation to differences in physical properties of the FF and mineral soil and in root distribution between the ecosystems.

Mean annual transpiration values were 1193 mm in the SP, 1198 mm in the HT, 1214 mm in the LT and 1217 mm in the FP. The largest differences between actual and reference transpiration were observed in the SP, which can be explained as follows: 1) transpiration by the SP forest largely depend on the FF water availability (up to almost 30% of reference transpiration) where water storage capacity is low (see Chapters 2 and 6) in this ecosystem soil water availability is relatively low (see Chapter 7). Whilst forest demand for water were almost constant over the years, gross rainfall varies from year to year. However, gross rainfall being three times larger than actual transpiration, the surplus of rainfall over transpiration (gross rainfall-transpiration) was hardly sensitive to variation in the actual transpiration. During the short dry season in 1997 transpiration was somewhat suppressed, i.e. by a factor of 0.43. In other periods the depletion rate of stored soil water was significative lower than total rainfall surplus and enabled the actual transpiration to be at the potential rate. Consequently, in the ecosystems studied, FF and soil water storage play a minor role in the supply of water to the forest. Only when droughts occur, storage becomes an important reservoir. This can be seen in the low net changes in FF and soil water storage on annual basis and even on a daily basis.

8.4.3 Evapotranspiration

Annual evapotranspiration was calculated as the sum of annual values for evaporation and transpiration in each ecosystem (Table 8.1). As has been discussed in previous Chapters, the largest evapotranspiration value was found in the FP, resulting from both the highest evaporation of intercepted water and the highest transpiration. Over the total period, daily mean ET ranged from 4.2 to 4.7 mm d^{-1}. Calculated mean annual ET in the Middle Caquetá ranged from 1560 to 1725 mm yr^{-1}.

When compared with results from other studies within Amazonia, ET values from Colombian Amazonia are higher than those found for some areas in Central Amazonia (Lesack, 1993; Shuttleworth, 1988) and than the mean value reported by Bruijnzeel (1990) in one of the most comprehensive studies on the available information for ET in tropical lowland forests (see Table 2). Although the mean annual ET values for the ecosystems studied are of similar magnitude as those found by Franken and Leopoldo (1984), the values for ET components differ considerably. The proportion of drainage relative to gross rainfall in this study are higher than their values, but differences are compensated by the higher evaporation of intercepted water by the forests in the Middle Caquetá, when compared with plots of Barro Branco and Bacia Modelo in Central Amazonia. The causes for the differences in values are not fully clear, since methods and parameter values used in the various studies are not identical. However, differences in net interception by the forest canopy resulting from differences in forest canopy and rainfall distribution seem to play a role.

Results from this study concerning trends of ET in the Middle Caquetá contradict the conclusion by Lesack (1993), who concluded that actual ET may decline significantly during wetter than normal years. Our results show that transpiration can indeed be lower, but this is fully compensated by evaporation of intercepted water. Interception depends on rainfall distribution and forest characteristics. Therefore, certainly influences total annual ET, as indicated in Chapter 3. Results from the different forest ecosystems confirm a further statement by Lesack (1993), that ET rates are spatially heterogeneous driven by the differences in forest structure. Our results also confirm the conclusion of Bruijnzeel (1990), that values of ET can be substantially higher during wettest years or in areas with high rainfall amounts. The latter is the case in the Middle Caquetá area, when compared, for instance, with Central Amazonia.

8.4.4 Drainage

Comparison of the temporal dynamics of drainage with incoming net rainfall indicates that the fraction of drainage differs between years, with the highest value during 1994 in all ecosystems. Drainage, expressed as the percentage of gross rainfall, ranged from 52% to 58% with the lowest value for the FP, which is in agreement with the highest interception and transpiration in this ecosystem. These percentages are higher than most values reported in earlier studies from the Amazonia forests (Elsenbeer and Cassel, 1991; Poels, 1987; Franken and Leopoldo, 1984; Nortcliff *et al.*, 1979), and similar to that by Lesack (1993). However, we have to consider that gross rainfall is considerably higher in the Middle Caquetá.

It is clear from Table 1 that the water balance surplus is almost zero, which is explained by the nature of the models applied, which balance inputs and outputs, and by the changes of FF and soil water storage. Additionally, soil water storage did not change considerably over the years, while in FF relatively large changes occurred. Larger changes could be expected to occur in the two compartments at the end of the dry period, as indicated in Chapter 7.

8.5 CONCLUSIONS

Through the compartment approach, the relative importance of each compartment for the water balance and their role in the partitioning of water could be assessed. Additionally, it allowed for the identification and quantification of hydrological differences between ecosystems in both space and time.

The combination of field data and calibrated models allowed for the quantification of the components of the water balance in the various forest compartments of the ecosystems studied. The methodologies employed also allowed the quantification of individual ET components, namely evaporation of intercepted water and transpiration. Water balance estimates for the different compartments highlighted the magnitude involved in each compartment and their role on water partitioning. It also indicated the hydrological differences between ecosystems and the point at which these differences occur.

No marked changes in actual transpiration occurred so far during the 4 years period. Differences in water use by the forests are small, which is consistent over that period. This was explained by the rainfall distribution and by the soil water storage dynamics, resulting in an excess of available water over forest demands for most of the year. Actual transpiration is of similar magnitude in the ecosystems studied and main differences are restricted to the source of the transpired water. In average 34% of the SP forest transpiration was supplied by the FF, whereas in the FP, as contrasting ecosystem, the FF contributed with only 14% to forest transpiration. Although water drains rapidly from the upper soil horizons and the capacity of the soils to store available water is relatively small, water seems not to be a limiting factor for growth. Rainfall distribution is the key factor to maintain forest transpiration at the potential rate and the FF and soil water storage capacity of undisturbed forests is high enough to meet forest ET demands during most of the dry periods.

Values of ET for the forest ecosystems studied vary and differences mainly result from differences in evaporation of intercepted water by the forest canopies and to less extent to differences in soil water conditions. Evaporation of intercepted water contributed on average with 23% to 29% to total ET. Although ET values appeared in the area studied than some values cited in literature, mainly those from Central Amazonia, these larger values could be explained by differences in net interception by the forest, between the various forests.

Drainage represented 52% to 58% of gross rainfall in ecosystems studied. These values were found to increase with decreasing canopy cover. However, an independent check, e.g. based on catchment discharge measurements, lacks.

9. GENERAL CONCLUSIONS

As stated in the introduction, in this hydrological study a compartment approach was used. Thus, in *Chapters* 2-7 water dynamics and hydrological processes in each forest compartment are separately dealt with and conclusions are drawn regarding the specific properties of and processes in these compartments. In *Chapter* 8, the results were integrated into a long-term quantification of the water balance for the four forest ecosystems and attention was paid to the role of each compartment and connected fluxes in the overall water balance. This final chapter is meant to highlight the main results from the hydrological research and to discuss these in the context of the more general aims of the Tropenbos Colombia programme, paying attention to their implications for nutrient cycling and forest management.

Long term data on meteorological, hydrological, FF and soil water dynamics and models were used to characterise the hydrology of the four forest ecosystems in the Middle Caquetá, Colombian Amazonia, and to quantify water fluxes and stocks. Results are to be considered as base line data on the hydrology of undisturbed humid tropical forests, which can be used for comparisons, both at the ecosystem level and at the compartment level (Figure 9.1). They show that differences between ecosystems in the magnitude of water fluxes connected with individual forest compartments are mainly due to differences in forest structure, forest floor thickness, soil properties and fine root distribution. Within the range of ecosystems studied, the largest differences in hydrological behaviour and water fluxes at compartment level were observed between the forest ecosystems on the Tertiary sedimentary plain (SP) and the rarely inundated floodplain (FP).

At canopy level, this study clearly demonstrated that rainfall interception is a.o. a function of structural forest characteristics e.g. canopy cover and LAI. The range of variation of these characteristics in studied forests contributed considerably to the explanation of differences (e.g. in evapotranspiration) between these systems, as well as between the systems in the Middle Caquetá area and those in other parts of the Amazon basin. The forest floor (FF) appeared to play a significant role in the water uptake by the forests and drainage to the mineral soil. This partitioning was strongly determined by the thickness of the FF and, to a lesser extent, by the fine roots in this compartment. Therefore, the FF in the SP has the largest water storage capacity, merely because of its thickness. The calibrated FF interception model allows for the partitioning of FF net rainfall into uptake and drainage. Model results showed that roots take up the largest amount of water from the FF in the SP, as compared with FF's in the other ecosystems. The FF in the FP is the thinnest among forests studied and contributes little to the supply of water to the forest. The mineral soil had a high water content during most of the studied period in all ecosystems, but water availability appeared to be low, mainly in the SP. Soil water storage slightly decreased during the droughts, the largest decreases being observed in the FP ecosystem. For the upper part of the mineral soil, the soil water flux model predicted high flux rates upon inputs, which is in line with its observed high macro and mesoporosity and well developed structure. As soil water content appeared not to be a limiting parameter for root water uptake during most of the studied period, water uptake by roots from the different soil layers mostly depended on fine root distribution. Although rainfall distribution in the study area showed to be the key factor in maintaining actual transpiration at almost potential rate, during the droughts the FF and upper part of the mineral soil acted as buffer compartments for water supply to the forests.

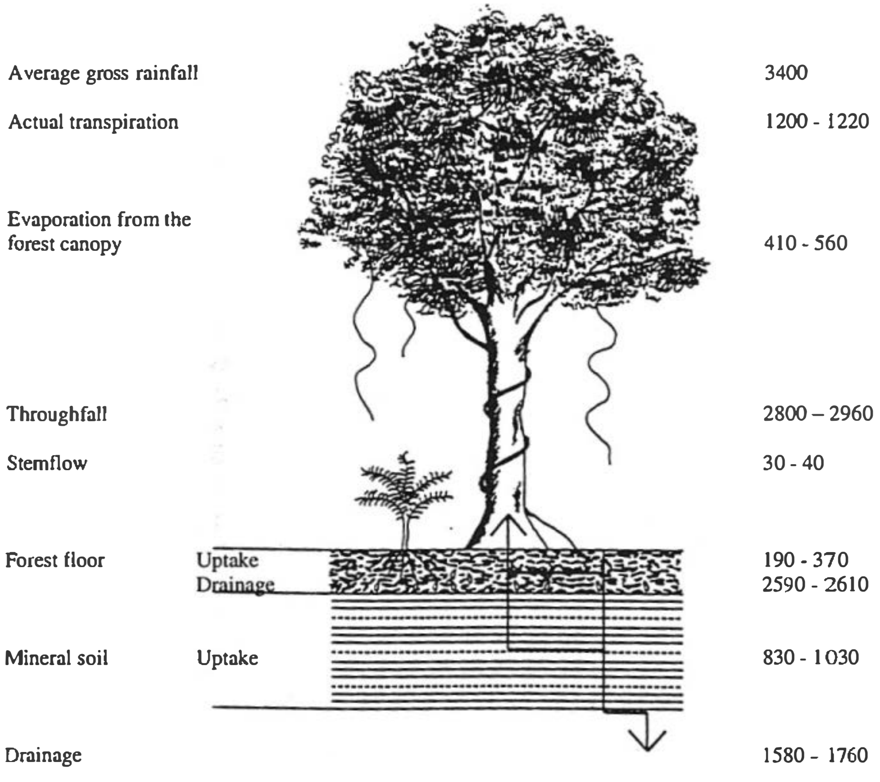

Figure 9.1 Ranges of monitored and modelled hydrological fluxes (mm) through the forest compartments in ecosystems studied in the Middle Caquetá, Colombian Amazonia.

Recent research demonstrated the important role played by deep roots in water supply to the forest in central Amazonia (Hodnett *et al.*, 1996; Nepstad *et al.*, 1994) and thus raises the question whether such a phenomenon is more widespread. We have to conclude that this is not the case in the study area: A truly dry period does not exist and a short dry one (January to February) does not last long enough to significantly affect forest transpiration. Moreover, fine roots appeared to be concentrated in the FF and on top of the mineral soil (first meter) in ecosystems studied. As to the substrate, water supply to the forests is largely determined by the moisture conditions in the FF and mineral topsoil. In more detail, water dynamics in the FF are very high and this layer dries out at a much faster rate than the mineral soil, while the water content of the mineral soil is much less variable and its dynamics strongly decrease with depth. Saturated conditions (high water table), which can impede deep root growth, were not observed in any of the ecosystems studied. Therefore, neither lack of moisture stress nor lack of oxygen can explain the concentration of fine roots in the FF and top of the mineral. It is therefore concluded that root distribution most probably is determined by soil chemistry, notably gradients in nutrient availability rather than by moisture.

9.1 IMPLICATIONS FOR NUTRIENT CYCLING

Various studied showed that atmospheric deposition in Amazonian ecosystems is low (Brouwer, 1996; Lesack and Melack, 1991; Poels, 1987), but solute concentrations in rainfall after passing the forest canopy increase. Actual concentrations in throughfall seem to depend largely on nutrient concentrations in the tree tissues (Brouwer, 1996; Luisão, 1989; Medina and Cuevas, 1989; Proctor *et al.*, 1983). This enrichment may result from washout of dry deposition and some in-situ nutrient releases by vegetation (crown leaching and exudates). It is evident therefore that any change in forest canopy cover will cause changes in inputs to the FF although atmospheric inputs remain constant. Nutrient fluxes in the soil are of a more complex nature. They are influenced by the rate of dissolution and production of soluble chemical compounds, by the rate of removal by uptake and by soil moisture fluxes. Nevertheless, impacts on forest ecosystems affecting these fluxes will have a considerable impact on nutrient cycling in the soil compartment, as for example through increased leaching, and in systems with low nutrient availability may lead to declining chemical soil fertility. The characterisation of these hydrological patterns, flow paths and velocities in this study is therefore of great importance in managing ecosystems with low nutrient availability.

The FP ecosystem has the thinnest litter layer (FF) with the least fine roots. This resulted in the lowest water uptake from this compartment, which implies that forests in this ecosystem hardly depend on the FF water availability and probably also on FF nutrient availability. In this case, the upper part of the mineral soil is in fact the main reservoir for water and nutrients. Contrary, the SP has the highest percentage of fine roots in the FF, which is probably related to the strong competition for nutrients. Water uptake from the FF compartment is largest in this ecosystem, leading to the conclusion that among the ecosystems studied, this system depends most strongly on FF water and nutrient status dynamics. Land-use changes generally imply a breakdown of the FF and concurrently of the roots in this compartment. Using the results from *Chapter* 6, impacts can be quantified as up to 35% of the fine roots eliminated and up to about 30% of the total water uptake, but impacts evidently vary considerably between the systems studied. Further impacts include elimination of FF related nutrient fluxes and changes in physical conditions for microbial decomposers and other soil organisms, connected with the disappearance of the FF and altered water dynamics in the underlying mineral soil. The latter will also affect forest regeneration through altered conditions for germinating seeds and young shoots.

The combination of rainfall distribution and soil hydraulic properties in the area results in an almost constant high matric potential in the soils and allows water fluxes to occur almost instantaneously with the onset of storms. The water balance study indicates that moisture surplus in the ecosystems studied is on average 58% of gross rainfall. The combination of these specific soil characteristics and the high rainfall intensity during specific events may negatively affect the nutrient availability for plants, since it may result in a proportional high loss of nutrients during such events. Such losses are likely to increase upon land-use changes since these changes generally lead to an increase in plant-available nutrients and such nutrients are apt to be leached. Soil leaching will be accelerated in particular during the first stage of a land-use change, when FF and root system disappear and nutrients released can easily be leached, especially when accompanied by burning. The fact that in the soils studied clay minerals hardly contribute to the cation exchange capacity and this capacity largely depends on the organic matter, implies that the magnitude of losses and thus impacts will depend on the relative importance of the FF in terms of the water balance and stocks of organic matter and nutrients. In other words, the largest impacts on chemical soil fertility can be expected for systems such as those of the sedimentary plain, whereas that of the floodplain systems will be least affected.

The fact that within shifting cultivation, land preparation i.e. cutting and burning the natural forest is mainly practised during the short dry period, this besides being practical since wet debris does not burn, diminishes nutrient leaching. This might also explain why some authors report that no considerable changes occur on soil properties with traditional land-use systems (Tomasella and Hodnett, 1996; Proradam, 1979). Large losses of nutrients could be expected if this preparation would be during the wet seasons.

9.2 IMPLICATIONS FOR FOREST MANAGEMENT

Although the results from this study pertain to undisturbed forests, they can be used to predict some impacts of forest management and large scale environmental changes. These include deforestation or large scale changes in forest composition and structure, and climate change.

The way deforestation will affect the hydrology of a system at a local scale is still unclear and will be very much site dependent. For instance, trends in changes of transpiration due to land-uses changes are diverse and difficult to be hypothesised without comparable data, or without making assumptions. Results from this study indicate that at least in the short run elimination of the forest cover will cause increases in streamflow. For the research sites, although some bare soil evaporation can be expected, streamflow is expected to be about 1600 mm yr^{-1} larger than at the present, merely because of the reduction in interception and transpiration. Situations, however, can be much more complex as for example with the effect of large scale land-use changes on the eastern slopes of the Andes. The seasonal distribution of rainfall in that area is reflected in the fluctuations of the water level of the River Caquetá (changes of about 10m). These seasonal changes lead to a continuous enrichment of flooded areas used by local communities for crop plantations and other sources of proteins. Any change in the river discharge in the upper part of the basin of the River Caquetá, whether induced by changes in climate resulting from changes in land use in the Amazon basin or by changes in hydrology of the Andean slopes, will directly affect this floodplain and its hydrological functioning.

Models can be used, for instance, for scenarios predictions of changes in forest hydrology induced by climate changes. As an example, trends on transpiration during a prolonged dry period were simulated by cutting off rainfall, after allowing a full storage of the FF's and mineral soils and leaving other conditions unchanged. As general input for ecosystems studied, we use climate data from the AWS during 1997 and gross rainfall was set to zero after day 80. Other conditions, as well as forest parameters remained as measured or calculated for each forest. This hypothetical example is only an attempt to identify general tendencies as derived from the models, which were constructed or calibrated as part of this study. The accuracy of these predictions can only be assessed and improved by comparing model results with new field data.

Figure 9.2 presents the trends in reduction of the actual transpiration in the forest ecosystems for both the FF and the mineral soil. Results indicate that the ratio of actual–reference transpiration decreases progressively as FF and soil water storage (first metre of the soil profile) becomes completely depleted. As expected, there were differences between ecosystems in the shape of the trends and in the decreasing lines of the ratios. After the 52nd day without rainfall, the FF in the SP becomes completely dry whereas those in the other ecosystems were already dry by day 30. In the mineral soil, however, though actual transpiration continues during the simulated period (ratio > 0), it decreases already considerably after day 5. As compared to the other ecosystems, the ratio decreases more sharply in the SP, reaching the lowest of all values at the end of the simulated period. Based on these results it can be concluded that although a reduction in rainfall would affect all ecosystems, the SP-system will be the first to be affected, due to its strong dependence on FF moisture and low soil water availability.

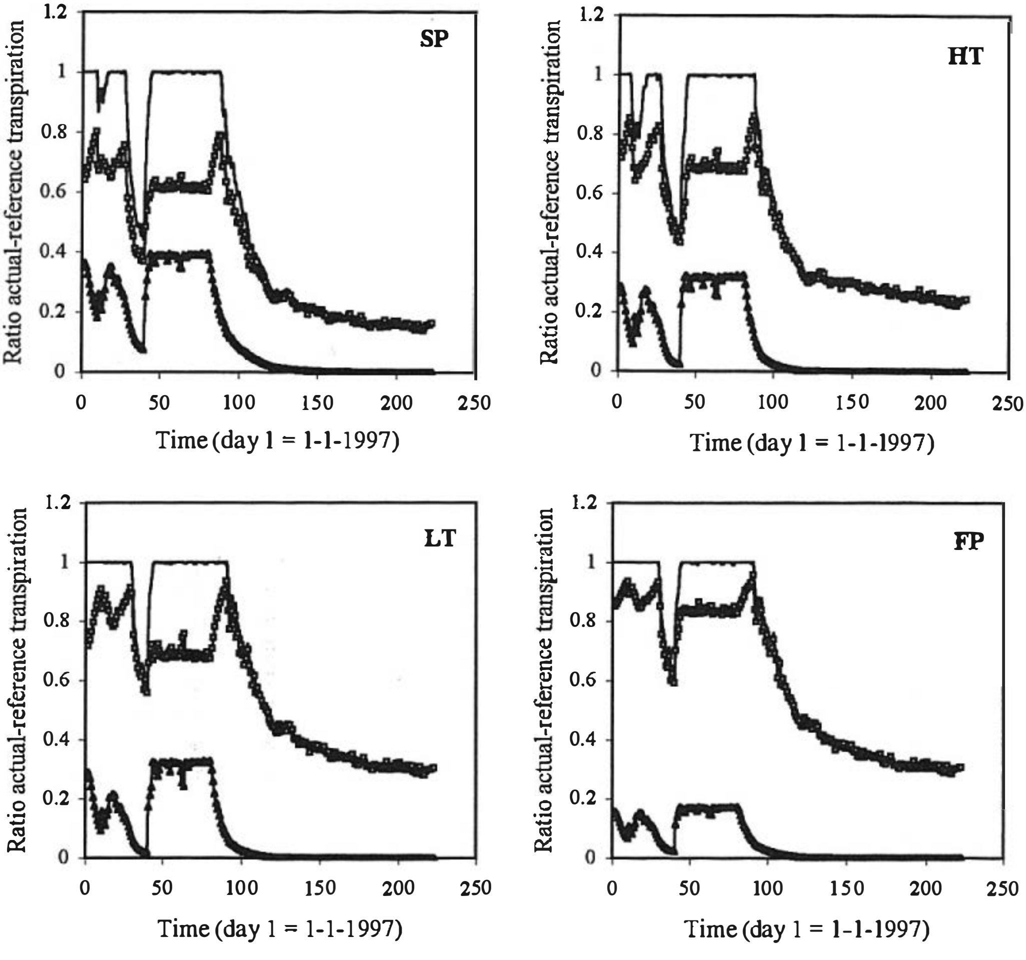

Figure 9.2 Ratio of simulated water uptake from both the forest floor (—▲—) and the mineral soil (—□—) and the reference transpiration (Monteith, 1965) during a hypothetical dry period in the four forest ecosystems studied in the Middle Caquetá, Colombian Amazonia. The ratio of the total water uptake (actual transpiration) and reference transpiration is also indicated (—).

In this hypothetical situation, drought is purely defined in terms of a rainfall deficit, which evidently is a simplification. In reality, responses will be more complex, since

such climate change in the long term will lead to changes in relevant forest characteristics (e.g. trees with other root strategies) and soil conditions.
Another application of the results pertains to the significance of Northwest Amazonian rain forests for the Amazon basin in terms of their relative contribution to evapotranspiration in this basin and the subsequent generation of rainfall by the Andes. The forest ecosystems of the floodplain appeared to intercept the highest amounts of rainfall of the systems studied. However, at the scale of Amazonia this relatively high interception is hardly relevant since floodplains are limited to rather narrow strips along the main rivers. More important is the difference between forests in areas with higher average annual rainfall and short dry periods, such as in Northwest Amazonia, and those in lesser humid areas with clear dry periods, such as in Central Amazonia. Quantification of the difference in evaporation of intercepted water based on our results, indicates that in areas with an annual rainfall similar to the Middle Caquetá (3400 mm yr^{-1}) this evaporation is 1.36 times higher per unit area than in areas with a rainfall of about 2500 mm yr^{-1}. This is exclusive of transpiration, which may well be reduced during dry periods, thus further contributing to the reduction of the large-scale exchange of water with the atmosphere.

Man-induced climate change is one of the main issues for scientists in the current decade, and probably will continue to be so during the first decades of the next century. CO_2 concentrations, sequestration and emissions are the specific topics to deal with. Global Climate Models (GCMs) become a powerful tool to investigate these changes, as they allow for quantification and statistical manipulation of the past, present and future climate patterns and the impact of a range of human activities at relatively low costs and providing general insight into the processes occurring and responsible for the changes in climate. On the other hand, it is clear that the accuracy and reliability of detailed global models will further increase, when information on specific areas becomes available. An example is formed by the large projects in central Amazonia (e.g. ABRACOS) which contributed important information for the application of coupled vegetation-atmosphere models and provided relevant data for the calibration and validation of GCMs, as concluded by Nobre *et al.* (1996). In these projects, differences in ecosystems and sites, as described in this thesis, were not considered

Finally, it has to be stated that this comprehensive discussion of the implications of results from this research for forest management and policies is far from complete. The full implications will only become clear when integrating these results with those from other projects within the framework of the Tropenbos Colombia programme, but this is beyond the aims of this thesis. Nevertheless, results from this study can be used as baseline information, among others, by local policy makers and planners to define criteria for the orientation or definition of Amazonian oriented policies. These results together with those from other studies may also support institutions and Colombian government in the agreements with involved countries in the Amazon basin for a joint management of ecosystems and Colombian role in global issues (e.g. Global Climate Change).

SUMMARY

Sustainable land use is increasingly seen as one of the solutions in the struggle against negative impacts of man on tropical rain forest and its resources. In the Amazon basin, the main focus of research is on the effect of deforestation on global climate and biodiversity, while lesser attention has been paid to the functioning of natural and disturbed ecosystems. Nevertheless, information on this functioning is of vital importance for management aiming at sustainable land use. Such information concerns topics like biotic interactions and the cycling of water and nutrients between both various ecosystems and ecosystem compartments, as well as effects of land use on this functioning. The present study represents the first long-term and probably unique hydrological study for Colombian Amazonia and forms part of a larger project on the hydrology and nutrient cycling in representative forest ecosystems in the Middle Caquetá area, which forms part of the Tropenbos Colombia research programme. This project generated information on the hydrologic functioning of natural forest ecosystems, which can be used for nutrient cycling studies, serve as reference for impact studies and in support of the development of sustainable types of land use.

One of the main outcomes of previous research in the Middle Caquetá area was that considerable differences exist between forest types, species diversity and soil types in the various physiographic units. The main units, in increasing order of nutrient stocks, were the Tertiary sedimentary plain, and the high terrace, low terrace and floodplain of the River Caquetá. The main objective of this study was the assessment of the water balance of representative forest ecosystems in these four main units, by describing and quantifying the temporal and spatial dynamics of the hydrological fluxes through the forest compartments. In order to meet the research main objective, a top-down water fluxes study was followed in which a monitoring programme on relevant parameters and processes was carried out for about five years (1992-1997) on climate and water content, storage and drainage in the different forest compartments.

Because of the difficulties in measuring of some water fluxes (e.g. soil water fluxes) and of the complex functioning of forest ecosystems, in this study models were either constructed or used to simplify these systems, to allow for a better understanding of ecosystem functioning when measurements did not provide information on the individual contribution of simultaneous processes (e.g. interception-transpiration, water uptake-drainage). Moreover, dynamic models in this study provided a physical description of the processes related to each forest compartment and contributed to the quantification of the water balance components. They were also used to fill gaps in measurements (e.g. throughfall).

The first step in the research was to characterise the climatic conditions, as data were not available. Data on gross rainfall, temperature, relative humidity, solar radiation,

wind speed and direction were collected each 20 minutes with an Automatic weather Station (AWS) installed in the open. With the use of the data and applying Monteith's model (Monteith, 1965), the reference transpiration was calculated for the period studied. Monthly values of climatic parameters, including those of calculated reference transpiration and measured Class A-pan evaporation are presented in Chapter 2. This Chapter also includes an overview of the research site, including vegetation, soils and main land uses in the area. Results for gross rainfall (amounts, duration and intensity) were in line with data on previous years from the Araracuara station. Reference transpiration to be used as input for the FF and mineral soil, was calculated based on these climatic data.

After the characterisation of the above forest canopy conditions (climate), the second step was the study of the partitioning of gross rainfall into throughfall and stemflow in the forests studied and the main factors influencing the dynamics of this partitioning. Chapter 3 is an analysis of this partitioning and examines the existence of relationships with climate and forest characteristics. Throughfall appeared to be dependent on both gross rainfall and forest structure. The percentage of throughfall ranges from 82 to 87% of gross rainfall and varies with rainfall size in all ecosystems. Stemflow contributes very little to net rainfall. Evaporation during rainfall has a linear relation with rainfall duration and the ratio between evaporation and gross rainfall increases with forest cover in the ecosystems studied. It is concluded that rainfall partitioning strongly depends on rainfall characteristics but also on forest structure, defined as forest cover or LAI.

In Chapter 4, a further step in the study of net rainfall dynamics is made, being the use of a physically based interception model in order to describe and quantify the temporal dynamics of net rainfall. The model appeared to be sensitive to the storage capacity. Therefore, storage capacity parameter was calibrated for each forest. Values for the other parameters in the model were either used as deduced from the measurements or set to unity, as the model did not show to be sensitive to changes in those parameters. The model was capable of reproducing accurately measured values by using as input the values of parameters deduced from the measurements. This accuracy increased after the calibration of the storage capacity parameter. Values of forest storage, deduced from the calibrated parameters, increased from the SP towards the FP, which agrees with the measured trend. The validation of the calibrated model showed that this is capable of predicting sets of daily and weekly measurements of net rainfall outside the calibration period with similar accuracy as for the calibration period. Model predictions showed that the dynamics of predicted net rainfall by the physical based model are physically more realistic and differ from those predicted by the static model presented in Chapter 3.

Measurements of the water content in the forest floor (FF) and in the mineral soil were carried out using Time Domain Reflectometry (TDR) equipment. Different calibration studies suggest that when using TDR to investigate the water content of FF or soil materials, TDR measurements should be calibrated. In Chapter 5, we present the results of the calibration of TDR measurements, which was carried out using volumetric water content determinations from FF and soil samples. Volumetric water content of the samples was fitted with linear functions against the refraction index calculated from the TDR travel time measurements. These linear regressions produce a R^2 of 0.94 for the FF and 0.88 for the mineral soil. Using existing calibration parameters from other studies, water content is either underestimated or overestimated. Deduced regression parameters from the linear functions of measured water content and the refraction index in the FF and mineral soil were used to translate TDR travel time measurements into volumetric water content.

In the forest ecosystems studied, commonly a thick litter layer (or forest floor) with abundant fine roots is present. The thickness of this FF differs between ecosystems, being thickest in the sedimentary plain. An important outcome from this study is the characterisation of the hydrological role played by this FF in the context of undisturbed forests in Colombian Amazonia, in which related processes were also characterised. In Chapter 6 the FF water dynamics are studied. FF characteristics and storage capacity were investigated and FF water content dynamics were monitored during two years in the ecosystems studied. To simulate the dynamics of the FF water fluxes, storage, root water uptake and drainage to the mineral soil, a dynamic model was developed and calibrated. Results showed that the presence of a thick litter layer (or FF), and the concentration of fine roots determine the net rainfall partitioning into uptake and total drainage to the mineral soil. Results pointed to differences between ecosystems in the FF water storage capacity, water content and water uptake dynamics and amounts. The FF in the SP is capable of storing the highest amount of water, due to its highest thickness and this FF supplied the forest with about 30% of total water uptake during the period studied. Conditions contrast more with those in the FP ecosystem, with the thinnest FF and with the lowest contribution to the forest transpiration. Drainage also varied between ecosystems, ranging from 87% to 93% of net rainfall.

The interpretation of Rutter's interception model to the FF offered a quantitative description of the water fluxes associated with the litter layer, where a high proportion of fine roots acts as a sink. A major advantage of this simple model is that its conceptual basis is supported by observations (FF water storage), even with information on parameters not used for its calibration (FF drainage). A new technique was also developed to investigate FF drainage or litterflow (flux plates). These measurements supported model predictions in which the accuracy of predictions was very high. The model is meant to distinguish between preferential flow and proper drainage, while measurements can not. However, the model also offers several new applications:

- It can be applied in forests with FF's without active roots; in such a case direct evaporation may play a more relevant role.
- It allows the identification of the FF flow characteristics and the quantitative separation of processes occurring simultaneously.

- The model can therefore provide valuable information with the dynamics occurring at the FF compartment related to nutrient release and uptake.

Despite its simplicity, the model was capable of accurately reproducing field data. The number of parameters in the model is certainly its main disadvantage, although some of them are physical based parameters, which can be investigated in the field (e.g. FF water storage, evaporation efficiency, interception efficiency).

Chapter 7 explores the role played by the mineral soil in the water fluxes in the entire ecosystem, and the dynamics of these fluxes. Water content and water tension were monitored at various sites and soil depths in the four forest ecosystems. Vertical water fluxes through the porous media and root water uptake were simulated with a dynamic model, by using measured conditions as inputs. Main findings relate to the low water availability in the soils studied (mainly in the SP), as indicated by the water retention characteristics and field measurements. However, soil water storage is high and almost constant over the period of study, with the exception of droughts. The rainfall distribution and the high water storage of the mineral soil appeared to be the most important parameters in maintaining water uptake or actual transpiration very similar to reference transpiration for most time of the year in studied ecosystems, except for the short dry periods when actual transpiration decreased to almost one third of the reference. This water uptake also differs between ecosystems studied being the lowest in the SP and the highest from the FP. The FF's together with the upper soil layers, where fine roots are concentrated, are responsible for the supply of most of the water demanded by the forests. Water content dynamics in the upper soil layers showed to have more variability than deeper layers, which was connected to the soil properties and uptake by roots. Moreover, the distribution of rainfall in this part of Amazonia showed to be an important factor in the maintenance of actual transpiration at almost potential rate. However, the water availability in the FF and upper part of the mineral soil act as the buffer compartments during those periods where rainfall is low.

Focussed on the project's main objective, overall measurements and models from this study were used for the quantification of a long-term water balance for the different forest compartments in the forests studied. Results of these water balances are summarised in Chapter 8. The annual water balances during the four years period showed that the fraction of evaporation of intercepted gross rainfall was about constant over this period and that there are differences between ecosystems in their net evaporation, being the highest in the FP. Found values are also higher than most values reported for central Amazonian forests. Differences in evaporation values led to differences in evapotranspiration between the ecosystems studied, the values of the latter differing from those reported in the literature. Overall results explain trends in ET when climate conditions (mainly rainfall amounts) and forest structure change. It is the compartment approach which enables to identify the ecosystem compartments and processes involved in such changes in the overall water balance.

At the onset of this research, information on the hydrological functioning of Colombian Amazonia was about nil and certainly differed from other sites within the Amazon basin such as the central Amazonia in Brazil where large research projects have been carried out (e.g. ABRACOS, LBA) and Northeast Amazonia (Jetten, 1996; Brouwer, 1996; Poels, 1987). This was clearly stated during a congress on forest ecosystems, entitled "Consolidation of the national research net" by the Colombian governmental institute Alexander van Humboldt (Colombia, 1996) in which one of the main conclusions was that there is a lack of basic information and knowledge on ecosystem processes. Chapter 9 highlights the most general conclusions and the implications of overall results for nutrient cycling and forest management. It also includes a scheme of top-down water fluxes in a forest, with the ranges of values for the water balance in the ecosystems studied. Results from the present study, in agreement with the objectives of the Tropenbos Foundation, contribute to enlarge local knowledge related to the functioning of a large part of the Colombian territory and to the better understanding of processes in undisturbed forests in Colombian Amazonia. The extensive collected data and overall results are unique for this part of the Amazonia and can be used as baseline information, among others, by local policy makers and planners. These results together with those from other studies may also support Colombia to develop joint management of the Amazon basin with other Amazonian countries in the context of local and global issues (e.g. Global Climate Change).

RESUMEN

En las últimas décadas los estudios enfocados al manejo y uso sostenible del suelo y de los recursos naturales en ecosistemas frágiles como la Amazonia, se han convertido en una de las principales herramientas en la lucha contra los impactos negativos del uso excesivo del bosque y otros recursos. En la Cuenca Amazónica el foco principal de la investigación científica actual se ha centrado en los efectos causados por la deforestación sobre el cambio climático local y global y en la disminución de la biodiversidad. Poca atención y esfuerzo se han puesto en la parte del funcionamiento de estos ecosistemas naturales y de aquellos que han sido alterados por el hombre, a pesar que esta información es de gran importancia para el manejo sostenible de la cuenca. Dicha información se refiere a la parte de las interacciones de organismos y plantas y el ciclo del agua y de los nutrientes entre los diferentes ecosistemas y compartimentos del ecosistema, asimismo a los efectos causados por los diferentes tipos de usos del suelo en el funcionamiento de dichos ecosistemas. El presente es uno de los primeros estudios y probablemente el único que se ha llevado a cabo en forma detallada y de largo plazo en la Amazonia Colombiana, en el cual se han investigado el ciclo del agua y de los nutrientes en cuatro ecosistemas forestales naturales, representativos de los tipos de bosque de esta parte de la cuenca Amazónica. Este estudio forma parte de los proyectos de investigación apoyados por la Fundación Tropenbos con el fin de proveer información científica básica sobre el funcionamiento hidrológico de los ecosistemas forestales en la Amazonia Colombiana, el cual pueda ser utilizado como punto de referencia para estudios de impacto y para el desarrollo de programas de manejo sostenible de los ecosistemas estudiados.

Investigaciones previas al presente proyecto dentro del área en estudio, generaron una información general y detallada acerca de los tipos de suelos y vegetación en las diferentes unidades fisiográficas. Una de las principales conclusiones de estos estudios está relacionada con las diferencias existentes entre las diferentes unidades en cuanto a suelos, tipos de bosque y diversidad de especies. Dichas unidades se refieren al plano sedimentario (Terciario), el plano aluvial del río Caquetá (Cuaternario) y las mesas de areniscas. El plano aluvial está compuesto esencialmente por terrazas altas, terrazas bajas, plano aluvial inundable esporádicamente y plano aluvial inundable frecuentemente. El presente estudio está enmarcado dentro de los estudios sobre los procesos en ecosistemas naturales de la Amazonia, el cual tuvo como principal objetivo el estudio de la hidrología y el balance hídrico en cuatro ecosistemas forestales en el Medio Caquetá, Amazonia Colombiana, por medio de la descripción y cuantificación de la dinámica espacio-temporal de los procesos hidrológicos y flujos del agua a través de los diferentes compartimentos del bosque. Con este objetivo se llevó a cabo un seguimiento detallado de los flujos y stocks del agua desde la parte superior del dosel hasta las áreas de drenaje a través de un programa de monitoreo de dichos flujos y de cada

uno de los parámetros y procesos relacionados con dichos flujos, durante el período 1992 – 1997.

Debido a que algunos flujos del agua presentan cierta dificultad para su medición (ej. flujo del agua en el suelo) y en vista de lo complejo de los procesos a medir en cada uno de los compartimentos de los ecosistemas, en el presente estudio se desarrollaron y/o utilizaron diferentes modelos matemáticos para la simulación de dichos procesos. Con la aplicación de estos modelos, se pretende llevar a cabo una caracterización más completa y detallada de los procesos hidrológicos en los ecosistemas. Además, con el fin de poder cuantificar y conocer la contribución de cada proceso en el ciclo hidrológico del ecosistema (ej. Intercepción de agua por el dosel y su posterior evaporación, transpiración. Toma de agua por las raíces desde la hojarasca y desde el suelo, drenaje, etc.), especialmente en aquellos casos cuando uno o más procesos son activos y difícilmente separables. En este estudio, los modelos permiten dar una descripción física de los procesos en cada compartimento del bosque y su contribución a cada uno de los componentes del balance hídrico de los ecosistemas. Asimismo los modelos fueron utilizados para llenar vacíos en la información colectada en campo, por medio de extrapolación o interpolaciones de dicha información.

El primer paso en la presente investigación consistió en la caracterización de los factores climáticos, debido en parte a la ausencia de información detallada en el área de estudio. Información sobre precipitación total, temperatura, humedad relativa, radiación solar, velocidad y dirección del viento y evaporación fue colectada cada 20 minutos a través de una estación automática instalada en una área libre de vegetación. Mediante el uso de esta información y con la aplicación del modelo deducido por Monteith (1965) se calculó la transpiración potencial durante el periodo de estudio. Los valores mensuales de cada uno de los factores climáticos y de la transpiración potencial, además de un análisis breve de cada resultado y la dinámica del clima se presentan en el capítulo 2 del presente libro. Se incluye igualmente datos sobre la evaporación mensual medida a través de un tanque de evaporación de clase A. Asimismo se presentan las generalidades del área de investigación, en la cual se incluye los tipos de suelo (apéndice 1), vegetación y una descripción de los diferentes usos del suelo y del bosque en el área de investigación. Los resultados encontrados concerniente a la distribución de la precipitación, intensidad y valores anuales están de acuerdo con los valores promedios de los años previos en la estación de Araracuara (IDEAM). La transpiración potencial es usada a través de la investigación como datos de entrada para los modelos sobre flujos del agua en el dosel, la capa de hojarasca y en el suelo.

Una vez caracterizado el clima y mediante el análisis de los datos colectados se llevó a cabo el estudio de la distribución de la precipitación total por encima del dosel y de los diferentes flujos dentro del dosel como son el flujo del agua a través del tronco de los arboles o excorrentía troncal y la cantidad de agua que pasa a través del dosel, además de caracterizar los factores principales que controlan dicha partición o distribución de la precipitación total una vez impacta el dosel del bosque. El capítulo 3 presenta un análisis detallado de esta división del agua en el dosel de la vegetación y se determinan las diferentes relaciones existentes con los factores climáticos y las características principales de la vegetación, como son la estructura del bosque y la cobertura del dosel. La cantidad de agua que pasa a través del dosel está relacionada con ambos, la cantidad y distribución de la precipitación total y la estructura del bosque. El porcentaje de agua que atraviesa el dosel de la vegetación varía entre el 82 y el 87% de la precipitación total, el cual varía igualmente con la cantidad e intensidad de la precipitación. La contribución de la excorrentía troncal a la precipitación neta dentro del bosque es muy baja, entre 1 y 1.5% de la precipitación total. Esta excorrentía está relacionada con la cantidad de precipitaciones y la duración de los eventos. Existe igualmente una relación lineal entre la intercepción de agua por el dosel y la cobertura del dosel de la vegetación. En conclusión, la distribución de la precipitación total una vez impacta el dosel de la vegetación depende considerablemente de las características de la precipitación (cantidad, duración e intensidad) e de la estructura de la vegetación, la cual fue definida en el presente estudio por la cobertura del dosel y el índice de área foliar.

En el capítulo 4 se estudian más profundamente los procesos de distribución de la precipitación total en el dosel de la vegetación a través de la aplicación de un modelo físico, con el cual se describen y cuantifican las variaciones temporales de dicha distribución. El análisis de sensibilidad del modelo a cada uno de los parámetros, indica que éste es muy sensitivo a la capacidad de almacenamiento de agua por el dosel y menos sensitivo a los demás parámetros como son la eficiencia de la evaporación del agua interceptada por el dosel, la resistencia aerodinámica del dosel al viento y el parámetro de drenaje del agua desde el dosel hacia la superficie dentro del bosque. Consecuentemente, se llevó a cabo la calibración del parámetro de mayor sensitividad para cada uno de los tipos de bosque estudiados y los valores de los demás parámetros fueron deducidos de las medidas de campo o se hicieron igual a la unidad, debido a su baja influencia sobre los procesos estudiados. Los valores encontrados en la calibración del parámetro de almacenamiento de agua por el dosel de la vegetación son menores para el bosque del plano sedimentario y aumentan en dirección del plano inundable. Estos resultados estuvieron de acuerdo con los valores encontrado en las mediciones de campo en cada uno de los bosques estudiados. La validación del modelo con datos diferentes a los utilizados para la calibración del modelo indica que el modelo puede reproducir con gran exactitud la dinámica de la precipitación neta y sus valores en cada evento por separado o de medidas semanales. Los resultados del modelo, en cuanto a la dinámica de la precipitación neta, indican que físicamente las predicciones del modelo son más realistas que aquellas encontradas en la aplicación de los modelos lineales.

El monitoreo del contenido de humedad de la hojarasca o capa de *litter* y del suelo se llevaron a cabo mediante el uso de un equipo de medición del tiempo utilizado por una onda electromagnética en su propagación a través de un medio conductor con propiedades previamente identificadas (Time Domain Reflecytometry, TDR).

Estos conductores o sensores fueron instalados a diferentes profundidades tanto en la capa de hojarasca como en el suelo. Diferentes estudios de calibración de medidas de campo realizadas con un equipo TDR han sido presentados para diferentes tipos de suelos y otros materiales. Dichos estudios coinciden en concluir que las medidas de la humedad deben ser calibradas para cada caso específico. Por consiguiente las medidas de humedad de la hojarasca y del suelo fueron debidamente calibradas en el presente estudio. En el capítulo 5 se presenta en forma detallada los procesos de calibración y la metodología utilizada tanto para el muestreo de los materiales estudiados así como para la calibración de las medidas. La humedad volumétrica de cada una de las muestras, tanto de hojarasca como de suelo, presentaron una relación lineal con el índice de refracción calculado de las medidas en campo con el equipo TDR. Estas relaciones presentaron un R^2 de 0.94 para la capa de hojarasca y de 0.88 para el suelo mineral. Las relaciones encontradas en el presente estudio así como los valores de los parámetros de las regresiones, fueron comparados contra los resultados de estudios similares en otras áreas. Al utilizar los valores de las regresiones de estos estudios, el contenido de humedad de los materiales estudiados en el presente trabajo es o bien sobrestimado o subestimado. Las regresiones encontradas en el presente estudio son posteriormente utilizadas para convertir las medidas de TDR en campo en valores de humedad volumétrica para la capa de hojarasca y el suelo mineral respectivamente.

En los ecosistemas forestales de la Amazonia Colombiana es común la presencia de una capa gruesa de hojarasca o litter. Dicha capa de hojarasca y su grosor o abundancia parece estar relacionada con la baja disponibilidad de nutrientes en el suelo mineral y en la misma hojarasca. Adicionalmente esta capa presenta abundantes raíces entre finas y medias, las cuales crecen y se esparcen entre la hojarasca formando una especie de esponja entre el ambiente interno del bosque y la superficie del suelo. Uno de los principales aportes del presente estudio está relacionado con la caracterización de la hidrología en la capa de hojarasca, el estudio de los procesos relacionados y el papel que desempeña dicha capa en la hidrología del bosque. El capítulo 6 presenta los resultados obtenidos en dicho estudio en cada uno de los ecosistemas investigados. De esta manera se llevo a cabo una caracterización detallada de la capa de hojarasca, su distribución espacial y temporal; asimismo se llevó a cabo estudios para determinar la capacidad de almacenamiento de agua por dicha capa y posteriormente se realizó un monitoreo de la dinámica del contenido de humedad durante dos años. Con el fin de simular los flujos del agua a través de la capa de hojarasca, los cambios en el almacenamiento del agua a través del tiempo, la toma de agua por las raíces desde dicha capa y el drenaje hacia el suelo, se desarrolló, calibró y validó un modelo matemático que permitió simular dichos procesos en forma dinámica. Los resultados de campo indican que la cantidad de agua que atraviesa la capa de hojarasca y la cantidad de agua tomada por las plantas depende del grosor de dicha capa y de su cantidad de raíces, además de las características de la precipitación neta. Se encontraron diferencias significativas entre los bosques estudiados en cuanto a la capacidad de almacenamiento de agua por la hojarasca y en la cantidad de agua tomada por las raíces desde esta capa, siendo mayor en el plano sedimentario. Contrariamente, en el plano inundable es mayor la cantidad de agua que drena hacia el suelo o drenaje parcial. En términos generales, la cantidad de agua tomada por las raíces desde la capa de hojarasca alcanzó un 30% del agua total transpirada por el bosque y el drenaje varió entre el 87% y el 93% de la precipitación neta en los ecosistemas estudiados.

El modelo desarrollado en el presente estudio y presentado en el capítulo 6 permitió llevar a cabo una descripción cuantitativa de los procesos y los flujos del agua a través de la capa de hojarasca, determinándose que dicha capa actúa como un reservorio de agua disponible para el bosque. Una de las mayores ventajas de dicho modelo es que su base conceptual, basada en relaciones físicas, está apoyada por observaciones de campo (ej. Mediante medidas de almacenamiento de agua por la capa de hojarasca) y con aquella información relacionada con parámetros no utilizados durante la calibración, como son las medidas de campo sobre drenaje de la capa de hojarasca. Dichas medidas de campo sirvieron además de comparación con las predicciones del modelo, encontrándose que existe una gran precisión del modelo para predecir las dinámicas de almacenamiento de agua por la hojarasca y el drenaje. El modelo permite separar igualmente la cantidad de los flujos de agua que atraviesan la capa de hojarasca sin ser interceptados o flujos preferenciales y el drenaje propiamente dicho; mientras dicha separación no puede ser establecida a través de las observaciones de campo. Adicionalmente, el modelo ofrece varias posibilidades entre las cuales se pueden mencionar las siguientes:

- Puede ser aplicado en condiciones de hojarasca sin raíces o con raíces no activas. En dichas condiciones la evaporación desde la capa de hojarasca podría ser un parámetro determinante.
- El modelo y su calibración permite la identificación de las principales características relacionadas con el flujo y la dinámica del agua en la capa de hojarasca y la separación cuantitativa de los procesos relacionados con dicha capa, esencialmente aquellos que actúan simultáneamente (ej. Toma de agua por las raíces y drenaje).
- Adicionalmente el modelo puede ser utilizado para estudiar la dinámica de los nutrientes en la capa de hojarasca y la de la absorción de nutrientes (solubles) por las raíces a través del estudio de la dinámica del agua en dicha capa.

A pesar de que una posible desventaja del modelo podría ser el número de parámetros, los valores de algunos de estos parámetros se pueden determinar en campo (almacenamiento de agua por la hojarasca, evaporación, la intercepción de agua por la hojarasca, etc.), mientras que otros requieren ser calibrados.

En el capítulo 7 se presentan los resultados del estudio de la dinámica del agua en el suelo en cada uno de los cuatro unidades de paisaje estudiadas. Este estudio muestra el papel desempeñando por el suelo en la distribución del agua que entra y la dinámica de dichos flujos. El contenido de humedad y tensión de humedad del suelo fueron monitoreados durante 2 años consecutivos a diferentes profundidades del suelo en las cuatro unidades del paisaje. Los flujos de agua a través del perfil del suelo fueron simulados mediante la aplicación del modelo SWIF (Flujos del agua en ecosistemas forestales), mediante el uso de algunas medidas de campo como datos de entrada al modelo, lo cual ofrece la ventaja sobre procedimientos alternos por otros modeladores, permitiendo la aplicación del modelo sin llevar a cabo ningún proceso de calibración de parámetros. Entre los resultados mas sobresalientes, se encontró que los suelos de la Amazonia Colombiana, en el área de estudio, tienen una baja capacidad de retención de humedad disponible, especialmente aquellos en el plano sedimentario y los de la terraza alta del río Caquetá, a pesar de que dichos suelos presentan un almacenamiento de humedad alto durante casi todo el año. Por lo anterior y de acuerdo con la dinámica de las curvas de retención de humedad para cada horizonte de los suelo estudiados, la distribución de la precipitación y la alta capacidad de almacenamiento de agua por estos suelos, son los principales factores responsables de que la transpiración de los bosques que soportan se lleve a niveles de transpiración potencial durante casi todo el año, excepto durante los períodos cortos de verano (enero y agosto) cuando la transpiración actual se reduce ostensiblemente. De acuerdo con los resultados del modelo en cada paisaje, la cantidad de agua tomada desde el suelo presenta una relación directa con la distribución y el contenido de raíces finas, pero su valor varía entre los paisajes, siendo mayor en el plano inundable y menor en el plano sedimentario Terciario. Los horizontes superiores de los perfiles de suelo presentaron una mayor variabilidad en la dinámica del contenido de humedad durante la mayor parte del año, mientras que los horizontes inferiores presentaron una baja dinámica, siendo casi constante el contenido de humedad y menor que en los horizontes superiores. Lo anterior estuvo relacionado con las propiedades del suelo, como textura y estructura y con la distribución de raíces finas en el perfil. A pesar de que la distribución de la precipitación total en el área estudiada es el factor mas importante en la dinámica del agua del suelo y en la transpiración, el contenido de humedad de la capa de hojarasca y de la parte superior del suelo mineral contribuyen a la transpiración total y actúan como compartimentos de mitigamiento de humedad requerida por las plantas, especialmente durante aquellos períodos de verano.

De acuerdo con el principal objetivo de la investigación que se presenta en este libro, el total de las medidas de campo durante el período de monitoreo y los modelos desarrollados y/o calibrados fueron utilizados para la cuantificación del balance hídrico para cada uno de los compartimentos del bosque y cada uno de los tipos de bosque estudiados. En el capítulo 8 se presentan los resultados obtenidos en el período 1992-1997. Estos resultados indican que durante los 4 años la fracción de agua interceptada por el dosel de la vegetación y posteriormente evaporada (evaporación) fue constante durante el período, pero existen diferencias significativas entre los valores de la intercepción neta entre los ecosistemas estudiados. Esta evaporación fue mayor en el ecosistema del bosque inundable y la mas baja en el del plano sedimentario. Comparativamente con otros tipos de bosque dentro de la cuenca Amazónica, los valores encontrados de evaporación en los bosques del Medio Caquetá son mayores que la mayoría de aquellos reportados en otros estudios. En general, los resultados obtenidos en la presenta investigación y relacionados con los valores de evaporación del agua interceptada por el dosel del bosque, explican las tendencias de la evapotranspiración en los ecosistemas y condiciones climáticas estudiadas; estas tendencias están estrechamente relacionadas con las características de precipitación total y la estructura del bosque. Las diferencias en los valores netos de evaporación genera como resultado una diferencia significativa entre los valores totales de evapotranspiración reportados en este estudio y aquellos de otros estudios en bosques de "tierra firme" en el Brasil. En este capítulo se concluye igualmente que la metodología utilizada para el estudio del balance hídrico por compartimentos del bosque, permitió la identificación de cada uno de los procesos específicos y la cuantificación particular de cada componente de dicho balance y su contribución para el balance general del ecosistema como unidad.

Al inicio de la presente investigación la información disponible sobre estudios hidrológicos en la Amazonia Colombiana era y sigue siendo casi nula, excepto por el presente trabajo. Esto difiere totalmente de otras áreas dentro de la cuenca Amazónica, donde gran número de investigaciones se han llevado a cabo, especialmente en la Amazonia Brasileña (ej. ABRACOS, LBA, etc.) y el noreste de la Amazonia (Jetten, 1996; Brouwer, 1996, Poels, 1987, etc.). Lo anterior fue claramente expuesto durante el congreso sobre la consolidación de la investigación nacional llevado a cabo en Colombia en 1996 por el instituto Von Humboldt. Una de las conclusiones de este congreso fue que existe una marcada falta de conocimientos en cuanto al funcionamiento de los ecosistemas naturales y de sus procesos internos. Adicionalmente al capítulo 8, el cual es concluyente de por sí, el capítulo 9 resalta las conclusiones generales y presenta un análisis de las implicaciones de los resultados obtenidos en la presente investigación y el ciclo de nutrientes en bosques de la Amazonia Colombiana y con el manejo de dichos ecosistemas. Igualmente se presenta en forma esquemática el rango de valores encontrados para cada una de las variables analizadas en el balance hídrico de los cuatro tipos de bosque estudiados. Los resultados obtenidos en la presente investigación, los cuales están relacionados con los objetivos de la Fundación Tropenbos y los delineamientos del país sobre investigación de la Amazonia (Colciencias), contribuyen a engrandecer el conocimiento local sobre el funcionamiento de los ecosistemas Amazónicos y a un mejor entendimiento de los procesos relacionados con el flujo del agua y de los nutrientes en cada uno de los compartimentos de bosques naturales en la Amazonia. Adicionalmente, la información colectada durante el período de estudio es única en su género para esta parte de la Amazonia y por lo tanto puede ser utilizada, en conjunto con los resultados de otros estudios, como información básica por todas aquellas personas o institutos encargados de la planeación, manejo y uso del los recursos naturales y como una herramienta de apoyo para el diseño de políticas de manejo de la Amazonia en conjunto con los países de la cuenca y en el contexto de proyectos más globales, como por ejemplo en aquellos relacionados con el cambio climático global.

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Appendix 1

SOIL DESCRIPTION

Altitude: 60 m above mean level of the River Caquetá
Parent material: Tertiary sediments
Geomorphic unit: dissected Tertiary sedimentary plain
Position: convex summit
Topography: highly dissected
Slope: flat
Humidity regime: udic
Drainage: very well drained
Vegetation: natural forest
Disturbance: none
Classification
USDA: typic Kandiudult
FAO: xanthic Ferralsol

Profile description:

Litter	17 – 0 cm. Organic material composed of leaves 33%, twigs and seeds 15% and very fine and fine roots 52%; non compact; loose consistence; fibric; fine roots increase with depth in the ectorganic horizon; some faunal activity (ants and termites); clear and sharp boundary towards mineral soil.
Ah	0 - 3 cm. Dark brown (7.5YR 3/4) sandy clay loam; granular; friable slightly sticky and plastic; abundant very fine and fine roots and few coarse roots; presence of faunal activity (ants, termites and worms); clear and irregular boundary to. pH = 4.1
A	3 – 12 cm. Yellowish dark (10YR 4/4) sandy clay loam; friable, sticky and slightly plastic; subangular blocky; abundant coarse, medium and fine pores; abundant very fine and fine roots, few coarse roots; presence of faunal activity (ants, termites, worms); Some charcoal fragments; clear and smooth boundary to. pH = 4.0
Bt_1	12 - 50 cm. Yellowish brown (10YR 5/6) clay, moderate medium to fine subangular blocky; friable; sticky and plastic; common coarse, medium and fine pores; few, fine and common coarse roots; some faunal activity (worms); some rounded quartz gravel and some charcoal fragments; clear and smooth boundary to. pH = 4.6
Bt_2	50 –160 cm. Bright brown (10YR 5/8) clay; moderate subangular blocky, firm; very sticky and slightly plastic; common medium and fine pores; very few, fine and few coarse roots. Some charcoal fragments and few rounded

quartz gravel. pH = 4.9

	sand	silt	clay
Ah	58	31	11
A	48	24	28
Bt_1	31	17	51
Bt_2	28	13	59

Altitude: 60 m above mean water level of River Caquetá
Parent material: sediments from the Tertiary
Geomorphic unit: dissected Tertiary sedimentary plain
Position: very steep slope of dissections
Topography: steeply dissected
Slope: steep 30° (to the east)
Drainage: very well drained
Vegetation: natural forest
Disturbance: none (some small gaps by falling trees)
Classification
USDA: typic Paleudult
FAO: haplic Acrisol

Profile description:

Litter	8 - 0 cm. Organic material composed of leaves 41%, twigs and few seeds 12% and fine roots 47%; slightly compact structure; fibrous; abundant very fine and fine roots increasing with depth; presence of abundant faunal activity; clear boundary. In the contact zone decomposed organic material is mixed with mineral soil particles.
Ah_1	0 -2 cm. Dark brown (10YR 3/3) sand; granular; very friable; non sticky non plastic; abundant very fine and fine roots; presence of some fauna (ants and termites), smooth boundary to. pH = 4.0
Ah_2	2 –18 cm. Yellowish brown (10YR 4/4) sandy loam; moderate medium granular; friable; slightly sticky and slightly plastic; abundant coarse, medium and fine pores; abundant very fine, fine and common coarse roots; presence of some fauna (ants and worms); some charcoal fragments; clear and smooth boundary to. pH = 4.0
A/B	18 – 40 cm. Dull yellowish brown (10YR 5/4) sandy loam to sandy clay loam; moderate subangular blocky; friable; slightly sticky and slightly plastic; common fine and coarse roots; common coarse, medium and fine pores; some charcoal fragments; boundary gradual and smooth to. pH = 4.5

Bt_1 40 - 75 cm. Yellowish brown (10YR 5/6) sandy clay; weak medium subangular blocky; friable; sticky and plastic; few medium and fine pores; few fine roots and common coarse roots; Some charcoal fragments; boundary gradual and smooth to. pH = 4.7

Bt_2 75 –160 cm. Bright yellowish brown (10YR 6/8) clay; sticky and very plastic; very few medium and few coarse roots. pH = 5.1

	sand	silt	clay
Ah	84	11	15
A	81	7	12
A/B	70	13	17
Bt_1	37	16	47
Bt_2	33	12	55

Altitude: 45 m above mean level of River Caquetá
Parent material: Tertiary sediments
Geomorphic unit: Dissected Tertiary sedimentary plain
Position: Bottom of V – shaped valley
Topography: steep highly dissected
Slope: Flat
Drainage: Well drained
Vegetation: Natural forest
Disturbance: None
Classification
USDA: arenic Kanhapludults
FAO: acri Ferralsols

Profile description:

Litter 5 - 0 cm. Organic material composed of leaves 48% twigs and seeds 14% and very fine and fine roots 38%; non compact; loose consistence; fibrous character; presence of faunal activity (ants, termites and worms); clear and wavy boundary. A special feature of the bottom of the ectorganic layer is the presence of quartz grains within the layer.

A 0 - 20 cm. Dark brown (10YR 3/4) sand; with slight podzolization; structureless; non sticky and non plastic; abundant coarse, medium and fine pores; abundant very fine, fine and medium roots; presence of faunal activity (ants, termites and worms); clear and smooth boundary to; pH = 4.1

Bt_1 20 –70 cm. Dark yellowish red (10YR 3/4) sandy clay loam; weak medium subangular blocky; friable; slightly sticky and plastic; common coarse, medium and fine pores; few fine and common medium and coarse roots; diffuse and smooth boundary to; pH = 4.3.

Bt_2 70 –120 cm. Bright yellowish brown (10YR 5/6) sandy clay loam; weak medium subangular blocky; friable; sticky and plastic; common medium and fine pores; very few medium and few coarse roots; some charcoal fragments; pH = 4.5

	sand	silt	clay
Ah	58	31	11
A	48	24	28
Bt_1	31	17	51
Bt_2	28	13	59

Altitude: 25 m above mean level of River Caquetá
Parent material: Pleistocene fluvial sediments of River Caquetá
Geomorphic unit: high terrace
Topography: moderately dissected
Slope: flat
Drainage: moderately to well drained
Vegetation: natural vegetation
Disturbance: None
Classification
USDA: typic Kandiudult
FAO: xanthic Ferralsol

Profile description:

Litter 4 - 0 cm. Organic material composed of leaves and twigs 32%, roots 60% and coarse branches 8%; non compact; fibrous; resilient consistence; common faunal activity and clear and irregular boundary to:

Ah 0 - 5 cm. Dark brown (10YR 4/3) sandy clay loam; coarse granular; friable; slightly sticky and slightly plastic; abundant very fine and fine roots common medium and fine pores; presence of faunal activity, clear irregular boundary to:

A 5 –30 cm. Dull yellowish red (10YR 5/4) clay loam; weak medium subangular blocky; friable moist; sticky and slightly plastic, common coarse, medium and fine pores; common fine medium and coarse roots; gradual and smooth boundary to:

Bt_1 30 – 65 cm. Yellowish brown (10YR 5/6) clay loam; weak coarse subangular blocky; firm moist, sticky and plastic; few medium and fine pores; few fine and common medium and coarse roots, gradual smooth boundary to:

Bt_2 65 – 110 cm. Pale brown (10YR 6/3) clay; medium coarse subangular blocky; friable, very sticky and very plastic, very few medium and fine coarse roots.

	sand	silt	clay
Ah	45	40	15
A	32	24	44
Bt_1	24	20	56
Bt_2	14	18	68

Altitude: 25 m above mean level of River Caquetá
Parent material: Pleistocene deposits from River Caquetá
Geomorphic unit: high terrace
Topography: undulating
Slope: nearly flat
Drainage: Moderately to well drained
Vegetation: Natural vegetation
Disturbance: None
Classification
USDA: typic Hapludult
FAO: haplic Acrisol

Profile description:

Litter 6 - 0 cm. Composed of leaves and small twigs 65%, very fine and fine roots 28% and coarse material 7%; non compact; loose consistency; presence of abundant fauna (mainly ants and termites); clear and smooth boundary to:

Ah 0 - 4 cm. Dark yellowish brown (10YR 3/4) sandy loam; moderate granular; friable; slightly sticky and slightly plastic; abundant medium and fine pores; abundant very fine and fine roots; common medium and coarse pores and some faunal activity, clear and smooth boundary to. pH = 4.1

A 4 –30 cm. Yellowish brown (10YR 5/6) sandy clay loam, weak medium subangular blocky; friable; slightly sticky and plastic, common coarse, medium and fine pores; common fine medium and coarse roots; some charcoal fragments; gradual and smooth boundary to. pH =4.2

Bt_1 30 – 70 cm. Bright brown (7.5YR 5/8) clay; moderate medium angular blocky; sticky and plastic; few medium and fine pores; few fine and common coarse roots; gradual boundary to. pH = 4.4

Bt_2 70 – 125 cm. Bright reddish brown (5YR 5/8) clay; strong coarse angular blocky, firm; sticky and plastic; very few coarse roots. pH = 4.4

	sand	silt	clay
Ah	58	26	16
A	47	25	28
Bt_1	36	16	48
Bt_2	23	13	64

Altitude: 15 m above mean level of River Caquetá
Parent material: alluvial deposits from River Caquetá
Geomorphic unit: Pleistocene low terrace of River Caquetá
Topography: flat with small depressions and some shallow fluvial incisions
Slope: almost flat
Drainage: moderately well drained
Vegetation: natural forest
Disturbance: none
Classification
USDA: typic Paleudult
FAO: haplic Acrisol

Profile description:

Litter 3.8 – 0 cm. Organic material composed of clearly fresh leaves, twigs, some seeds and few fine and coarse roots. Slightly compact; loose consistency; fibric; some fauna (ants and worms); clear and smooth boundary to the mineral soil.

Ah 0 – 9 Dull yellowish brown (10YR 4/3) sandy loam; moderate medium granular; very friable; slightly sticky and slightly plastic; abundant very fine and fine roots; common medium and coarse pores; clear and wavy boundary to:

A/B 9 – 45 cm. Yellowish brown (10YR 5/4) silt loam; moderate coarse subangular blocky; very friable; slightly sticky and slightly plastic; common fine and medium roots; common coarse, medium and fine pores; some charcoal fragments; clear and smooth boundary to:

Bt_1 45 – 75 cm. Bright brown (7.5YR 5/6) silty clay; moderate medium subangular blocky; friable; slightly sticky and plastic; few fine and common medium and coarse roots; few coarse, medium and fine pores; gradual and smooth boundary to:

Bt_2 75 –120 cm. Yellowish red (5YR 5/8) clay; with brownish yellow mottles (10YR 6/6); moderate coarse angular blocky; friable; slightly sticky and plastic; few medium and common fine pores; few coarse roots.

	sand	silt	clay
Ah	41	45	14
A/B	32	39	29
Bt_1	24	30	46
Bt_2	21	31	48

Altitude: 15 m above mean level of River Caquetá
Parent material: alluvial deposits from River Caquetá
Geomorphic unit: Pleistocene low terrace of River Caquetá
Topography: flat with small depressions and some shallow fluvial incisions
Slope: almost flat
Drainage: moderately well drained
Vegetation: natural forest
Disturbance: none
Classification
USDA: typic Paleudult
FAO: haplic Acrisol

Profile description:

Litter 2 – 0 cm. Organic material composed of clearly fresh leaves, twigs, some seeds and few fine and coarse roots. Slightly compact; loose consistency; fibric; some faunal activity; clear and smooth boundary to:

Ah 0 – 4 cm. Brown (7.5YR 4/3) loam; moderate medium granular; very friable; slightly sticky and slightly plastic; abundant fine and medium roots; frequent fine and medium pores; clear and wavy boundary to:

A/B 4 – 55 cm. Brown (7.5YR 4/5) silt loam; moderate medium subangular blocky; very friable; slightly sticky and slightly plastic; common fine, medium and coarse roots; common fine and medium pores; abundant charcoal fragments; clear and smooth boundary to:

Bt 35 – 120 cm. Yellowish red (5YR 5/8) clay; moderate coarse subangular blocky; friable; sticky and plastic; very few fine, medium and coarse roots; few coarse, few medium and coarse pores; some charcoal fragments.

	sand	silt	clay
Ah	36	39	25
A/B	34	35	31
Bt	23	28	49

Altitude: 10 m above mean level of River Caquetá
Parent material: Holocene deposits of River Caquetá
Geomorphic unit: Rarely inundated flood plain of the River Caquetá
Topography: flat
Slope: Flat
Drainage: Moderately to well drained
Vegetation: Natural forest
Disturbance: None
Classification
USDA: typic Tropaquept
FAO: dystric Cambisol

Profile description:

Litter 2 – 0 cm. Mixture of leaves; few twigs and very few seeds; few very fine and common fine roots; slightly compact; loose; some fauna (ants and worms); gradual irregular boundary to:

A 0 – 8 cm. Bright yellowish brown (10 YR 6/6) with few Dull yellowish brown (10 YR 5/5) silty clay to silty clay loam; weak medium subangular blocky; very friable; slightly sticky and slightly plastic; abundant fine and common medium and coarse roots; common fine and medium pores; clear and smooth boundary to:

Bw_1 8 – 60 cm. Bright brown (7.5 YR 6/6) abundant contrasting orange mottles; silty clay loam, weak medium subangular blocky; very friable; sticky and plastic; few fine roots, common medium and coarse roots; few medium and common fine pores; and thin cutans on ped faces; gradual and smooth boundary to:

Bw_2 60 – 100 cm. Bright brown orange (7.5 YR 5/6) with abundant bright brown mottles (7.5YR 5/8); clay loam; moderate coarse subangular blocky; friable; sticky and slightly plastic; presence of some Fe nodules; very few fine roots and few medium and coarse roots; common thin cutans along pores gradual boundary to:

Bcg > 100 cm. Grey (2.5 YR 7/1) with abundant yellowish reddish mottles (7.5 YR 7/1) clay loam; massive; sticky and plastic and few coarse roots.

	sand	silt	clay
A	22	46	32
Bw_1	28	48	24
Bw_2	24	43	33
Bcg	20	41	39

Altitude: 10 m above mean level of River Caquetá
Parent material: clayey sediments of the River Caquetá
Geomorphic unit: rarely inundated flood plain
Topography: convex
Slope: flat
Drainage: well drained
Vegetation: natural
Disturbance: none
Classification
USDA: typic Dystropept
FAO: dystric Cambisol

Profile description:

Litter 3.2 – 0 cm. Mixture of fresh leaves (75%), twigs (13%) and seeds (12%). Common fine roots and few medium roots; slightly compact; loose consistency and clear presence of faunal activity; gradual boundary.

Ah 0 – 3 Bright yellowish brown (10YR 6/6) with some brown mottles (10YR 4/6) clay loam; moderate coarse angular blocky; slightly sticky and slightly plastic; abundant fine roots; few medium roots; common medium and fine pores; some faunal activity; diffuse boundary to:

Bw_1 3 – 25 cm. Bright yellowish brown (10YR 6/5) with fine brown mottles (10YR 4/6) clay loam; moderate and coarse angular blocky; slightly sticky and slightly plastic; few fine roots and medium roots; common medium and fine pores; diffuse boundary to:

Bw_2 25 – 50 cm. Dull yellow orange (10YR 6/4) with some orange mottles (7.5YR 6/6) clay loam; moderate and coarse angular blocky; slightly sticky and slightly plastic; few medium and coarse roots; few medium and fine pores; common cutans on ped faces; gradual boundary to:

Bw_3 50 – 95 cm. Brownish grey (7.5YR 7/3) with abundant reddish brown medium contrasting mottles; (5YR 5/4) clay; weak and medium angular blocky; sticky and plastic; few medium and coarse roots; common cutans on pores and ped faces; gradual and smooth boundary to:

C > 95 cm. Light grey (2.5Y 7/2) and Brown (10YR 4/4) mottle; clay; massive; sticky and plastic; very few coarse roots.

	sand	silt	clay
Ah	25	47	28
Bw_1	18	42	40
Bw_2	16	39	45
Bw_3	20	35	45
C	16	33	49