Monitoring and modelling hydrological fluxes in support of nutrient cycling studies in Amazonian rain forest ecosystems
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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 (Abunza 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,
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Colombian Amazonia. Moreover, comprehensive and detailed studies of soils and vegetation of forest ecosystems in this area (Duivenvoorden and Lips, 1995; Alvarez, 1993; Londono, 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.
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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.