Monitoring and modelling hydrological fluxes in support of nutrient cycling studies in Amazonian rain forest ecosystems
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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 Caqueta Colombia (0° 37' - 1° 24' S and 72° 23' - 70° 43' W). The climate is classified as equatorial superhumid Afí (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 km². 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.

<table>
<thead>
<tr>
<th>Soils</th>
<th>SP</th>
<th>HT</th>
<th>HT</th>
<th>FP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Classification</strong></td>
<td><strong>USDA</strong></td>
<td><strong>FAO</strong></td>
<td><strong>USDA</strong></td>
<td><strong>FAO</strong></td>
</tr>
<tr>
<td>USDA</td>
<td>typic Kandiudult</td>
<td>xanthic Ferralsol</td>
<td>typic Paleudult</td>
<td>typic Tropaquept</td>
</tr>
<tr>
<td>FAO</td>
<td>haplic Acrisol</td>
<td>haplic Acrisol</td>
<td>haplic Acrisol</td>
<td>dystric Cambisol</td>
</tr>
<tr>
<td><strong>Horizon</strong></td>
<td><strong>Thickness (cm)</strong></td>
<td><strong>Texture</strong></td>
<td><strong>Thickness (cm)</strong></td>
<td><strong>Texture</strong></td>
</tr>
<tr>
<td>Ah</td>
<td>12</td>
<td>sandy clay loam</td>
<td>Ah</td>
<td>30</td>
</tr>
<tr>
<td>A/B</td>
<td>45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Dry bulk density (kg m$^{-3}$)</strong></td>
<td>1346 (±108)</td>
<td>1298 (±49)</td>
<td>1210 (±126)</td>
<td>1121 (±58)</td>
</tr>
<tr>
<td><strong>Percentage of fine roots</strong></td>
<td>27</td>
<td>70</td>
<td>72</td>
<td>41</td>
</tr>
<tr>
<td>Bt$_1$</td>
<td>40</td>
<td>clay</td>
<td>Bt$_1$</td>
<td>30</td>
</tr>
<tr>
<td><strong>Thickness (cm)</strong></td>
<td>38</td>
<td></td>
<td></td>
<td>50</td>
</tr>
<tr>
<td><strong>Texture</strong></td>
<td>clay</td>
<td></td>
<td>clay</td>
<td></td>
</tr>
<tr>
<td><strong>Dry bulk density (kg m$^{-3}$)</strong></td>
<td>1415 (±109)</td>
<td>1390 (±95)</td>
<td>1340 (±109)</td>
<td>1224 (±66)</td>
</tr>
<tr>
<td><strong>Percentage of fine roots</strong></td>
<td>28</td>
<td>10</td>
<td>6</td>
<td>40</td>
</tr>
<tr>
<td>Bw$_1$</td>
<td>60</td>
<td>clay</td>
<td>Bw$_2$</td>
<td>50</td>
</tr>
<tr>
<td><strong>Thickness (cm)</strong></td>
<td>110</td>
<td></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td><strong>Texture</strong></td>
<td>clay</td>
<td></td>
<td>clay</td>
<td></td>
</tr>
<tr>
<td><strong>Dry bulk density (kg m$^{-3}$)</strong></td>
<td>1510 (±77)</td>
<td>1524 (±98)</td>
<td>1525 (±73)</td>
<td>1330 (±57)</td>
</tr>
<tr>
<td><strong>Percentage of fine roots</strong></td>
<td>9</td>
<td>2</td>
<td>3</td>
<td>7</td>
</tr>
</tbody>
</table>
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 ($\theta$) 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:

$$W_s = \sum \theta_i \Delta z_i, \quad (7.1)$$

### 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:

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

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.

$$R_{eff,z} = R_z \frac{\theta_z}{\theta_{s,z}}, \quad (7.3)$$

Thereupon, the amount of water uptake at a certain depth is calculated from the reference plant transpiration ($E_{p,*}$) 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.
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).
Monitoring and modelling hydrological fluxes

Volumetric water content (m^3 m^-3)

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 m² 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 m³m⁻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.
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.
Monitoring and modelling hydrological fluxes

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.

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

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.
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.
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)
Monitoring and modelling hydrological fluxes

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.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>SP</th>
<th>HT</th>
<th>Depth (cm)</th>
<th>LT</th>
<th>FP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NRM SE</td>
<td>R²</td>
<td>n</td>
<td>NRM SE</td>
<td>R²</td>
</tr>
<tr>
<td>10</td>
<td>0.018</td>
<td>0.92</td>
<td>134</td>
<td>0.031</td>
<td>0.90</td>
</tr>
<tr>
<td>15</td>
<td>0.020</td>
<td>0.87</td>
<td>135</td>
<td>0.026</td>
<td>0.84</td>
</tr>
<tr>
<td>20</td>
<td>0.017</td>
<td>0.89</td>
<td>133</td>
<td>0.025</td>
<td>0.89</td>
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<tr>
<td>30</td>
<td>0.017</td>
<td>0.91</td>
<td>133</td>
<td>0.029</td>
<td>0.89</td>
</tr>
<tr>
<td>50</td>
<td>0.012</td>
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<td>134</td>
<td>0.015</td>
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<td>80</td>
<td>0.021</td>
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<td>0.022</td>
<td>0.79</td>
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<td>120</td>
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<td>0.87</td>
<td>131</td>
<td>0.018</td>
<td>0.72</td>
</tr>
<tr>
<td>160</td>
<td>0.022</td>
<td>0.78</td>
<td>134</td>
<td>0.013</td>
<td>0.71</td>
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</tbody>
</table>

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.
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.](image)

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 Jenik (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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