

# Hydrological sensitivity analysis to LUC in Tropical Mountainous Environment

Mauricio Edilberto Rincón Romero, Ph.D.  
Grupo de investigación en Geomática Aplicada  
Universidad del Valle, Calle 13 # 100 – 00. Cali – Colombia. Tel 57 2 333 4897. Mobile 316 446 1607  
[maurorin@univalle.edu.co](mailto:maurorin@univalle.edu.co) <http://giga.univalle.edu.co>

Mark Mulligan, Ph.D.  
Environmental Monitoring and Modelling Research Group  
Department of Geography, King's College London Strand, LONDON, WC2R 2LS.  
Tel 44 20 7848 2280. Mobile 44 77 9626 5616 Fax 44 20 7848 2287  
[mark.mulligan@kcl.ac.uk](mailto:mark.mulligan@kcl.ac.uk) <http://www.kcl.ac.uk/geography>

## Abstract

*The research objective was to determine the effects of Land Use and Cover Change (LUCC) on the hydrological cycle, in particular evaluating the hydrological sensitivity of overland flow and erosion to LUCC and the spatial variability of this sensitivity in a Tropical Montane Cloud Forest (TMCF). Small catchment was selected with this purpose, at southwest of Colombia, near of Pacific coast.*

*Complexity of environmental TMCF behaviour is currently studied to increase knowledge moreover taking into account the effects of Global Climate Change (GCC). Biodiversity in both fauna and flora are special subject research worldwide. Environmental change on this particular environment has strong effect when LUCC occurs, mainly where agricultural frontier move boundaries of rainforest and also where illicit crops increases land demand.*

*LUCC scenario with different land conversion was built to be coupled in a spatial dynamic distributed hydrological model as surface land parameters change. Hydrological model was designed for this particular environment running at one-hour time step for a full year simulation period. Model runs on Geographical Information Systems (GIS) platform with raster spatial structure with 25m pixel size resolution.*

*Hydrological variables were summarised after several simulation were some of specific parameters were changed to produce sensitivity changes results. Sensitivity analysis was carryout to identify the main effect of LUCC on the hydrological cycle on this fragile ecosystem.*

*This is considered as the first step on the watershed simulation to integrated several additional aspect in the model, such social, cultural, political and economic issues, in order to produce a power tool as decision support system on the catchment planning task. This initiative belongs to the proposal for Applied Geomatic Laboratory for Complex Systems at Universidad del Valle – Colombia.*

## 1. Introduction

In the last decades researchers are including in the catchment's studies activities like hydrological simulation models; more of them looking the better approach to represent the natural behaviour to improve the understanding of what happen with the scenario in particular conditions. This is an activity that has been research's worry of several sciences branches, each of then focused to find out appropriate answers in a sector of the general knowledge, as far as the capabilities allow them to reach. In this race it is not the exception; here we present an exercise where the importance of particular hydrological ecosystems behaviour is investigated in order to improve the understanding of the surface land cover role in the hydrological cycle within the tropical mountainous cloud forest (TMCF). Behaviour of nature is the focus of complex systems; its representation throughout models and simulations applying General Systems Theory (GST), which couple elements, its relations, functions, patterns and system products of represented process within the model.

Of the world's 12000 million hectares of tropical forest in 1988, 3600 million hectares were tropical rain forest and tropical cloud forest, 40% of which were located in Latin America (Park, 1992). FAO (1997) reported that about 15 million hectares of tropical forest are lost each year because of the advance of the agricultural frontier, the economic exploitation of timber and more recently illicit crops. In terms of complex systems, physical processes should be altered with the land use and land cover change (LUCC), and with them the water within the hydrological cycle as articulator axis, to preserve the life and its natural function for this particular TMCF ecosystem.

## 2. Review of hydrological modelling

One of the approaches to understand the ecosystem hydrological behaviour is to represent it throughout hydrological modelling. Hydrological models aim to simplify the process by selecting a system's fundamental aspects at the expense of incidental detail (Anderson and Burt, 1985). The first integrated hydrological model, called the Stanford Watershed Model (Singh, 1995), was reported in the literature in 1966 by Crawford and Linsley. During the following decades, hydrological modelling improved significantly because of advances in technology and computer hardware.

Hydrological models can be characterised by the type of relations used within the routines. The relationship between real and models processes can be represented either empirically or physically. Empirical models tend to have high predictive ability but their physical explanatory power is often low. They are sometimes called "Black box" or "input/output" models. These terms are usually applied to those models whose internal operation does not aim to directly represent "real" operative processes, even at an abstract mathematical level (Kirkby et al., 1993). Statistical analysis faces several methodological and interpretative difficulties, such as measuring complex dependent variables, and spatial aggregation of data in large units. The existence of a statistically significant association does not establish a causal relationship. Moreover, a regression model that fits well in the region for which it was designed might not function well in other regions, because it should not be transferred beyond the physical limits for which it was developed, parameterised and calibrated.

Physical models based on physical processes, are modelled on the understanding of physical mechanisms and often make large demands in terms of computational time and data requirements. Nevertheless, such models offer increased explanatory and experimental power. However, because of the higher number of assumptions that are necessary, their predictive capacity is often equal or worse than that of empirical models. Beven (1989) argued that highly complex, physically-based models are possible at smaller scales. However, larger-scale models must be simple to allow parameterisation. Woolhiser (1996) pointed out that simpler models are often more accurate than physically-complex models, but are difficult to scale up to larger watersheds. Parameter generalisation within the watershed involves simple representations of main model elements. Several variables such as soil characteristics which are important at reduced scales for detailed studies are also important at the watershed level, increasing model complexity while not necessarily adding precision to the results.

Spatial variability within a catchment is currently addressed by several techniques; lumped models expressed by ordinary differential equations that describe simple hydraulic laws. These models do not take into account the spatial variability of processes, inputs, boundary conditions, or the system's geometric characteristics. Instead, a single value for properties and parameters is applied to the entire watershed. Some examples are HEC-1 (Hydrologic Engineering Center, 1981) described by Feldman (1995), RORB (Laurenson and Mein, 1995), and SSARR (USA Army Engineer, 1972) described by Speers (1995). Distributed models focus on the spatial variability of processes, inputs, boundary conditions and system characteristics. The spatial distribution of features and their spatial inter-relationships are especially important to explaining physical processes within the watershed. Examples are SHE (Abbott et al., 1989) described by Bathurst et al. (1995), SWMM (Metcalf et al., 1971) as described by Huber (1995).

Models can also be classified according to the type of equation used and the resulting output. Model results can be a singular, or a population of answers. Processes can be described either by deterministic or stochastic equations. Deterministic models have just one possible outcome, whilst stochastic models have a population of answers. In most cases both types of equations occur within the same model.

## 3. Objective

To identify the effects of LUCC and its pattern on the hydrological cycle in a catchment of TCMF, throughout the analysis of the spatial variability of hydrological sensitivity of land use change.

#### 4. Study area description

This study was carried out in the Tambito natural reserve, located in the Andean region of Cauca, in southwestern Colombia (Figure 1), approximately 75 km from the Pacific coast (between 77°01' and 76°58' longitude W and 2°28' and 2°32' latitude N). The natural reserve is in a watershed of Tambito river, which is the study. Elevation ranges between 1400 and 2800 masl. Landscape characteristics include steep slopes and high mountains.

The typical vegetation of the area is TMCF, with a high biodiversity index for vegetation, mammals, and reptiles (Fundación Proselva, 1996). The approximate area covered by the watershed is 1500 hectares, of which 95% is under forest and the rest consists of isolated patches of grassland, often created by migrant colonisers. Temperature averages 19 °C, rising to 24 °C at noon and falling to 12 °C at dawn. Precipitation can reach up to 4000 mm per year in the lower areas of the watershed. Although rains fall throughout most of the year, July and August are the driest months. The drainage network is dense (29 m ha<sup>-1</sup>), with no permanent rills just gullies.

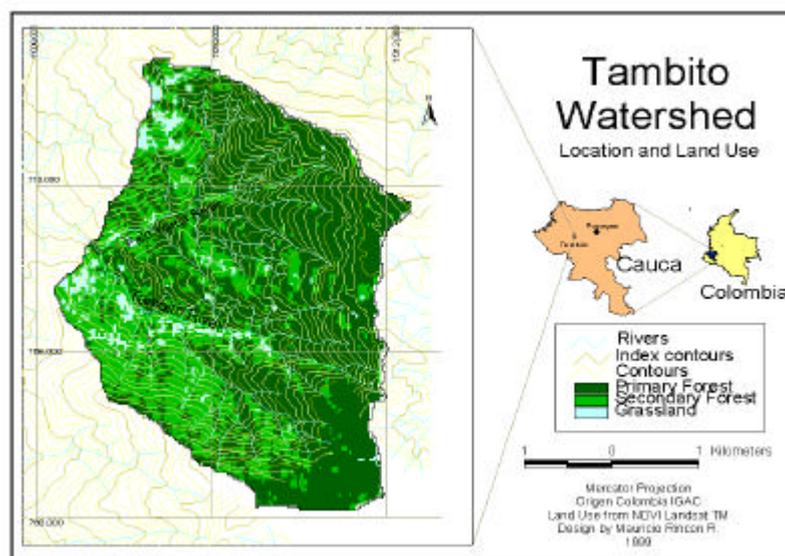


Figure 1 Study area location

#### 5. Research approach

TMCF small catchment was selected in Colombia southwest area to carry out the experiment. A simple catchment's conception is coupled within a 2.5D hydrological spatial distributed model running on GIS tool with LUCC scenario to represent its hydrological function, in order to identify the effect of LUCC on the hydrological cycle in the TMCF. Complexity of integration of hydrological issue with LUCC is carried out in a combination of several model runs, where each iteration of LUCC scenario were integrated to the hydrological model in a run of model for a year period. Each run uses one different iteration of LUCC condition. The number of model runs is as much as iteration of LUCC exists in the scenario up to the advance of deforestation pattern reach full catchment converted to pasture.

Complex systems conception gives the basis of adopted strategy. Despite natural processes are complex, within the model were taken into account the more representative aspects in the hydrological cycle. The hydrological processes are simulated within the model throughout the whole catchment in the same conditions, but the local environmental conditions of each pixel within the catchment produce their own hydrological response for each point. In each time step once the vertical hydrological movement is advanced, the surface connectivity is taking place; that's why it is called 2.5D model. Model time step is one hour time with 25m pixel size spatial resolution. Each run uses the same generic environmental conditions of precipitation data.

Connectivity and relationships between different elements within the model outline the pattern of fluxes of water and energy. The exchange of energy and water produce the water balance for each point within the catchment and also each of them contribute to produce the output results in both in a single value for the whole catchment and also in a surface for each variable. Hydrological variables (overland flow and erosion output data) were summarised at the end of each run, in order to compile model output results to build up the database for the analysis as accumulative value after each year simulation for each iteration of the LUCC scenario.

Each element within the model that is used as a water container (atmosphere, vegetation, soil surface and underground soil) were assessed and parameterised with field data collection. The amount of water flux was estimated by the model according the environmental condition of each time step for each point within the catchment.

The analysis is carried out in terms of: 1) single value for the whole catchment for each iteration; 2) surface analysis of accumulative output surface for a year run, which show out the spatial variability of catchment hydrological response and, 3) sensitivity analysis for hydrological variables to identify which and where each environmental variable is more sensitivity for the hydrological model conception. Sensitivity analysis involves comparing hydrological outputs of model variables, such as overland flow and erosion generated between different iterations of different land use scenarios patterns. Sensitivity is assessed as the change in model outputs (overland flow and erosion) per unit change in deforested area. The hydrological model used was designed to operate on an hourly time step, and runs with the same parameters and input data (with the exception of land cover) for all scenarios. The scenario of LUCC counts with 22 iterations before the watershed is completely deforested.

## **5.1 LUCC scenario**

The initial LUCC was derived from a Landsat TM image (Fundación Proselva, 1991), using the Normalised Difference Vegetation Index (NDVI), which was reclassified with the help of signature classes extracted from the texture pattern on aerial panchromatic photographs for four classes of reflectance: two forest types, grassland and clouds. Then three distinct population of vegetation pixel classes from the NDVI were recognised for the LUCC classes (Rincón-Romero, 2001): primary forest, secondary forest, and grasslands (Figure 1).

Three kinds of land uses were distinguished within the study area, on the assumption that these have different hydrological impacts (Bonell and Balek, 1993; Calder et al., 1995): (a) primary forest, (b) secondary forest, and (c) deforested areas. Different land cover combinations were found in the Tambito watershed. The hydrological parameters for both primary and secondary forest were found on the basis of field measurement, to be very similar. The analysis will therefore only differentiate between two classes, since these were quite different in properties: (a) forests and (b) grasslands.

The LUCC scenario was designed using criteria of advancing deforestation fronts rather than a spatially complex pattern of deforestation. The LUCC transformation in each iteration is carried out relative to various physical properties of the landscape such as change in the vegetation type, and then changes in vegetation parameters. The iterations are not related to temporal changes, but are used as step changes throughout which LUCC occurs.

The LUCC pattern was derived from cellular automata, as designed and implemented by Mulligan et al. (2000). This scenario simulates the conversion of forest to pasture as spreading from roads and agricultural frontiers, in an epidemiological fashion or a propagation wave through 22 iterations in this catchment.

## **5.2 Model description**

A 1D model was initially implemented at the plot scale in a spreadsheet form. The same model routines were then implemented using GIS for the 1D and 2.5D spatial distributed model. The 1D and 2.5D models are based on 25-m grid cells and cover approximately 6 km<sup>2</sup>. Flux

physical properties are included in the surface flux interchange between cells. Overland flow in the 1D model is computed for the hydrological balance among soil moisture, porosity, and rainfall, and does not accumulate for the next time step. Spatially distributed components were added for surface flux exchange in the 2.5D model. This accumulates the overland flow and feedback with the surface remaining water for the next pixel down-slope direction in the next time step, until it reaches the drainage channel or was infiltrated in cross-down direction or evaporated toward the atmosphere. All routines were run under this time interval, updating all variables every hour. The GIS software used for modelling was PCRaster (Utrecht University, 1996).

### 5.3 Model module sequence

Model execution starts with the reading of date and precipitation data from the input file. With the date and time the solar module computes the incident solar radiation for each pixel. Then cloud cover is computed followed by net radiation, which is used in the computation of potential evaporation. Intercepted rainfall is computed using an image of vegetation type, which the first image of the scenarios, derived from TM Landsat image (Museo de Historia Natural, 1989), and the following iterations use the vegetation cover images created from remote sensing data and then with the dynamic LUCS scenario, which are complemented with vegetation parameters. The potential evaporation module is then used to compute canopy evaporation using the energy extinction according to LAI. Evaporated water from the canopy and effective rainfall (direct rainfall plus throughfall) are outputs from the interception module. This effective rainfall is used in the infiltration module to estimate the soil water infiltrated, recharge and surface water as overland flow. The overland flow module computes the accumulated surface water, which is moved between cells; then erosion is finally computed.

The units used within the models are  $\text{KJ}\cdot\text{m}^{-2}$  for energy and  $\text{mm}\cdot\text{h}^{-1}$  for water fluxes. All fluxes for the analysis use this unit in order to be able to compare and evaluate the results. Erosion is computed as depth of removed soil ( $\text{mm}\cdot\text{h}^{-1}$ ).

Cumulative images and average values are used to summarise flux values within the sub-models. The main model outputs variables are: solar radiation, cloud cover, net radiation, rainfall interception, effective rainfall, infiltration, matric potential, hydraulic conductivity, soil moisture, recharge, overland flow and erosion.

### 5.4 Data used in the model

The only input data variable in the model is rainfall. In the 1D model the rainfall value is used directly from the input file. In the 2.5D model rainfall it is distributed through the catchment surface using a rainfall elevation function derived from IDEAM weather station (20 de Julio – 2200 masl-) and Tambito weather station (1450 masl), (Mulligan et al., 2000) using the annual rainfall. The derived rainfall distribution function combined with the elevation and rainfall of Tambito station is presented in Rincón-Romero (2001).

### 5.5 Modules and model characteristics

The model starts with the energy balance and solar radiation module, which computes the incident energy in the top atmosphere at hourly intervals, depending on earth movements and topographic characteristics. Iqbal (1983) describes the solar radiation routines used in the module, which gives extraterrestrial solar radiation (I<sub>0</sub>) in  $\text{KJ h}^{-1}$ . Cloud and atmospheric attenuation are then taken into account to calculate the attenuation energy, which is computed using a sinusoidal function of elevation angle (Rincón-Romero, 2001). Net radiation was computed as the difference between measured incoming solar radiation ( $\text{KJ h}^{-1}$ ) and reflected energy by surface ( $\text{KJ h}^{-1}$ ) (Jetten, 1994, Mulligan, 1996), which values were obtained from recorded weather station data. Then Net radiation is modelled by the regression solar radiation model ( $R_t$ ) and net radiation calculated  $R_n$  ( $\text{KJ h}^{-1}$ ). Potential evaporation ( $E_p$ ) is computed by a simple relationship between net radiation ( $R_n$ ) and the computed average latent heat ( $L$ ) and is  $2.445 \text{ cal g}^{-1}$  (Mulligan, 1996).  $E_p$  is given in  $\text{mm h}^{-1}$ .

Precipitation was downscaled using the PATTERN model (Mulligan, 1996) which, in turn, uses the Monte Carlo rainfall generator and is based on local data from weather stations in areas near the study site. Data for a complete year, at an hour resolution, were thus obtained because the rainfall data available at the weather stations were incomplete. Rainfall was spread on the surface watershed pixel by pixel using digital elevation model (DEM) and a linear regression based on rainfall monthly average and elevation of the nearest IDEAM weather station data. The selected weather stations were located on the same elevation range and latitude to Tambito hydrological stations. From this criteria the annual rainfall of the source data is 7325 mm at the lower area of the watershed, and the modelled annual average by  $m^2$  for the watershed yield up to 12000mm (Rincón-Romero, 2001). To compute the rainfall intercepted by vegetation, the interception module uses Rutter's modified (1971, 1975, and 1977) model, which was designed for modelling time steps shorter than 1 hour.

In the case of forests, the intra-canopy evaporation was calculated as energy extinction, using the exponential extinction curve relative to cumulative leaf area. This was calculated based on photosynthetic active radiation (PAR) data collected at the forest plot with sensors at three different height (2,4, and 6m) (Rincon-Romero, 2001). The light extinction coefficient  $k$  was computed at 0.2672. Effective precipitation derived after interception (including through fall) was calculated as the rainfall reaching the soil (Rain  $mm\ h^{-1}$ ). The vegetation parameters used in interception module were derived from collected samples.

Based on the amount of rainfall that reaches the soil (Rain) ( $mm\ h^{-1}$ ), the infiltration module computes the amount of water that enters the soil as infiltration and the remaining surface water as overland flow. Infiltration is computed according to Green and Ampt (1911) ( $l\ mm\ h^{-1}$ ), comparing effective rainfall intensity and soil capacity for infiltration with the instantaneous hydraulic conductivity (Rincon-Romero, 2001). Porosity, derived from soil samples, was 0.61 ( $m^3/m^3$ ); initial soil moisture parameters are 0.37 ( $m^3/m^3$ ); and soil depth, 1000 mm; these values were adopted from the soil samples data and due to abrupt landscape and the high variability of soil depth through the watershed. Pedo-transfer function was used to calculate hydrological conductivity, matric potential, saturated hydrological conductivity, and recharge (Recharge  $mm\ h^{-1}$ ) (Saxton et al., 1986). These values are computed for every time interval and are integrated within the models. The flow diagram (Figure 2) indicates the flux path and module sequence for calculation.

The overland flow module computes the amount of water remaining on the surface and the amount of water moving on the surface between cells. This module computes Hortonian overland flow, subsurface flow, saturation overland flow, and ground water.

Where Inflow and Outflow are the inflow surface water coming from the up slope pixel and the out flow is the surface water going to the next pixel down slope direction, which is going to be used as part of overland flow in the next time step in the following pixel in the 2.5D model. For the 1D model these variable were not taken into account.  $E_t$  is the fraction of surface water evaporation computed as available surface water proportion of  $E_p$  ( $mm\ h^{-1}$ );  $I$  is the infiltration for this time step ( $mm\ h^{-1}$ ).

Overland flow is then used in the erosion module to calculate the amount of detached soil per cell, using Thornes (1983, 1990) approach. The parameter values used in the erosion equation were determined empirically –erodibility factor  $k$  0.19,  $m^2$  and  $n$  1.6667– taking in account the analysis by Thornes and Gilman (1983) and were determined empirically. Erosion is given in  $mm\ h^{-1}$ . Erodibility factor  $k$  was determined by soil physical properties for sandy loam soil with an organic matter content more than 3.5%, derived from USLE erodibility factor table (Kirkby and Morgan, 1980).

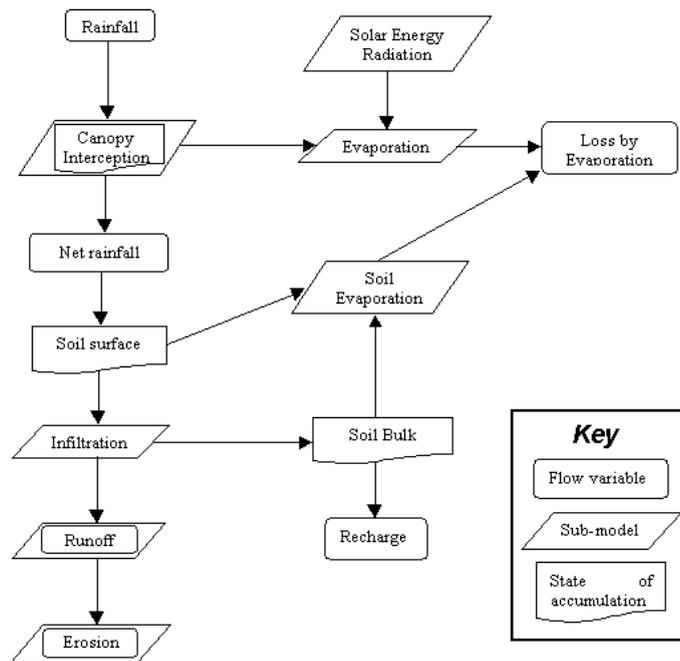


Figure 2. General diagram of hydrological model.

## 6. Results

The hydrological model sensitivity is reported first of all, at the plot scale (1D model) for all parameters within the model, secondly at the catchment scale (2.5D model), analysing the implications of surface connectivity and the relationships between hydrological flux changes with the landscape topographic variables of forested and deforested areas. The collection of initial parameter values was described in the previous chapter, as well as the data used for model parameterisation.

Sensitivity analysis for the 1D model indicates which are the most important parameters within the model and the most sensitive variables to parameter changes (table 1). Sensitivity analysis for the 2.5D model shows the relationship between overland flow and erosion sensitivities with respect to landscape topographic characteristics, and in relation to the position of deforested area within the catchment. Sensitivity analysis identifies the most sensitive areas to land use change and the relationship of these with the surface physical properties.

From the parameter sensitivity analysis in the 1D model, the most important parameters within the model are vegetation cover, soil texture, soil porosity and soil depth. Erodability factor  $k_1$  and  $m$  and  $n$  parameters of the erosion equation produce important changes only in erosion. From this is clear that erosion is the most sensitive variable from the model. Other parameters produce small changes in the hydraulic variables, which are taken into account in the analysis. Vegetation cover protects soil from direct rainfall and according to the type of vegetation, change in OF and E can be very significant within the watershed. Table 2 shows a summary of variables sensitivity to parameters variation.

Parameter	Initial value
A value in the net radiation equation	0.85
B value in the net radiation equation	16.97
Light extinction in the evaporative energy inside of forest canopy	0.27
Leaf area index	3.26 m <sup>2</sup> . m <sup>-2</sup>
Canopy maximum storage capacity	0.2 mm
Vegetation cover	91%
Soil texture (sand, clay and silt)	57.03% , 21.8% , 21.23%
Soil porosity	0.61%
Soil depth	1000 mm
Erodibility factor $K_I$	0.2
$m$ value of erosion equation	2
$n$ value of erosion equation	1.67

Table 1 Parameters used in the physical hydrological model

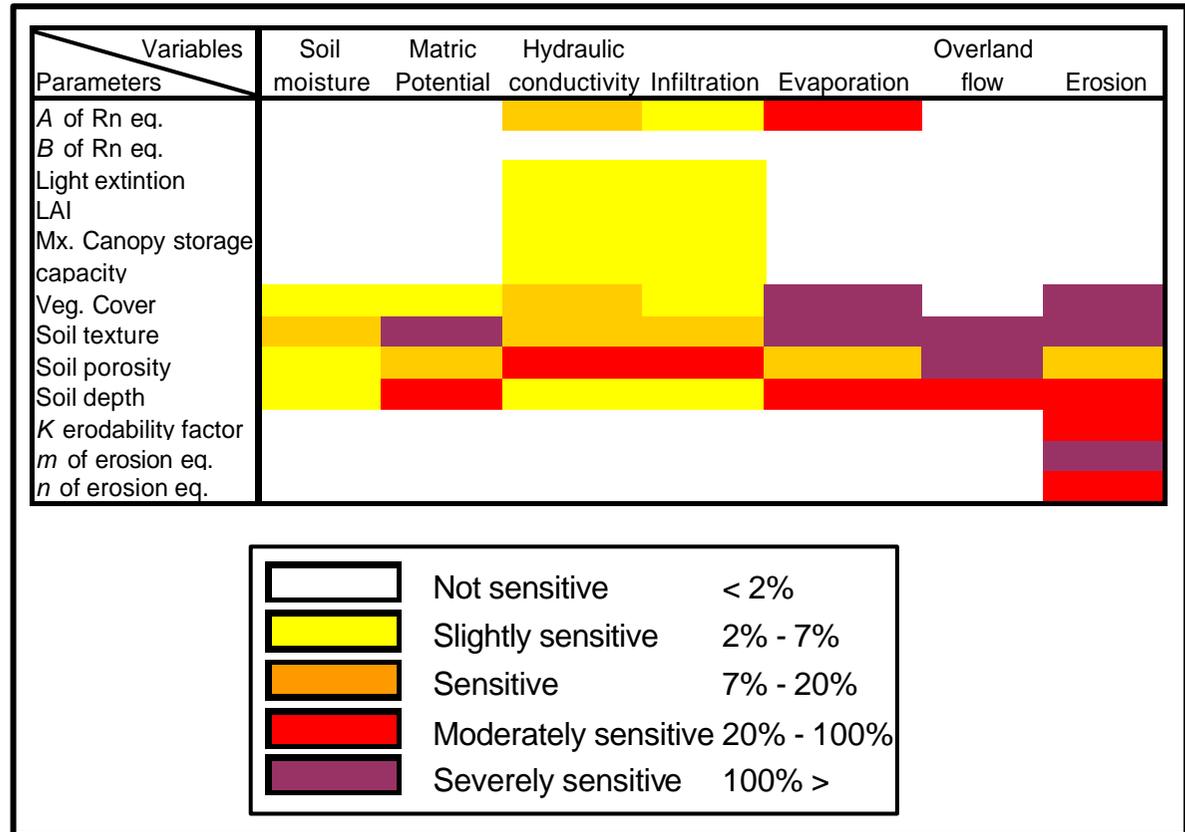


Table 2 Summary of 1D sensitivity analysis by classes

Sensitivity analysis was carried running for a year simulation period for each iteration at an hourly time step, using the 2.5D model developed in PCRaster (Utrecht University, 1996) for the whole catchment. Model initial conditions were taken from modelled results produced at the end of a one-year pre-run. Overland flow (OF) and erosion (E) were the variables taken into account in the analysis. The last nine months of the simulated year were summarised using the one year average by  $\text{m}^2$  for each of the flux variables. This was done to avoid the inclusion of data from the period when the model was adjusting to initial conditions. Three months were shown to be enough time for model recovery (see Rincón-Romero, 2001). Three different initial soil moisture conditions were used to run the model with the same rainfall events where the soil moisture takes similar pattern after the first 600 hours. The model was parameterised with the parameters adopted and with the initial image of LUCC scenario. The simulated period includes two rainy seasons and one dry season, and accounts for more than 6000 time steps in the model process.

Graphical analysis for overland flow (OF) within the scenario was undertaken and presented in a set of 9 graphics (Figures 3, 4 and 5):

- 1- Pixel average for the catchment of one year total yielded by the variables (OF in mm).
- 2- Percent variation for each variable between each LUCC iteration, given as a percentage.
- 3- Sensitivity of the variable to LUCC, which is the percent of variation between two consecutive iterations divided by the change in deforested area between the same iterations. This gives the net response per unit of deforestation. They are shown on the same scale for all scenarios to allow comparison of the sensitivities.
- 4- Total deforested area by iterations (ha) compared with mean altitude of deforested area by iteration (masl).
- 5- Mean slope and aspect of deforested area by iteration. Both are presented in degrees.
- 6- Mean topographic index and mean distance to river of the deforested area.
- 7 to 9- show the same type of information than 1 to 3, but for the erosion variable.

The OF yields different throughout the iterations. LUCC scenario has one of the largest deforested areas in the initial iterations, it is ranked third due to the average yield of OF.

The LUCC pattern in SC1 is very varied. Deforestation occurs at the beginning in the lowest part of the catchment (lower mean altitude) and where the slope is small. More than half of the area (816.4 ha) is deforested in the first four iterations, which produces an additional 35 mm in OF and 10 mm in E. For this reason, the percentage of variation of OF and E decreases rapidly. Mean altitude and mean slope of the deforested area increases gradually through the iterations, but the area deforested per iteration decreases. A few oscillations of slope in the deforested area at the end of the scenario, have some relation with the variations in OF sensitivity. The decreasing trend of mean topographic values and mean distance to the river also have some similarities with the OF sensitivity in the last iterations. Despite those variations, the OF sensitivity was very low, without large changes (range 0.002 to 0.01).

Erosion is driven mainly by overland flow, so it can be expected to have a similar behaviour. The total deforestation in the catchment produces  $3294 \text{ m}^3$  of additional erosion for the simulation period. For clarity, these values are of soil transported within the catchment, which is not necessarily equivalent to soil removed from the catchment (because of redeposition). Most of this soil is, in fact, re-deposited in other localities within the catchment. Re-deposition of this removed soil is not calculated here.

The erosion yields with the same trend as the pattern of LUCC. The minimum erosion is at the beginning of the scenario, and then increases gradually following the curve of LUCC. From this, it is clear that erosion is directly related to LUCC pattern. Erosion variation is much larger in than OF variation, ranging from 2 to 10%; percent variation of E is very similar to the percent variation of OF. The relation between E and OF is high, but the erosion sensitivity changes strongly in the final few iterations. The erosion sensitivity ranges from 0.25 to 0.6. LUCC produce that OF sensitivity decreases in the last iteration, erosion sensitivity increases markedly. The erosion sensitivity oscillations indicate that there are some differences between the physical properties of the deforested areas in each iteration.

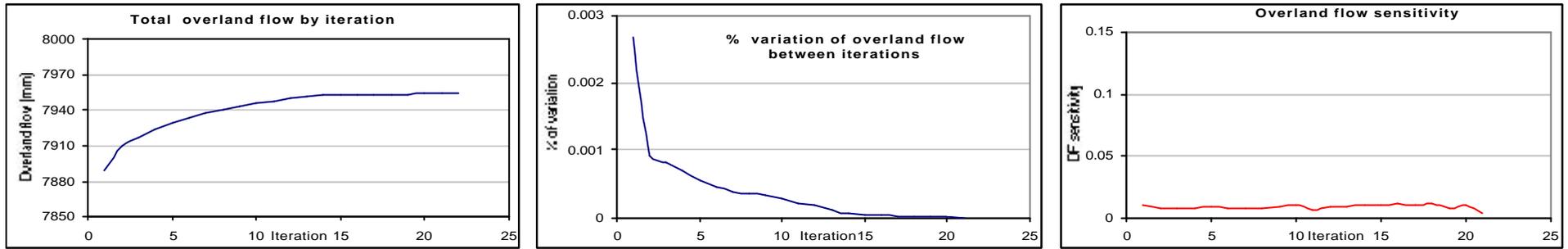


Figure 3 Overland flow sensitivity

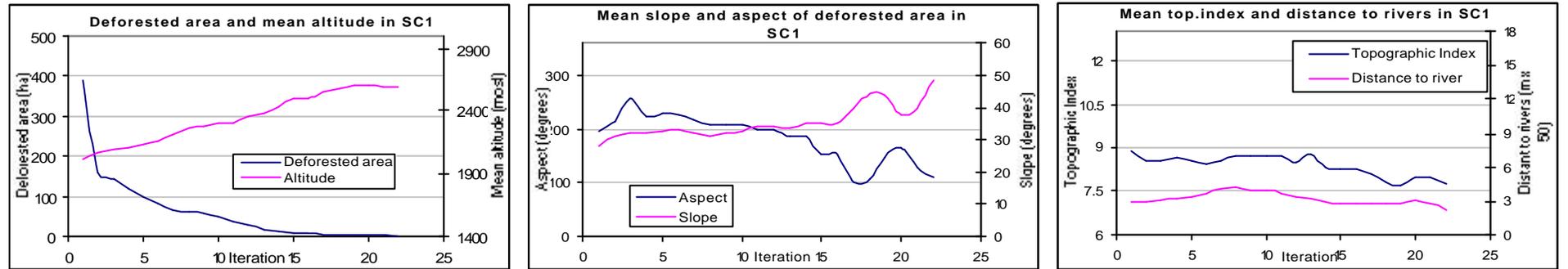


Figure 4 Mean topographic variables for deforested areas

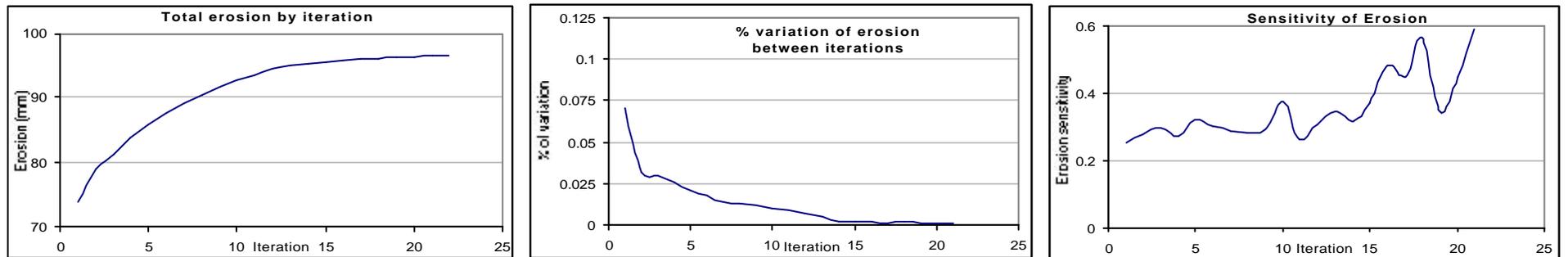


Figure 5 Erosion sensitivity

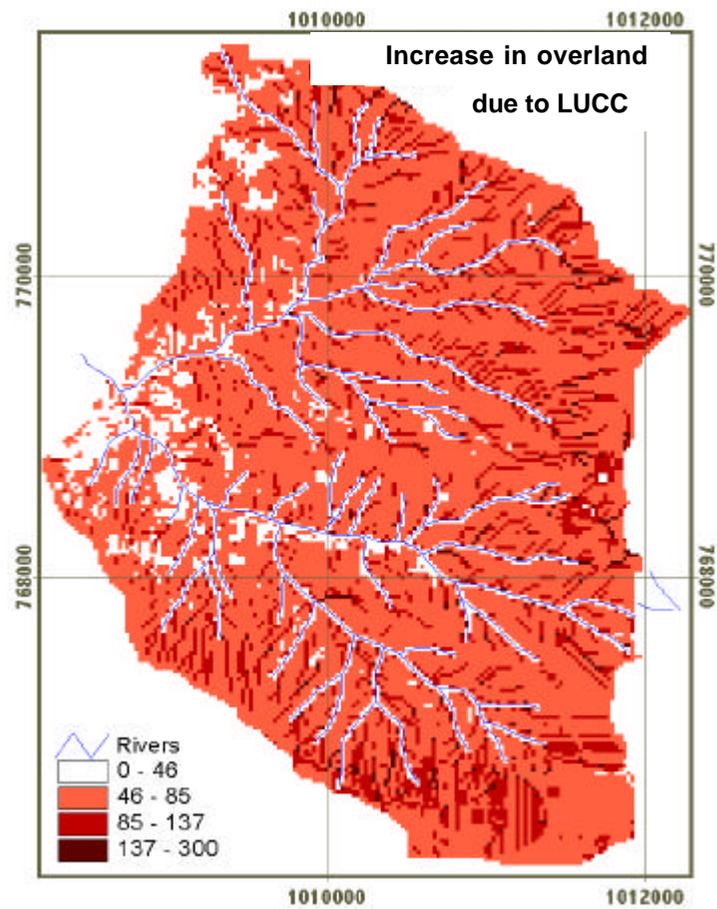


Figure 6 Changes in overland flow due to LUCC (units in mm) for a modelled year.

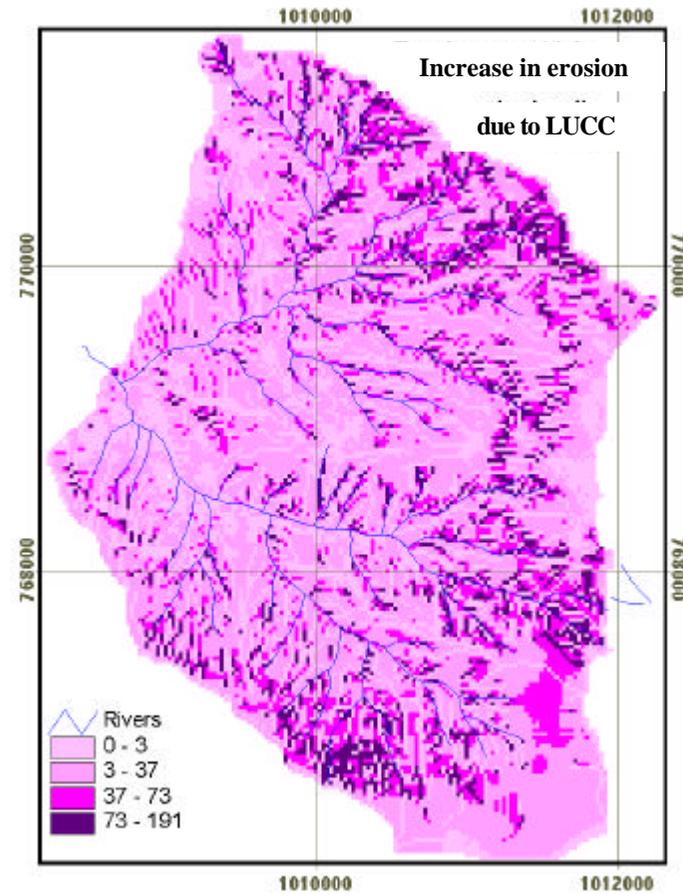


Figure 7 Changes in erosion due to LUCC (units in  $\text{mm m}^2$ ) in a modelled year

Generally E sensitivity is moderately sensitive (between 0.2 to 0.6), which needs to be considered. The highest E sensitivity occurs in the last iteration, where the deforestation occurs in the highest and steepest part of the catchment. Consequently, the mean slope of the deforested area has a great effect on OF sensitivity and E sensitivity, as does mean elevation and mean distance to rivers of the deforested area. Areas close to river channels also had high E sensitivity values. The aspect variable was not a significant control, though it appears to have some effects due to its impact on soil hydrology through evaporation.

From results it can be concluded that those areas at the top of the catchment produce the highest OF sensitivity and E sensitivity. Those areas nearest to the rivers (within 150 m), which have the steepest slopes, also produce high OF sensitivity and E sensitivity. Slope is an important factor because it determines overland flow and in particular, erosion directly. Altitude is an important factor because rainfall is highest at high elevations within the catchment and proximity to rivers is also significant factor because of the cumulative effect of runoff from large contributing areas.

From the spatial distributed analysis overland flow increased up to 300mm in a year for the areas with steepest slopes as a product of LUCC. Areas within the river channels were not taken into account, because the overland flow in these areas has different behaviour than on land areas. About 15% of the catchment area has less than 46mm of increment in overland flow. Most of these areas are in the lower part of the catchment (related with altitude) with the exception of high altitude areas at the northern side of the catchment that also has low slope. About 68% of the catchment area has an increment in overland flow between 46 and 85mm, which occurs throughout the catchment, with shallow slopes (lower of 26%) and distance from the river channels. About 14% of the area has an increase in overland flow of between 85 and 137mm, in the areas with moderate slope (around 30% of slope) or with a connection to the areas with steep slopes in an up-slope direction. Just 3% of the area shows an increase in the overland flow up 300 mm due to LUCC. These areas have steep slopes, generally with high elevation. The effects of overland flow connectivity are clearly identified.

The increment in erosion due to LUCC is strongly related to the slope of the area. Figure 6 and 7 shows those increments over the catchment with a clear relation with the steepest areas. Less than 14% of the catchment has an increment in erosion between 0 and 3mm a year. These areas are in both the highest and the lowest parts of the mountain of the catchment (related to altitude) and areas of moderate slope. About 45% of the area shows erosion increases of between 3 and 37 mm a year; those areas are where the slope is steep. 17% of the area shows increases in erosion of between 37 to 73 mm a year; they are in steeper slope areas in the down-slope direction furthest away from the river channels. Finally, the largest increases in erosion, due to LUCC, occur in areas nearest to river channels, in the highest parts of the catchment (related to elevation) with steepest slopes; those areas represent about 22% of the catchment.

## **7. Conclusions**

In terms of results clearly the landscape characteristics in the catchment combined with hydrological properties and LUCC describe different hydrological response and in consequence the LUCC effect were highlighted.

.The overall achievement of this study, is not only obtaining a better understanding of the spatial distribution of hydrological sensitivity given the spatial pattern of LUCC, but also going some way to provide an advanced and robust tool to help decision makers to develop and protect the environment, and produce the basis for further research on TMCF hydrology and the impacts of LUCC.

The sensitivity analysis of the spatial variability of hydrological sensitivity within the watershed has identified the importance of the spatial distribution of landscape physical properties with respect to where the LUCC occurs and the differing levels of impact if the same LUCC is applied to different parts of a catchment.

In terms of strategy, The GST applied in the model conception and moreover systems complexity addressed in this exercise shows that landscape natural representation still a challenge and also a long way to go, but the results included here assess an effort done with good approach, in order to adapt tools, knowledge, strategy, data and general concept to highlight aspect of natural process that are needed to take into account in a catchment planning process, and more precisely all regarding with LUCC.

Further research is needed in this field with in addition to natural processes also can be include social, cultural, political and as well economic aspects within the model, to continue building these approaches in more realistic way and also increasing the model complexity but also simplified the output result for easy understanding of this reality in that artificial representation of natural processes.

## 8. References

Abbott, M. B., Bathurst, J. C., Cunge, J. A., O'Connell, P. E., and Rasmussen, J. 1989. An Introduction to the European System – Systeme Hydrologique Europeen, "SHE", 2. Structure of a physically-based, distributed modelling system. *Journal of Hydrology*, 87: 61 – 77.

Anderson, M. G., and Burt, T. P. 1985. *Hydrological forecasting*. John Wiley & Sons Ltd. Chichester, UK.

Bathurst J. C., Wicks J.M., and O'Connell P. E. 1995. The SHE/SHESED Basin Scale Water Flow and Sediment Transport Modelling System. In: Computer models of Watershed Hydrology. Edited by Vijay P. Singh. Department of Civil and Environment Engineering Louisiana State University, Baton Rouge, LA 70803-64405, USA.

Beven, K. J. 1989. Changing ideas in hydrology – the case of physically-based models. *Journal of Hydrology*, 105: 157 – 172.

Bonell, M, and Balek, J. 1993. Recent Scientific Developments and Research Needs in Hydrological Processes of the Humid Tropics. In: Hydrology and Water Management in the Humid Tropics. Hydrological research issues and strategies for water management. Edited by Michael Bonell, Maynard M, Hyfschmidt and John S. Gladwell. International hydrology series, Cambridge University press, UK.

Calder, I.R., Hall, R.L., Bastable, H.G., Gunston, H.M., Shela, O., and Chirwa A. 1995. The impact of land-use change on water resources in Sub-Saharan Africa. A modelling study of lake Malawi. *Journal of Hydrology*. 170, 1-4: 123-135.

FAO, Food and Agriculture Organization, 1997.  
[Http://www.fao.org/gtos/about/gtodbdir/GTOSa001.html](http://www.fao.org/gtos/about/gtodbdir/GTOSa001.html).

Feldman, A. D. 1995. HEC-1 Flood Hydrograph Package. Computer models of Watershed Hydrology. Edited by Vijay P. Singh. Department of Civil and Environment Engineering Louisiana State University, Baton Rouge, LA 70803-64405, USA.

Fundación PROSELVA. 1996. Land use map of the Tambito watershed. Internal document, Universidad del Cauca.

Green, W. and Ampt, A. 1911. Studies on Soil Physics – Oart I. The flow of air and water through soils. *Journal of Agricultural Science*, 4: 1-24.

Huber, W. C. 1995. EPA Storm Water Management Model – SWMM. Computer models of Watershed Hydrology. Edited by Vijay P. Singh. Department of Civil and Environment Engineering Louisiana State University, Baton Rouge, LA 70803-64405, USA.

Iqbal, M. (1983). An introduction to solar radiation. Academic Press. Toronto, Canada.

Jetten, V.G. (1994) Modelling the effects of logging on the water balance of a tropical rainforest. A study in Guyana. Tropenbos Series 6. The Tropenbos foundation. Wageningen.

Department of Physical Geography, Faculty of Geographical Sciences. Universiteit Utrecht, P.O.Box 80.115,3508 TC Utrecht, The Netherlands.

Kirkby, M.J. and Morgan, R.P.C. 1980. Soil erosion. John Wiley & Sons Ltd. Norwich, UK.

Kirkby, M. J., Naden, P. S., Burt, T. P., and Butcher, D. P. 1993. Computer Simulation in Physical Geography. John Wiley & Sons. Chichester, U.K.

Laurenson, E. M., and Mein, R. G. 1995. RORB: Hydrograph Synthesis by Runoff Routing. In: Computer models of Watershed Hydrology. Edited by Vijay P. Singh. Department of Civil and Environment Engineering Louisiana State University, Baton Rouge, LA 70803-64405, USA.

Mulligan, M. Rubiano, J. and Rincón-Romero, M. 2000. Hydrological sensitivity to progressive deforestation in a tropical montane environment. Submitted to Hydrological Processes.

Mulligan, M. 1996. Modelling the complexity of landscape response to climatic variability in semi arid environments. In: M.G.A. Anderson & S.M. Brooks (eds.) Advances in Hillslope Processes, Wiley, Chichester: 1099-1149.

Museo de Historia Natural, 1989. TM Landsat image for the study area.

Pack, C. C. 1992. Tropical Rain Forest. Biddles Ltd. Guildford and King's Lynn. UK.

Rincón-Romero, M. 2001. Modelling the hydrological sensitivity to land use change in tropical mountainous environments. Ph.D. thesis King's College, London, UK.

Rutter, A.J. Kershaw, K.A. Robins, P.C. and Morton, A.J. 1971. A predictive model of rainfall interception in forests. 1. Derivation of the model from observations in a plantation of Corsican pine. Agricultural Meteorology 9:367-384.

Rutter, A.J. Morton, A.J. and Robins, P.C. 1975. A predictive model of interception in forests. II. Generalization of the model and comparison with observations in some coniferous and hardwood stands. Journal of Applied Ecology 12:367-380.

Rutter, A.J. and Morton, A.J. 1977. A predictive model of rainfall interception in forests. III. Sensitivity of the model to stand parameters and meteorological variables. Journal of Applied Ecology 14:567-588.

Saxton, K.E. Rawls, W.J. Romberger, J.S. and Papendick, R.I. 1986. Estimating generalized soil-water characteristics from texture. Soil Science Soc. American Journal 50:1031-1036.

Singh, V. P. 1995. Computer Models of Watershed Hydrology. Vijay P. Singh (ed.). Water Resources Publications. USA.

Speers, D.D. 1995. SSARR model. Computer Models of Watershed Hydrology. Water Resources Publications. Edited by Vijay P. Singh. USA.

Utrecht University, 1996. PCRaster Environmental Software V.O.F. Derk-Jan Karssenbergh, and the Department of Physical Geography. The Netherlands.

Thornes, J.B. and Gilman, A. 1983. Potential and actual erosion around archaeological sites in southeast Spain. Rainfall simulation, runoff and soil erosion. Catena Supplement 4, Braunschweig: 91-113.

Thornes, J.B. 1990. The interaction of erosional and vegetation dynamics in land degradation: spatial outcomes. Vegetation and erosion processes and environments. J. Thornes (ed.). John Wiley & Sons Ltd., London, UK.

Woolhiser, D. A. 1996. Search for Physically-Based Runoff Models – A hydrologic El Dorado. Journal of Hydrology, 122, 3: 122 - 129.