CONTRASTING TWO CATCHMENTS WITH HYDROLOGICAL MODELLING IN THE GUATIQUIA RIVER BASIN, PARAMO CHINGAZA, COLOMBIA

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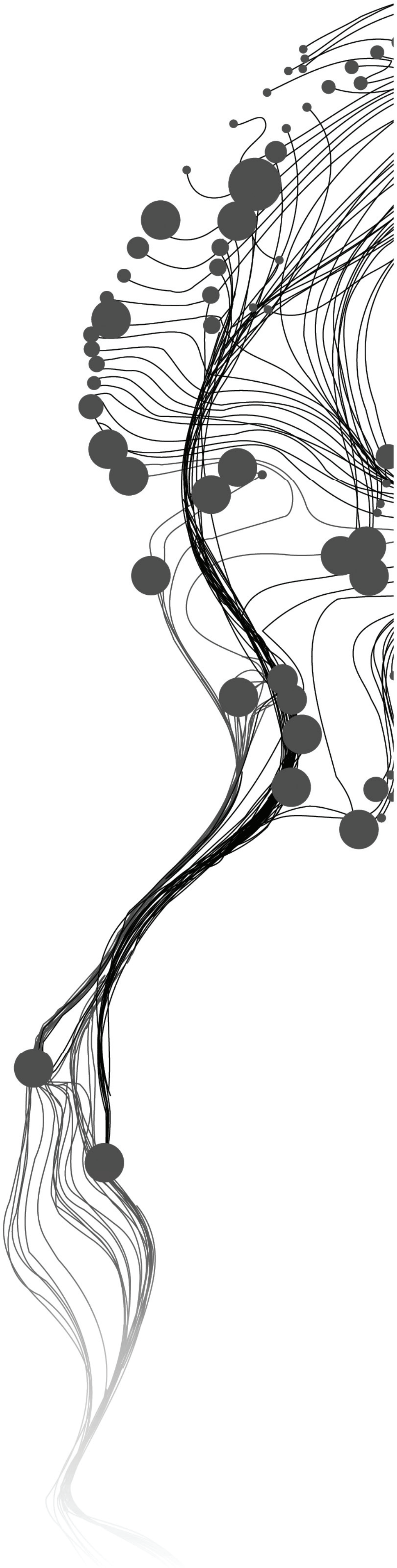

MOUNTAIN HYDROLOGY COLOMBIA

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ABSTRACT

The water cycle in the Andes mountains is poorly understood due to lack of research and reliable data series. Understanding the role of a land cover or an ecosystem in local and regional rainfall runoff relations is just required to take decisions over a catchment, as extreme climatic conditions and changing landscapes, pose a threat on water supply. For watershed management, in this case water supply, it is valuable to have answers or approaches based on research.

In order to have a better understanding of the local hydrological cycle and its relation with the land cover, a hydrological analysis was done. A quality analysis was performed on the data acquired from different initiatives and remote sensing and GIS is used to investigate the landscape and land cover. A land cover change was assessed since 1977 with Landsat images.

Finally it is a successful application of the Topmodel (Beven & Kirby 1979) to simulate run-off for alpine and forested catchments in the tropical Andes region. Even though the simulations are not able to reproduce the complete observed behaviour of the run-off for the systems studied, it satisfactorily explains the behaviour for some parts of the hydrograph. Correlation coefficients result in values as high as 0.87 for the Paramo catchment and 0.71 for the forested one. The errors present in the discharge measurements, as well as the fact that not all the precipitation events could be described, in addition to the propagation of incorrect rainfall measurement in overall precipitation for the catchment into the simulations, limit the correlation results. Sensitivity analysis of the simulations to changes in the parameters that control; recession, soil depth, transmissivity and root zone's effective depth, was done showing their importance and effect on the simulations. A calibration & validation exercise was done on split data sets. Finally the simulations for the two catchments were compared. The fitted parameters lie in a close range, being both systems at the moment explained with similar parameter values, coinciding with their characteristics; shallow soils and low hydraulic conductivity.

The ground meteorological data contained gaps. Using simple procedures the data series were completed and estimated daily rainfall from point measurements to the total precipitation over the studied systems. There was no general clear trend in precipitation records, while the 15 year temperature series show a considerable increasing trend. The study area showed no significant land cover change, consequence of an effective management of protected areas and the adaptation of management by local communities.

The temporal resolution & data quality is limiting the answers of this research. It is necessary for research to continue in this line, with finer temporal resolution and more instrumentation for local and regional watershed assessment.

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To my friends and fellow students, success and enjoy.

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1. INTRODUCTION

1.1. Background

Reliable estimation of the hydrological cycle over the Andes mountain region is important for basin management. Millions of people on different locations along the Andes and on its plains are being provided mountain water in with varying quality and quantity. For example the three highest capital cities in the world, Bolivia`s capital La Paz at 3650 meters above sea level (MASL) Ecuador`s capital Quito at 2800 MASL and Colombia`s capital Bogota at 2600 MASL are highly dependant on high mountain ecosystems as well as rain water. Many glaciers in the Andes however, like the Chacaltaya on which La Paz is dependent for its water supply, are disappearing.

High mountain ecosystems offer a significant importance for the environmental goods and services they offer to human communities and as reservoir for the species that inhabit it. They are considered as an environment where global climate changes will manifest notably (Ruiz, 2008, Garcia, 2003).

Even more when facing changing conditions and increasing water demand, watershed management requires knowledge on the processes in the hydrologic cycle. The water consumed in the Andes region comes from high mountain systems, being glacier, Paramo and forest ecosystems, determinant in the water provided by these catchments. The significance of the different land use and cover on the hydrological cycle on the Andes mountains is large, but still few studies exist.

For management decision and strategies it is important to have knowledge about the water cycle. In this cycle the precipitation is the source term and surface runoff and evapotranspiration, the sink terms. For the study area annual precipitation of 2000 mm to 2500 mm are common and values of 800 mm to 1000 mm of potential evaporation are commonly accepted. This leaves the runoff to be around half or more of the precipitation. Consequently in this cycle the precipitation is the source term and surface run-off and evapotranspiration, the most dominant sink terms.

It is of key importance to be able to estimate surface runoff at any point a catchment. This surface runoff can be measured at the outlet as stream discharge. Outflow is the expression of what is happening in the catchment. In relating discharge to surface runoff two variables are important; discharge rates and the time-delay of the surface run-off to produce discharge at the outlet. The amount of discharge depends greatly on the amount of water available through precipitation over the catchment, and the water loss through re-evaporation of the precipitation, evaporation from the soil and transpiration by the vegetation. The timing of the discharge depends primarily on the distance between the location of the rainstorm and the outlet. This is also affected by the routing of the discharge, the amount of precipitation and finally on the vegetation type, soil wetness, depth and hydraulic conductance.

So vegetation and soils grouped as an ecosystem inside a catchment should be determinant in the runoff generation and regulation. If conditions change, what would happen to its hydrological behaviour?

1.2. Problem Statemen and Relevance

Colombia has a history of extreme situations. In 1992 the country suffered from power shortages due to strong drought brought by El Niño phenomenon, plus mistakes in the reservoir controls. Daily for over a year throughout the country the electrical power was shut down from 9 to 18 hours having great social and economic impact. In the year 2010 the rainiest recorded in Colombia by IDEAM and EAAB, emergencies of great magnitude happened. In the near future such extreme conditions are predicted to become more frequent due to regional and global climate change. Having quality data is vital to gain detailed knowledge of the hydrological system. This knowledge is instrumental to predict future extremes, and is then a key factor for an effective watershed management.

The aim of this research is to contribute to the knowledge of the studied ecosystems. This knowledge is needed for the design and adaptation of national, regional and local water resources policies to climate change. The importance of the water supply and its link to Paramo ecosystem has placed it in political discussions. Colombian legislation and policy makers always link Paramo ecosystem, when considering water supply and high mountain nature conservation strategies and actions. Currently many efforts and funds are oriented that way; to prioritize, recover and protect natural systems. The results of this research in a watershed analysis help pave the way for more advanced applications like quantifying ecosystem function and services. It can also aid in the calculations of water supply for consumption and irrigation, hydro power and inputs for a flood plain in flood studies.

The following questions concerning the water supply form the Andes Mountains are important to address: For a catchment where there are plans to construct a reservoir, how much water are the different subcatchments providing and what is the impact downstream of removing 1? What is the role of a land cover or an ecosystem and soil on the runoff behaviour and what is the importance or value of one system over another? Paramo ecosystems have been attributed with water regulation capacity, such attribute is given by being able to retain water and slowly release in drier spells, assuring a constant water supply downstream. For forested systems not much priority has been raised, then studying the hydrological behaviour of these two systems could help for a better understanding of them, and the effect of replacing one land cover for another in a catchment, on the water cycle and runoff generation.

2. OBJECTIVES & RESEARCH QUESTIONS

2.1. Research Objective

The objective of this research is to identify and contrast the hydrologic behaviour of two watersheds with different land cover, a forested system with a Paramo system. This will be performed by calibration of rainfall run-off simulations to measurements and comparison of the fitting parameter and hydrographs for both catchments.

Specific objectives are to:

1. Analyze the land cover and its change in the selected catchments

2. Analyze the trend and variability of hydrological and climatic conditions.

3. Optimize a rainfall run-off model for each catchment.

4. Compare the parameters that gave the best runoff simulations for the different catchments.

2.2. Research Questions

1. What is the land cover of the selected catchments? How has it changed from the 1980s?

2. Is there any significant climatic conditions change for the catchments?

3. What is the difference in the parameter combination that best simulates each system?

3. BACKGROUND

3.1. Paramo Ecosystem

In the study area considerable representations of Paramo are present. These Paramo landscapes correspond to a post-glacial environment, where lakes fill numerous depressions and long and deep valleys are common (Villota, 2005). Paramo is a wetland ecosystem at high altitude in the upper Andes and is mostly found in the mountains of Venezuela, Colombia, Ecuador and northern Peru (Buytaert et al., 2006, Diaz-Granados et al., 2005). It shares characteristics with other humid tropical alpine systems in the world located in east Africa, known as Afroalpine belt and in Indonesia and Papua New Guinea (Buytaert et al., 2011). Hofstede (1995) refers to it as climax neotropical alpine grasses. In northern South America it stands between the Andean Forest and the snow line; generally can be located between 3000 and 4500 meters above sea level as illustrated by figure 3 - 1. There are different types of Paramo ecosystems due to a wide range of conditions that are present along the mountains in these altitudes (Castaño, 2002), and so the different types of Paramo ecosystems, that result from the combination of the climate, the rocks, the soil, topography and organisms (Zoneveld, 1979).

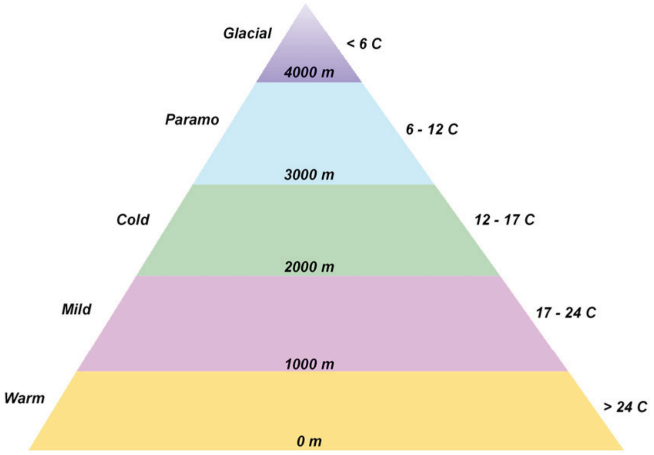


Figure 3 - 1: Altitude and regional climate systems for tropical Andes.

3.2. Land Cover

The land cover for Paramo is generalized as extended pastures. It varies from bare rock and exposed soil, patchy thick pastures to shrublands. Sphagnum bogs are found around water bodies and along saturated areas. They are a considerable water retainer (Buytaert et al. 2006, Tol G.J. & Cleed A.M. 1994), some up to 10 times their dry weight (Tobon, 2008).

In general the vegetation has adapted and specialized to the tropical alpine extreme conditions. They have low growth rates and a low evapotranspiration. Values of around 1 - 1.5 mm / day (Hofstede, 1995; Buytaert, 2004) have been calculated. Dense patches bushes and dwarf trees can exist in protected areas like small canyons along drainages.

3.3. Soil & Geology

Soils found in Paramo have volcanic origin. According to the World Reference Base for Soil Resources FAO they are classified as Andosols (black soil). They have a high content of organic matter, as the biologic degradation processes are slow in cold conditions. Aluminium in volcanic ash and organic matter combine and form alofans, resistant clusters of soil for microorganisms to degrade. These complex soils absorb water fast and release it slowly, with a retention capacity of 80 - 90 % at saturation (Buytaert, 2004; Iñiguez, 2003). Beneath these shallow soils (with layer thickness between 0.5 to 1 m.) with high contents of decaying matter, extends an impervious bed of claystone and sandstone.

3.4. Changing Landscape & Climate

Generally Paramo is pressured in several ways. The local community extracts flowers, leaves and plants to sell on the road or local shops, and on winter time, demand rises for lichens and mosses for decorations. Local farmers have been using increasingly the highland pastures for grazing and for crops like potatoe and onion. Some studies have been performed on the effect of land use changes on Paramo related with the regulation capacity, and determined that a ploughed and compacted Paramo will loose its regulation capacity. Relations between the used practice of burning grazing lands and expanding pastures upward through the Paramo, have also been analyzed (Buytaert et al., 2005, Hofstede, 1995). Deforestation, fragmentation and mining are creating serious impacts on these environments mountain.

Finally, land use change also has effect on local climate. Land use change at the slope scale affects microclimatic conditions at high mountain locations, therefore adding to the feedback mechanism of local and regional change in conditions, climatic anomalies. For example deforestation can cause loss of interception of rising clouds, and more vapour available for precipitation upland.

The alofan clusters of water absorbing soil mentioned earlier, maintain their structure at low temperatures. At increasing temperature scenarios, the Paramo will start loosing regulation capacity (Tobon, 2008) facing the entire system based on its supply on a near crisis. For a profile in a mountain an estimation of a shift upward of 100 meters was made for each 0.6 degree rise (Buytaert et al., 2006). If this happened, it could be considered an important regulation threat for future water availability. And not only water supply will be at risk by the rising temperatures, the alofan cluster when degrading will release the carbon, liberating high loads to downstream systems.

4. STUDY AREA

4.1. Study area: Northern Andes

The study area is shown in a national map (Figure 4 - 1) where its location as part of the Orinoco basin can be observed. The predominant local climate can be described as low temperature, high moisture, low radiation due to persistent clouds, low atmospheric pressure, intense UV radiation and constant drying effect of the wind (Buytaert et al. 2006). In the figure 4 - 1, the 3000 meter elevation line is depicted with the location of the study site in a red circle.

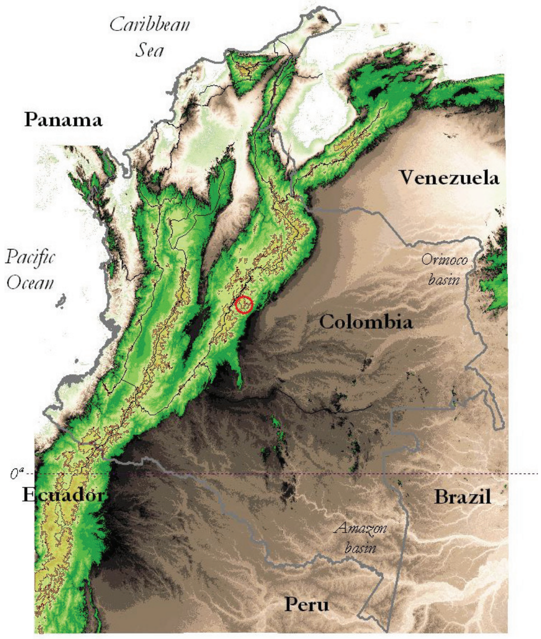


Figure 4 - 1: Location of the study site in a topographical national map.

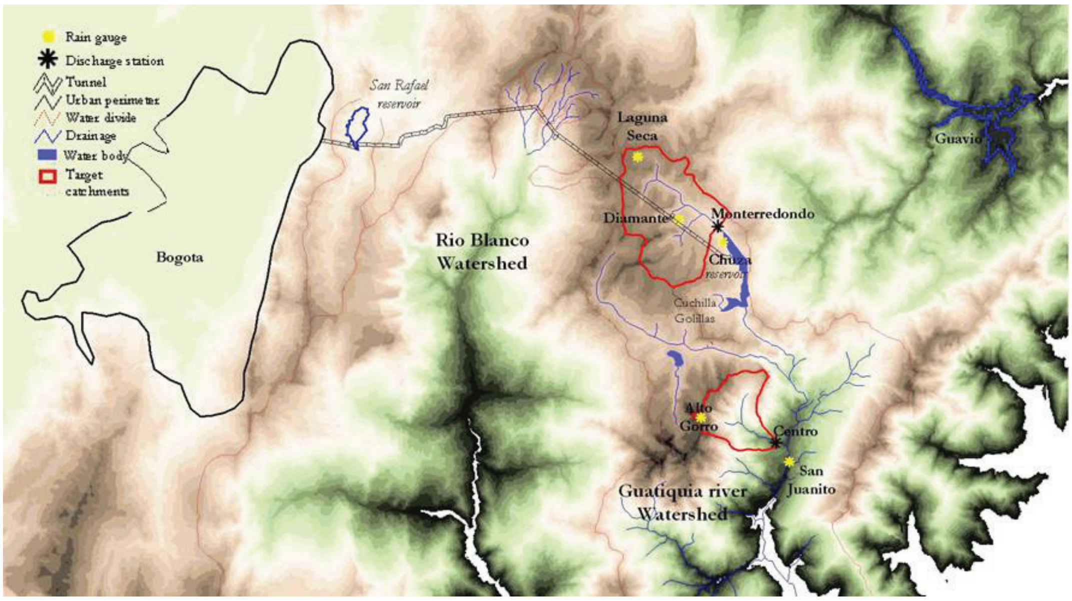


Figure 4-2: Area of interest.

Water supply for a growing city like Bogota is vital, most of the water (80%) consumed in it and surroundings, estimated around 8 million people (EAAB), come from the Chingaza system. From the Chuza water body tunnels take the water to the capital.

San Rafael reservoir serves as a stand by storage before its distribution. Some extra currents from Blanco river are drained into the tunnels, adding to the supply, as San Rafael's reservoir catchment does too.

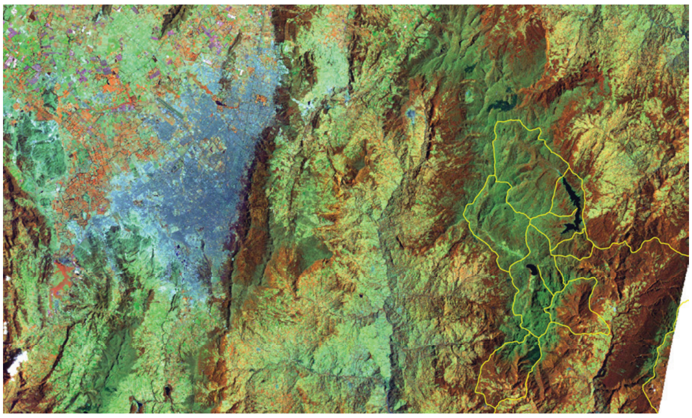


Figure 4 - 3: Landsat image of interest area.

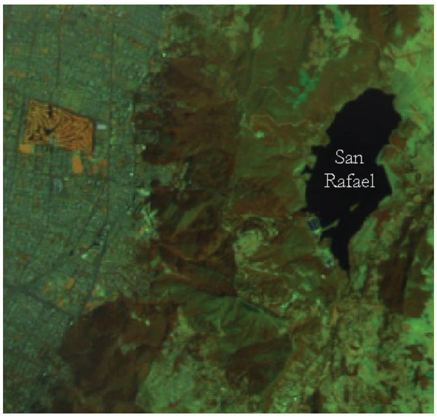


Figure 4 - 4: Landsat zoom in.

Two catchments are chosen for this research: the Chuza and the Guajaro watersheds, each described below and shown in Figure (4 - 2-6). These catchments are located some 18 km apart.

- **Chuza.** Located at 40 km from Bogota, the Chuza catchment is almost 100% Paramo, except for some bushes and tree patches located in protected, concave areas. For the present research this catchment is considered to be 100% Paramo. The Chuza watershed is about 7000 ha. It ranges in altitude from 3000 MASL at its outlet to 3800 MASL at its highest peak. From its altitudinal range it is a typical Paramo, and by its location and hydrology, a typical wet Paramo.

- **Guajaro.** The land cover for the Guajaro catchment, is 25% Paramo at the high altitudes, 70% Forest in the middle and 5% cattle grassing grasses at the low part, in the Guatiquia river valley, bordering area of the Chingaza national park. The Guajaro watershed is about 2900 ha. As the Chuza catchment they are subcatchments of Guatiquia river that drains into the Orinoco river. The Guajaro catchment ranges in altitude from 1800 MASL at its outlet, to 3900 MASL at its highest peak, Alto del Gorro, giving the name to the nearby station.

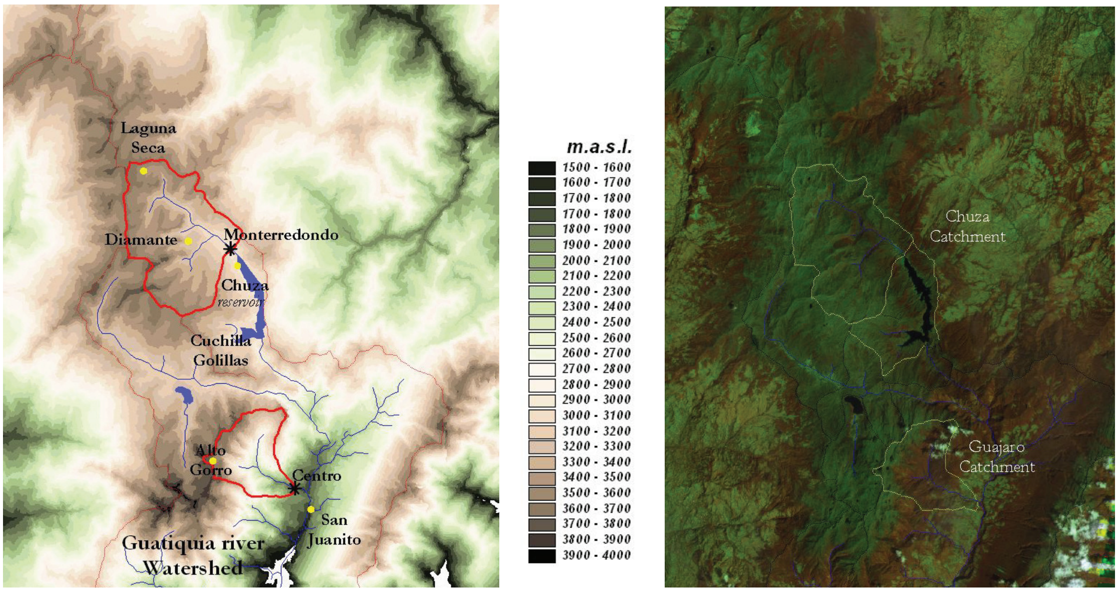


Figure 4 - 5: Studied catchments; SRTM & Landsat backgrounds.

4.2. Measurement Stations

- **Chuza catchment**. There is one discharge station at its outlet and 2 rainfall stations. This catchment within the Chingaza national park (Figure 4 - 6) has been preserved in a natural state since 1977 as a key component of the water supply system for Bogota city and surroundings, and its importance for Andes biodiversity (4.60 N, 73.72 W).

- **Guajaro catchment.** Has one discharge station at its outlet and one rainfall station at its highest part, Gorro peak (4.46 N, 73.68 W).

Records at the stations consisted of daily measurements of precipitation, pan evaporation and average daily runoff. Other stations outside the catchments were used to complete rain series and to analyze temperature, like the San Juanito station close to the Guajaro catchment (Figure 4 - 5).

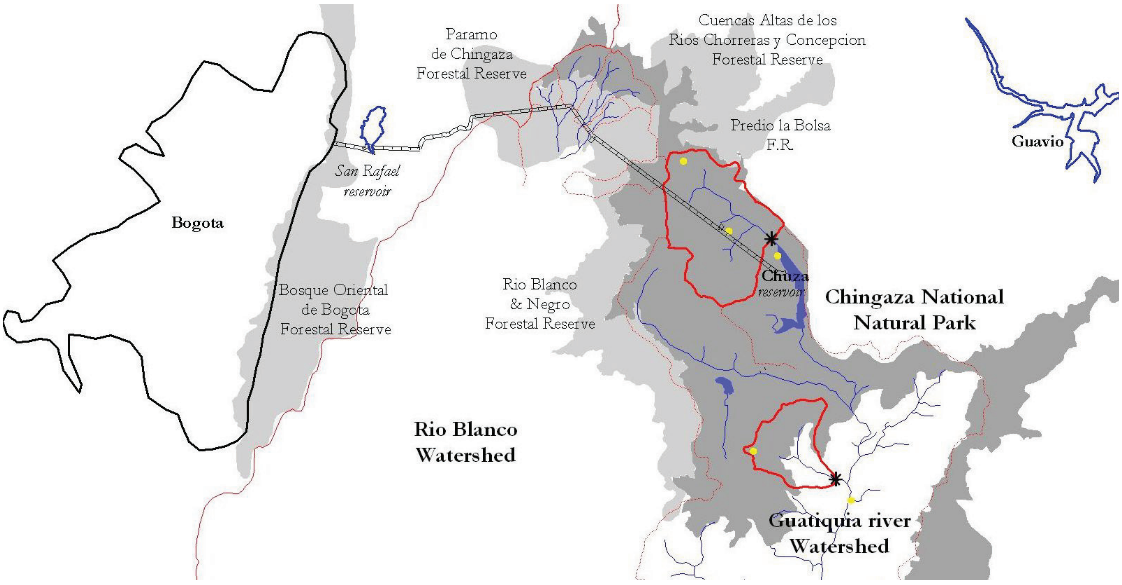


Figure 4 - 6: Protected lands declared and managed in the area.

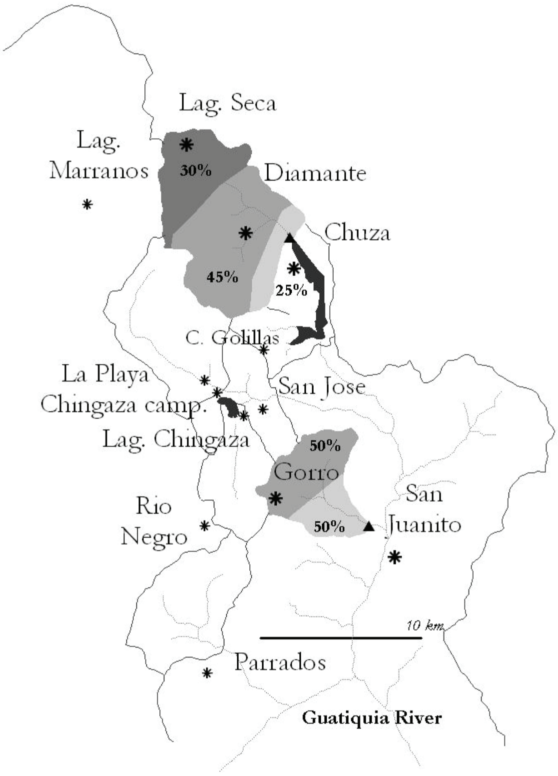


Figure 4 - 7: Rain gauge location and weight.

5. MATERIALS & METHODS

5.1. Materials

5.1.1. Remote Sensing Data

Data from the Landsat MSS, TM & ETM sensors was obtained online through the Glovis USGS website. In total 9 images were collected to visually asses the land cover change in the interest area. The dates of when the scene; Path 8 & Row 57, were taken can be seen in table 5 - 1. Some other ETM scenes were downloaded but discarded for the stripes of missing data they have, due to satellite failure since 2003.

Table 5 - 1: Landsat data set.

MSS	Jan 07 1977
TM	Mar 22 1985
TM	Jan 02 1988
TM	Mar 22 1988
TM	Dec 22 1989
TM	Mar 28 1990
TM	Aug 30 1997
ETM	Nov 16 1999
TM	Jan 01 2001
TM	Jan 22 2010

The computer work and GIS processing was done on the ITC computer clusters. The softwares used include, Ilwis, Arc Gis and Erdas.

5.1.2. Meteorological and Hydrological Data

The recorded data set was provided by the aqueduct of Bogota EAAB, in a framework of a project carried out with Conservation International Colombia and IDEAM.

5.1.3. TOPmodel IDL Code

The runoff model used is an IDL code converted from a version in FORTRAN called TMOD9502 by Scott Peckham (2002) and was provided by Tom Rientjes from the WREM department at ITC. It is a version already used in previous research in the department at Gilgel Abay basin, Ethiopia (Gumindoga 2010).

5.2. Methods

The objective of this research is to identify and compare the hydrologic behaviour of the Chuza and Guajaro catchments, which have different land cover. This will be performed using optimization of rainfall run-off modelling to measurements. The difference between the two systems can then be investigated by comparison of the fitting parameter combination and hydrographs. In order to achieve the research objectives the following methodology is used.

To have a summarized idea of the research steps, the flow diagram is drawn (Figure 5 - 1). First the area and topic were approached by a literature review. The hydrological and meteorological measurements are investigated for completeness and consistency. Parallel, a landscape and land cover assessment was performed using Landsat images. The SRTM DEM was processed then to obtain basic topographical parameters input for the Topmodel. The spatial data is finally translated into tables; area of topographic indexes and distance of fractions of the catchment to its outlet. The point data series were analyzed and completed to represent the catchments. Once the inputs were prepared, the simulations in IDL were done and the outputs were analyzed.

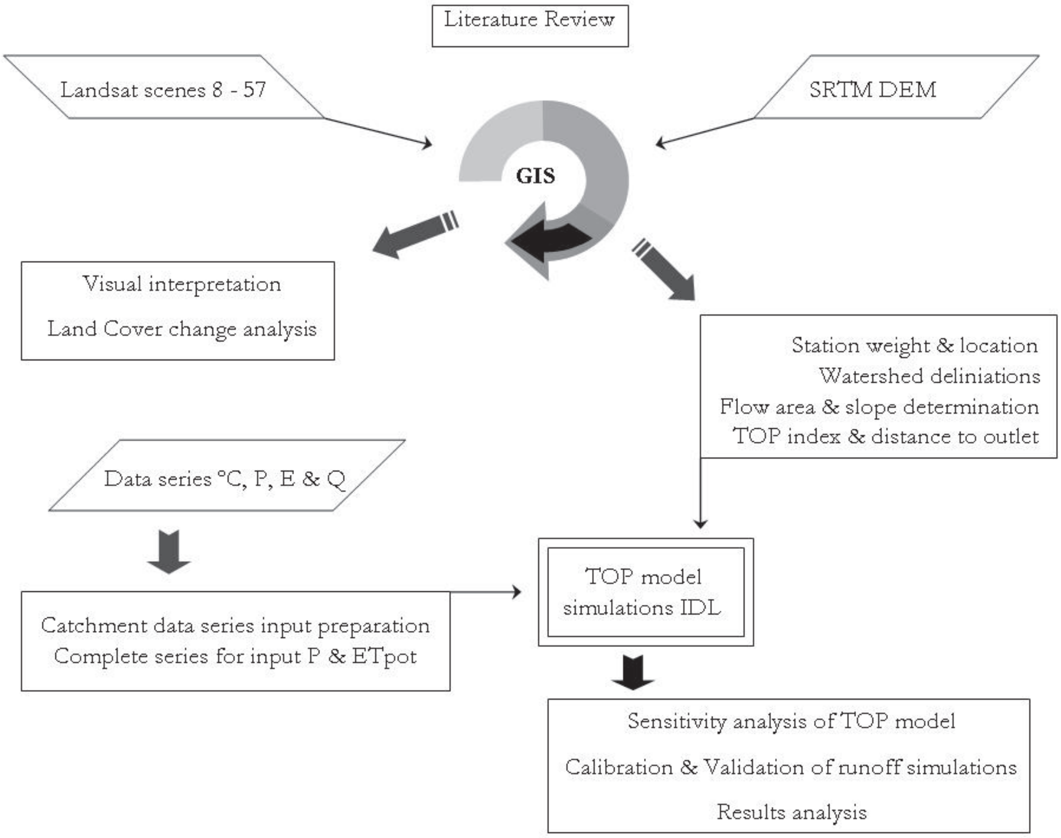


Figure 5 - 1: Research flow diagram.

5.2.1. Inspection of Hydrological and Meteorological Measurements

IDEAM provided a data set from the INAP project, of a small watershed, with temporal resolution of 15 minutes, from 2008, but could not be fully used due to lack of details on the cross section in order to convert hydraulic state into discharge. The data was plotted and analyzed, it shows potential to work on, but the runoff calculation must be correct for the exercise to be successful. Variables like channel velocity flow and concentration time for that catchment was used to set the values for the TOP simulations.

Discarding the first detailed system and before deciding on which daily-based system to work on, the measured data was analysed. Monthly water balances were calculated to have measure of the reliability of the data. Plots were prepared for the catchments, where per catchment, the relation of the stations precipitation was analyzed with the discharge. Response times were assessed, peaks where found on the same day or one after the storm. Much of the data series provided was discarded in this step because the discharge was not following the rain patterns and the had suspicious behaviours of fail data like, sudden rise or drops, flat peaks, erratic fluctuations, not a consistent base flow in yearly dry periods and not to mention; completeness. Series were also discarded because; there was uncertainty on the location of the run-off gauge, which resulted in mismatching volumes in respect with the precipitation.

The general absence of evaporation data at high altitudes creates a real limit for studies like the present one in Colombia; there is a high uncertainty on the calculation of actual evapotranspirated volumes, especially at high temporal resolution. Even more is the absence of sunlight radiation measurements to correctly estimate this variable. The potential evapotranspiration required for the model will set a limit on the simulations, forcing the water balance. Even though the actual evapotranspiration is low in the study area and is not as determining as the precipitation, being a minor component in the water balance, it has to be correctly measured and estimated. Further, lacking measurements of interception, infiltration and hydraulic conductivity tests, adds to the uncertainness of the estimation of the components in the local water cycle.

The monthly water balances for the series was analyzed, most of the records did not permit the application of the data to the run-off modelling, therefore were discarded. The two best data sets, representative for a catchment were then selected to compare; Chuza and Guajaro. Later the measured runoff series was compared to the simulation in continuous annual series plots and annual total plots and tables.

5.2.2. Land Cover & Change Assessment

The Landsat images were processed with ERDAS and visualization and digitization was afterwards carried out with Arc GIS. Supervised and non supervised classifications were performed for the general area and subsets to observe differences and obtain the best representation of the landscape. Area for each land cover in the different catchments was calculated.

The land cover and change detection were visually assessed. Images were overlaid and swiped one after the other, to detect changes. Where the changes were observed, those units were digitized and their area calculated.

5.2.3. TOPmodel Approach

Topmodel is a saturation excess run-off model, where the streams are generated from saturated zone. It is based on the Kinematic theory which considers gravity as a mayor force, and includes the topographic index as a fixed hydraulic head to drive the water to the outlet.

The Topmodel developed by Beven & Kirby in 1979, has been widely used and modified. As its author describes it as (in Rientjes 2010);

> "TOPmodel is not a hydrological modelling package. It is rather a set of conceptual tools that can be used to reproduce the hydrological behaviour of catchments in a distributed or semi-distributed way, in particular the dynamics of the surface or subsurface contributing areas."

It is based on the Topographic Index, $\ln(a/\tan B)$ or $\ln(a/To \tan B)$, where **a** is the accumulated upslope area that drains to a point (this is proportional to the volume of water likely to be moving through the cell under steady - state flow, tan *B* is the local slope angle which is used to approximate the hydraulic gradient at the water table in that grid cell. Parameter To is the soil transmissivity when the water table is just at the soil surface.

5.2.3.1. Assumptions

As part of the simplification of reality that the model definition has, this model considers that the soil and land cover is homogeneous over the catchment. This is more realistic for small catchments, where there is less variability and is close to the first assumption.

The model assumes there is no deep infiltration, reflecting the conditions in the study area. It considers a series of subsystems located below the soil surface acting as storages that control water flow. It further considers a water table that interacts with the root zone stores (Figure 5 -2). Other important assumptions are:

1. There is a saturated zone in equilibrium with a steady recharge rate over an area draining from upslope.
2. The saturated zone or water table runs parallel to the surface meaning that the effective hydraulic gradient is equal to the slope, tan *B*.
3. The transmissivity profile may be described by an exponential function of storage deficit or depth of the water table, with a value of To when the soil is just saturated to the surface (zero deficit).

If these assumptions are combined, one can derive an equation for the local soil moisture deficit D_i, at any point of the catchment as:

$$D_i = \overline{D} + m\,(\lambda - \ln(a/To \tan B)) \qquad (1)$$

λ: mean value of topographic index over the catchment.
To: lateral (horizontal) transmissivity when the soil is just saturated - area/time.
m: effective depth or active storage of the soil, rate of decline of transmissivity of the soil profile, length in meters.

5.2.3.2. Parameter Definition

Literature review and a sensitivity analysis (results are presented later in the document) both indicate that the model is most sensitive to the following parameters:

1. ***m.*** This parameter controls the rate of decline of T(z). This is the parameter of the exponential transmissivity function or recession curve It controls the effective depth of the soil profile (m).
2. **lnTo.** This parameter is the natural logarithm of the effective transmissivity of the soil just when saturated $\ln(m^2/\mathrm{h})$.
3. **Srmax.** This parameter represents the maximum root zone storage deficit, soil profile storage available for transpiration, available water capacity in meters.

The following parameters must be set, but are not determining the simulations as the sensitive parameters:

1. ***TD.*** Is a time delay constant for routing unsaturated flow (hour).
2. ***CHV.*** Is for channel flow outside the catchment, if the gauge is downstream of the outlet (m/h).

3. ***RV.*** Channel flow velocity - internal subcatchment routing velocity (m/h).
4. ***SRO.*** Initial value of root zone deficit in meters.

5.2.3.3. Inputs & Outputs

The Topmodel requires as input the catchment variables (in different files) to be able to simulate run-off:

- Topographic index
- Distance to outlet
- Precipitation
- Potential evapotranspiration
- The observed discharge for the first time step, to initialize the base flow.

With a set of parameters the output of the simulations can be calibrated with the observed runoff to validate its performance and reliability.

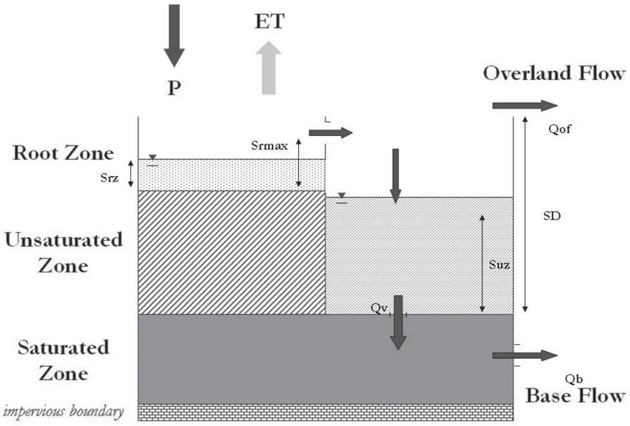


Figure 5 - 2: Topmodel structure of a grid cell (adapted from Takeuchi K., et al. 1999).

Srz: is the actual root zone storage deficit.
Suz: is the actual unsaturated zone storage.

As output a continuous simulation of the following variables is obtained:

- **Q.** Total simulated run-off
- **Quz.** Unsaturated zone flow
- **Qb.** Base flow
- **Sbar.** Catchment deficit
- **Qof.** Overland flow
- The maximum contributing area for the simulation.

5.2.3.3.1. Digital Elevation Model

From the DEM processing two important inputs for the model are derived; the topographic index and distance to outlet files. For the terrain analysis several DEMs were used; the ASTER and SRTM 30 m. The DEMs were analyzed together with a DEM produced from elevation curves each 50 m. and the SRTM 90m., the last version gave the best overall representation of the landscape and was selected to produce the topographic data. To obtain the inputs for the topographic index and distance to outlet, some routines and raster operations were performed in ILWIS software: Under the DEM hydro processing routines the fill sinks, flow determination and network & catchment extraction were performed. Draining upslope area of each pixel, slope calculation and distance to outlet was also calculated.

5.2.3.3.2. Rainfall

Precipitation measurements are obtained using the rain gauges in the study area. However the time series provided were not 100% complete. Several procedures were done to complete the gaps the most realistic way according to the data acquired.

1. The first step was to temporally standardize the data sets. As they are taken manually; a person has to walk every day to the station, write down the data and by radio or internet submit the series, some values and days are missing. This data collection method creates problems when trying to combine several series. The temporal standardization process was done using a Matlab script. It consisted in creating a consecutive series from the first day to the last of the measured series. Once the complete list of days was created, a procedure to copy the value of the recorded data on that day to the list created was run. Completeness and correlations were evaluated (Table 6 -1 to 6 - 3). As several stations were included, and the data series contained more than the interest value, a matrix was created storing the different stations. The additional data which had the most value for this exercise was the accumulated values, flagged with the letter a.

The procedure to complete the series was simple but time consuming as it was done manually. Where there was an accumulated value of rain, the objective was to redistribute that volume along the days it was not recorded. For example (Table 5 - 2) stations A, B and C are recording data but for some reason the operator missed four days; B station. Observing that the total accumulated precipitation for those four days and the current one is 57 mm., station A is chosen to give the rain fall pattern for those days, because it has an accumulated of 44 mm., closer than station C, which recorded 26 mm. The first step is to calculate the percentage of the daily rain of station A for those five days and secondly multiply to the accumulated in station B to get the distribution of rain along the days. As result obtaining a series that follows the pattern of a near station maintaining the rain depth from its location.

Table 5 - 2: Series completion procedure example.

Day	St. A	flag	St. B	flag	St. C	flag	% St. A	mod St. B
1	15				3		0.34	19
2	5				2		0.11	6
3	10				3		0.23	13
4	3				0		0.07	4
5	11		57	a	18		0.25	14

2. For the Paramo system, 2 rainfall stations and an extra neighbouring one, Chuza, were used to calculate a single rain file, as it has the most complete record. The stations were weighed in the following way: Laguna Seca (3620 MASL) with 30 %, El Diamante (3350 MASL) with 45 % and the remaining 25 % to Chuza (3100 MASL) station, Figures 4 - 2, 4 - 5 & 4 - 7.

3. For the Forest system, which had one rainfall station inside the catchment, an extra neighbouring one was used to calculate a single rain file, and other neighbouring ones (Parrados and Rio Negro) were used to complete specially Alto Gorro (3750 MASL) station, due to its far location, it had many days without recording. The complete set for the two stations was weighed equally to divide their contribution to the catchments rainfall, with 50% each per day. Due to lack of measurements, a constant interception rate of 15% was assumed to account for this process; the gross rainfall from the 1800 meter elevation was reduced 15% to obtain net rainfall.

5.2.3.3.3. Potential Evapotranspiration

For the potential evapotranspiration that the model requires as input for the Paramo system, adjustments were done to the original class A Pan evaporation data recorded at 1800 MASL. First an approach to elevation correction was intended by shifting the evaporation recorded at an elevation of 1800 MASL to 3000 MASL. Trying to make the evaporative forcing more according to the conditions at higher mountain locations, monthly ratios between multiannual monthly pan evaporation values were calculated between an old record of Chingaza station with the recent from San Juanito station (Figure 5 - 3). Chingaza records date from 1969 to 1984 and San Juanito, go from 1993 to 2009. Although the time series do not overlap, it was assumed that the long-time average monthly potential evaporation of the two stations could be compared. The daily pan evaporation for the time period of this study was converted from an altitude of 1800 MASL to 3000 MASL by multiplying the measured values from the lower elevation by the ratio (calculated from the long-time series) for the each month.

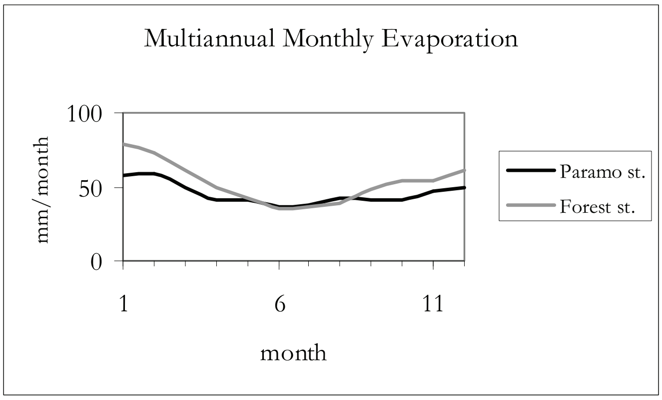


Figure 5 - 3: Multiannual monthly evaporation.

To convert pan evaporation to potential evapotranspiration the following operation was done:

$$ET_{pot} = E_{pan} \times k_p \times k_c \tag{2}$$

Where ET_{pot} is the potential evapotranspiration, E_{pan} is the pan evaporation, $k_p = 0.8$ is the pan coefficient (after Maidment 1993), and $k_c = 1.4$ is the crop coefficient. Note that the pan coefficient was obtained using an assumed average fetch of 100 meters, a 70% relative humidity and a moderate wind speed of 2 m/s, measured at the area (with the average ranges a little below 2 m/s).

5.2.4. Manual Calibration & Validation

For the calibration & validation exercises the following parameter values in Table 5 - 3, were combined and assessed with the two selected objective functions (see 5.3.1). The following set of parameters was defined and combined for the final simulations done. Before arriving to this set, wider ranges were taken in the initial runs of the model. Observing the outputs, the set was narrowed down to values around the best combinations to perform a final structured analysis.

Table 5 - 3: Defined parameter set.

m	lnTo	Srmax
	2	0.003
0.015	3	0.005
0.020	4	0.007
0.025	5	0.009
		0.011

The calibration and validation procedures were performed with separate data sets, the specific dates can be seen in the Table 5 - 4.

Table 5 - 4: Calibration & validation periods for Paramo and forest systems.

		from	to
Paramo	Calibration	27 June 2007	31 July 2007
	Validation	20 September 2008	13 November 2008
Forest	Calibration	4 August 2006	15 August 2006
	Validation	7 September 2006	30 September 2006

5.3. Calibration of TOP model Simulations

The Topmodel is calibrated using the measured discharge at the outlet of the catchment. Objective functions are used in the calibration process to select parameter values from a defined set of numbers, as they give a value that reflects upon the similarity of the simulations with the recorded data.

5.3.1. Objective Functions

Two objective functions were chosen to asses the similarity of the simulated runoff with the observed one. The Nash - Sutcliffe (R^2) coefficient was selected to contrast the behaviour of the hydrograph, while the Relative Volumetric Error (RV_E), was selected to evaluate the total runoff modelled.

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (Q_{obs} - Q_{sim})^2}{\sum_{i=1}^{N} (Q_{obs} - \overline{Q}_{obs})^2} \tag{3}$$

$$RV_E = \left[\frac{\sum (Q_{sim} - Q_{obs})}{\sum Q_{obs}} \right] * 100\% \tag{4}$$

As the correlation coefficient NS approaches 1, the simulation has more similarity with the observed data. The volumetric error of 0 indicates the same volume was simulated as it was measured, values can range to positive and negative infinite. Negative values are sub estimations, while the positive overestimation.

5.3.2. Visual Assessment Criteria

For the visual assessment of the hydrographs the following criteria was used:

- Correct initialization, end and beginning of annual cycle.
- Matching base flow.
- Presence of the peak (identification of a storm).
- Identification of an isolated storm by a peak in a dry period.
- Reaction to the first storms after dry periods.
- Height, timing and extent of the peak.
- Base of the peak, lower width and base flow limit for wet periods.
- Recession and climbing limbs (especially long recessions).
- How well the simulation is for periods of high frequency peak and recession.
- If the measurements seemed shifted (systematic error), the general pattern was observed.

5.4. Contrasting Run-off Between Catchments

As a final exercise the simulated run-off for the two systems was plotted together for 2007 - 2009 to compare their behaviour. The contrast was done between the overall best fitting parameter and the best combination for each system. The best fitting parameter was identified with the calibration & validation process. The best combination for each system was selected from the optimization plus visual assessment, to differentiate best fitting sets for the different catchments. The general aim was to identify differences in recession periods where Paramo catchment was expected to show slower water release than forest catchment.

6. RESULTS & DISCUSSION

6.1. Inspection of Precipitation & Discharge Measurements

6.1.1. Monthly Precipitation Behaviour

To have an idea on the precipitation behaviour along the year in the study area, the monthly averaged precipitation values were plotted per catchment (Figure 6 - 1). It can be observed how the dry periods lie at the beginning and end of the year where the receding run-off period should be expected. The driest periods are in the beginning of the year. The rainy period is stronger in the middle of the year with some intensification before its end. These averages were calculated with series of 20 to 40 years, considered enough time to produce an acceptable average, and as it can be observed following figure, the exercise shows consistent results.

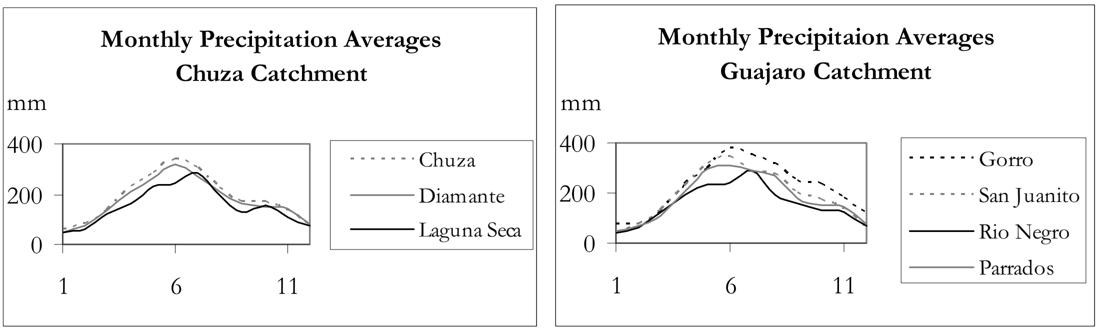


Figure 6 - 1: Monthly precipitation averages for the rain gauges.

As it can be seen and further discussed in section 6.1.3, there is an inverse relation between the catchments precipitation behaviour. While in Chuza the higher elevation has less precipitation, at Guajaro catchment, higher elevations receive more rainfall.

6.1.2. Relating Precipitation Measurements

Before the combination of the rain gauge point measurements were converted into precipitation over the catchments, the series were analyzed to establish close or far relations. As it can be observed in the Tables 6 - 1 to 6 - 3, San Juanito and Parrados located 14 km south west, had the best relation. For higher elevation Diamante and Chuza 5 km apart had good relation.

Table 6 - 1: Correlation coefficients for Chuza catchments stations.

% gap		Chuza	Diamante	Lag. Seca
5	**Chuza**	1		
36	**Diamante**	0.74	1	
39	**Lag. Seca**	0.58	0.56	1

Table 6 - 2: Correlation coefficients for Guajaro catchments stations.

% gap		San Juanito	Parrados	Alto Gorro	Rio Negro	Evap. San J
7	**San Juanito**	1				
26	**Parrados**	0.80	1			
59	**Alto Gorro**	0.58	0.54	1		
46	**Rio Negro**	0.56	0.59	0.46	1	
27	**Evap. San J**	-0.18	-0.20	-0.23	-0.20	1

Table 6 - 3: Correlation coefficients between other neighbouring stations.

% gap		Chuza	Cuch. Chuza	Cuch. Golilias	La Playa	Lag. Chingaza	San Jose	Lag. Marranos	Chingaza camp.
9	**Chuza**	1							
74	**Cuch. Chuza**	0.90	1						
2	**Cuch. Golillas**	0.68	0.46	1					
36	**La Playa**	0.50	0.45	0.52	1				
18	**Lag. Chingaza**	0.50	0.37	0.49	0.45	1			
80	**San Jose**	0.59	0.43	0.47	0.45	0.89	1		
40	**Lag. Marranos**	0.33	0.31	0.35	0.33	0.29	0.26	1	
17	**Chingaza camp.**	0.54	0.39	0.53	0.55	0.49	0.38	0.29	1

Note that for Chuza the percent in gaps increases from Table 6 - 1 to 6 - 3 and this is because the last matrix created had more records, the dates are previous to 1990. Also to note is the inclusion of the pan evaporation in Table 6 - 2, just to show the inverse relation it has with precipitation. Third to note is that the correlations are performed without taking into account the accumulated precipitation values, only daily recorded rainfall was related. Even low correlation values like 0.5, can be interpreted to have some value when relating variable series like daily rainfall data.

6.1.3. Annual Totals

Manually the data for the years of 2006 until 2009 was treated to input in the model. The rest of the years the data is just added to complete the year total, so still when they are annual, there is still some uncertainty due to gaps and accumulated values passing to the next year, lowering the actual and incrementing the later.

As mentioned before, the runoff of a catchment is the water that comes in minus the one that goes out. As simple as it sounds is not; trying to reconstruct climatic events from recorded in incomplete and sometimes unreliable data sets.

Table 6 - 4: Annual totals for Chuza - Paramo catchment.

units: m		Chuza	Diam	L Seca	Weighted average	Original	Shifted		
Year	**Q**	**P3100**	**P3350**	**P3620**	**P av.**	**ET pan**	**ET pot**	**P-Q**	**Q/P**
1994	2.88	2.41	1.67	1.79	1.89	0.26		-0.99	1.52
1995	1.80	0.96	0.84	0.80	0.86	0.28		-0.95	2.10
1996	1.18	0.55	0.62	0.13	0.45	0.19		-0.73	2.60
1997	1.02	2.13	0.98	0.73	1.19			0.17	0.86

1998	1.44	2.02	1.46	0.33	1.26	0.57		-0.18	1.14
1999	1.27	2.32		2.00	2.14	0.80		0.87	0.59
2000	1.59	2.73	2.17	2.13	2.30	0.83		0.70	0.69
2001	1.21	2.33	2.15	1.86	2.11	0.85		0.90	0.57
2002	0.77	2.63		1.90	2.23	0.76		1.46	0.35
2003	1.98	2.27	2.18	1.88	2.11	0.45		0.13	0.94
2004	1.75	2.77	2.51	2.28	2.50			0.75	0.70
2005	1.32	2.06	1.85	1.70	1.86	0.28		0.54	0.71
2006	0.69	2.37	2.50	2.16	2.36	0.77	0.75	1.68	0.29
2007	1.05	2.25	2.32	1.95	2.19	0.84	0.81	1.14	0.48
2008	1.08	2.38	2.14	2.06	2.18	0.80	0.77	1.10	0.49
2009	1.56	2.16	2.09	1.72	1.99	0.79	0.77	0.43	0.78

As it can be observed in Figure 6 - 2, 6 - 4 & Table 6 - 4, there is obviously something wrong with the initial years. The total water that is annually going out of the catchments is more than what was calculated going in. For the Paramo case, data is quite suspicious and only some years follow the acceptable range of 0.5 to 0.7 discharge precipitation relation. The difference between precipitation and run-off should be close to the actual evapotranspiration value somewhat lower than the potential one. An acceptable range for this relation is from 500 to 800 mm. Some studies state that as Paramo has no hydraulic stress, meaning no dry condition and always wet, the actual evapotranspiration can reach close to the potential.

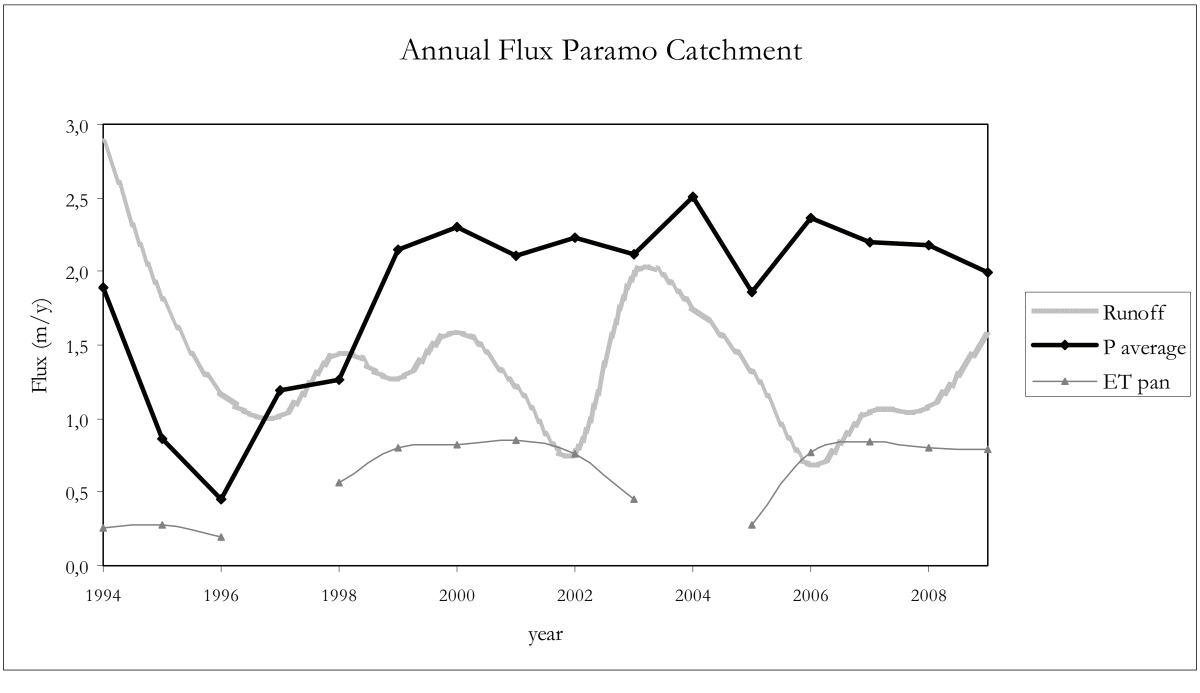


Figure 6 - 2: Annual flux Paramo catchment.

The evaporation measurements show a steady behaviour (Figure 6 - 2 & Table 6 - 4) of around 800 mm of potentially evaporable water in the area. It has to be taken into account that this value is a transformation and it is more suitable to analyze in lower elevation conditions, nevertheless it offers a close estimation.

The relation between the annual precipitation registered by the rain gauges is maintained along the study period. The precipitation from the 3100 elevation is always higher than the one recorded at the 3620 MASL station. The station located at 3350 MASL (Figure 6 - 3) is always in the middle, being close to the weighed average calculated for the total precipitation over the Chuza catchment. Values of 2000 to 2500 mm of annual rainfall are accepted over the area.

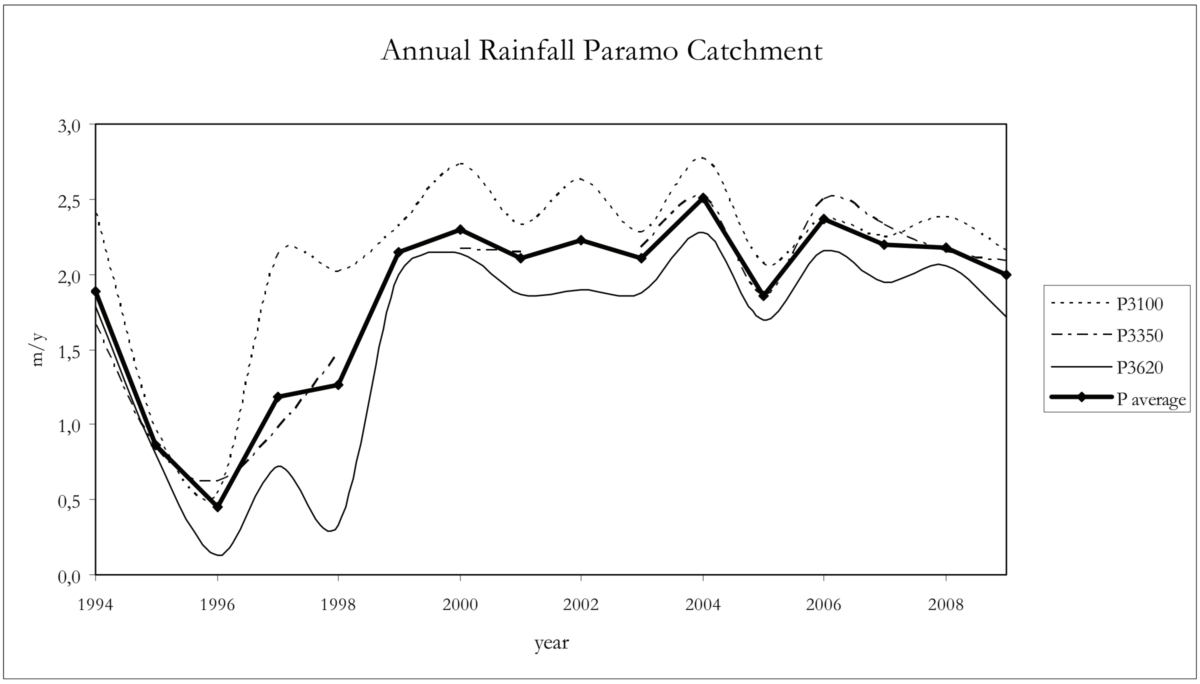


Figure 6 - 3: Annual rainfall Paramo catchment.

For this system the constant average of annual rain maintains in the 2000 - 2500 mm. The stations for 1800 MASL San Juanito and 2100 MASL Parrados have a very similar record (Figure 6 - 4 & Table 6 - 5). After the year 2000 it can be seen that follows the same pattern as 3100 MASL Chuza. For the years of 2004 and 2006, seems as average of the stations 3450 MASL Rio Negro, with less rain, and 3750 MASL Gorro with more. The evaporation can be observed relatively constant in time, except for some gaps in the recorded data that make some noise.

Table 6 - 5: Annual totals for Guajaro - forest catchment.

units: m		San Juanito	San Juanito - 15 %	Parrados	Rio Negro	Alto Gorro	Gorro Modif.	P av. Guajaro	Original	Modif.		
Year	**Q**	**P 1800**	**P 1800**	**P 2100**	**P 3450**	**P 3750**	**P 3750**	**P av.**	**ET pan**	**ET pot**	**P-Q**	**Q/P**
1994	2.72	2.41		2.56	1.86	1.60			0.26			
1995	3.29	2.02		1.87	0.83	2.27			0.28			
1996	3.15	2.57		2.35	0.95	2.18			0.19			
1997	0.65	1.92		1.68	0.32	1.25						
1998	1.45	2.28		2.18	1.45	2.78			0.57			
1999	2.87	2.29		2.26	1.29	2.76			0.80			
2000	1.41	2.36		2.29	1.62	3.12			0.83			
2001	3.12	2.07		2.11	1.84				0.85			

2002	2.99	2.48		2.34					0.76			
2003	2.23	2.16		2.05	2.12				0.45			
2004	2.13	2.74		2.63	2.44	3.10						
2005	1.49	2.26		2.37	1.83	2.32			0.28			
2006	1.98	2.38	2.03	2.39	2.21	2.71	3.06	2.54	0.77	0.86	0.57	0.78
2007	3.20	2.12	1.80	2.10	1.92	1.83	2.59	2.19	0.84	0.94	-1.01	1.46
2008	3.28	2.06	1.75	2.31	2.31	2.75	2.74	2.25	0.80	0.90	-1.03	1.46
2009	3.75	1.68	1.43	1.77	0.78	2.24	2.41	1.92	0.79	0.88	-1.83	1.95

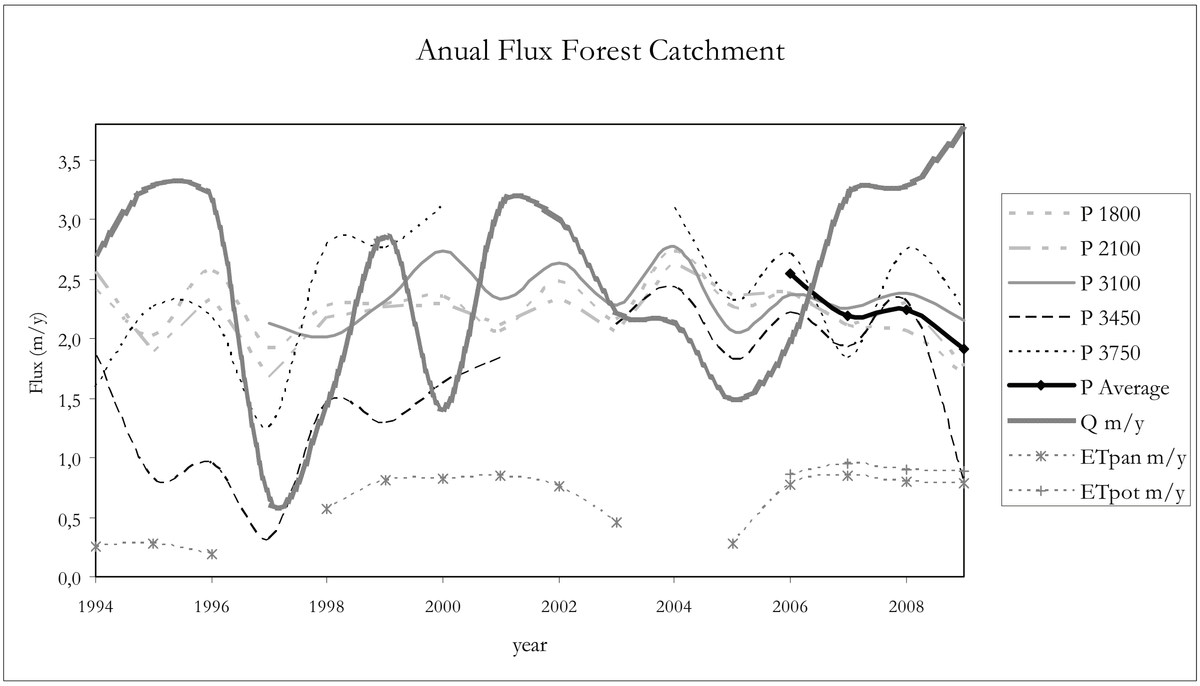


Figure 6 - 4: Annual flux forest catchment.

For the initial period of 1994 to 2003, the runoff data seems quite high when compared to the precipitation data. In several cases is well over the precipitation, like in the ones selected for modelling. In the figures 6 - 8, 6 - 9 and appendix B, it can be observed how for different years the initial flow is different, revealing error in measurement. As well as initial flow wrongly recorded, many parts of the record are suspiciously unreal when runoff fluctuation changes drastically, where jumps and drops are visible.

The inverse relation between the catchments' elevation and precipitation relation can be explained by the location with respect to incoming moist air and precipitating clouds. The two catchments are receiving moisture from the Orinoco river basin. In a Landsat scene acquired, there is a thick cloud just below 3000 MASL covering the Guatiquia river valley. Guajaro catchment is located in the facing direction of the incoming wind from the west (Figure 4 - 1 & 4 - 2) and creates the first barrier where warm moist air and clouds rise, condense and precipitate. Chuza catchment is located further and it is receiving cooler and less moist air, having more precipitation on lower elevation. In this catchment it can be generalized that precipitation events at higher locations input less volume, but are more frequent, resulting in almost permanent wet conditions. Even further west, beyond Chuza's water divide, the slopes of upper Blanco river basin are drier, because water has already precipitated along the rising mountain.

6.2. Trend Inspection of Meteorological Measurements

6.2.1. Rainfall Long Time Series

Chuza station offered a quite long time record, but no clear pattern or cycle could be observed with this general approach. The annual totals were plotted for the Chuza catchment in the Figure 6 -5 and the pattern mentioned earlier for this catchment, of lower altitudes to receive more rain can be observed.

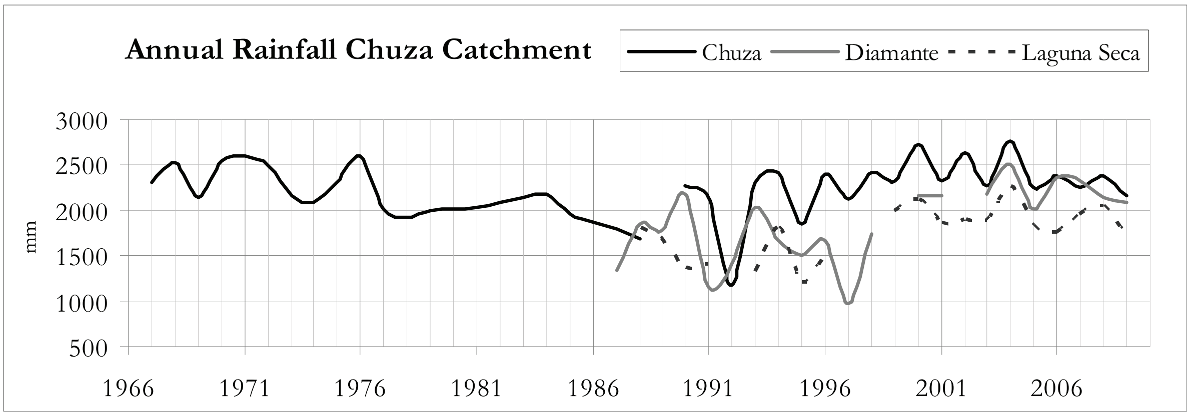


Figure 6 - 5: Rainfall series recorded in the Chuza catchment 1967 - 2009.

6.2.2. Temperature Trend

For the San Juanito meteorological station the mean, min-max. plot reveals that the temperature has been rising. The three measurements show increment through time since 1993. Where there is a clearer increment is in the maximum temperatures, telling that the days are turning warmer.

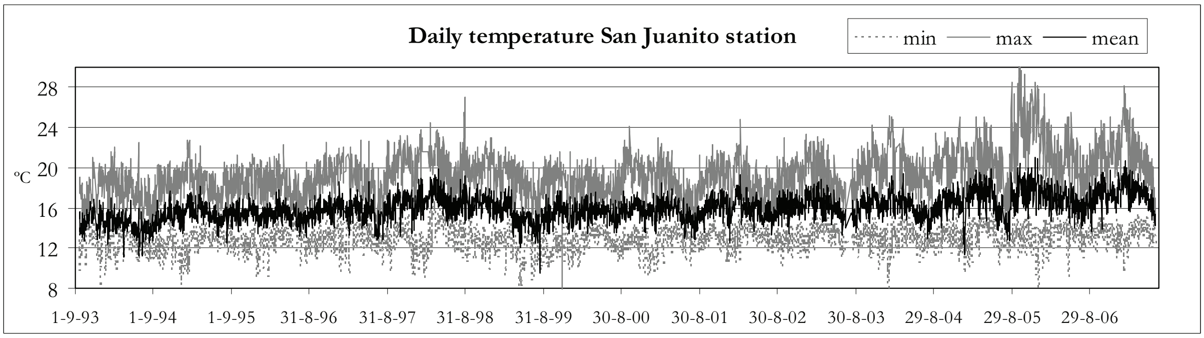


Figure 6 - 6: Daily temperature San Juanito station 1800 MASL.

To support the analysis and have a clearer view of the phenomenon, an annual mean of daily mean temperature was calculated (Table 6 - 3) and plotted in Figure 6 - 6. The average annual temperature has rised about 2.5 ºC in 15 years, the series begin with a temperature around 14.5 ºC and ends with 17 ªC. The standard deviation for the mean temperature in a year is around 1 ºC.

For a profile in a mountain an estimation of a shift upward of 100 meters was made for each 0.6 degree rise (Buytaert et al., 2006). This warming will affect the distribution of ecosystems and biodiversity along the altitudinal gradient of the Andes. According to Tobon (2008) and Garcia (2003) it will produce degradation of Paramo soils affecting its regulation capacity and potentially release great loads of carbon stored in these systems.

Table 6 - 6: Annual mean of daily mean temperatures for San Juanito station 1800 MASL.

year	mean	St. Deviation
20/09/1993	14.7	0.92
1994	14.6	1.02
1995	15.5	0.82
1996	15.4	0.82
1997	15.9	1.12
1998	16.6	1.08
1999	15.2	1.18
2000	15.6	0.85
2001	15.7	1.02
2002	16.0	0.99
2003	16.2	1.03
2004	16.2	1.05
2005	17.0	1.66
2006	16.9	1.13
30/06/2007	17.5	1.25

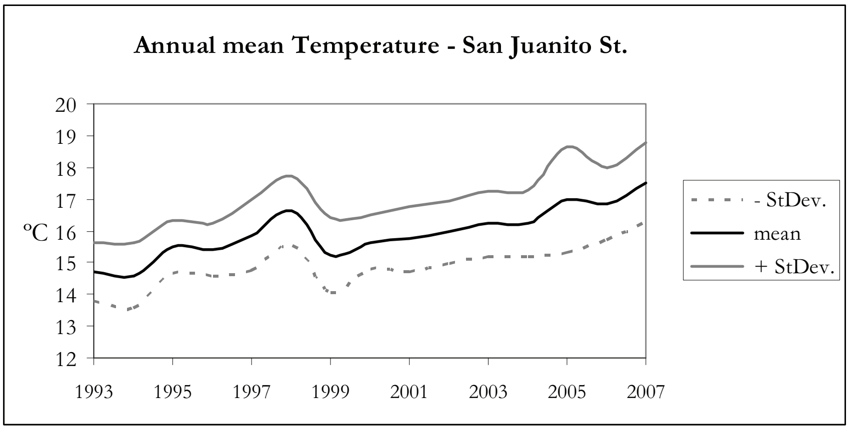


Figure 6 - 7: Annual mean of daily mean temperatures for San Juanito station 1800 MASL.

Is climatic change or global warming already manifesting through natural populations change? There are a number of studies assuring the decline in high mountain amphibian species through out the world, one example is La Marca and collaborators (2005). The claim is that a rise in temperature or change in humidity has caused a wide spread of a fungus that attacks the moist amphibian skin. Carbon release from stocks catalyzing changing conditions is worrying as well as habitat, biodiversity loss and extinction, which have negative impacts in the functioning of the ecosystems.

6.3. Land Cover Assesment

6.3.1. Land Cover

The result of the land cover assessment is shown in Figures 6 - 8 & 6 - 10:

- The Chuza catchment is almost 100% Paramo, except for bushes and tree patches located in protected, concave areas. For the present research this catchment is considered to be 100% Paramo.

- The land cover for the Guajaro catchment is 25% Paramo at the high altitudes, 70% Forest in the middle and 5% cattle grassing grasses at the low part, in the Guatiquia river valley, bordering area of the national park. For the present research this catchment is considered to be 100% Forest.

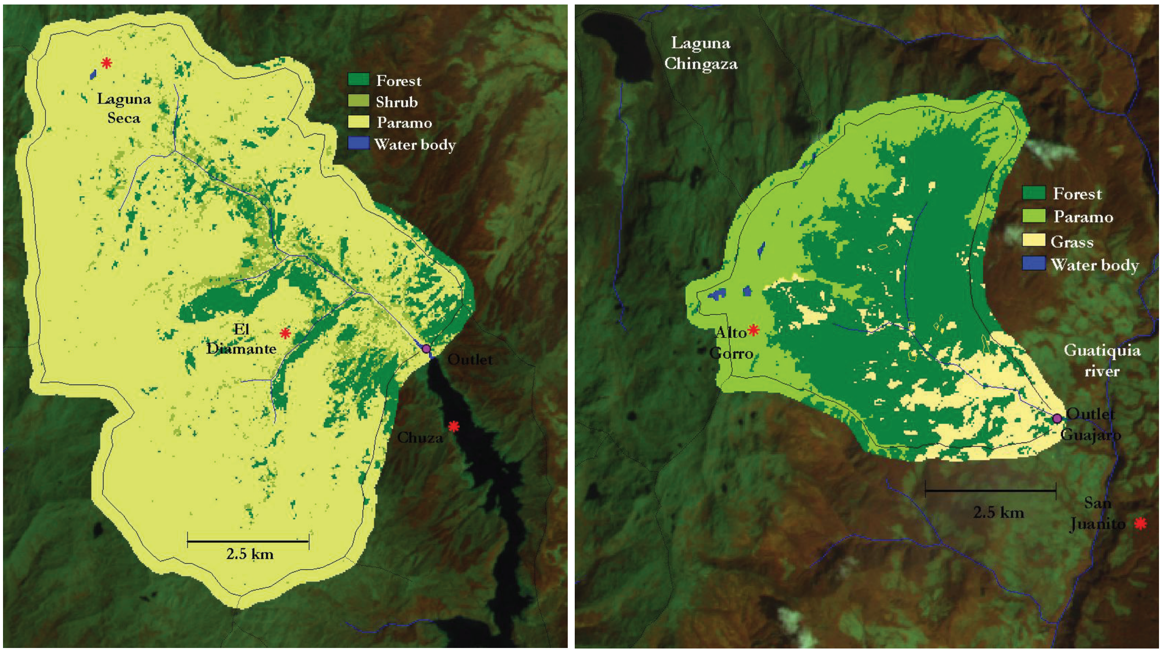


Figure 6 - 8: Land cover; Chuza (left) & Guajaro (right) catchments.

6.3.2. Land Cover Change

For the selected area there has been no significant land cover change observable from Landsat images Figure 6 - 9 & 6 - 10. Small clearing were observed in the middle part of the Guajaro catchment but were considered to have low hydrologic impact the five units where change was detected were measured and their total was less than 10 ha, that overall recovered in time where the vegetation seemed denser over the years. This is indicating an effective management of the area by the regional and environmental authorities working with the community to maintain it in a natural state promoting natural resources protection.

Even when land cover change is not evident in this locality, it is happening daily in other areas with the same importance and more vulnerable to deteriorate by not being backed up by environmental legislation and conservation initiatives and activities. For example the east limit of the Chingaza park is bordered by grass and agroecosystems, they extend up to the water divide, being the protected boundary in this part.

Both catchments have presence of small water bodies of around five to ten hectares, and more of smaller size. These water bodies along the study period maintain their level, indication of permanent water input.

There is only one case, with Siecha lagoons located north of the Blanco river water divide, where they are observed with low levels up to 1991 and with high levels since 1997. For the twin lagoons, each catchment is about 30 ha, located at the top of the mountain with only rain as input for a very small area, which makes their level a useful indicator of the local conditions.

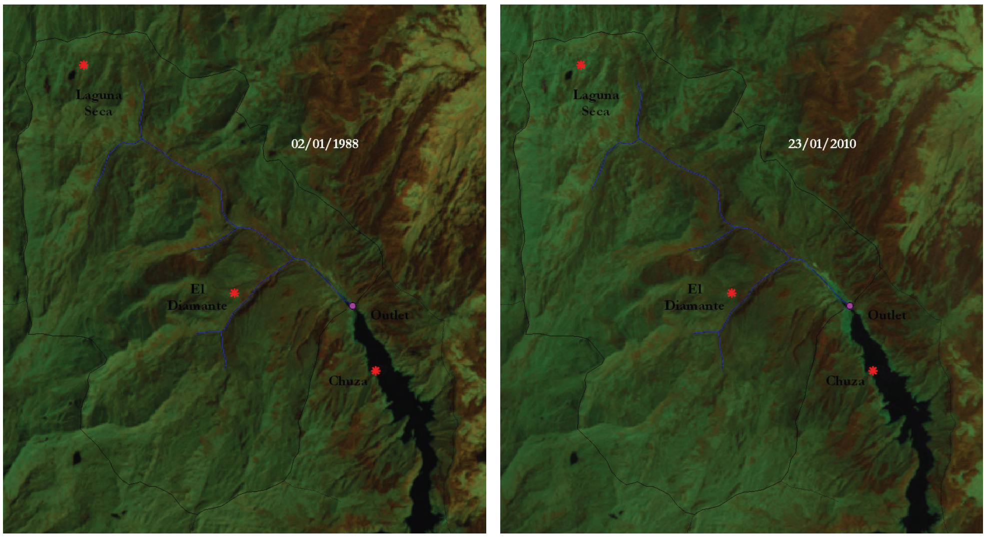


Figure 6 - 9: Landsat TM scenes Chuza catchment 1988 & 2010

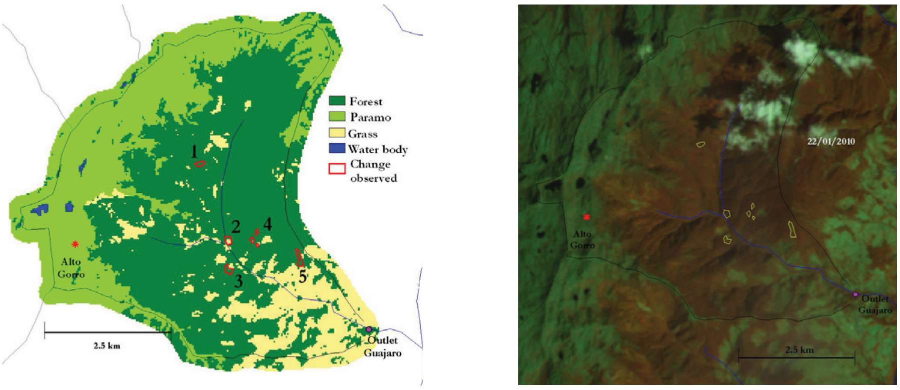


Figure 6 - 10: Landsat TM Guajaro catchment & observed change 1989 - 2010

6.4. Topmodel Results

Before the Topmodel can be run, two spatially distributed topographic indexes must be calculated. From the DEM processing the two topographical inputs for the model are derived; the distance to outlet and topographic index calculation results are described in this section.

6.4.1. Distance to Outlet

The longest distance for a water drop to travel to the outlet of the Paramo catchment, is almost 13 km. The longest flow path for the forested watershed is below 10 km, 99% of catchment is already located within 9 km distance from the outlet (Figure 6 - 11 & 6 - 12).

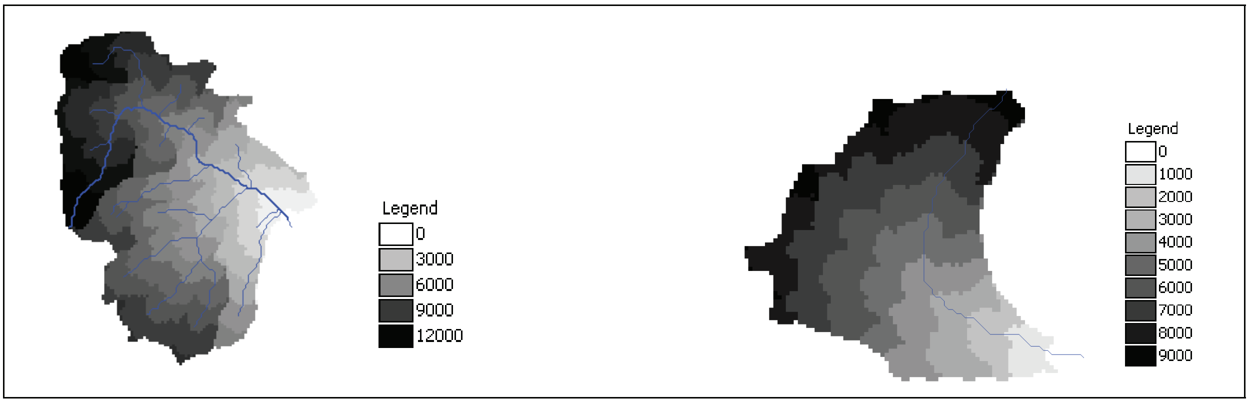


Figure 6 - 11: Distance to outlet Chuza - Paramo & Guajaro - forest catchments.

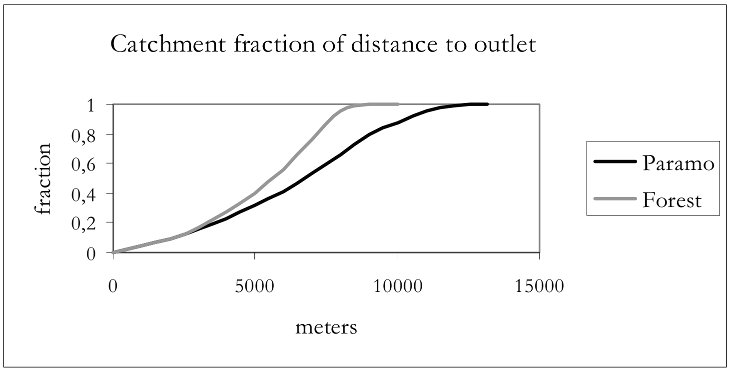


Figure 6 - 12: Catchment fraction of distance to outlet.

6.4.2. Topographic Index

The average topographic index of the Paramo catchment is higher than the forest catchment, indicating more saturation conditions or more possible saturated areas in the Paramo catchment. The forested catchment has more area around its averaged topographic index (Figure 6 -13 & 6 - 14).

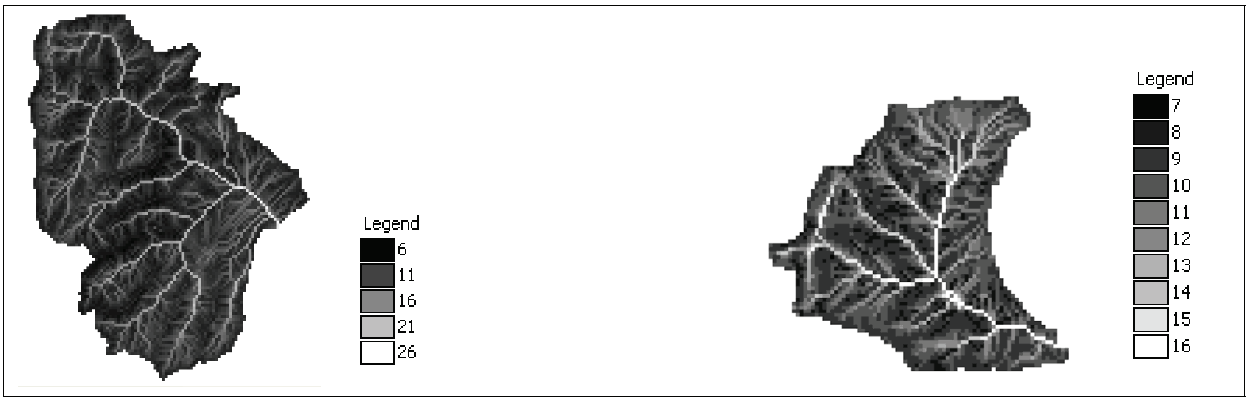


Figure 6 - 13: Topographic index Chuza - Paramo & Guajaro - forest catchments.

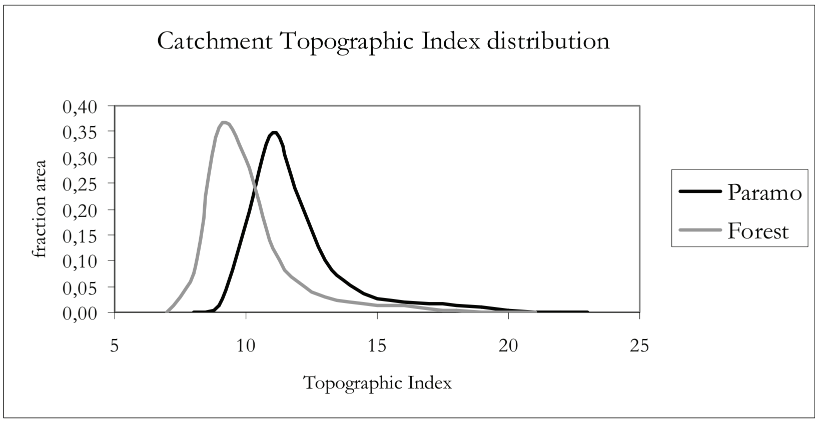


Figure 6 - 14: Catchment topographic index distribution.

6.4.3. Sensitivity Analysis of the TOP Simulations to Changes is 3 Parameters.

For the sensitivity analysis, calibration & validation exercises the most important parameters were:

- **m**. Describes depth and release of water by the soil matrix as it is looses moisture.
- **To.** Affects the horizontal transmissivity of water flow in time.
- **srmax.** Determines the depth of the root store and water available for evaporation.

The values in Table 6 - 7 were combined and the simulations assessed with the two objective functions explained in section 5.3. The following set of parameters was combined for the final simulations done.

Table 6 - 7: Defined parameter set for runoff simulations.

m	lnTo	srmax
	2	0.003
0.015	3	0.005
0.020	4	0.007
0.025	5	0.009
		0.011

6.4.3.1. Sensitivity to Changes in - m - Parameter

Topmodel is most sensitive to the m parameter. This parameter controls the recession of the hydrograph. For higher values, like 0.04, the simulated base flow was overestimated and the peak discharge underestimated. The best fits for the study area were with low values for the m parameter. Simulations with values around 0.015 and 0.2 best represented the recession of the observed discharge.

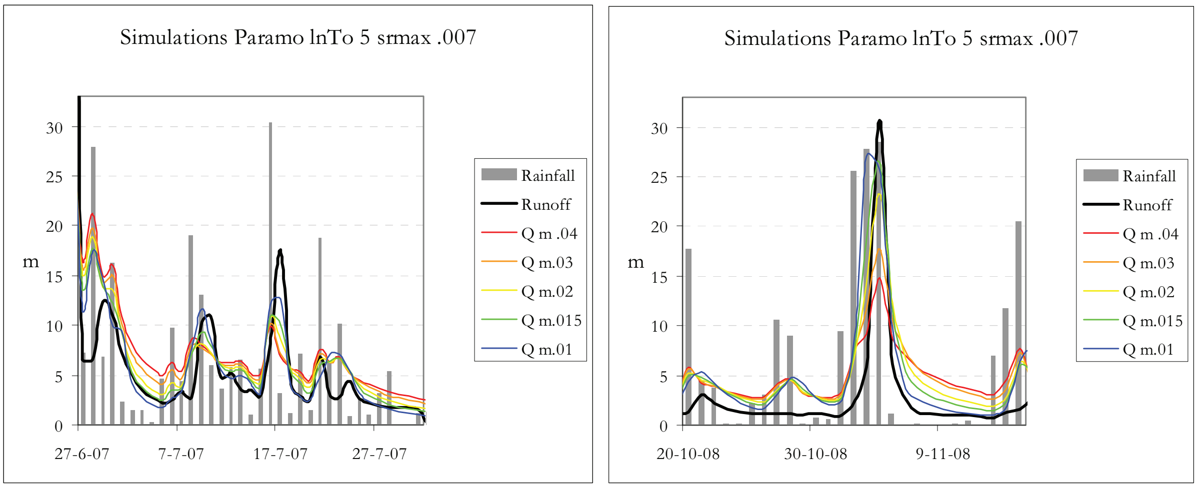


Figure 6 - 15: Simulations of Paramo catchment runoff changing - m - parameter.

Even when the initialization is better with higher values of m, on the long run the best simulations are achieved with lower values. It seems that initialization problems are solved rather quickly, because after several storm events, the simulations follow closer the observed data.

As it can be seen in Figure 6 - 15 & 6 - 17, the higher the m value is set, base flow and peaks decrease. When comparing with the measured runoff, the best fit comes with lower values of m - parameter. As m describes the release of water by the soil matrix, lower values reflect upon shallow soils like the ones in the study area.

For an area of deeper soils where the same version of the model was applied, the combination of m 0.04 To 5 srmax 0.1, gave the best fitting combination. Peak flows that are much higher than the observed peaks, are obtained with lower values of m, when it is set at 0.015 in Gilgel Abay basin, the peaks are not realistic. For smaller values of m the proportion of rainfall that reaches the outlet via a surface route increases. Larger values of m express deeper effective soils as more water to infiltrate. For subsurface flow with a lower value of m, its volume will decrease and water travelling quicker arriving at the outlet almost at the same time as the surface flow. The result is high peak discharge and very little contribution to the base flow after the rain event.

6.4.3.2. Sensitivity to Changes in - lnTo - Parameter

Once recognized the influence of the m parameter on the runoff simulations, the effect of changing values on the lnTo parameter was analyzed. Parameter lnTo affects timing, describing the horizontal transmission of water flow in time. When exploring the value limits initially, when setting the parameter above 15, it began to have less effect on the simulations, as the value increased the simulations did not change considerably.

With lower values of lnTo, peaks come early and for higher values of the parameter, peaks come later. In some cases a value of 2 produces acceptable simulations, but in some other cases the best fit comes with a value of 5 (Figures 6 - 16 & 6 - 17).

Then the issue of temporal resolution of the data set in contrast to the real world events in nature has to be taken into account, having daily data and considering the peak flow is produced within 24 hours. One day shift is understandable under these circumstances; a small catchment, fast processes and different location of the rain event to the outlet, plus data recording at different times of the day. Then a final value of the parameter for a higher temporal resolution set could fall in that 2-5 range.

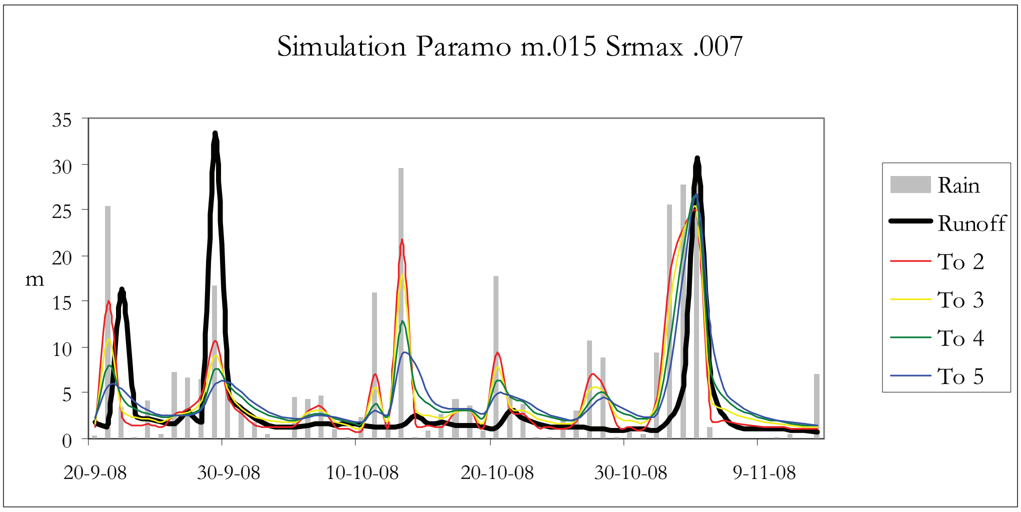


Figure 6 - 16: Simulations of Paramo catchment runoff changing - lnTo - parameter.

The best simulations were obtained based on the m 0.015 lnTo5 combination. However with lnTo 2, in the Forest calibration period it works better (Figure 6 - 17), in Figure 6 - 16, the peak came too early using lnTo 2, in Figure 6 - 17) setting lnTo 5, the peak is late one day.

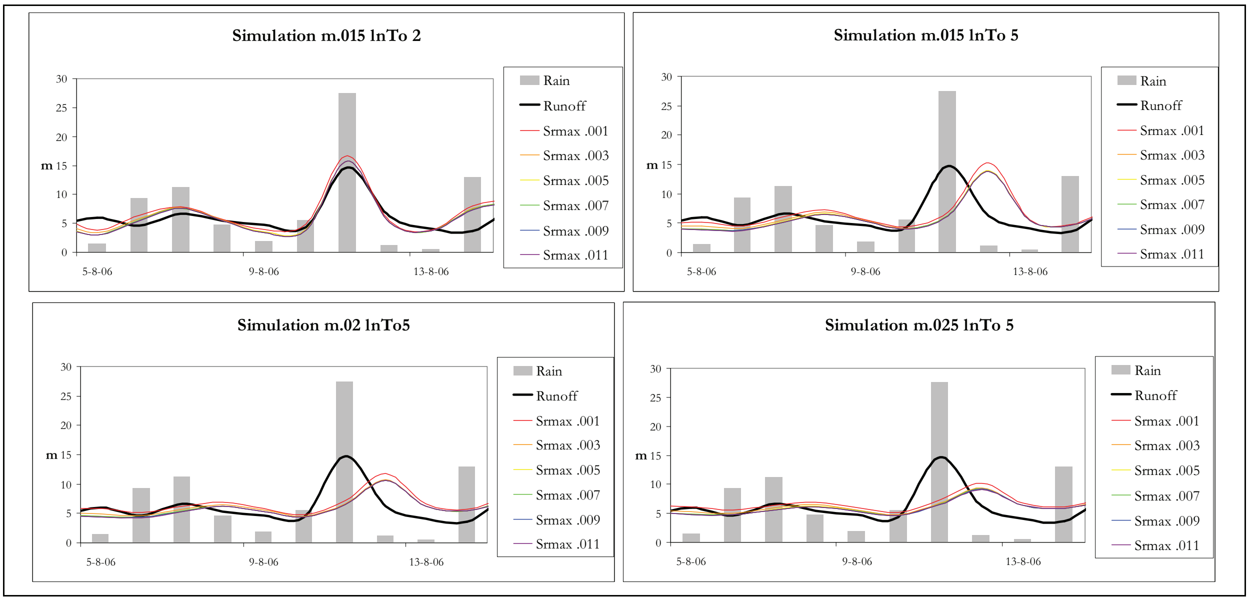


Figure 6 - 17: Simulations for Guajaro - forest catchment (calibration set)

With To 2, the simulated peaks come too early for this validation period for Paramo (Figure 6 - 18). This is notable in the first and last peaks.

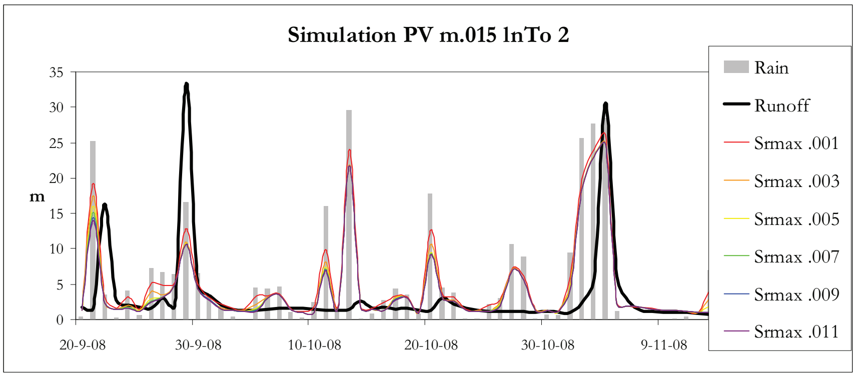


Figure 6 - 18: Simulation m .015 To 2, for Chuza - Paramo catchment (validation set).

When To 5 is used (Figure 6 - 19), the peaks shift to a better timing in relation with the observed series.

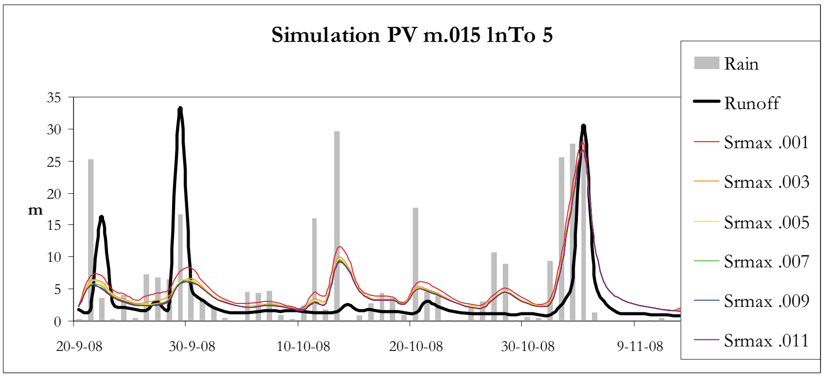


Figure 6 - 19: Simulation m .015 To 5, for Chuza - Paramo catchment (validation set).

For the change in To parameter, Gigel Abay reports describes slight changes in the simulations, where in this analysis it is considered to have an important effect on the discharge, as it controls the time extent of the peak flow.

6.4.3.3. Sensitivity to Changes in - srmax- Parameter

At low values of srmax the peaks go higher, also seems to react more to the storms setting lower values for this parameter. It can be visible especially with the value of 0.001, that the peak goes higher than the pattern followed by the rest of the simulations from higher parameter values. Lower values like 0.0005 are out of the accepted range, it was discarded because the first days of the simulation there is a huge discharge. This behaviour is not realistic, more so when there is little or no rain in those days. It seems like it is releasing all the water stored in the first time steps. Higher values damp the output as there is more space to store water in the root zone, with a low value the root zone storage is shallow and will saturate quickly, resulting in fast travelling surface runoff.

In the Gilgel Abay basin the values of srmax finally used were from 0.005 to 0.25. In this research values as low as 0.0005 were used and had fair simulations, but was discarded because it created too much problem at initialization, still values of 0.001 could work sometimes.

6.4.4. Calibration & Validation

As the runoff data is showing some problems and the calculated rainfall events for the catchment from point measurements are not fully representing the real rainfall inputs in all of the days, the calibration & validation process has to be taken as an exercise and an approach to a value range, rather than a final optimum parameter set for each catchment.

When a simulation is compared to measurements, it is assumed that those measurements are representing the real world behaviour. If there are flaws in the observed records, even when simulations are performed correctly, when assessed with objective functions or visually, the correlation will be low.

If precipitation events that force the observed run-off cannot be fully reproduced, it can be explained by: errors on the measured rainfall that propagate into the total precipitation calculation for the catchment and how point measurements are representing the rainfall received by the catchment, where heterogeneous spatial distribution of precipitation is present due to local orographic effects. In addition precipitation in relation with altitude has to be further clarified but was not deepened in this case.

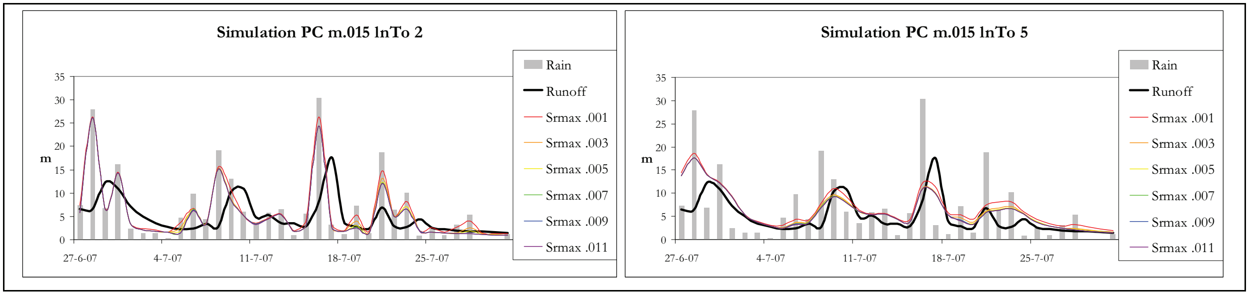
Still, it is demonstrated that the combination method applied is successful in describing some storms, as some events could be simulated correctly. Which in turn mean that the precipitation that forced the observed series was correctly estimated.

6.4.4.1. Calibration

For the calibration exercise let us take the Paramo set as an example. In this part of the procedure the aim was to get as close as possible the base flow and recession tail. As it can be seen on the Figure 6 - 20 & Table 6 - 8, the m.015 To 5 with srmax 0.011 combination gave the best results. When just analysing the first slow recession (* second set of results), the NS coefficient gives a good result, 0.87 with almost 20% volume error, using the srmax value of 0.011. With this similar recession, still in the rest of the hydrograph for those days, the mismatch decreases the NS value to 0.31.

Table 6 - 8: Paramo calibration runs.

m.015 lnTo 5 - srmax:	0.001	0.003	0.005	0.007	0.009	0.011
NS	0.14	0.28	0.30	0.30	0.31	0.31
Rve	38.0	26.5	24.2	23.2	22.7	22.4
* NS	0.82	0.86	0.86	0.87	0.87	0.87
* Rve	24.0	21.0	20.5	20.2	20.1	19.9



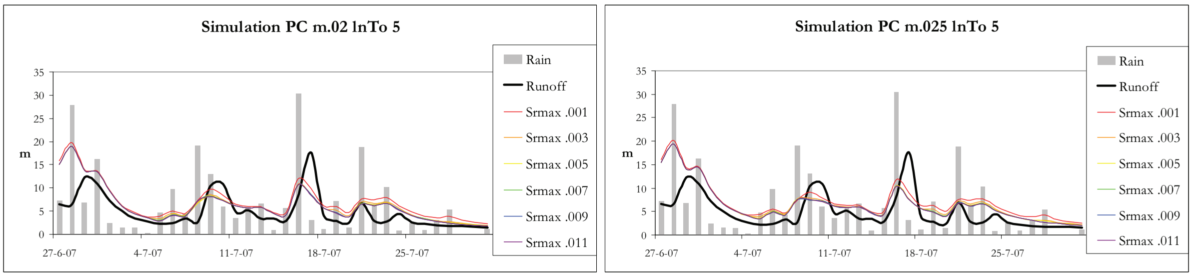


Figure 6 -20: Simulations for Chuza - Paramo catchment (calibration set)

The calibration for forest gave some good results (Figure 6 - 17 & Table 6 - 9). When the combination of parameter m 0.015 To 2 srmax 0.009 was used, the peak and recession were simulated quite well. Note that this is the case a lower transmissivity is working.

Table 6 - 9: Forest calibration runs.

m.015 lnTo 2 - srmax:	0.001	0.003	0.005	0.007	0.009	0.011
NS	0.60	0.70	0.70	0.70	0.71	0.70
Rve	12.3	4.2	1.6	1.0	0.7	0.7

6.4.4.2. Validation

For the Paramo validation (Figures 6 - 18, 6 - 19 & Table 6 - 10), the best result was to combine the parameters in the following way; m 0.015 To 5 srmax 0.011. When analysing only the last peak, the correlation coefficient raises up to 0.87

Table 6 - 10: Paramo validation runs.

m.015 lnTo 5 - srmax:	0.001	0.003	0.005	0.007	0.009	0.011
NS	0.26	0.31	0.32	0.33	0.33	0.33
Rve	61.5	43.3	39.1	36.9	35.6	34.8

For the Paramo catchment, values of m 0.02 also gave good simulations (Appendix A), but overall in the calibration & validation exercise, the set which simulated well for both periods was the past combination.

As it can be seen in the Figures 6 - 18 to 6 - 21 and Table 6 - 11, the combination of m.015 and To 5 represents well some parts of the hydrograph for both Paramo and forest systems. For this forest catchment the NS value is still lower with this combination than the calibration part, it is the best result. Additionally, for the first peak the match is almost the same.

Table 6 - 11: Forest validation runs.

m.015 lnTo 5 - srmax:	0.001	0.003	0.005	0.007	0.009	0.011
NS	-0.27	0.15	0.23	0.26	0.28	0.28
Rve	60.0	37.1	29.7	25.4	22.8	21.0

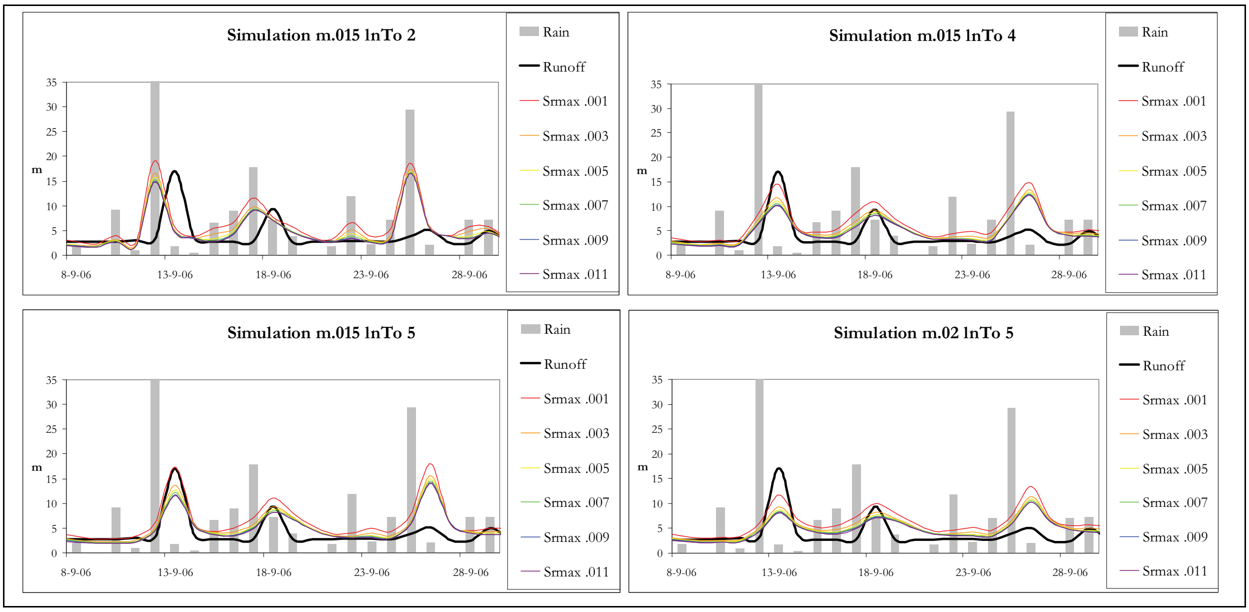


Figure 6 - 21: Simulations for Guajaro - forest catchment (validation set).

6.5. Annual Simulations

Judging by the analysis of the simulated hydrographs, the annual simulation totals can be used for an approach to identify volumetric errors on the recorded discharge, improve annual water balance calculation, the relation between precipitation and runoff in the studied catchments, estimating its annual water supply.

6.5.1. Annual Simulations Paramo

The annual simulations for Paramo (Figure 6 - 22 & Table 6 - 12) show a similar pattern for the years. Around 70 % of the precipitated water runs off and is available at the outlet of the catchment. It was simulated to be around 1500 mm/year.

Table 6 - 12: Observed and simulated annual totals - Paramo catchment.

units			*m*	*.015*	*.015*	*.02*	*.02*						
mm			*To*	*2*	*5*	*4*	*5*						
			srmax	*.009*	*.011*	*.011*	*.011*			P-*Q*	P-$\bar{Q}$	*Q*/P	$\bar{Q}$/P
year	P	ET$_{pot}$	*Q* obs	Paramo *Q* simulations				$\bar{Q}$ sim	St.Dev	Obs	Sim	Obs	Sim
2006	2366	746	687							1679		0,29	
2007	2190	814	1140	1570	1596	1590	1590	1587	11	1050	604	0,52	0,72
2008	2189	775	1071	1630	1668	1660	1680	1660	21	1118	530	0,49	0,76
2009	2030	772	1553	1440	1473	1470	1480	1466	18	477	564	0,77	0,67

In the annual plots (Figure 6 - 22) the overall behaviour of forest run-off can be observed. For the year 2009, the observed data has some peaks which seem unreal. In general the discharge behaviours should look like the simulated one.

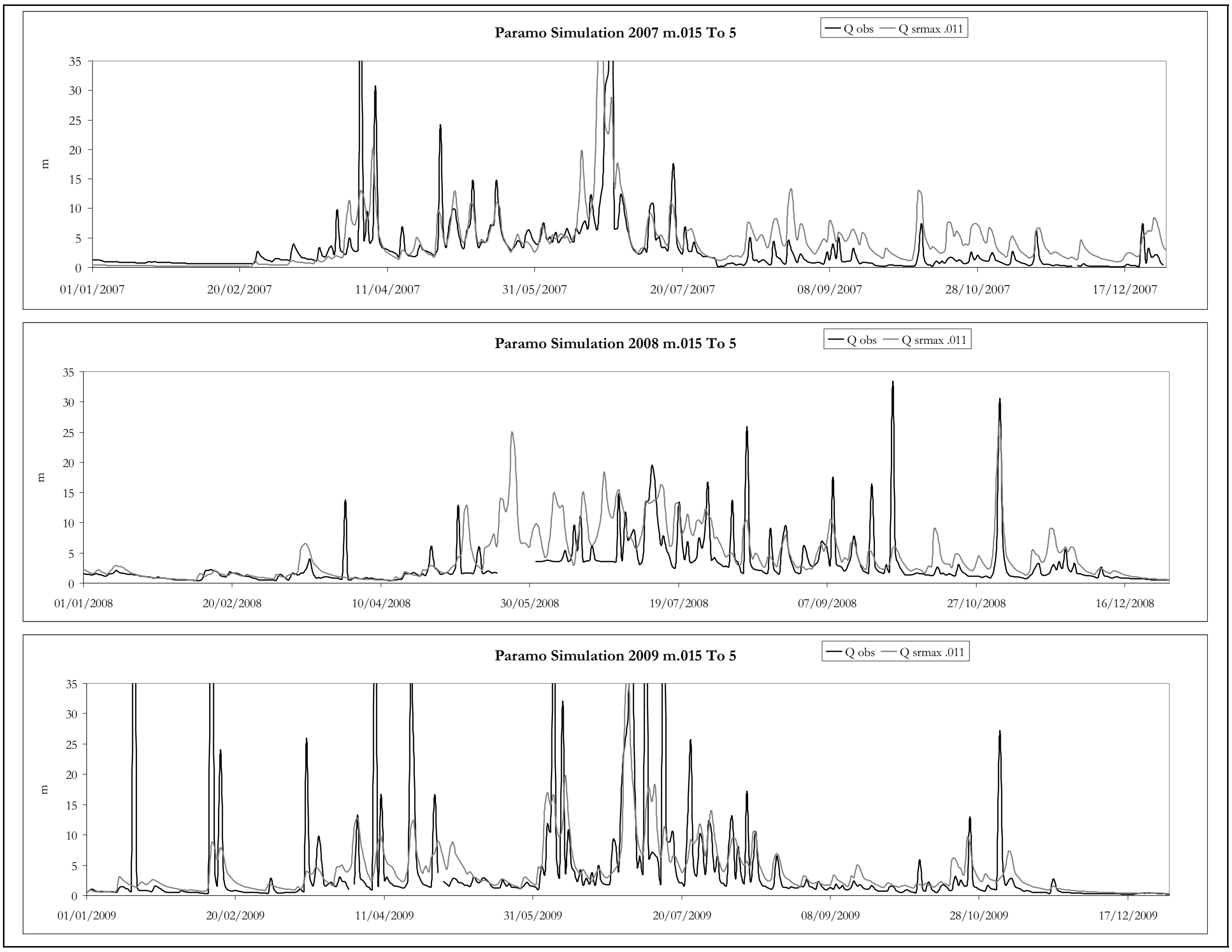


Figure 6 - 22: Paramo run-off simulations 2007 - 2009.

6.5.2. Annual Simulations Forest

The annual simulations for forest (Figure 6 - 23 & Table 6 - 13) show a similar pattern for the years and with the Paramo catchment. Around 70 % of the precipitated water runs off and is available at the outlet of the catchment. The total annual simulated value is more varying than the Paramo catchment, but can also be averaged to be around 1500 mm/year or slightly more.

Table 6 - 13: Observed and simulated annual totals - forest catchment.

units			*m*	*.015*	*.015*	*.02*	*.02*						
mm			*To*	*2*	*5*	*3*	*5*						
			srmax	*.009*	*.011*	*.011*	*.011*			P-Q	P-$\overline{Q}$	Q/P	$\overline{Q}$ /P
year	P	ET_{pot}	Q obs	Forest Q simulations				$\overline{Q}$ sim	St.Dev	Obs	Sim	Obs	Sim
2006	2545	863	1975	1900	1910	1920	1910	1910	8	570	630	0,78	0,75
2007	2193	944	3202	1550	1550	1550	1540	1548	5	-1009	643	1,46	0,71
2008	2245	900	3276	1660	1670	1680	1680	1673	10	-1031	573	1,46	0,74
2009	1919	884	3745	1310	1310	1320	1310	1313	5	-1826	608	1,95	0,68

In Figure 6 - 23 the run-off behaviour of the forest catchment can be seen since 2007 until 2009. It has to be noted comparing to the Paramo series and simulations, how erratic the level at the beginning and end of the year is, revealing measurement error. Sudden jumps, drops and flat peaks also highlight flaws in the measurements. Measured steady run-off when there are simulated recessions also reveals instrumentation error. In general the criteria presented in section 5.3.2 was used to asses the hydrographs.

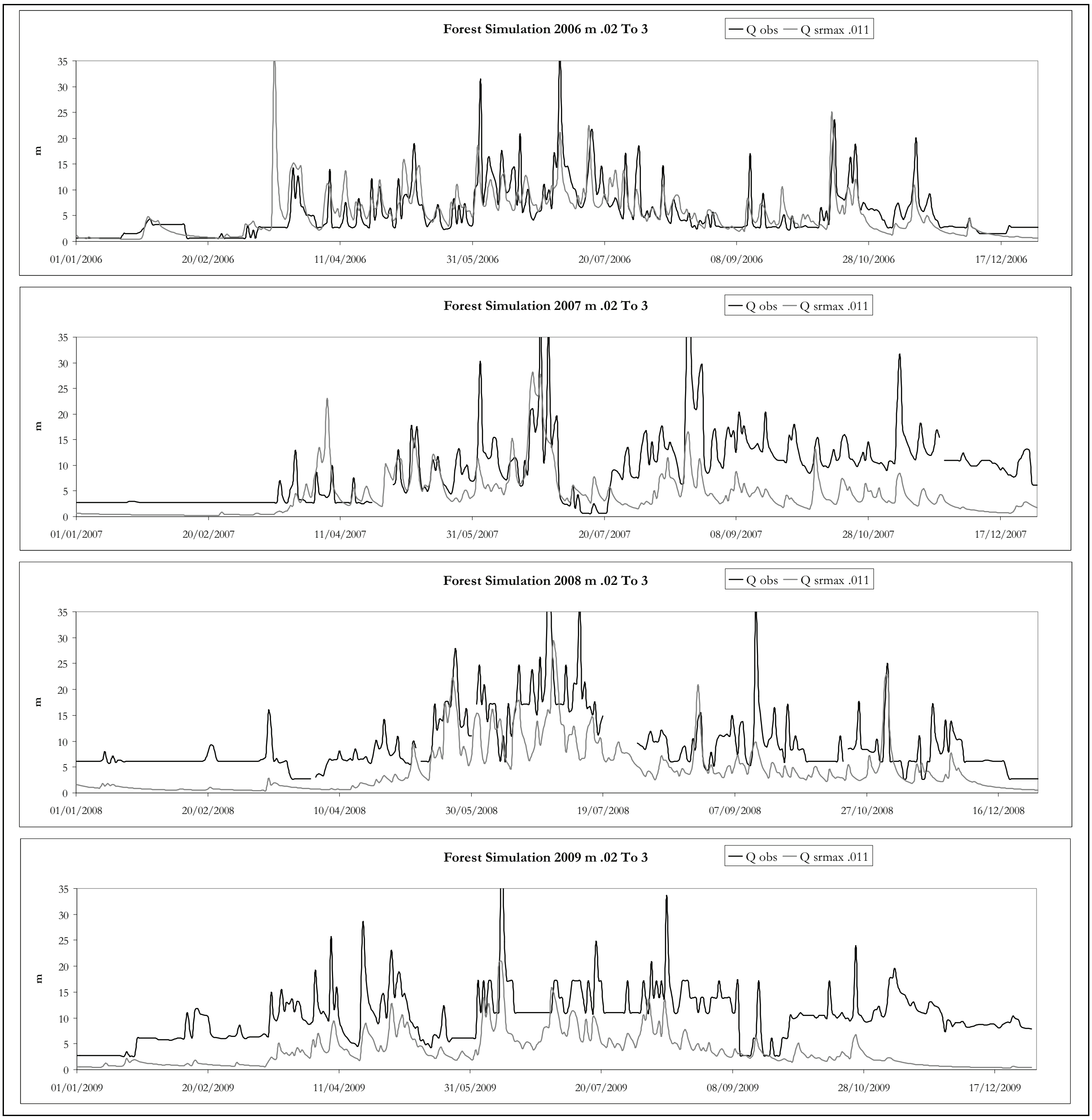


Figure 6 - 23: Forest run-off simulations 2006 - 2009.

6.5.3. Contrasting Observed and Simulated Annual Totals

The resulting averaged rain volume for the simulation years is similar for both catchments. Even when the Chuza station was used to give pattern to missing values for the Guajaro rain input, it only gave the pattern of the storm events, as the total values were the accumulated ones for the missing days (see section 3.2.3.3.2). As there is a similarity in the rain input and the potential evapotranspiration is also close, the yearly runoff ranges in the same level for both systems; it can be seen in the annual simulations in Tables 6 - 13, 6 - 14 & Figure 6 - 24. The run-off's relation with precipitation maintains around 0.7.

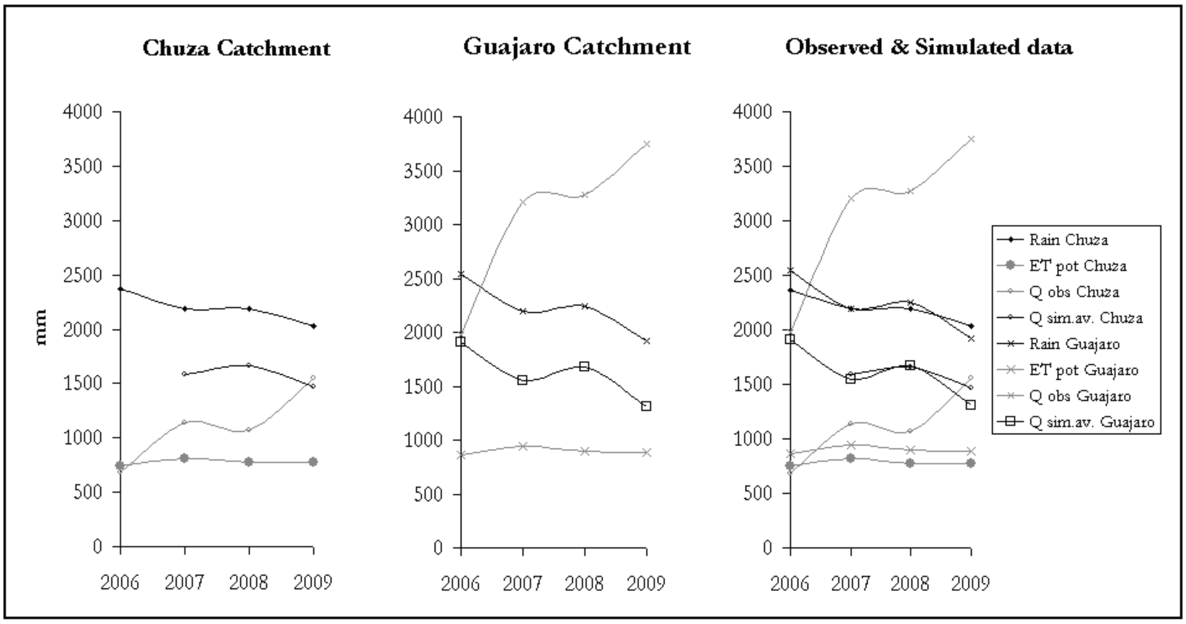


Figure 6 - 24: Observed & averaged simulated data, annual totals.

6.6. Hydrograph Comparison

As a final step the simulated behaviour of the two catchments is compared. With the optimization exercise (Appendix A), the following parameter combination gave overall satisfactory result:

m	To	srmax
0.015	5	0.011

The resulting simulations for the year 2007 for both systems can be observed in Figure 6 - 24.

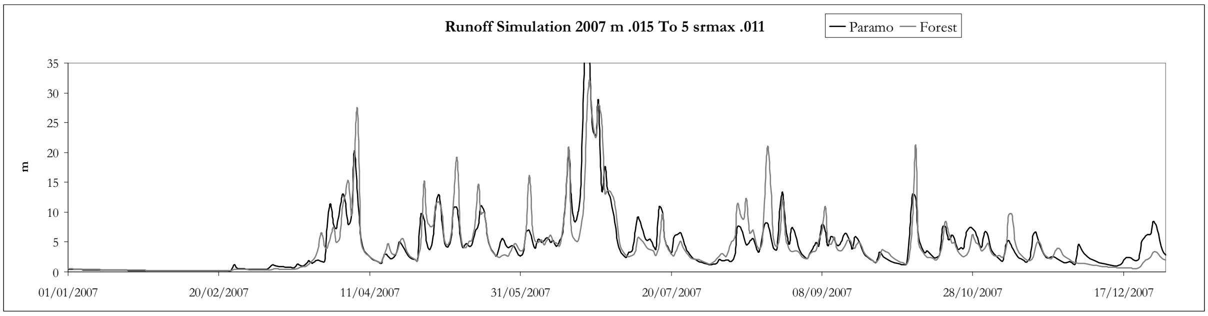


Figure 6 - 25: Paramo & forest simulations with same parameters for 2007.

Additionally by visual assessment (see section 5.3.2) the hydrographs presented in Appendix B were examined having in mind the optimization results and the following parameter combinations were selected as best fitting for each system:

Table 6 - 14: Best fitting parameter combinations.

	m	To	srmax
Paramo:	0.015	5	0.009
Forest:	0.02	3	0.011

By contrasting the simulations obtained with different parameters for different catchments,

It was expected to obtain different sets of best fitting combinations for the different catchments because they are different. The parameter combination for forest may reflect on the system; by having a higher m parameter value indicating thicker soil and a slight higher value of srmax parameter indicating a higher root zone storage profile. A higher value of transmissivity could be expected due to the rooting system of big trees, but for this case by visual inspection a lower value was selected.

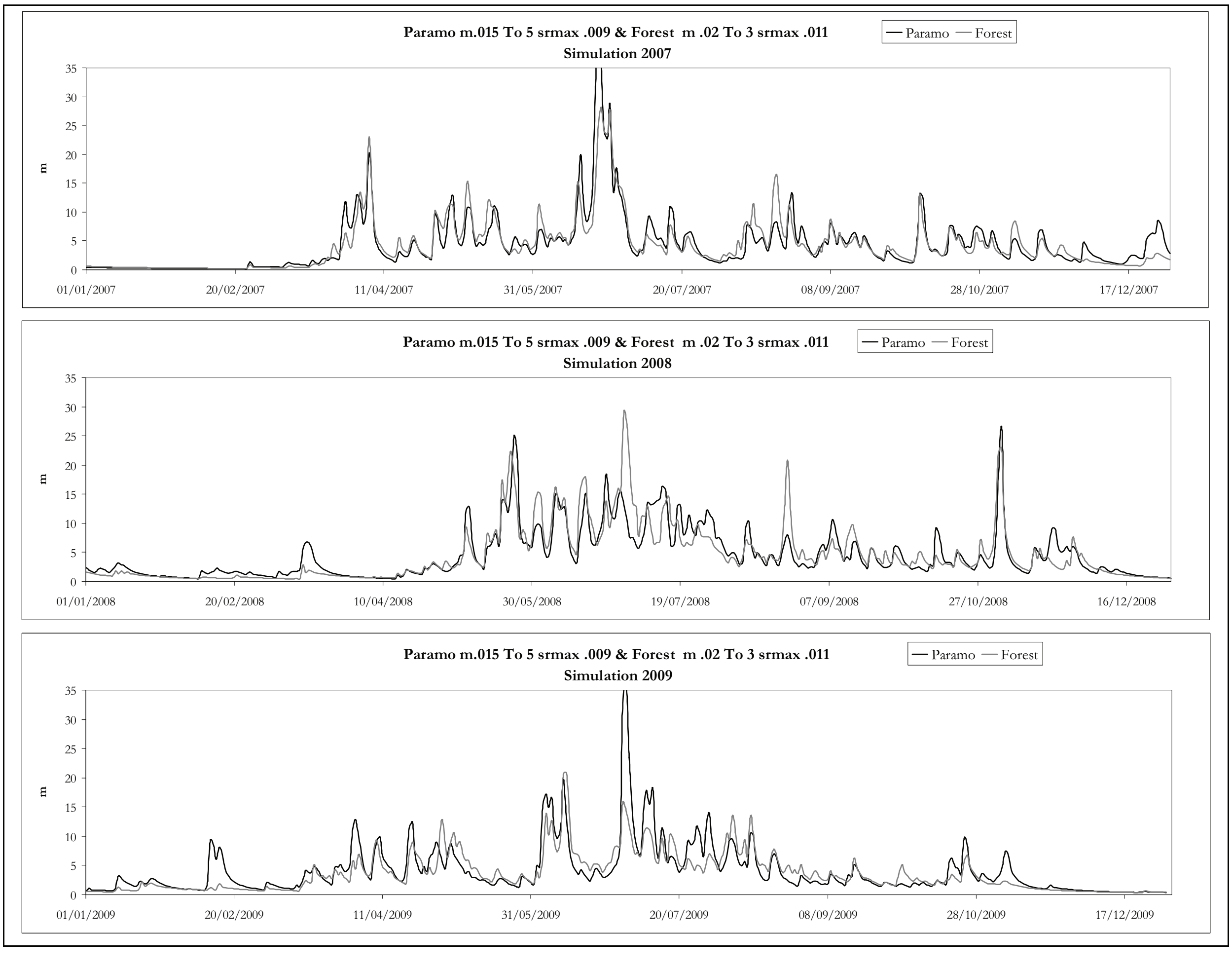


Figure 6 - 26: Paramo & forest simulations with different parameters 2007 - 2009.

As the theory states, Paramo has a high water storage capacity and slow release offering a sustained base flow and water provision in dry periods. This behaviour in contrast to a forest catchment was analyzed, but no evident differences were observed. The recession days after rainy periods were observed, generally a couple of months before the middle of the year and before its end. The base flow for December and January matches for both systems.

This similar run-off behaviour is also showing according to the calculations the precipitation in the range of 20 or 25 km, that is the distance between the catchments, is generally adding similar volumes to the catchments for annual cycles, but variation is present in the recorded daily behaviour of precipitation recorded with the rain gauges.

Currently there are plans to establish a reservoir above San Jose station (Figure 4 - 7) to include in the future water provision for Bogota`s region. So what is the impact of removing *X* volume of water in the Guatiquia watershed to populations downstream who depend on those catchments for water provision, are currently structured in using that resource and will have increasing demands in the future? Evaluating catchments like in this research help answer questions like this and support decision making. A next step would be to evaluate the water demand for the downstream catchment, which presents a challenge on its own.

This type of estimation can also be applied in calculating the water balance for catchment of the Chuza reservoir, of which the studied catchment; Chuza, is only a gauged subcatchment on the reservoir's catchment. Further studies can include estimating the supply of the whole catchment, plus the run-off from Blanco river's catchments which drain into the tunnels and San Rafael watershed, to have an idea of the total water supply for Bogotá's region (Figure 4 - 2).

7. CONCLUSIONS & RECOMMENDATIONS

7.1. Conclusions

In this study the hydrological processes of two typical tropical Andes catchments were investigated. In particular Paramo and forest land covers. The assessment was done through hydro - meteorological measurements, GIS and spatial data and rainfall run-off modelling. The following results were apparent when:

1. Analysing the trend and variability of the hydrological and climatic conditions, no evident change or pattern was identifiable in the annual rain data analyzed. On the other hand, there is an evident increase of temperature observed at San Juanito station at 1800 MASL. The annual mean of daily mean temperature increased from around 14,5 ºC in 1994 to 17 ºC in 2009, having a considerable potential impact on the natural systems.

2. Analysing the land cover change in the selected catchments, no significant land cover change is evident in the influence area of the Chingaza national park and other forest reserves. This is in contrast to rest of the Andes mountain where deforestation and habitat loss is a large problem. A stable and recovering land cover around protected areas indicate a positive management and community agreement with the protection objectives

3. Optimizing the rainfall run-off for each catchment, simulated peaks matched most of the series to the observed data, indicating that the model identifies correctly the storms and they were in those cases correctly represented by the rain gauge combining exercise. An incorrect daily representation of the rain that fell on the catchment will produce mismatches with the real runoff. Considerable of gaps and errors on the observed hydro - meteorological records limit the extents of the research.

4. Comparing the parameters that gave the best run-off simulations for the different catchments, it was observed that the more influencing parameter for the run-off simulations is the m parameter, followed by the transmissivity parameter lnTo and with less, influence the srmax parameter which describes the depth of the root zone. While the compared catchments are different in landscape and land cover, close parameter values serve to simulate correctly some parts of the hydrograph. The combination values set for both catchments describe shallow soil profile and slow hydraulic conductivity, typical of the area.

5. Comparing the run-off simulations for both systems, even when the runoff was simulated acceptably for each catchment with different parameters, the simulated hydrographs for the two catchments plotted together, follow a similar pattern. Although combining the rain data from different stations in a different way, the rain series for the two catchments were similar for the annual total, the daily rain depth revealed variability.

Water provision from the studied catchments is ruled by the presence and volume of precipitation, more than topographic or landscape determinants like soil and vegetation. If the precipitation regime changes so will run-off water supply.

7.2. Recommendations

The data quality especially the runoff measurements at Guajaro outlet - Centro station, create great uncertainty, as it is not possible to validate the simulations completely. If the current meteo - hydrological measuring system does not record the actual processes and events in a correct manner, the investment and efforts on it are lost, and the application for what they were intended is not possible. There needs to be an improvement on the data collection and analysis, as well as further fund raising for instrumentation and promoting research linked to the recorded data series.

Reliable data series of higher temporal resolution are needed for ecosystem analysis. The INAP initiative since 2008 has some real time series, some other few automatic stations have been established, but still there needs to be more care on recording the data correctly, continuously and to make the data available for studies. There is uncertainty on evapotranspiration, temperature and radiation for higher elevations and how is rainfall affected by the present orographic effects that create a heterogeneous and variable spatial precipitation pattern. More instrumentation and research is needed in this line.

Colombian legislation and policy makers always link Paramo ecosystem, when considering water supply and high mountain nature conservation strategies and actions. Currently many efforts and funds are oriented that way; to prioritize, recover and protect natural mountain systems. To learn more about the components in the water cycle and have an effective watershed management, a systemic and integrated approach over the landscape is recommended.

APPENDIX

Appendix A: Output of the objective function calculation to the simulations performed with the parameter set.

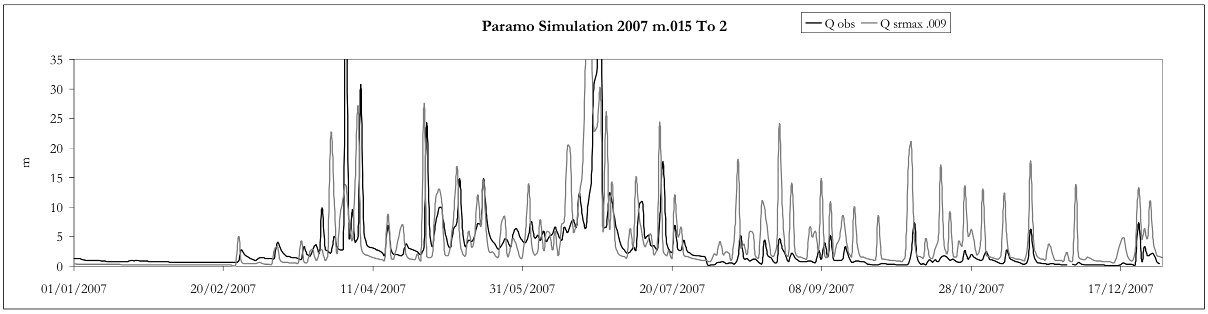
Forest									**Paramo**					
0.001	0.003	0.005	0.007	0.009	0.011		m.015 lnTo 2		0.001	0.003	0.005	0.007	0.009	0.011
0.60	0.70	0.70	0.70	0.71	0.70	c	NS	c	-1.91	-1.69	-1.66	-1.64	-1.64	-1.63
12.3	4.2	1.6	1.0	0.7	0.7	c	Rve	c	24.2	12.9	10.4	9.0	8.6	8.4
-2.25	-1.56	-1.37	-1.29	-1.23	-1.19	v	NS	v	-0.22	-0.12	-0.07	-0.05	-0.04	-0.03
57.1	35.7	28.1	24.1	21.6	20.1	v	Rve	v	55.6	38.2	32.9	30.6	29.4	28.7
0.001	0.003	0.005	0.007	0.009	0.011		m.015 lnTo 3		0.001	0.003	0.005	0.007	0.009	0.011
0.69	0.69	0.69	0.69	0.69	0.69	c	NS	c	-1.16	-0.92	-0.92	-0.88	-0.88	-0.87
11.6	4.1	2.0	1.3	1.0	0.7	c	Rve	c	27.8	16.5	16.5	12.9	12.6	12.4
-0.73	-0.28	-0.17	-0.11	-0.09	-0.08	v	NS	v	0.01	0.09	0.09	0.12	0.13	0.14
60.5	38.2	30.4	26.1	23.5	21.6	v	Rve	v	58.1	40.8	40.8	34.1	33.0	32.1
0.001	0.003	0.005	0.007	0.009	0.011		.015 lnTo 4		0.001	0.003	0.005	0.007	0.009	0.011
0.05	0.15	0.14	0.13	0.13	0.13	c	NS	c	-0.32	-0.16	-0.13	-0.12	-0.12	-0.11
8.7	1.6	-1.1	-1.7	-2.0	-2.3	c	Rve	c	32.6	21.8	19.1	18.1	17.6	17.4
-0.22	0.14	0.19	0.23	0.24	0.25	v	NS	v	0.19	0.27	0.28	0.28	0.29	0.29
60.3	37.8	30.8	26.5	23.8	22.0	v	Rve	v	60.1	42.6	38.2	35.9	34.7	33.9
0.001	0.003	0.005	0.007	0.009	0.011		m.015 lnTo 5		0.001	0.003	0.005	0.007	0.009	0.011
-0.54	-0.43	-0.44	-0.45	-0.45	-0.45	c	NS	c	0.14	0.28	0.30	0.30	0.31	0.31
6.8	-0.7	-3.4	-4.0	-4.3	-4.5	c	Rve	c	38.0	26.5	24.2	23.2	22.7	22.4
-0.27	0.15	0.23	0.26	0.28	0.28	v	NS	v	0.26	0.31	0.32	0.33	0.33	0.33
60.0	37.1	29.7	25.4	22.8	21.0	v	Rve	v	61.5	43.3	39.1	36.9	35.6	34.8
0.001	0.003	0.005	0.007	0.009	0.011		m.02 lnTo 2		0.001	0.003	0.005	0.007	0.009	0.011
0.55	0.65	0.67	0.68	0.68	0.69	c	NS	c	-1.75	-1.56	-1.53	-1.52	-1.51	-1.51
14.2	6.5	3.7	3.1	2.8	2.6	c	Rve	c	25.6	14.3	11.8	10.7	10.3	10.1
-2.00	-1.34	-1.15	-1.05	-0.99	-0.95	v	NS	v	-0.17	-0.09	-0.05	-0.02	-0.01	0.00
56.9	35.5	27.9	23.5	21.0	19.5	v	Rve	v	55.6	37.4	32.5	30.0	28.8	28.0
0.001	0.003	0.005	0.007	0.009	0.011		m.02 lnTo 3		0.001	0.003	0.005	0.007	0.009	0.011
0.66	0.69	0.69	0.69	0.69	0.69	c	NS	c	-1.05	-0.85	-0.81	-0.80	-0.79	-0.79
13.6	5.2	2.2	1.5	1.2	1.0	c	Rve	c	30.3	19.6	17.1	16.1	15.7	15.4
-0.75	-0.30	-0.20	-0.15	-0.12	-0.10	v	NS	v	0.08	0.15	0.16	0.18	0.18	0.19
59.4	36.0	29.4	25.1	22.6	20.8	v	Rve	v	57.4	40.5	35.7	33.4	32.2	31.4
0.001	0.003	0.005	0.007	0.009	0.011		m.02 lnTo 4		0.001	0.003	0.005	0.007	0.009	0.011
0.34	0.36	0.35	0.35	0.34	0.34	c	NS	c	-0.38	-0.21	-0.18	-0.17	-0.16	-0.16
10.9	2.6	-0.4	-1.0	-1.3	-1.6	c	Rve	c	37.4	26.4	23.9	22.8	22.4	22.1
-0.27	0.05	0.13	0.16	0.17	0.17	v	NS	v	0.25	0.30	0.31	0.32	0.32	0.32
59.3	35.6	27.9	23.6	21.0	19.4	v	Rve	v	61.4	43.5	38.6	36.5	35.3	34.4
0.001	0.003	0.005	0.007	0.009	0.011		m.02 lnTo 5		0.001	0.003	0.005	0.007	0.009	0.011
-0.06	-0.02	-0.02	-0.03	-0.03	-0.03	c	NS	c	-0.08	0.06	0.08	0.08	0.08	0.09
8.8	0.4	-2.4	-3.0	-3.4	-3.6	c	Rve	c	43.3	32.0	29.5	28.8	28.4	28.2
-0.13	0.15	0.21	0.23	0.24	0.24	v	NS	v	0.27	0.33	0.34	0.35	0.34	0.34
57.8	34.5	27.0	22.8	20.2	18.4	v	Rve	v	61.9	44.1	39.2	37.0	36.1	35.2
0.001	0.003	0.005	0.007	0.009	0.011		m.025 lnTo 2		0.001	0.003	0.005	0.007	0.009	0.011
0.51	0.61	0.63	0.64	0.64	0.64	c	NS	c	-1.63	-1.45	-1.41	-1.41	-1.40	-1.39
15.9	8.4	5.7	5.2	4.8	4.6	c	Rve	c	26.3	15.5	13.0	11.9	11.5	11.3

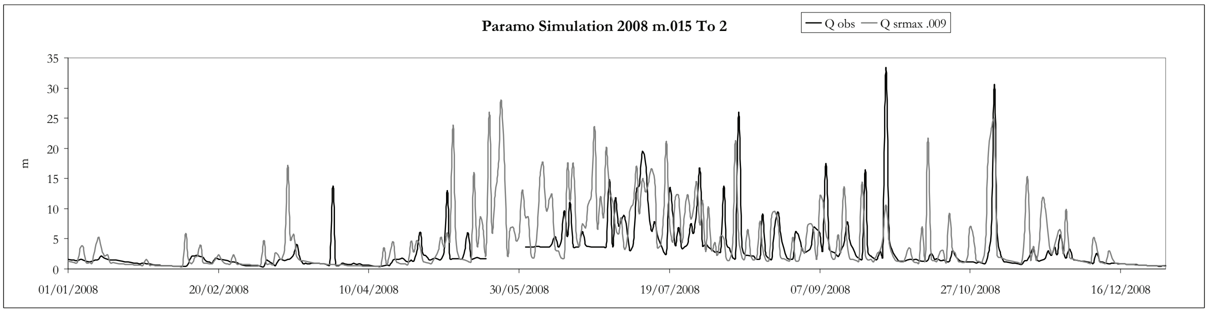
-1.82	-1.21	-1.05	-0.97	-0.92	-0.89	v	NS	v	-0.14	-0.06	-0.01	0.01	0.02	0.03
56.4	35.0	27.2	22.9	20.4	18.8	v	Rve	v	55.4	37.9	33.0	30.5	29.3	28.5
0.001	0.003	0.005	0.007	0.009	0.011		m.025 lnTo 3		0.001	0.003	0.005	0.007	0.009	0.011
0.61	0.64	0.65	0.65	0.65	0.64	c	NS	c	-1.03	-0.81	-0.77	-0.76	-0.75	-0.75
14.4	5.7	2.5	1.9	1.5	1.3	c	Rve	c	33.1	21.5	19.1	18.1	17.7	17.5
-0.75	-0.31	-0.24	-0.20	-0.17	-0.16	v	NS	v	0.11	0.16	0.18	0.19	0.20	0.20
57.9	35.0	28.6	24.5	22.0	20.3	v	Rve	v	57.2	40.8	36.0	33.6	32.5	31.6
0.001	0.003	0.005	0.007	0.009	0.011		m.025 lnTo 4		0.001	0.003	0.005	0.007	0.009	0.011
0.37	0.39	0.39	0.39	0.38	0.38	c	NS	c	-0.43	-0.26	-0.24	-0.23	-0.22	-0.22
12.3	3.5	0.4	-0.2	-0.6	-0.8	c	Rve	c	41.1	29.9	27.5	26.5	26.1	25.8
-0.32	0.00	0.06	0.10	0.10	0.11	v	NS	v	0.23	0.28	0.29	0.30	0.30	0.30
57.4	33.0	25.7	21.6	19.5	17.8	v	Rve	v	61.7	43.4	38.7	36.4	35.1	34.3
0.001	0.003	0.005	0.007	0.009	0.011		m.025 lnTo 5		0.001	0.003	0.005	0.007	0.009	0.011
0.06	0.10	0.10	0.09	0.09	0.09	c	NS	c	-0.22	-0.09	-0.07	-0.06	-0.06	-0.05
10.5	1.8	-1.3	-1.9	-2.3	-2.5	c	Rve	c	47.1	36.7	34.2	33.2	32.8	32.7
-0.18	0.08	0.14	0.16	0.17	0.17	v	NS	v	0.26	0.29	0.30	0.30	0.30	0.30
56.0	32.3	24.9	20.8	18.6	16.8	v	Rve	v	63.3	45.3	40.4	38.2	36.9	36.1

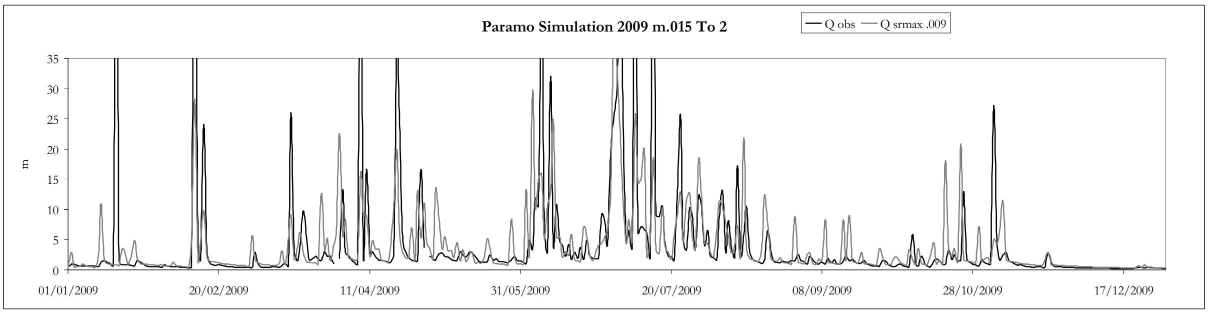
Appendix B: Annual runoff simulation results

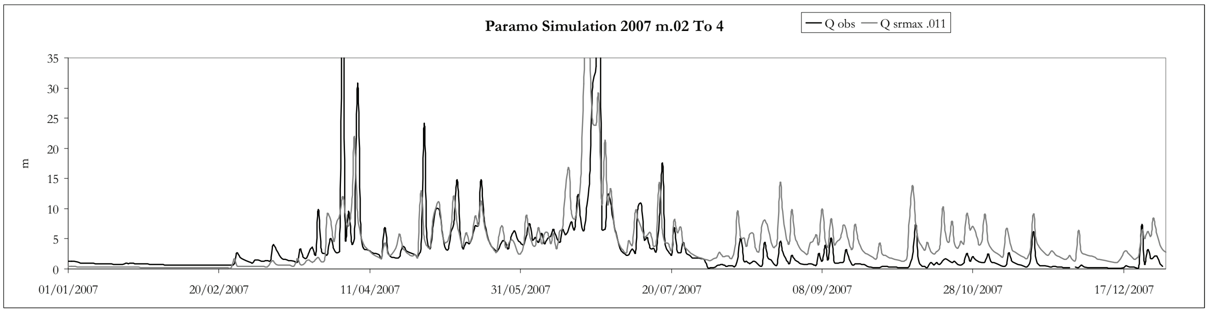
To observe the behaviour of the recorded runoff and the simulated one, some plots were prepared.

Paramo simulations





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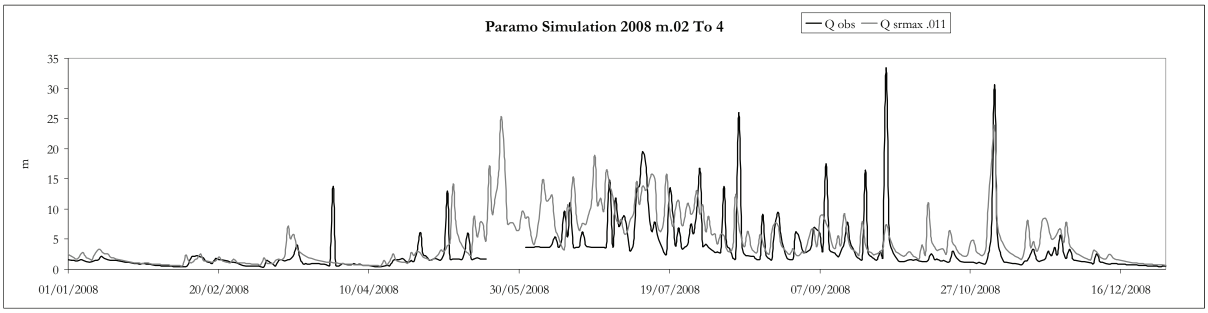
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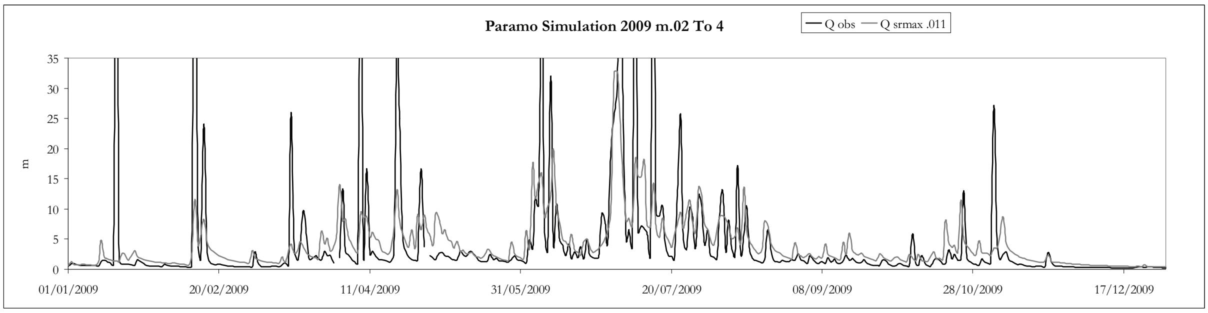
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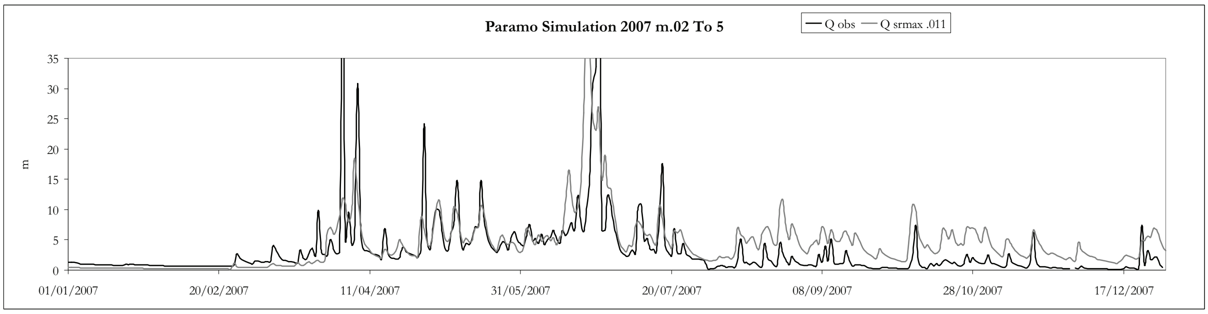
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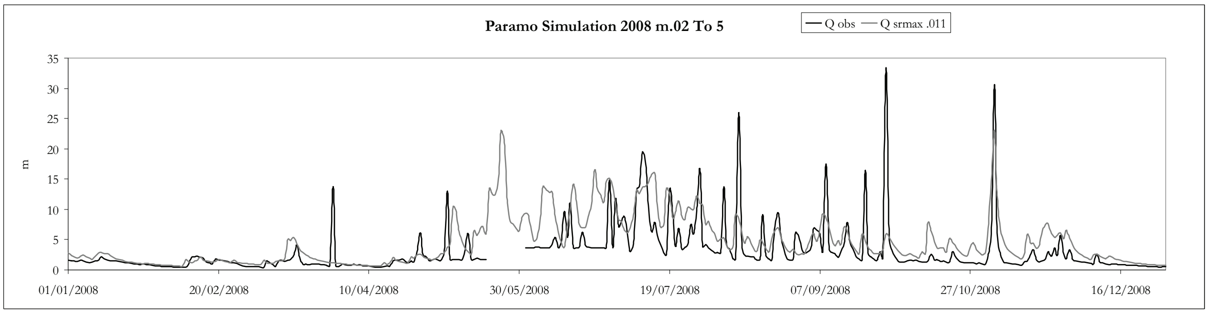
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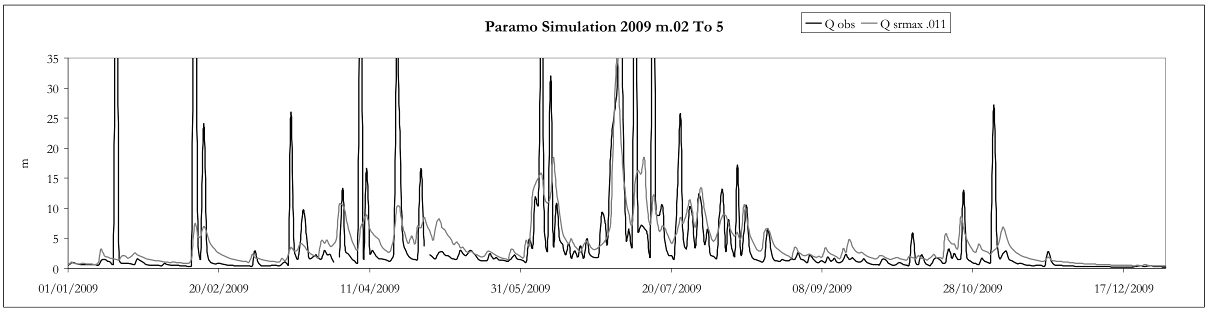
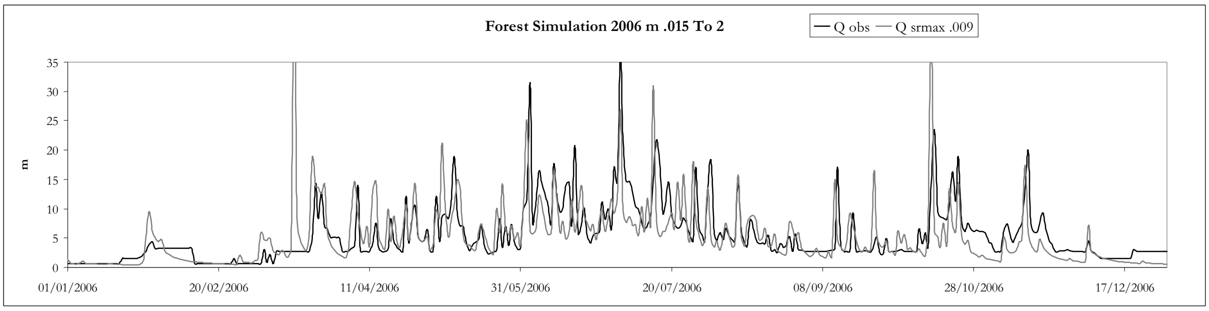
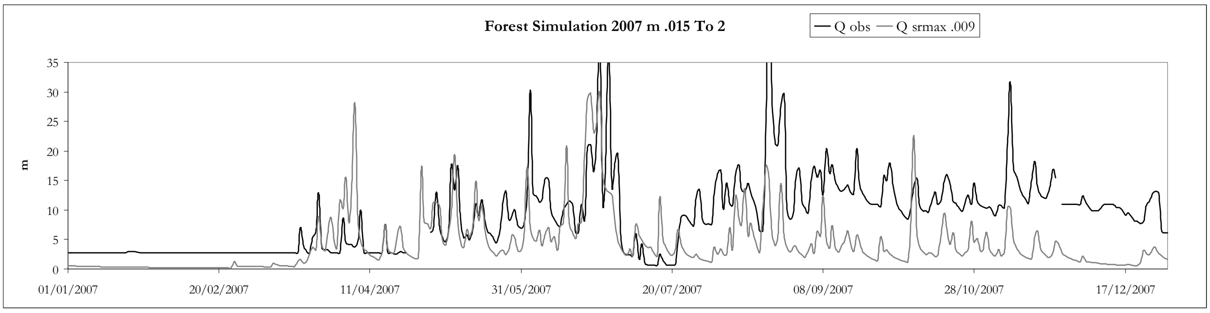
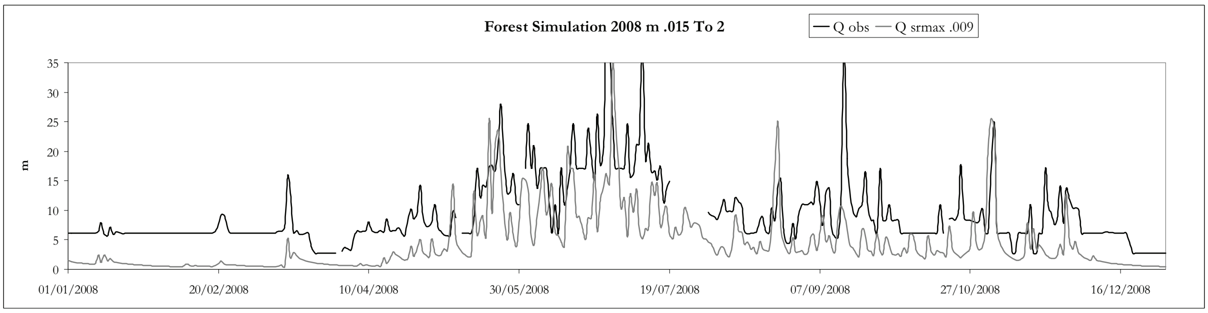
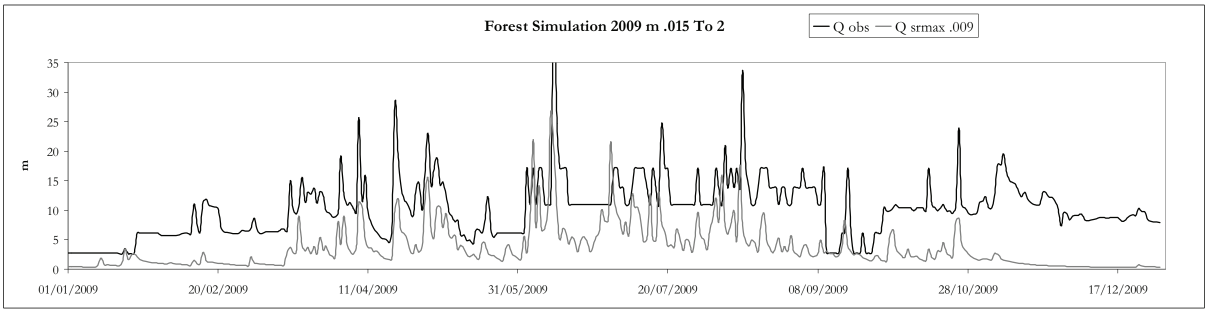


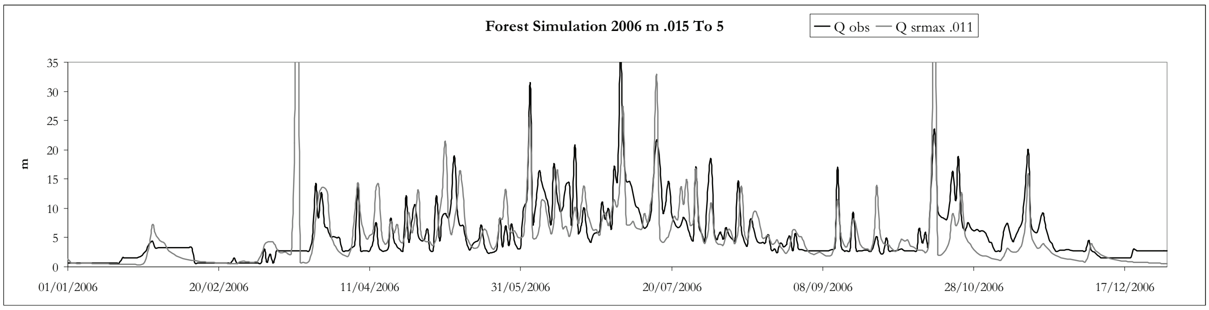
Forest simulations







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01/01/2006
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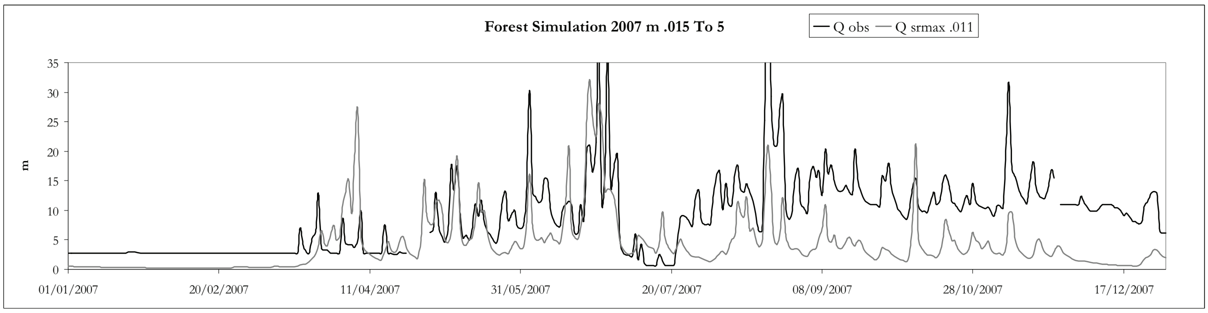
31/05/2006
20/07/2006
08/09/2006
28/10/2006
17/12/2006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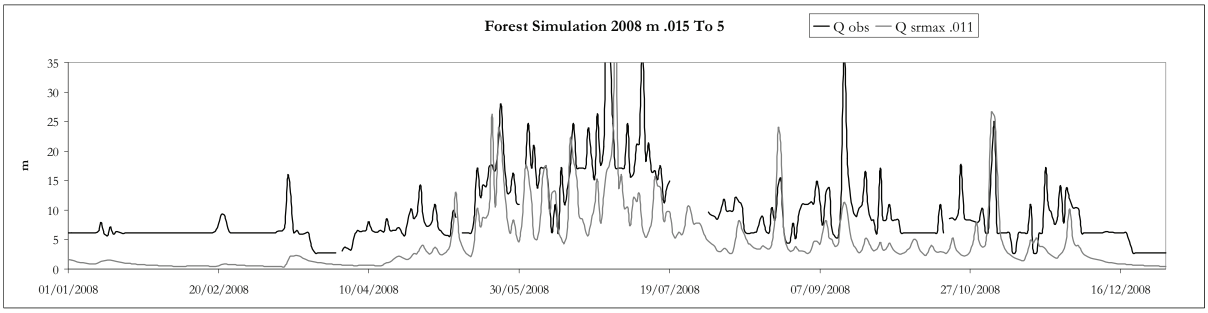
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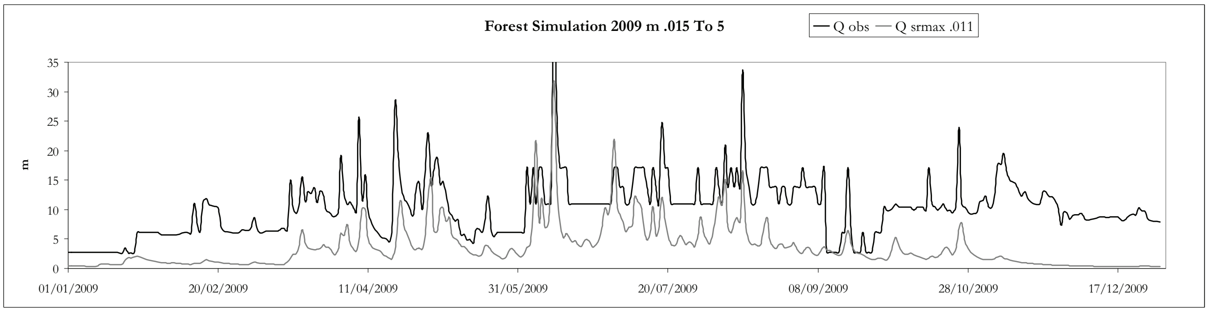
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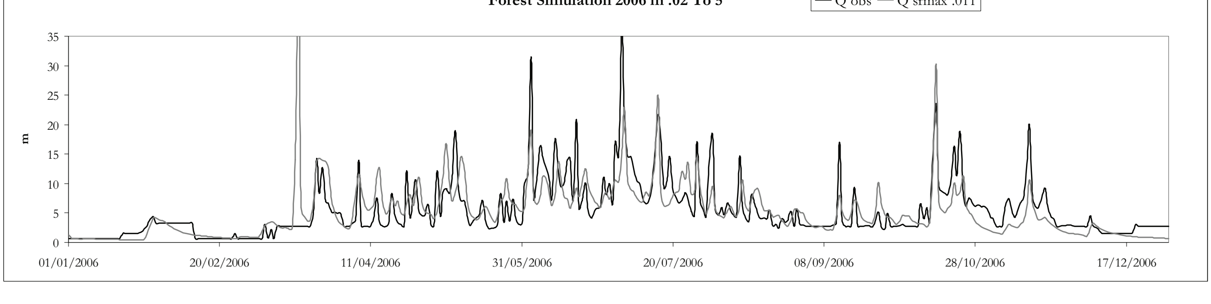
17/12/2009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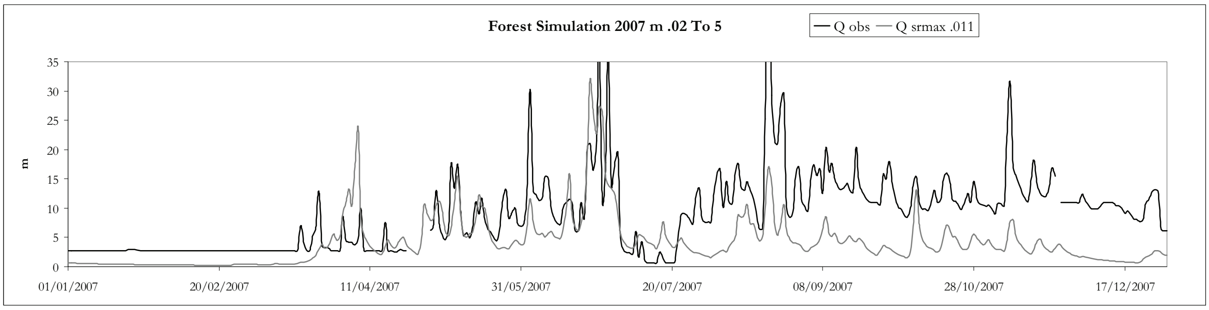
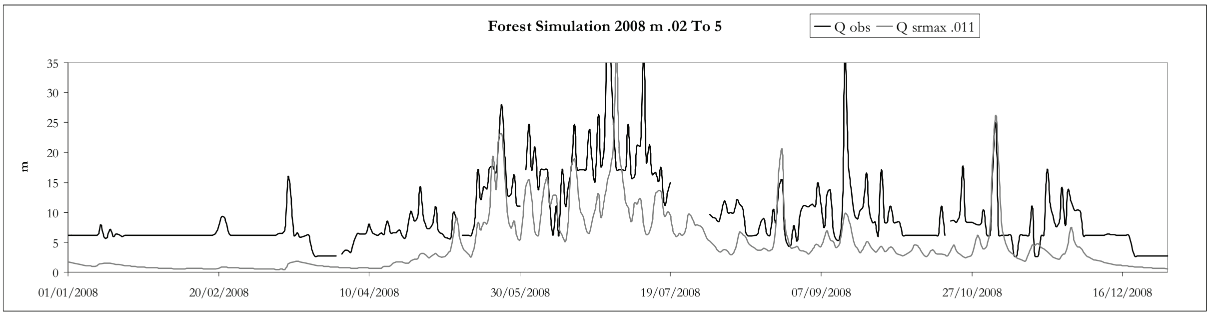
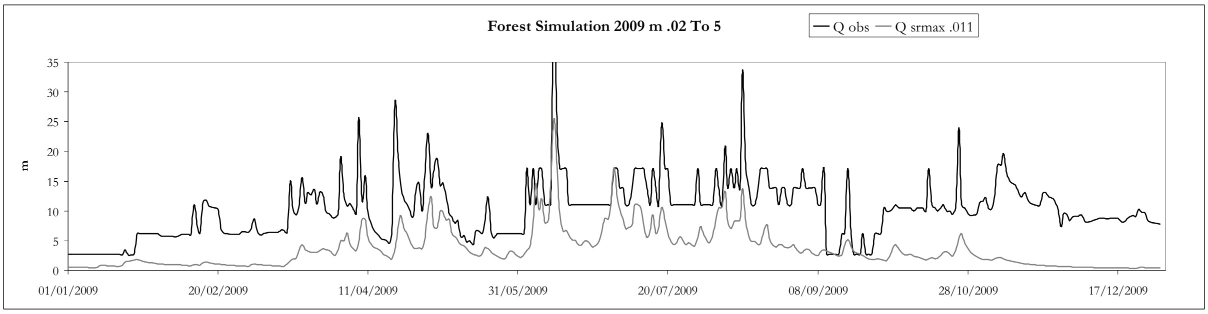
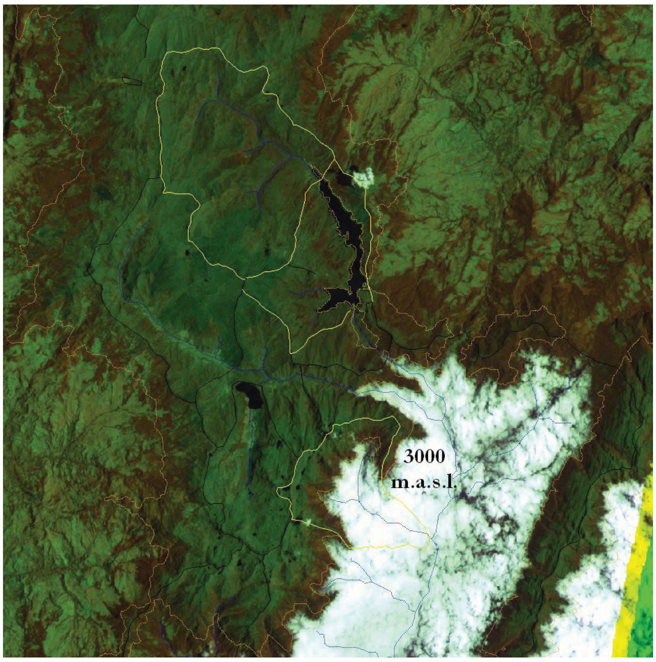






Apendix C: Landsat image; Cloud over Guatiquia Valley.



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