# RUNOFF MODELLING OF THE UPPER CABRA RIVER BASIN PANAMA

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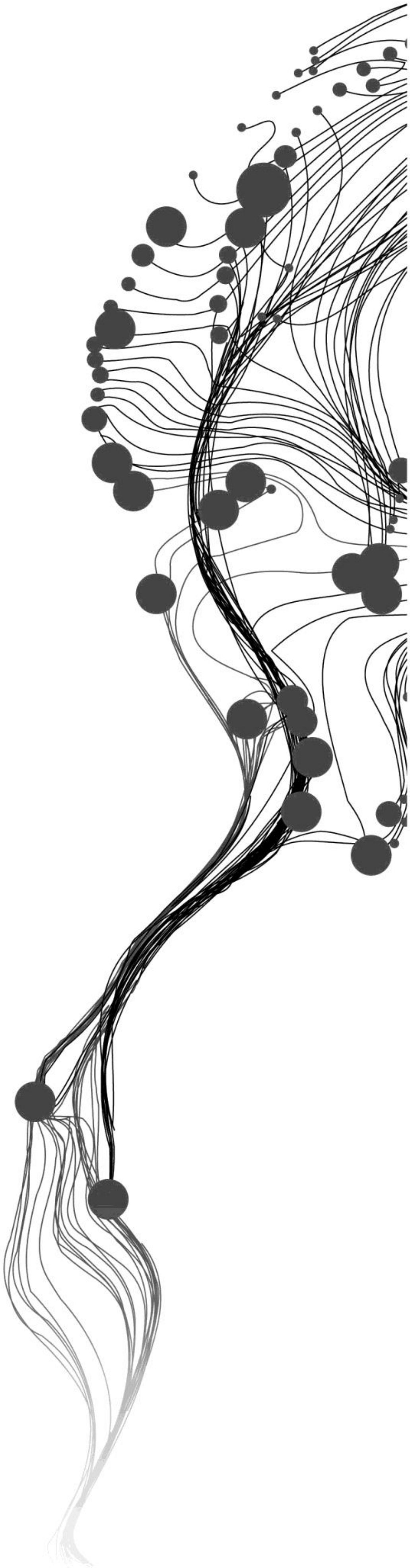

# RUNOFF MODELLING OF THE UPPER CABRA RIVER BASIN PANAMA


HAROLD HOYOS GOEZ
Enschede, The Netherlands, March, 2011


Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Water Resources and Environmental Management

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# ABSTRACT

Estimation of the surface runoff in the catchment is important for the urban planning and the design of flood control structures. Monitoring and estimation of peak discharge is the main objective in water resources planning and management and can be achieved by surface runoff modelling. Even though a variety of rainfall-runoff models are available, a selection of a suitable rainfall-runoff model for a given catchment is essential to ensure efficient planning and management of catchments. The objective of this study is to simulate the rainfall runoff in Cabra river basin using hydrological models. HBV-96 semi distributed and HEC-HMS lumped models are selected for this research. To meet the objective of the study, geographical information systems and remote sensing information were used. The data sets of this study were collected in Cabra catchment Rainfall, stage, temperature, Digital elevation model (DEM) were collected. Rainfall and tests were carried out to filter wrong information. Stage data is corrected and converted into discharges according to rainfall. Correction of discharges was attempted. Data screening is performed to the rainfall and discharge time series. Rainfall and runoff time series quality is very poor. The aerial rainfall is calculated using Thiessen polygon and the potential evapotranspiration is calculated using Thornthwaite method following the local standards. Land cover of the study area was classified using supervised classification of Landsat TM images; the DEM is processed using ArcGIS tools. The hourly runoff is simulated for Cabra river basin using HBV-96 and HEC-HMS. The model HBV-96 is calibrated using manual calibration the performance of the calibration is measured by Relative volume error ($RV_E$) and Nash and Sutcliffe (NS), the performance is acceptable. The model HEC-HMS is calibrated by trial and error and by optimization trials, the performance of the calibration is measured by $RV_E$ and NS. In the outcome the performance of the model was very poor, and the probable cause of the failure to simulate the relation of the rainfall and runoff is the observed data taken at a daily time step much longer than the response of the catchment, and simulated data is hourly time step besides the low quality of the rainfall and runoff time series.

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# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# 1. INTRODUCTION

Surface runoff hydrographs, peak estimation and discharge are important factors in flood related analyses in order to have accurate flood estimations that are required for designs of management related studies. Beyond its use in several hydrologic and hydraulic analyses, peak discharges and flood estimation is essential for saving human lives and protecting properties (Olivera and Maidment 2000). cited by (Gül, Harmancıoğlu, & Gül, 2010)

Panama has one of the highest rainfall intensities in the world; and makes the region prone to flooding events, with an annual average rainfall of 2100 mm.

Panama projects a widening of the canal for 2014 and its economic benefits will be reflected in the country development and city growing. Panama City is growing fast and needs areas for housing. The solutions so far are huge skyscrapers in the city itself and more urban type constructions in the Panama "satellite" settlements bringing antropic changes to the basins and, putting pressure to rural catchments and mainly conditioning the surface runoff by demographic increase, consequently, altering the runoff production.

## 1.1. Research problem

The relation rainfall and surface runoff in the upper catchment is not well understood in Cabra river basin that is characterised by high rainfall intensities, high peak discharges and a rapid response of the catchment. Specifically, a quick change in runoff has been observed in the few last years as settlements were intervened by human and urbanization processes in the floodplains. Cabra river basin (58.69 $km^2$) is mostly urbanized in the medium catchment, with an average population of 14.000 thousand people. In the last decade several flood events occurred, generating high economic losses and damages to the infrastructure. The significant dates of flooding events are 25 September 1994, 27 July 1995, 26 September 1997, 8 December 1998, 6 September 1999 and 17 September 2004. The 2004 flooding event caused 13 casualties, 2580 houses became flooded and 13.000 people were affected. Being the Cabra River basin in the vicinity of Panama city and the international airport the project of understanding the surface runoff and peak discharges has become a challenge for The National Authority of Environment (ANAM), in order to protect life and avoid high economic losses.

## 1.2. Objectives

The main objective of this study is to simulate rainfall runoff in the upper Cabra river basin.

### 1.2.1. Specific objectives

1. To evaluate catchment runoff by using hydrological models.
2. To determine the response of the upper catchment to extreme rainfall events.
3. To calibrate the model using the available discharge curves against the hydrographs resulting from the model.
4. To statistically evaluate rainfall time series and to identify rainfall recurrence periods.
5. To assess the time-space distribution of rainfall.
6. To parameterize the land cover by satellite imagery.
7. To evaluate the program of instrumentation and data collection implemented for the Panamanian authorities and suggest improvements

## 1.3. Research questions

From the objectives, the following research questions have been formulated:

Objective 1

1. According to the sub catchment (basin) characteristics and available information, which model is suitable to model the current conditions?
2. What is the input effort required for the potentially applicable models?

Objective 2

1. How are runoff response times to rainfall events?
2. Is the discharge variations well correlated with rainfall events of different intensity?

Objective 3

1. Which procedure is suitable to calibrate the model, considering the limitations of the available data?

Objective 4

1. Which methods are more appropriate for determining the rainfall recurrence periods?

Objective 5

1. What is the result of the frequency analysis of the intense events in the study area?

Objective 6

1. What are the predominant land use and land cover of the upper basin?
2. How to characterize the basin land surface?

Objective 7

1. Is the actual instrumentation establishment adequate to the purpose of modelling and flood prevention in the Cabra basin?

## 1.4. General methodology

The research was conducted in three phases:

### 1.4.1. Pre_Fieldwork

Basic data collection such as image downloading from Landsat TM Archive, Literature review, contacts connection with the University of Panama, discussion with the supervisors and working plan scheduling, were part of the preparation for fieldwork.

### 1.4.2. Fieldwork

A field campaign was conducted in September 2010 during which the following data was collected.

- Daily Meteorological data from stations Altos de Pacora, Loma Bonita, Utive and Tocumen from years 1980 to 1999.
- Rainfall data every 15 minutes for stations Rancho Cafe and Cerro Pelon years 2009 to 2010.
- Daily stage data for Rancho Cafe station years 2009 to 2010.
- Cross sections river survey using levelling equipment, discharge calculation using the current meter.
- DEM 30 m x 30 m spatial resolution, texture map, and aerial pictures.
- Daily temperature and wind speed for Tocumen station years 2009 to 2010.
- Survey of the downstream flooded area in 2004 using GPS.

### 1.4.3. Post_Fieldwork

The activities carried out consisted in:

- Analysis of the rainfall by extreme frequencies distributions for estimation return periods.
- Analysis of rainfall for discharge peaks variation in short intervals for determining how the response of the river to the rain, in order to evaluate data consistency.
- Stage to discharge retrievals per unit of the cross section.
- Land use classification for images of 1984 and 2010 to assess landuse changes.
- Hydrological modelling using HBV and HEC-HMS.
- Analysis of alternatives to the actual data collection establishment, discussions and recommendations.

# 2. STUDY AREA AND DATA COLLECTION

## 2.1. Study Area

### 2.1.1. Geographic location

Cabra is an urban Catchment located at the east of Panama City at 1009.687 N and 678.939 E. It belongs to a hydrographical network between the rivers *Abajo* and *Pacora*. The main effluents composing this hydrographical network are *Abajo, Juan Diaz, Pacora*, *Tocumen* and *Cabra rivers*. The total area of the catchment is 58.69 Km² and the overall region is partially urbanized, with relatively large number settlements in the middle section of the basin. The main stream originates at an elevation of 770 m.a.s.l in Cerro Pelon Mountain ending at the coast of the Pacific Ocean, flowing from the north to the south along a river length of 30 km.

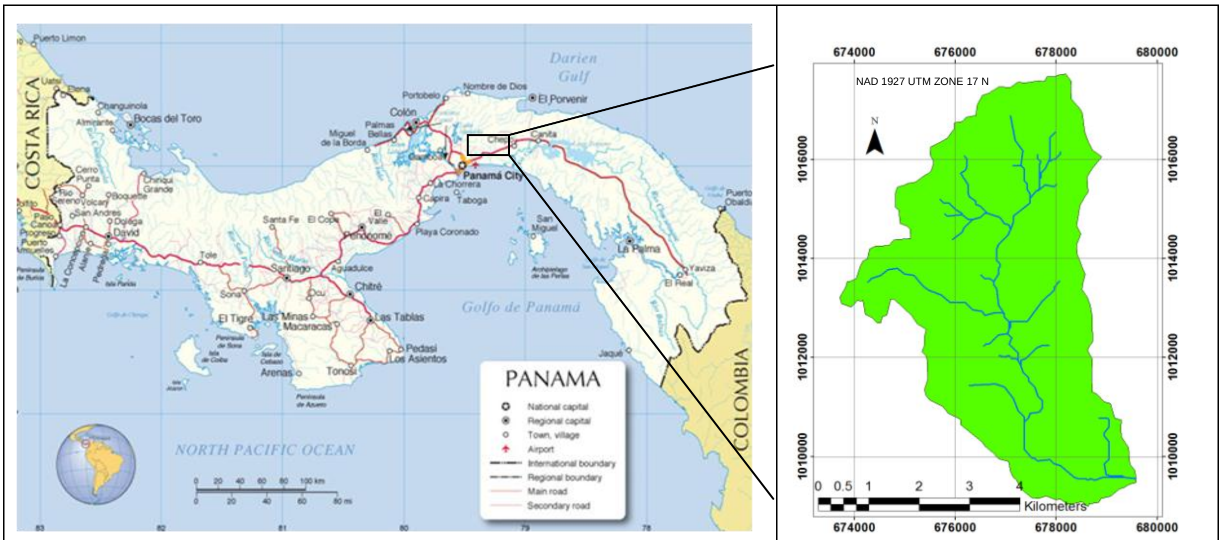


Figure 2 - 1: Geographic location Cabra river basin

### 2.1.2. Geomorphology

Upper Cabra river basin elevations range between 770 m.a.s.l and 114 m.a.s.l according to a DEM 30m x 30 m spatial resolution that is provided by The National Authority of Environment (ANAM). (See Figure 2-2). Cabra River basin has three altimetry regions: the low lands from 0 to 100 m.a.s.l, the medium hills from 100 to 300 meters and the mountains located between 300 and 1007 m.a.s.l.

The low lands are conformed of non consolidated deposits, alluvial floodplains and swamps. The medium hills are limited in north and south by the tectonic faults; it is a hilly zone from the Panamanian formation which has been elevated by tectonic movements. The high mountains have been tectonically raised and belong to a volcanic crystalline structure named *Nudo de Mamoni* (Gonzalez D, 2010).

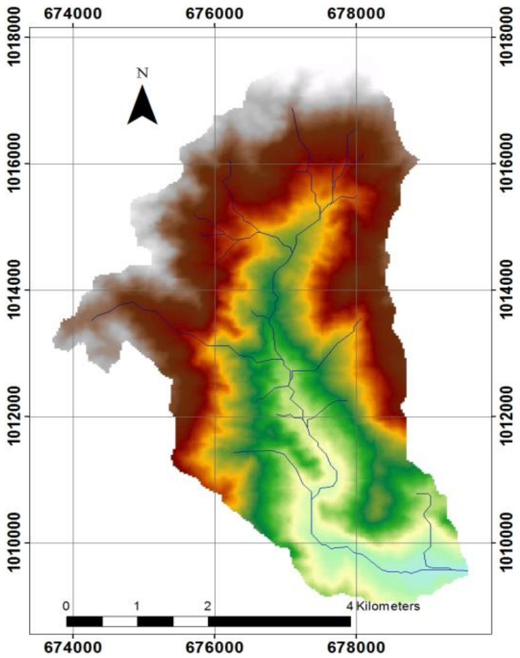


Figure 2 - 2: DEM upper Cabra river basin

#### 2.1.3. Climate

Panama has a tropical climate. Temperatures are uniformly high as is the relative humidity and there is little seasonal variation. Rainfall varies regionally from less than 2000 millimeters to more than 3,000 millimeters per year. Almost all of the rain falls happens during the rainy season, from April to December, varying in length from seven to nine months. In general, rainfall is much heavier on the Caribbean than on the Pacific side of the continental divide. Although rainy-season thunderstorms are common, the country is barely outside of the hurricane belt.

#### 2.1.4. Land Cover

Land cover map analyses was prepared for this study using a supervised classification to Landsat TM images from February 1984 and February 2010, using the maximum likelihood classifier algorithm, for the 2010 image the classification was corroborated with field pictures (see figures 5-6 and 5-7 section 5.1.5). The classification was done using only the two dominant main land covers Forest and Grass as shown in table 2-1.

Table 2 - 1: Cabra river basin land cover zones for the years 1984 – 2010.

| Year | Grass or Field Km² | Forest Km² |
|---|---|---|
| 1984 | 12.90 | 14.65 |
| 2010 | 12.31 | 15.24 |

### 2.1.5. Soil and Geology

The mountains of igneous extrusive and intrusive geological base have clay layers in which the concentrated runoff has excavated natural drain paths following a relative steep topography. The infiltration is deficient in clays and in steep terrains. The quaternary floodplains are mainly composed of loam, sand and sandy clay layers; the extended impermeable clay layers keep high freatic levels in the basin (Gonzalez D, 2010).

According to the texture map provided by ANAM the Upper Cabra river basin is mainly composed of Sandy Clay Loam in the upstream and Sandy Loam in the downstream as shown in figure 2-3. According to (Rawls W, 1982). Values for saturated hydraulic conductivity can be related to the basin soil textures for Cabra river basin. See table 2-2.

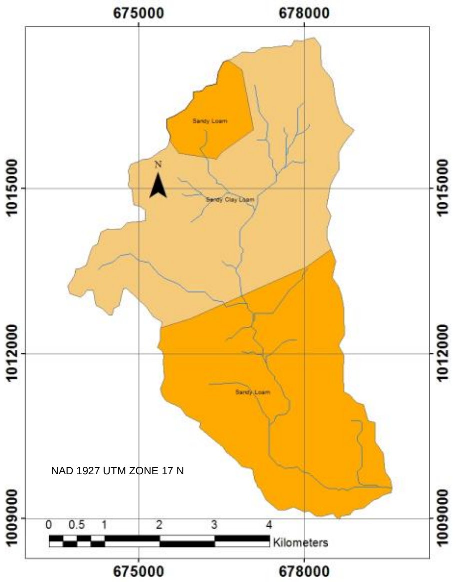


Figure 2 - 3: Soil texture upper Cabra river basin

Table 2 - 2: Saturated hydraulic conductivity related to soil textures in Cabra's basin.

| Soil Texture | Area Km² | Ks mm/h | Basin Location |
|---|---|---|---|
| Sand Clay Loam | 15.52 | 4.3 | Upstream |
| Sandy Loam | 12.03 | 25.9 | Downstream |

## 2.2. Data Collection

### 2.2.1. Meteorological data

In Cabra river basin daily rainfall data from 7 stations was obtained from the Panamanian Energy company ETESA, four of them at Altos de Pacora, Utive, Loma Bonita and Tocumen for the years 1980 to 1999 and for Cerro Pelon and Rancho Café stations rainfall observations are available at 15 minutes interval covering the period 2009 to 2010. Cerro Azul station was collected but time series were too short to be considered for this study.

Rainfall stations with daily data from years 1980 to 1999 were used to calculate the maximum extreme rainfall events for different return periods using extreme Frequency distributions. Wind speed and temperature data were collected for Tocumen station (airport at the south). (See figure 2-5).

In total, the data has been collected from seven meteorological stations within and around the basin as shown in figure 2-4.

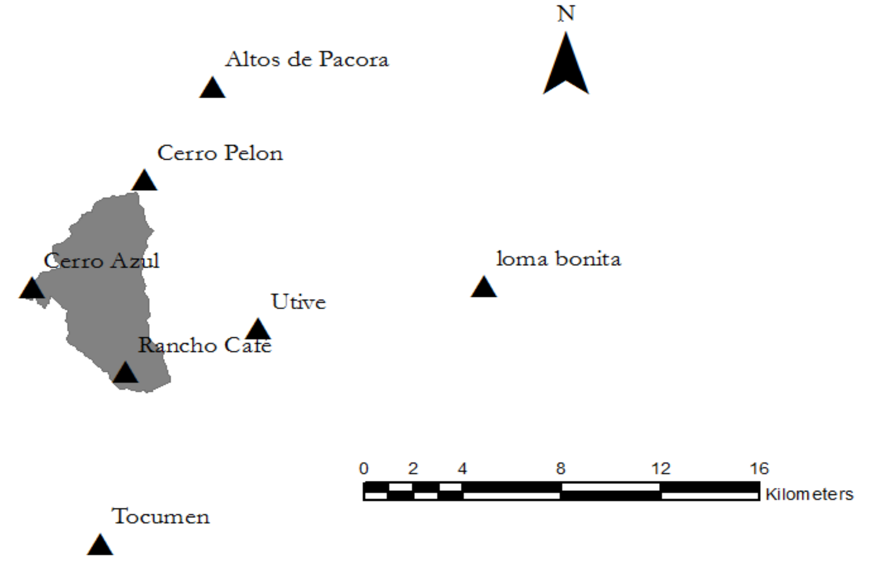


Figure 2 - 4: Meteorological stations for the study area.

Figure 2-5 shows weighted rainfall from Cerro Pelon and Rancho Cafe in the Upper Cabra basin.

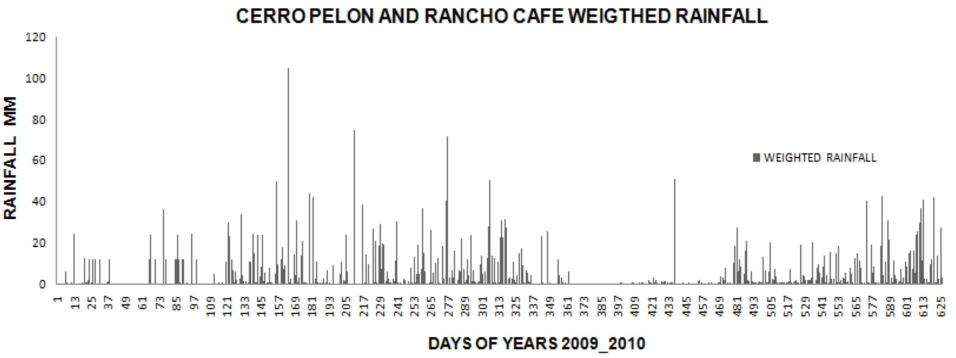


Figure 2 - 5: Weighted rainfall Cerro Pelon and Rancho Cafe

Table 2 - 3: Location of the rainfall stations and years of available data.

| Stations | X<br>m | Y<br>m | Elevation<br>m.a.s.l | Period of Data<br>Years |
|---|---|---|---|---|
| Altos de Pacora | -79.349.722 | 9.245.556 | 850 | 1980-1999 |
| Cerro Pelon | -79.374.722 | 9.208.889 | 770 | 2009-2010 |
| Cerro Azul | -79.416.667 | 9.166.667 | 660 | 1993-1998 |
| Rancho Café | -79.382.222 | 9.133.333 | 185 | 2009-2010 |
| Utive | -79.333.333 | 9.15 | 80 | 1980-1999 |
| Loma bonita | -79.25 | 9.166.667 | 100 | 1980-1999 |
| Tocumen | -79.391.944 | 9.065.556 | 14 | 1980-1999 |

### 2.2.2. Hydrological data

In Cabra river basin stage data was collected from ETESA Company for Rancho Cafe station, the stage data series is shown in figure 2-6 has a daily value for the years 2009 and 2010. The recording stage is transmitted daily to the central office, and checked periodically in the field. Figure 2-6 shows daily stage data records and the voids in the data for the years 2009 and 2010.

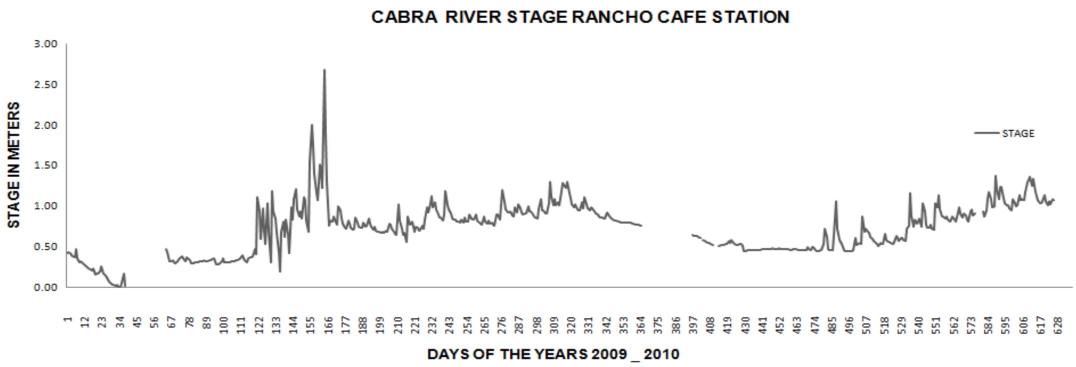


Figure 2 - 6: Daily stage Cabra's river at Rancho Cafe station 2009-2010

### 2.2.3. Stream Gauge

Cabra's stream gauge is located at a distance of 10.21 km from its origin upstream. It is composed mainly of a river stage which is connected to an electronic device that sends the information of rain and river stage to ETESA's offices as shown in figure 2-7. During the fieldwork campaign the main cross section located in Rancho Cafe was measured, as well as cross sections upstream and downstream of the gage including the measurement of the river longitudinal profile as shown in figure 2-9.

### 2.2.4. Stage datum Correction

The river stage had a difference in the measuring depth of, 0.86 m shorter than the measured cross section; that mean that the zero of the stage did not coincide with the point of zero flow; so primarily the difference of 0.86 was added to the recorded values of the measured stage shown in figure 2-7 for calculating the discharges.

However after doing some discharge calculations and some sensitivity trials in HBV software (see section 5.2), the river profile was analyzed and it was observed that the river gage was located in a section where a pool, was made by natural erosive power, as shown in figure 2-9. That pool was generating erroneous data measurements on the stage. The final decision was to use the original stage data and not to add any correction value to the stage.

Figure 2-7 shows Cabra's stage and river water level in 1 meter reading, figure 2-8 shows the stage measured cross section.

Figure 2 - 7: Cabra river stage Rancho Cafe.

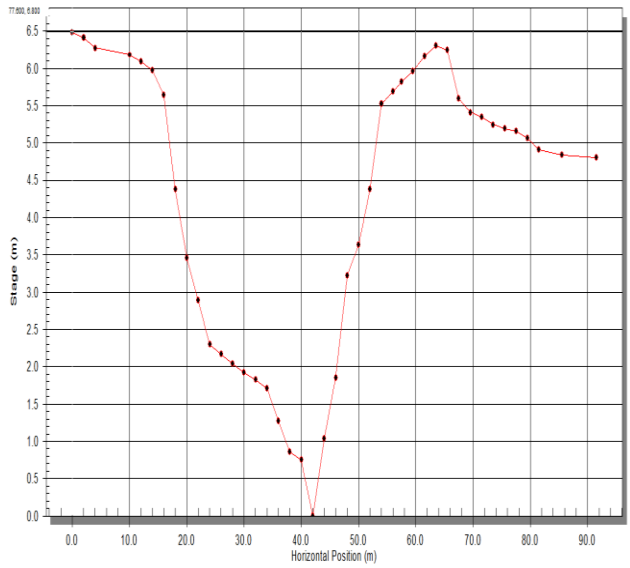


Figure 2 - 8: Cabra river cross section.

Figure 2-9 shows Cabra's river basin longitudinal profile. Flow direction from right to left; the encircled shows the location of the stage cross section, it is observed that the profile has two pools, which are affecting the stage measurements.

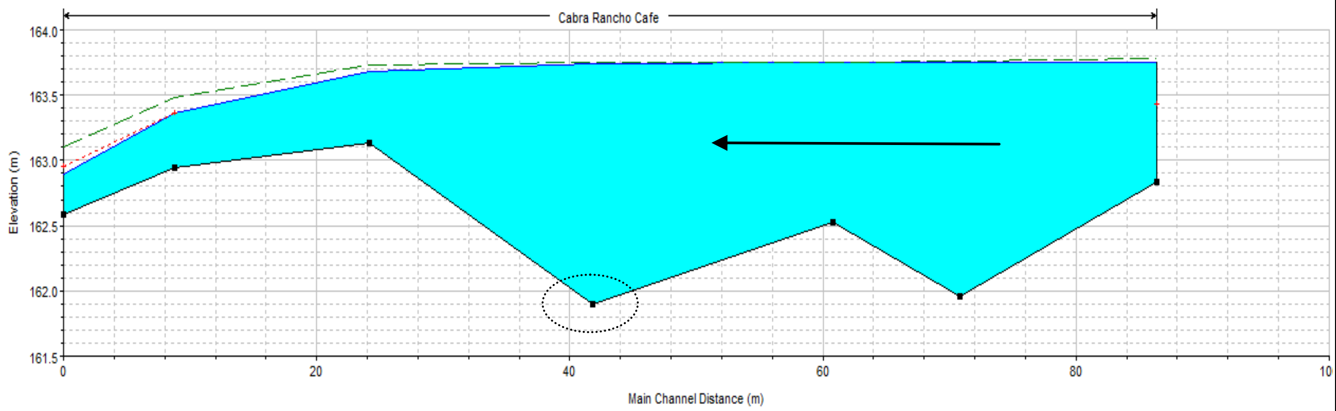


Figure 2 - 9: Cabra river longitudinal profile (HEC-RAS attempt) encircled location of Rancho Cafe cross section and the pool where the gage is located.

# 3. LITERATURE REVIEW

## 3.1. Rainfall-runoff estimation

The relation between rainfall and surface runoff and finally its resulted discharge in a watershed is an essential issue. River discharge observations for the evaluation of water resources or flood estimating damages are restricted and limited. Evaluation of the stream flow from rainfall estimation depends highly on the area of the catchment and rainfall intensity. Rainfall of short duration (minutes or hours) in small catchments it is not well defined, but the larger the catchment the better to establish a link between rainfall, high discharges and flooding. Even more when extreme short rainfalls occur in an area of varied topography, and different types of soils and geological characteristics, the complexity to understand the surface runoff increases (Shaw, 1994).

In small catchments, rainfall data from one rain gage, may be enough to assess the average annual or monthly on a small catchment. An individual rain gage may produce sufficient information to forecast the surface water runoff. A steady network of rainfall stations is necessary to estimate the distribution of rainfall in the catchment as well as discharges estimation (Haan, 1982). For small catchments it is convenient to apply averaged rates from a rain station to all grid cells, and for larger ones apply time distributed rainfall (Reuter, 2009). Some other hydrologic parameters such as temperature, humidity, solar radiation, evapotranspiration and soil moisture, should be measured for accurate water balance computations (Haan, 1982).

### 3.1.1. Extreme frequency distributions

The main objective of the extreme frequency analysis is to obtain the return periods based on a recorded data set of extreme historical events. For design objectives, the analysis focuses in extreme events with higher return periods than the observed one (Maidment, 1992). The applied statistical tool to extrapolate the known data set are the probability distributions (Haan, 1982). For calculating extreme rainfall events with larger return periods than the data set; the data has to be verified to match an extreme frequency distribution to allow for extrapolation of the return periods larger than the length of the time series. The related return periods are larger when are compared with the extent of the records. Effects of non uniform data records are that several extreme frequency distributions would fit the observed data (Chbab, 2002).

Fitting a suitable extreme frequency distribution that extrapolates, and adjust to the observed records for the proposed study, is a task that depends on the quality of recorded observations.

Several frequency distributions used in hydrology for extreme rainfall events include, Normal, Lognormal, Gumbel, Weibull, Generalized Extreme Value, Exponential and Pareto (Maidment, 1992).

Various of the above mentioned distributions will be used for predicting extreme rainfall events for the stations Utive, Loma Bonita, Altos de Pacora and Tocumen in the upper part of Cabra river basin.

## 3.2. Hydrological models

Hydrologic models are simplified representations of actual hydrologic systems that allow us to study the functioning of watersheds and their response to various inputs, and thereby gain a better understanding of hydrologic processes. Hydrologic models also allow us to predict the hydrologic response to various watersheds management practices and to have better understanding of the impacts of these practices (Arbind et al, 2009).

Understanding hydrological processes and their spatial and temporal patterns considered is basic for a sound water management. The application of hydrological models may help in various ways to understand and to assess future temporal distribution of water resources in the space and time dimension (Emiru, 2009).

An approach is classified as conceptual model approach if relatively simple mathematical relations are applied to simulate the observed real world behavior where in general, the input parameters have some relation or resemblance with the real world system characteristics. In most conceptual models, an attempt is made to add physical relevance to the variables and parameters used in the mathematical model. Conceptual approaches are mostly applied in rainfall-runoff hydrology (Rientjes, 2010).
A Semi-distributed model approach it is when the system under study is partitioned in relatively large units that often are selected and bounded by topographic divides within the catchment. Each unit often is a sub watershed and units thus are of various sizes and commonly are of irregular shapes (Rientjes, 2010). A semi-distributed approach considers the water balance into its code.

Two models were chosen for hydrological modelling of extreme rainfall events for the upper Cabra river basin:
The HEC-HMS was chosen because it is designed to simulate the precipitation runoff processes of watershed systems in a wide range of geographic areas such as large river basins and small urban or natural watersheds. HEC-HMS uses separate models to represent each component of the runoff process, including models that compute runoff volume, models of direct runoff and models of baseflow. Each model run combines a basin model, meteorological model, and controls specifications with run options to obtain results (Arbind et al, 2009). Some other reasons are because it is free software and has been successfully applied in many basins around the world is shown in annex A.

The semi-distributed HBV model was chosen because is one of the most used in rainfall-runoff modelling. The model has many applications in operational and strategic water management and has been successfully applied to catchment of various sizes and in large range of climatic settings (Rientjes, 2010). The model also was selected because of its availability, its moderate input requirements, and simulates major processes in the catchment.

# 4. METHODOLOGY AND IMPLEMENTATION

Based upon the methodology presented in figure 4-1 it is planned to reach the research study objectives.

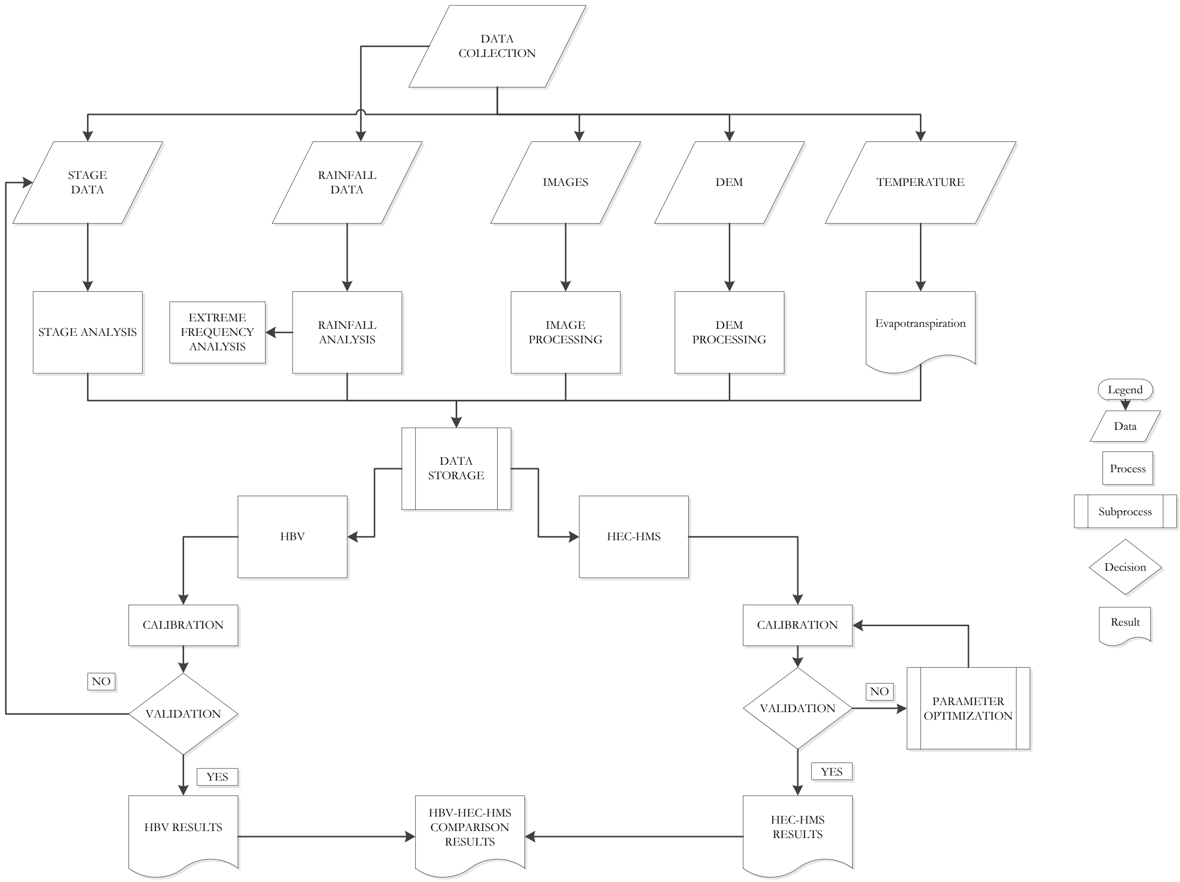


Figure 4 - 1: Research methodology.

## 4.1. Data processing

### 4.1.1. Accumulated daily rainfall

Rainfall data was used to identify the intensity and pattern in the Upper Cabra river basin over a period of 20 years from 1980 to 1999. Four stations with daily observations were selected for the analysis. The selection was based upon the availability of the data, the common period among them and the distance within the basin as shown in figure 2-4.

Daily rainfall from stations Altos de Pacora, Utive, Loma Bonita and Tocumen were used, Accumulated precipitation over the years 1980 to 1999 was performed for those stations to evaluate consistency.

The results of the accumulated daily rainfall show a common pattern that rain falls as a function of altitude, higher in the upstream basin for the station Altos de Pacora, turning down in the middle for two stations Utive and Loma Bonita and lowering in the downstream basin for Tocumen station. See graph results section 5.1.1. However the rainfall pattern is complex, without an evidence of rainfall from the small Cabra basin. As such a Thiessen polygon has been selected to weight the rainfall from the stations in the catchment.

#### 4.1.2. Rainfall analysis and Cabra River basin flooding events

Information about flooding in Cabra's river was searched in Local newspaper.

Dates for flooding events occurred in the basin are: 25 September 1994, 27 July 1995, 26 September 1997, 8 December 1998, 6 September 1999, and 17 September 2004. Rainfall data was obtained for the flooding dates.

The observation and pattern before any flooding event shows a series of continuous and successive rainfall for days in the catchment as shown in table 4-1. It is observed that in most of the cases within the period of flooding event, there is an extreme rainfall over 100 mm. The flooding events are not triggered by the hurricanes or tropical depressions close to the area.

Table 4 - 1: Daily precipitation before flooding events.

| DAILY PRECIPITATION IN MM FOR CABRA RIVER BASIN STATIONS BEFORE THE RESPECTIVE FLOODING EVENTS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **DATES OF FLOODING EVENTS** | | | **RAIN EVENTS BEFORE FLOODING** | | | **ALTOS PACORA** | **LOMA BONITA** | **UTIVE** | **TOCUMEN** |
| Year | Month | Day | Year | Day | Month | Upstream | Middle | Middle | Downstream |
| **1994** | **SEP** | **25** | 1994 | 20 | SEP | 16.6 | 19.7 | 16.5 | 31.7 |
| | | | 1994 | 21 | SEP | 4.3 | 50 | 0 | 40.9 |
| | | | 1994 | 22 | SEP | 2.7 | 41.1 | 3.6 | 1.6 |
| | | | 1994 | 24 | SEP | 35 | 39 | 0 | 3.2 |
| | | | **1994** | **25** | **SEP** | **46.2** | **28.7** | **0** | **140.7** |
| **1995** | **JUL** | **27** | 1995 | 15 | JUL | 15.2 | 6.9 | 2.5 | 5.2 |
| | | | 1995 | 16 | JUL | 11.9 | 3.2 | 13.4 | 27.4 |
| | | | 1995 | 17 | JUL | 24.4 | 4 | 3.9 | 5.8 |
| | | | 1995 | 18 | JUL | 15.5 | 19.4 | 0 | 11.8 |
| | | | 1995 | 19 | JUL | 25.9 | 20.4 | 64.6 | 14.2 |
| | | | 1995 | 20 | JUL | 26.7 | 17 | 11.9 | 0.2 |
| | | | 1995 | 21 | JUL | 44.6 | 19.7 | 4.9 | 4.1 |
| | | | 1995 | 23 | JUL | 46.2 | 17.7 | 22.8 | 13 |
| | | | 1995 | 25 | JUL | 54 | 0.4 | 0 | 0.4 |
| | | | 1995 | 26 | JUL | 19.6 | 42.5 | 8.7 | 23.1 |
| | | | **1995** | **27** | **JUL** | **125.3** | **25.2** | **189.2** | **93.1** |
| **1997** | **SEP** | **26** | 1997 | 21 | SEP | 26.2 | 26.8 | 81.9 | 1.9 |
| | | | 1997 | 22 | SEP | 3.9 | 0.7 | 2.7 | 57.6 |
| | | | 1997 | 23 | SEP | 54.1 | 46.4 | 7.5 | 45.2 |
| | | | 1997 | 24 | SEP | 54.3 | 129.5 | 112.6 | 30 |
| | | | 1997 | 25 | SEP | 68.8 | 67.2 | 1.4 | 68.6 |
| | | | **1997** | **26** | **SEP** | **11.4** | **48.5** | **0** | **0** |
| **1998** | **DIC** | **8** | 1998 | 1 | DEC | 4.9 | 0.8 | 0 | 4.8 |
| | | | 1998 | 2 | DEC | 35.4 | 6.2 | 5.9 | 69.1 |
| | | | 1998 | 3 | DEC | 26.1 | 21.4 | 0 | 1.3 |
| | | | 1998 | 4 | DEC | 7.2 | 79.6 | 0 | 111.2 |
| | | | 1998 | 5 | DEC | 34.3 | 42.7 | 29.7 | 1 |
| | | | 1998 | 6 | DEC | 35.4 | 51.6 | 39.5 | 1.4 |
| | | | 1998 | 7 | DEC | 45.9 | 68.8 | 39.6 | 32.9 |
| | | | **1998** | **8** | **DEC** | **24.4** | **0.9** | **34.2** | **39.5** |
| **1999** | **SEP** | **6** | 1999 | 1 | SEP | 34.6 | 0 | 0 | 0 |
| | | | 1999 | 2 | SEP | 22.2 | 1.5 | 0 | 2 |
| | | | 1999 | 3 | SEP | 14 | 3.1 | 0 | 0 |
| | | | 1999 | 4 | SEP | 34.9 | 0 | 0 | 4.2 |
| | | | 1999 | 5 | SEP | 17.2 | 19.3 | 27.3 | 0 |
| | | | **1999** | **6** | **SEP** | **14.3** | **0** | **0** | **0.5** |
| **2004** | **SEP** | **17** | 2004 | 15 | SEP | | 0.5 | | 38.4 |
| | | | 2004 | 16 | SEP | | 7.1 | | 2 |
| | | | **2004** | **17** | **SEP** | | **78.2** | | **57** |

### 4.1.3. Thiessen polygon's method

This method delimitates individual areas of influence around each of the rainfall stations. Thiessen polygons are polygons whose boundaries delimitate the area that is closest to each rainfall station relative to all other stations points.

The spatial average is calculated by weighting the individual stations with their representative area (Brutsaert, 2009).

Weighted Precipitation of the basin was calculated following equation (4-1).

$$P = \frac{1}{A_t} \times \sum_{i=1}^{n} Ai \times Pi \qquad (4\text{-}1)$$

Where:

| | | |
|---|---|---|
| $P$ | = Averaged aerial rainfall | (mm) |
| $A_T$ | =Total area of the upper basin | (m²) |
| $A_i$ | = Partial area of influence of the Thiessen polygon for the station i | (m²) |
| $P_i$ | = Precipitation of the station i | (m²) |
| $n$ | = Number of stations | |

Thiessen polygons was created using ArcGIS to determine which stations are in the area of influence in the upper Cabra basin, the results show that stations Cerro Pelon and Rancho Cafe have the highest weight in the upper basin compared with Loma bonita and Tocumen stations. Figure 4-2 Map of Cabra's upper basin, Thiessen polygon in blue shows the area of influence for each of the rainfall gages, the station Rancho Cafe has the highest weight in the upper Cabra basin.

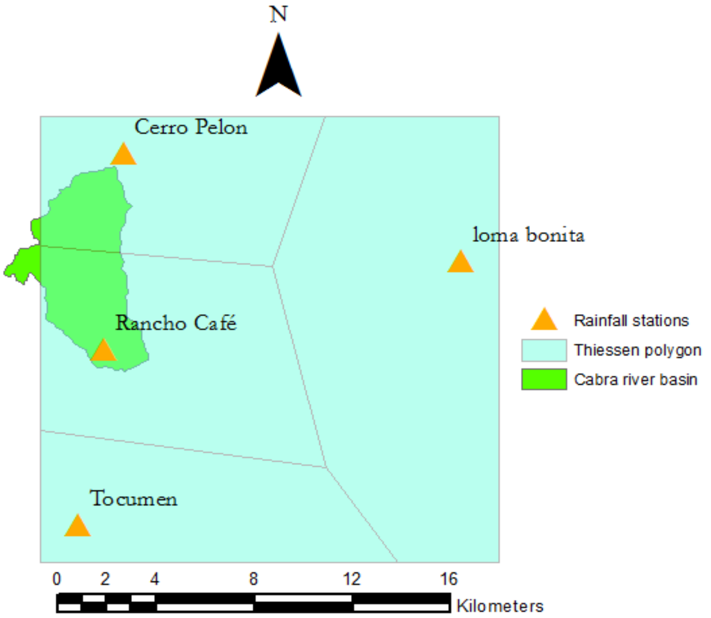


Figure 4 - 2: Thiessen polygons upper Cabra river basin.

Table 4 - 2: Thiessen polygons weights for upper Cabra river basin

| Stations | Weight | Elevation |
|---|---|---|
| Cerro Pelon | 0.35 | 770 |
| Rancho Cafe | 0.65 | 185 |

With the Rain stations in the area of influence and the stage data for Cabra River, a graphical analysis was undertaken to analyze the response of the stage to rainfall. Hence forth the stage is seen to be responding to rainfall for both stations as shown in figures 4-3 and 4-4.

Figure 4-3 shows the stage and rainfall from station Cerro Pelon, it is observed that the stage responds to the rain pulses, but not in the highest ones.

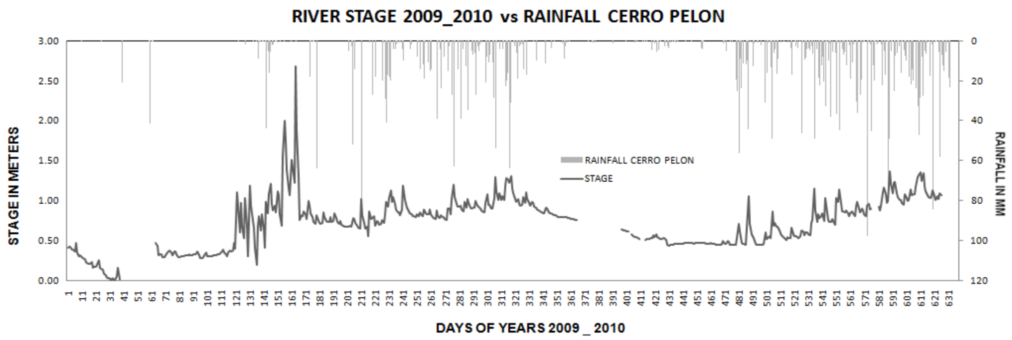


Figure 4 - 3: River stage and rainfall station Cerro Pelon

Figure 4-4 Shows the stage and rainfall from station Rancho Cafe. It is observed that the stage responds to the rain pulses, mainly in the highest peaks of the stage.

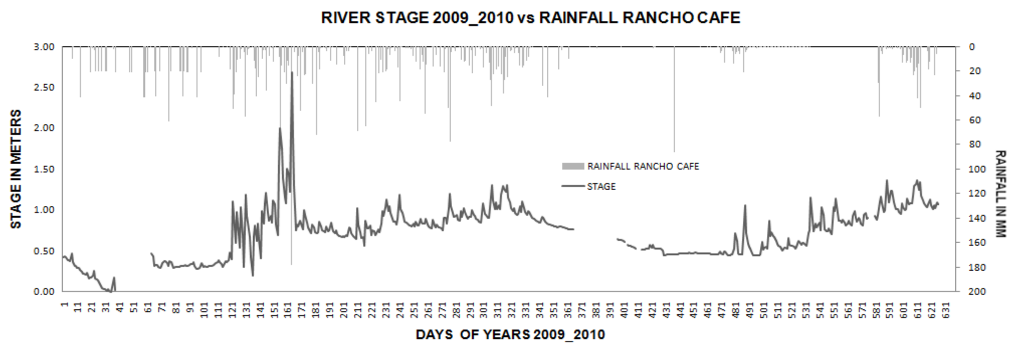


Figure 4 - 4: River stage and rainfall station Rancho Cafe

It is concluded that the stage responds to the rainfall pulses from both stations located in the Upper Cabra river basin.

Further analysis was made to rainfall and stage peaks, but taking shorter time steps for different dates of the river stage as shown in figures 4-5 and 4-6.

For this analysis Rainfall data has not yet being weighted using the Thiessen polygons.

Figures 4-5 and 4-6 show the stage and rainfall from both stations Rancho Cafe and Cerro Pelon, It is observed in the circled, that several water elevations are influenced by Rancho Cafe pulses or by Cerro Pelon rainfall pulses and various rain pulses do not have response of the stage. This irregular pattern foresees some difficulties in the modeling approach.

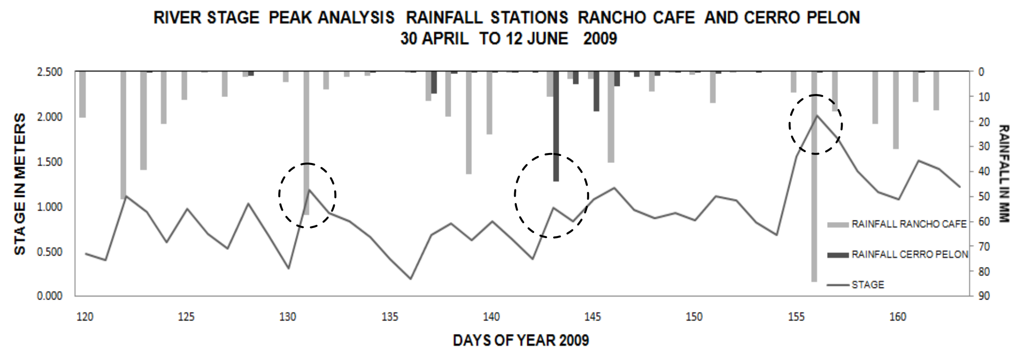


Figure 4 - 5: Rainfall and stage analysis 30 April to 12 June 2009

Figure 4-6 stage response to rainfall pulses from Rancho Cafe and Cerro Pelon stations

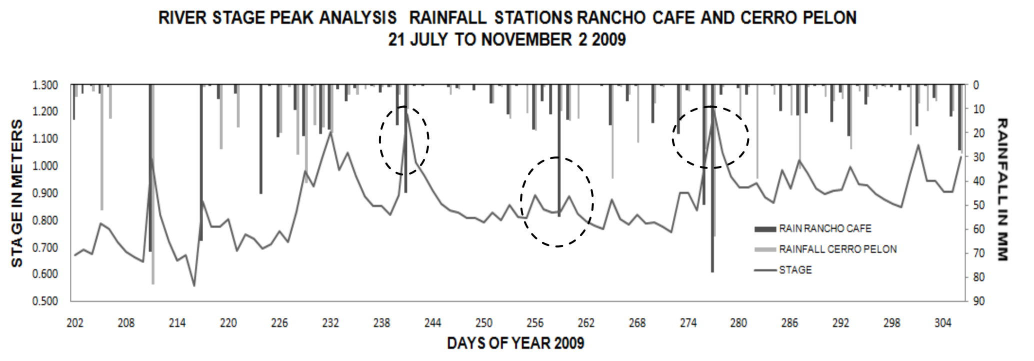


Figure 4 - 6: Rainfall and stage analysis 21 July to 2 November 2009

Further analysis was made taking 15 minutes time step as shown in figures 4-7 and 4-8 rainfall pulses and stage responses were evaluated for Rancho Cafe and Cerro Pelon stations.

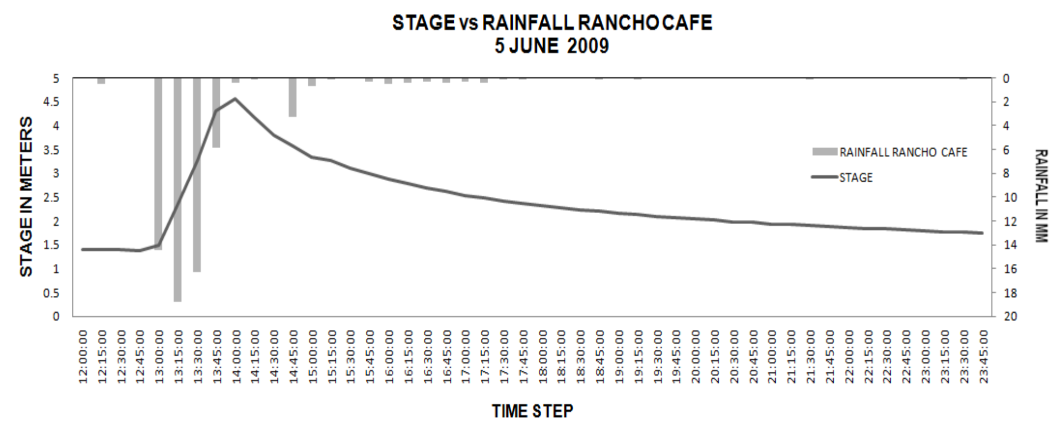


Figure 4 - 7: Rainfall and Cabra river stage response 30 July 2009 fifteen minutes time step

In figure 4-7 it is shown that the stage responds to the rainfall pulses of Rancho Cafe station, and the response time is very short, 45 minutes approximately for this analyzed event.
In figure 4-8 it is observed that the first pulses of rain from 4:00 to 5:30 do not have any stage response, and the rainfall from 6:30 to 8:00 has a reaction of the stage.

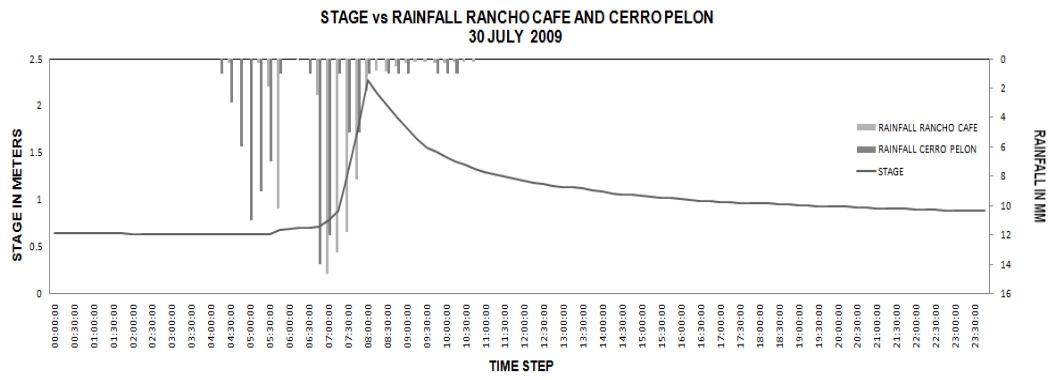


Figure 4 - 8: Rainfall and Cabra river stage response 30 July 2009 fifteen minutes time step

From the previous rainfall analysis is concluded that the catchment has a fast response to rainfall events and the stage data or the rainfall may be used cautiously.

### 4.1.4. Extreme frequency analysis

Extreme rainfall events causing flooding were studied for the Cabra river basin.
The aim of the Extreme frequency analysis is to predict events beyond the data set availability (Maidment, 1992).
For hydrology purposes several distributions are commonly used for predicting extreme events, among others are the normal, lognormal, Gumbel, Weibull, Exponential, and Pareto.
For the upper Cabra river basin, return periods of 10, 25, 50 and 100 years were calculated to the rainfall stations Altos de Pacora, Loma Bonita, Utive and Tocumen using the above mentioned extreme frequency distributions, for a daily data set from 1980 to 1999.

### 4.1.5. Chi-square analysis

An analysis was made to the results of the evaluated distributions using a Chi-square analysis, in order to determine which of the distributions best fit the data of each of the stations.
Chi-square is defined by the equation

$$X^2 = \sum_{i=1}^{N} \left[ \frac{y_i - f(x_i)}{\sigma_i} \right]^2 \tag{4-2}$$

$N$ = Number of data points
$\sigma^2$ = Variance, related to measurement error for $y_i$
$y$ = Independent variable, x = dependent variable
$f$ = Assumed relationship between x and y
$y_i$ = Observed mean
$f(x_i)$ = Predicted mean

The method of least squares is built on the hypothesis that the optimum description of data set is one which minimizes the weighted sum of the squares of deviations, $\Delta y$, between the data, $y_i$, and the fitting function f.
The sum of squares of deviations is characterized by the estimated variance of the fit, $s^2$, which is an estimate of the variance of the parent distribution, $\sigma^2$. The ratio of $s^2/\sigma^2$ can be estimated by $X^2/v$ where $v = N - p - 1$, $N$ is the number of observations and $p$ is the number of fitting parameters. $X^2/v$ is called the reduced chi-square statistic (Moore, 1999).
If the fitting function accurately predicts the means of the parent distribution, then the estimated variance $s^2$, should agree well with the variance of the parent distribution, $\sigma^2$, and their ratio should be close to one.
Table 4-3 shows rain stations for Cabra river basin and the best fitted extreme distributions according to chi-square analysis performed to the rainfall stations. Values of chi-square < 1 are considered optimum. Some other results and conclusions are treated in the discussion chapter 5 as well as distribution figures.

Table 4 - 3: Chi-square best fit extreme distributions for rainfall stations in Cabra river basin

| FUNCTION | ALTOS DE PACORA Chi-Square | UTIVE Chi-Square | LOMA BONITA Chi-Square | TOCUMEN Chi-Square |
|---|---|---|---|---|
| **Pareto** | 0.62 | 0.59 | 0.52 | 0.46 |
| **Weibull** | 0.70 | 0.37 | 0.52 | 0.81 |
| **Gumbel** | 0.75 | 0.37 | 0.52 | 0.94 |
| **Normal** | 1.42 | 0.48 | 0.78 | 1.85 |
| **Exponencial** | 1.51 | 1.80 | 1.62 | 2.17 |

### 4.1.6. Stage discharge calculation

The conversion from water elevation to discharge proved to be the most limiting difficulty in this thesis as many factors contribute is uncertainties. The organizations in charge of the measurements did not produce a rating curve. In this thesis an attempt was done to oversee that limitation both during the limited fieldwork and in the office, but the results obtained remain uncertain till a full campaign can be carried out. Two methods were evaluated. The area velocity method, consisting in the variation of the cross section wetted areas according to the river stage and applying the mean velocity measured in the field for each stage in the cross section.

The second method relies on WinXSPRO software (USDA, 2005), which is used to analyze stream channel cross sections and evaluate the relationships between discharge and channel geometry. The method uses the resistance manning's equation to a single cross section, the stream flow is computed using the simplified form of the continuity equation, where the discharge equals the product of velocity and cross sectional area of flow (USDA, 2005).

#### 4.1.7. Area velocity method discharge calculation

The cross section measured at Rancho Cafe was entered into WinXSPRO software and by each stage a flow area was defined. Obtained areas were multiplied by the field measured mean velocity using the equation 4-3.

$$Q = A \times V \qquad (4\text{-}3)$$

Where

| | |
|---|---|
| Q = discharge | ($m^3/s$) |
| A= Area of river cross section | ($m^2$) |
| V= Mean velocity | (m/s) |

Discharges were calculated for each of the stages and the stage discharge relation curve was obtained. Stage discharge curves using the two methods were plotted and compared as shown in figure 4-9.

#### 4.1.8. Discharge calculation with WinXSPRO software

WinXSPRO is a software designed to analyze stream channel cross section data for geometric, hydraulic and sediment transport parameters; WinXSPRO uses a resistance-equation approach (e.g., Manning's equation) to single cross section hydraulic analysis. The software allows entering of water-surface slopes such that the slope will vary with discharge to reflect natural conditions (USDA, 2005).

A stream flow at a cross section is computed using the simplified form of the continuity equation where discharge equals the product of velocity and cross-sectional area of flow.

There are two approaches used in WinXSPRO for Cabra river basin:

The first approach is the area velocity method which was explained above in section 4.1.7 that consisted in evaluating different stages for one unique cross section, a minimum and maximum value of stage is entered as well as a step among them. The software generates several stages and calculates the areas for each of the stages; the areas are multiplied by the field mean velocity.

The second approach used with the software was assuming conditions of uniform flow where conditions of constant width, depth, area and velocity and the water surface slope and energy grade line approach the slope of the stream bed.

For obtaining the stage discharge relation, the cross section measured in Rancho Cafe was entered, manning's roughness coefficient was by comparing with the ***n*** values for roughness characteristics from the United States Geological Survey (USGS) database (picture and diameter based); water slope data from fieldwork survey and all input was entered into WinXSPRO. The stage discharges curves were with the results of the two approaches mentioned above.

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \qquad (4\text{-}4)$$

| | | |
|---|---|---|
| Where | V = Average Velocity in the cross section | (m/s) |
| | n = Manning's roughness coefficient | ($m^{1/3}/s$) |
| | R = Hydraulic radius | $(m)^{2/3}$ |
| | S = Energy slope in water surface slope for uniform flow | $(m/m)^{1/2}$ |

Sensitivity analysis was performed varying the ***n*** roughness value and the water slope in order to observe the changes in discharge.

As a reference for calibration, the discharge and velocity obtained in the field were compared with the software results.

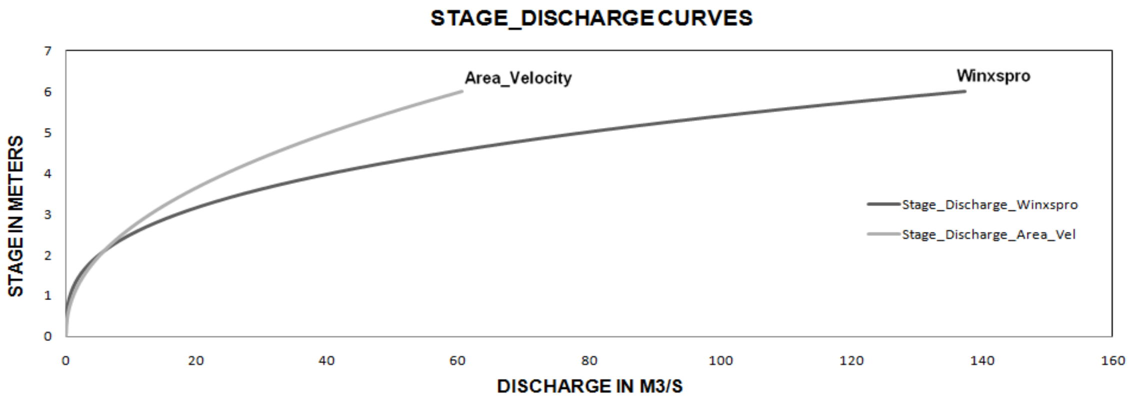


Figure 4 - 9: Stage discharge rating curves for Cabra river basin

Due to uncertainties the fan of results is wide and it is highly probable that the modelling output will not have and accurate discharge record to compare. In these circumstances, the obvious next step is an attempt for the data consistency.
With the stage discharge curves, calculated values of discharges were compared for the same stage in order to observe which one represents the discharges in the cross section as shown in table 4-4.
Finally all the stage field data set was converted into discharge using WinXSPRO stage discharge rating curve.

Table 4 - 4: Calculated discharges using area velocity and WinXSPRO software

| **Stage**<br>**m** | **Fieldwork measured discharge**<br>**$m^3/s$** | **Area velocity method**<br>**$m^3/s$** | **WinXSPRO**<br>**$m^3/s$** |
|---|---|---|---|
| 1 | | 1.13 | 0.64 |
| 1.5 | | 2.78 | 2.16 |
| **1.85** | **3.55** | **4.43** | **4.04** |
| 2 | | 5.27 | 5.11 |
| 2.5 | | 8.64 | 9.97 |
| 3 | | 12.96 | 17.21 |
| 3.5 | | 18.25 | 27.32 |
| 4 | | 24.56 | 40.76 |
| 4.5 | | 31.90 | 58.01 |
| 5 | | 40.31 | 79.55 |
| 5.5 | | 49.81 | 105.85 |
| 6 | | 60.44 | 137.39 |

#### 4.1.9. Data consistency analysis

A consistency analysis was done in order to identify presumable unreliable observations in the discharge time series. The considered period was 2009-2010.

Differences of precipitation ΔP and observed discharge ΔQ were calculated for daily time step using the equations 4-5 and 4-6, although the results are meaningful for rainy days only.

$$\Delta P = P_t - P_{t-1} \qquad (m^3/s) \qquad (4\text{-}5)$$

$$\Delta Q = Q_t - Q_{t-1} \qquad (m^3/s) \qquad (4\text{-}6)$$

Then a ratio |ΔP|/ΔQ was plotted against the time period 2009-2010 as show in figures 4-10 and 4-11.

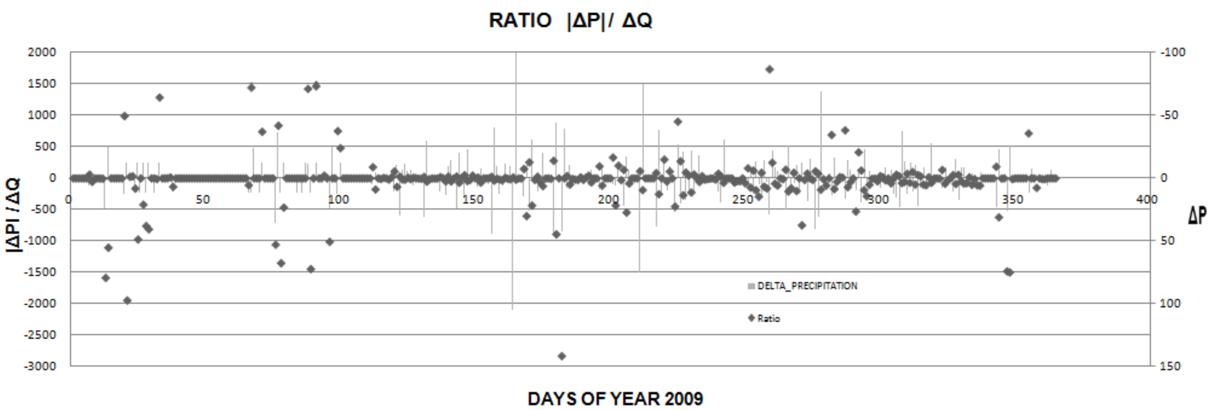


Figure 4 -10: |ΔP|/ΔQ ratio for the upper Cabra's river basin year 2009

In case of consistent observations the values of the ratio |ΔP|/ΔQ are relatively small, but depend very much in the area and runoff behavior of the catchment; for large catchments one may expect high values, and for small catchments one may expect small |ΔP|/ΔQ values. For Cabra River this value ranges from -2000 to 2000, this interval may change from basin to basin; the outliers from figures 4-10 and 4-11 were thoroughly analyzed and corrected independently.

The dispersion observed is a clear indication of the data inconsistency. This fact calls for effort in the correction of the series and establish a series of arguments to suggest a better data collection scheme.

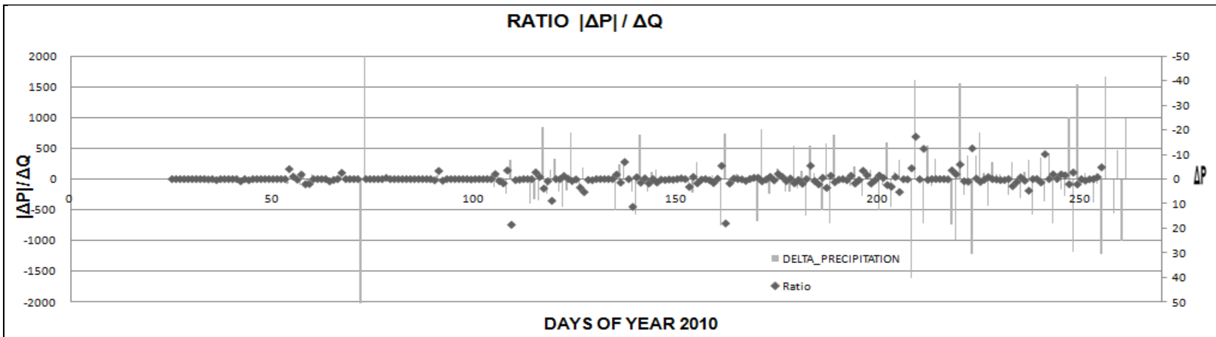


Figure 4 -11: |ΔP|/ΔQ ratio for the upper Cabra's river basin year 2010.

### 4.1.10. Outliers Correction Process

First the most extreme outliers were evaluated and examined within the 15 minutes precipitation to the original data, in order to detect errors in the rainfall records. Examples of the error detected by using this methodology are:

- Records that showed unusual patterns such as two rainfall events with the same intensity in less than one hour, figure 4-12.
- Equal intensity during the same day, figure 4-13.
- A rainfall event of 30 mm or more in 15 minutes figures 4-14 and 4-15.

All these errors were considered not a natural pattern and erased from the rainfall time series.

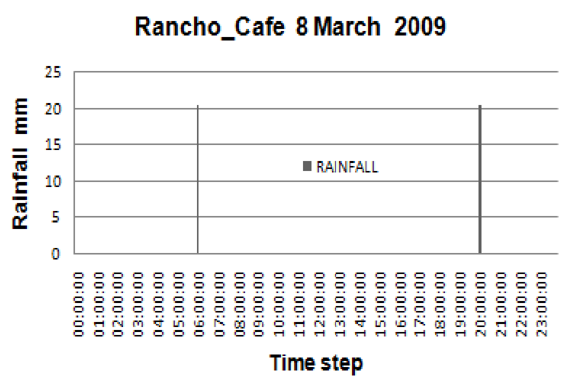


Figure 4 -12: March 8 fifteen minutes analysis.

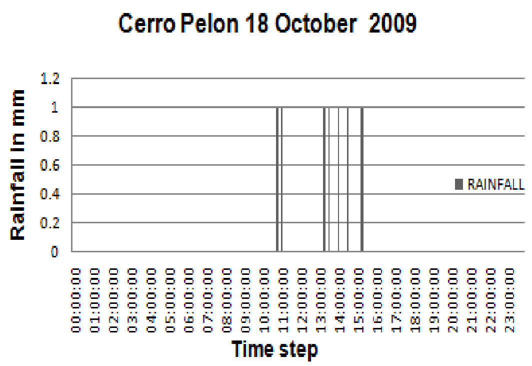


Figure 4 -13: October 18 fifteen minutes analysis.

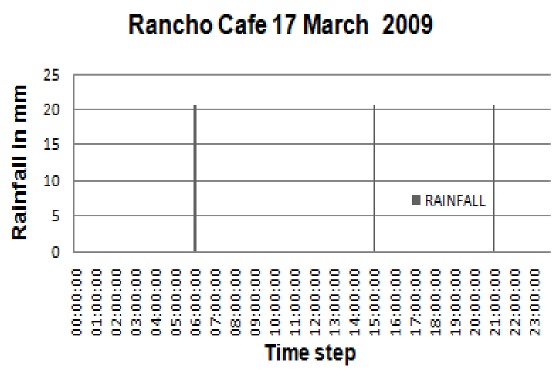


Figure 4 -14: March 17 fifteen minutes analysis.

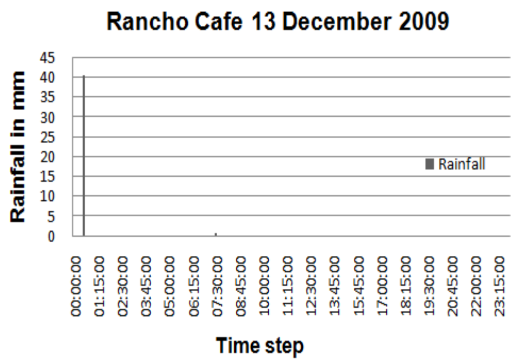


Figure 4 -15: December 13 fifteen minutes analysis.

Later on a process of smoothing the values of $|\Delta P|/\Delta Q$ was performed for each of the observed discharge records. The process consisted in applying a restriction interval within the range values of (5, 10, 15, 20, 30, and 40) over and below zero to the calculated ratio to all the discharge data set; then an average was calculated with the values fallen outside this restriction (outliers). The averaged value was obtained from the (outliers) and used to correct and smooth the fitted records of the data set; it is also ensured; that for every pulse in precipitation the discharge is reduced, too. (See results in section 5.1.3).

As a final step a corrected discharge was calculated using the above process using the smoothing ratio of 15, the values of the corrected and observed discharge were entered to HBV and HEC-HMS models to be used as reference for comparison between the observed and the simulated hydrographs. This procedure would not be necessary in case that data collection would be assured with a consistent calibration campaign.

#### 4.1.11. DEM

The Digital elevation model of 30 m spatial resolution was obtained from The National Environment Authority (ANAM). By DEM processing basin delineation, flow accumulation, flow direction, stream order, flow length, Area of the basin, among others characteristics were obtained. (See table 4-5).

Table 4 - 5: Cabra river basin physical characteristics.

| Area Total Basin Km² | Area Upper Basin Km² | Upstream River Length Km | River Stream Order No |
|---|---|---|---|
| 58.69 | 27.55 | 10.21 | 3 |

#### 4.1.12. Image processing

Landsat TM images were downloaded for the years 1984 and 2010 from *http:glovis.usgs.gov*, with 7 bands and 30 m spatial resolution, the delineated basin described in section 4.1.9 was used as subset for the image basin extraction. The images were processed using ERDAS, supervised classification and the maximum likelihood classifier was performed; a region of interest around homogeneous pixels was created which were used to train the whole images; the classification was compared to field pictures to verify the classification; results from the two images were compared to detect the land cover change for this period. As the HBV-96 model uses only forest and field as land cover types, the 2010 image was classified accordingly; and the area for each zone was measured depending on the basin altitude as shown in table 4-6.

Table 4 - 6: Zone types, elevation and land cover zone for Cabra river basin

| Zone types | Elevation m.a.s.l | Area Km² |
|---|---|---|
| Field | 185 | 1.41 |
| Field | 250 | 0.6 |
| Field | 350 | 2.1 |
| Field | 450 | 2.1 |
| Field | 550 | 2.03 |
| Field | 650 | 2.1 |
| Field | 750 | 1.96 |
| Forest | 650 | 5.14 |
| Forest | 750 | 5.41 |
| Forest | 770 | 4.7 |

#### 4.1.13. Temperature

Daily values of temperature from Tocumen station for the period 2009 and 2010 were obtained from ETESA and thus used for the calculation of daily evapotranspiration for Cabra's river basin.

#### 4.1.14. Evapotranspiration

Evapotranspiration is constituted by the total losses from the evaporating surface (soil and water) plus the plants transpiration.

HBV and HEC-HMS require monthly data of potential evapotranspiration. For the modeling of Cabra river basin; the Thornthwaite's method was applied using the equations from 4-7 to 4-11.

Thornthwaite requires monthly temperatures, and a monthly thermal index which vary pending on the region as shown in table 4-7. Thornthwaite's method was selected because Tocumen's station did not have availability of data, such as the Net radiation, a necessary value to use Penman Monteith's equation.

$$e = 16\left[10\frac{t}{I}\right]^{a} \qquad (4\text{-}7)$$

$$i = \left[\frac{t}{5}\right]^{1.514} \qquad (4\text{-}8)$$

$$I = \sum i \qquad (4\text{-}9)$$

$$e_c = f * e \qquad (4\text{-}10)$$

$$a = 0.6751*10^{-6} I^3 - 0.771*10^{-4} I^2 + 0.01792 I + 0.49239 \qquad (4\text{-}11)$$

Where

| | | |
|---|---|---|
| e | = Monthly evapotranspiration without any correction | (mm) |
| t | = Monthly average temperature | (°C) |
| I | = Yearly thermal index | |
| i | = Monthly thermal index | |
| $a$ | = Exponent that varies with the annual thermal index | |
| $e_c$ | = Corrected monthly evapotranspiration | (mm) |
| f | = Correction factor | |

Table 4 - 7: Correction factor for sunshine duration average

| | Latitud | E | F | M | A | M | $J_N$ | $J_L$ | A | S | O | N | D |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 50 | 0.74 | 0.78 | 1.02 | 1.15 | 1.33 | 1.36 | 1.37 | 1.25 | 1.06 | 0.92 | 0.76 | 0.70 |
| | 45 | 0.80 | 0.81 | 1.02 | 1.13 | 1.28 | 1.29 | 1.31 | 1.21 | 1.04 | 0.94 | 0.79 | 0.75 |
| | 40 | 0.84 | 0.83 | 1.03 | 1.11 | 1.24 | 1.25 | 1.27 | 1.18 | 1.04 | 0.96 | 0.83 | 0.81 |
| | 35 | 0.87 | 0.85 | 1.03 | 1.09 | 1.21 | 1.21 | 1.23 | 1.16 | 1.03 | 0.97 | 0.86 | 0.85 |
| Norte | 30 | 0.90 | 0.87 | 1.03 | 1.08 | 1.18 | 1.17 | 1.20 | 1.14 | 1.03 | 0.98 | 0.89 | 0.88 |
| | 25 | 0.93 | 0.89 | 1.03 | 1.06 | 1.15 | 1.14 | 1.71 | 1.12 | 1.02 | 0.99 | 0.91 | 0.91 |
| | 20 | 0.95 | 0.90 | 1.03 | 1.05 | 1.13 | 1.11 | 1.14 | 1.11 | 1.02 | 1.00 | 0.93 | 0.94 |
| | 15 | 0.97 | 0.91 | 1.03 | 1.04 | 1.11 | 1.08 | 1.12 | 1.08 | 1.02 | 1.01 | 0.95 | 0.97 |
| | 10 | 0.98 | 0.91 | 1.03 | 1.03 | 1.08 | 1.06 | 1.08 | 1.07 | 1.02 | 1.02 | 0.98 | 0.99 |
| | 5 | 1.00 | 0.93 | 1.03 | 1.02 | 1.06 | 1.03 | 1.06 | 1.05 | 1.01 | 1.03 | 0.99 | 1.02 |
| | 0 | 1.02 | 0.94 | 1.04 | 1.01 | 1.04 | 1.01 | 1.04 | 1.04 | 1.01 | 1.04 | 1.01 | 1.04 |

Source hydrology Maximo Villon Bejar page 336

## 4.2. Model implementation

### 4.2.1. HBV-96 model

The HBV model is an Integrated semi distributed Hydrological model system; a modern well-tested and operational tool used for runoff simulation and hydrological forecasting, applied in catchments and small unregulated rivers (SMHI, 2006).

The Upper Cabra river basin was simulated using corrected hourly precipitation from the rain stations Cerro Pelon and Rancho Café located in the basin from the period 2009-2010.

The general water balance equation that is solved in the model is:

$$P - E - Q = \frac{d}{dt}(SP + SM + UZ + LZ + lakes) \quad (4\text{-}12)$$

Where P: precipitation, SP: snow pack, UZ: upper ground zone, LZ: lower ground zone, Q: runoff, E: Evapotranspiration, SM soil moisture, Lakes: lake volume (SMHI, 2006).

### 4.2.2. Model structure.

The HVB-96 model can be best described as a semi-distributed conceptual model, however, allows for lumped applications. The approach uses sub-basins as primary hydrological units, and within these an area-elevation distribution and a simple classification of land use (forest, open cover lakes) are made.

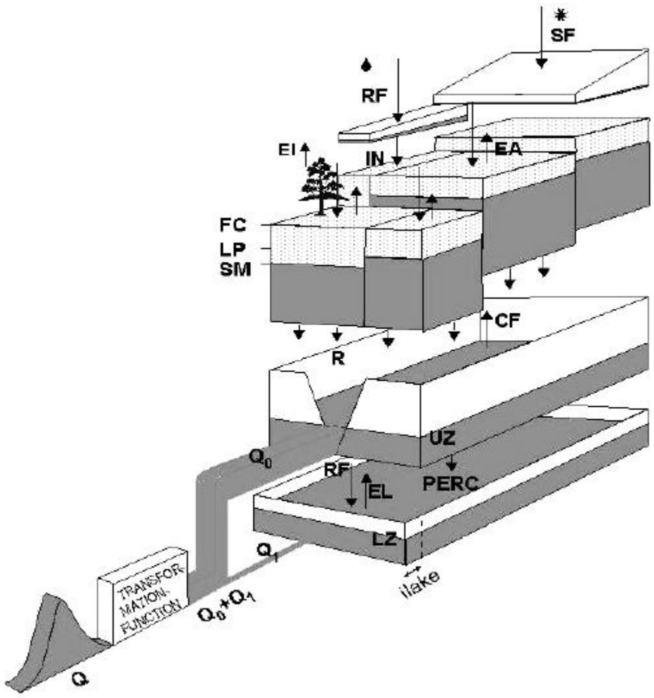


Figure 4 -16: HBV-96 model structure (SMHI, 2006).

Where SF: snow, RF: Rain, IN: infiltration, EA: actual evapotranspiration, EI: evaporation from interception, SM: soil moisture, FC: maximum soil moisture storage, LP: limit for potential Evapotranspiration, R: recharge, CFLUX: capillary transport, UZ: storage in upper response box, LZ: storage in lower response box, PERC: percolation, K4 and K: recession parameters, ALFA; recession parameters, $Q_o$ and $Q_1$: runoff components.

The model was run for the upper Cabra river basin; calibration was done to the above mentioned parameters, having for reference the estimated calculated discharge. HBV is a highly versatile model and it is recognized to be able to fin runoff in many distinctive situations. As such it is a perfect choice as the measured discharges remain uncertain. If discharges cannot be fit, the model will inform over boundary and limitations that can be translated into advices to improve the data collection.

#### Soil moisture and accounting routine

The soil moisture accounting of the HBV model is based on a modification of the bucket theory in that it assumes a statistical distribution of storage capacities in a basin. This is the main par controlling runoff information. This routine is based on the three parameters, BETA, LP, and FC.

BETA controls the contribution to the response function (ΔP/ΔQ) or the increase in soil storage (1-ΔQ/ΔP) from each millimeter of rainfall. LP is a soil moisture value above which Evapotranspiration reaches its potential value, and FC is the maximum soil moisture storage in the model (SMHI, 2006).

$$R = IN\left[\frac{SM}{FC}\right]^{BETA} \tag{4-13}$$

The equation above indicates that indirect discharge increases with increasing soil moisture content and that when no infiltration occurs, no indirect discharge is generated (SMHI, 2006).

Actual Evapotranspiration $E_a$ depends on the measured potential Evapotranspiration $E_p$, the soil moisture state and parameter LP which is a limit where above the Evapotranspiration reaches its potential value. Shown in the equations 4-8 and 4-9 (SMHI, 2006).

$$Ea = \frac{SM}{LP \times FC} \times Ep \quad \text{with SM <(LP * FC)} \qquad (4\text{-}14)$$

$$Ea = Ep \quad \text{with SM >= (LP * FC)} \qquad (4\text{-}15)$$

Where

| | | |
|---|---|---|
| SM | Computed soil moisture storage | (mm) |
| FC | Maximum soil moisture storage | (mm) |
| BETA | Empirical coefficient | |
| Ep | Potential Evapotranspiration | (mm) |
| Ea | Actual Evapotranspiration | (mm) |
| LP | Limit for potential Evapotranspiration | |
| R | Recharge | (mm) |
| IN | Infiltration | (mm) |

#### Response routine

The runoff generation routine is the response function which transforms excess water from the soil moisture zone to runoff. It includes the effect of direct precipitation and Evapotranspiration. The function consists of one upper, non-linear and one lower, linear, reservoir. These are the origin of the quick and slow runoff components of the hydrograph (SMHI, 2006).

The outflow from the upper reservoir is described as shown in the equation 4-16.

$$Q_O = k \times UZ^{(1+ALFA)} \qquad (4\text{-}16)$$

Where

| | | |
|---|---|---|
| $Q_o$ | = Reservoir outflow upper reservoir | (mm) |
| UZ | = Reservoir content upper reservoir | (mm) |
| K | = Recession coefficient upper reservoir | |

The outflow from the lower reservoir is described as shown in the equation 4-11

$$Q_1 = k4 \times LZ \tag{4-17}$$

| | | |
|---|---|---|
| $Q_1$ | = Reservoir outflow lower reservoir | (mm) |
| LZ | = Reservoir content lower reservoir | (mm) |
| k4 | = Recession coefficient upper reservoir | |

The soil routine parameters FC, LP, and Beta characterizes to influence the total volume, while the response parameters, k4, perc, khq, hq and Alfa influence the shape of the hydrograph rather than the total volume (Emiru, 2009). The value of Hq was calculated according to the equation.

$$Hq = \frac{(MQ \times MHQ)^{1/2}}{A} \times 86.4 \tag{4-18}$$

Where:

| | | |
|---|---|---|
| Hq | =Corresponds to the outflow from the response box, and is a high flow level at which the recession rate khq is assumed | (mm/day) |
| MQ | = Mean observed discharge for the whole period | ($m^3/s$) |
| MHQ | = Mean annual peak flows | ($m^3/s$) |
| A | = Area of the basin | ($km^2$) |

The values to calculate the above equation for the period 2009-2010 are shown in table 4-8 were obtained from the corrected discharges in section 4.1.8.

Table 4 - 8: Values for Hq calculation.

| **A** **Km²** | **MQ** **m³/s** | **MHQ** **m³/s** | **Hq** **mm/day** |
|---|---|---|---|
| 27.55 | 29.186 | 3.3 | 10 |

For the calibration the most sensitive parameters are k4, perc, Khq, fc, Alfa, and Beta

#### 4.2.3. HBV-96 calibration

The calibration of HBV was performed manually; the adjustment of parameters values was done by changing and simulating one parameter at a time and performing the simulation until the overall hydrograph shape mostly matched in peaks and baseflow to the observed discharge. The quality of the simulation was evaluated with the values of $R^2$.

The best parameter set will furthermore depend on the chosen time period, the chosen criterion and the chosen input data stations (Lindstrom, 1997).
The relative volume error $RV_E$ measure was applied to the simulated and observed flow data.
The $RV_E$ assesses the mass balance error between the observed and simulated counterparts. The $RV_E$ can vary between -∞ and +∞ but performs best when a value of 0 is generated since the accumulated difference between simulate ($Q_{sim(i)}$) and observed ($Q_{obs(i)}$) discharges is zero.

$$RV_E = \left[ \frac{\sum_{I=1}^{N} Q_{sim(i)} - \sum_{i=1}^{n} Q_{obs(i)}}{\sum_{i=1}^{n} Q_{obs(i)}} \right] * 100 \qquad (4\text{-}19)$$

Where
$RV_E$ = Relative volume error
$Q_{sim}$ = Simulated discharge
$Q_{obs}$ = Observed discharge

A relative volume error between + 5% or -5% indicates that a model performs well while relative volume errors between +5% and +10% and between -5% and -10% indicate a model with reasonable performance (Rientjes, 2010).
Note that this performance indicator might is not designed to compare peaks, but volumes. Floodings are caused by peaks.
Nash-Sutcliffe coefficient of efficiency (NS)
The Nash Sutcliffe coefficient of efficiency (NS) is perhaps the most common performance indicator for surface water models. NS values of 1 therefore indicate perfect fit. NS values between 0.9 and 1 indicate that the model performs extremely well. Values between 0.8 and 0.9 indicate the model performs very well while values between 0.6 and 0.8 indicate that the model performs reasonably well. Negative NS values indicate that the observed mean discharge is better predictor than the model simulation (Nash and Sutcliffe, 1970 cited by Rientjes 2009).

$$R^2 = 1 - \left[ \frac{\sum_{i=1}^{n} (Q_{sim(i)} - Q_{obs(i)})^2}{\sum_{i=1}^{n} (Q_{obs(i)} - \overline{Q_{obs}})^2} \right] \qquad (4\text{-}20)$$

Where
$R^2$ = Nash-Sutcliffe coefficient
$Q_{sim\,(i)}$ = Simulated discharge

$Q_{obs\,(i)}$ = Observed discharge

$\overline{Q}_{obs}$ = Mean observed discharge

#### Calibration parameters trials

Manual calibration was performed for several simulations trials and the selections of the optimal calibration parameters for Cabra river basin are shown in table 4-9. Hydrographs and HBV modeling results are show in section 5.

Table 4 - 9: Final set calibration parameters Cabra river basin

| Parameter | Definition | Range | 1 | 2 | 3 | 4 | Final Value |
|---|---|---|---|---|---|---|---|
| **Alfa** | Measure of Non Linearity to the upper response reservoir | 0.5 - 1.1 | 1 | 1 | 0.9 | 0.9 | 1.1 |
| **Beta** | Exponent in the equation for discharge from the zone of soil water | 1 - 4 | 1 | 1 | 2 | 2 | 2 |
| **Khq** | Recession coefficient for the upper response box when the discharge is HQ | 0.005 - 0.2 | 0.15 | 0.15 | 0.1 | 0.09 | 0.2 |
| **k4** | Recession coefficient for the lower response box | 0.001 - 0.1 | 0.1 | 0.01 | 0.001 | 0.01 | 0.01 |
| **Fc** | Maximum soil moisture storage (mm) | 100 - 1500 | 100 | 1000 | 350 | 800 | 200 |
| **Perc** | Percolation from the upper to the lower response box | 0.01 - 6 | 4 | 5 | 5 | 5 | 0.25 |
| **Lp** | Limit for potential evaporation | < = 1 | 1 | 1 | 1 | 1 | 1 |

#### 4.2.4. HEC-HMS model

The HEC-HMS is hydrologic modeling software developed by the US army Corps of Engineers Hydrologic Engineering Center (HEC). It is designed to simulate the rainfall runoff processes of catchments systems in a wide range of geographic areas such as large river basins and small urban or natural watersheds. HEC-HMS uses separate models to represent each component of the runoff process, including models that compute runoff volume, models of direct runoff and models of baseflow. Except when continuous Soil moisture and accounting (SMA) modeling is used, HEC-HMS uses uncoupled sub models which might compromise the water budget. Each model run combines a basin model, meteorological model, and controls specifications with run options to obtain results (Verma et al, 2010).

The Upper Cabra river basin was simulated using hourly precipitation from rain stations Cerro Pelon and Rancho Café located in the basin for the period 2009-2010 and daily observed flow was used for hydrograph calibration.

HEC-HMS transforms the rainfall excess into direct surface runoff through a unit hydrograph or by the kinematic wave transformation. Rainfall excess is computed for each time interval by subtracting infiltration losses from incoming precipitation. In order to compute direct runoff hydrograph by a unit hydrograph method, HEC-HMS uses a discrete representation of excess precipitation, in which a pulse of excess precipitation is known for each time interval (Verma et al, 2010).

HEC-HMS has been successfully applied in many countries around the world with similar meteorological conditions as in Cabra river basin as shown in Annex A.

#### 4.2.5. Watershed Physical Description

The physical representation of a watershed is accomplished with a basin model. Hydrologic elements are connected in a dendritic network to simulate a runoff process. Computation proceeds from upstream elements in a downstream direction. A classification of different methods is available to simulate infiltration losses (USACE, 2009). Two methods were used for transforming precipitation into surface runoff, Clark and Snyder unit hydrograph.

#### 4.2.6. Meteorology description

Meteorological data analysis is performed by the meteorologic model and includes precipitation, evapotranspiration, and snowmelt. The gage weights method uses an unlimited number of recording and non-recording gages.

Four different methods for producing synthetic precipitation are included. The frequency storm method uses statistical data to produced balanced storms with a specific exceedance probability. The SCS hypothetical storm method implements the primary precipitation distributions for design analysis using Natural Resources Conservation Service (NRCS) criteria (Soil Conservation Service, 1986). The user-specified hyetograph method can be used with a synthetic hyetograph resulting from analysis outside the program (USACE, 2009).

#### 4.2.7. Hydrologic simulation

The time span of a simulation is managed by control specifications, which include a starting date and time and an ending date and time, and a time interval. A simulation run is created by combining a basin model, meteorologic model, and control specifications (USACE, 2009).

For modeling the upper Cabra river basin several methods for surface runoff and infiltration were tested in HEC-HMS in order to achieve the best set of methods that represent hydrologically the characteristics and conditions of the catchment.

Finally the Clark and Snyder transform methods approach are nonlinear boussinesq baseflow method and the deficit and constant loss method were implemented, tested and calibrated to the observed flow.

Precipitation from rainfall stations, gage weights, observed flow and evapotranspiration were entered into HEC-HMS and control specifications section data was created for the period January 1 2009 to 18 September 2010.

#### 4.2.8. Transform method

**Snyder**

For the Snyder's transform method lag time and time of concentration were calculated using Kirpich's equation (1940) as shown in equations 4-19 and 4-20 were developed for small, agricultural watersheds. They were estimated by examining the required time for the stream to rise from low to maximum stage during a storm. The peaking coefficient was used for calibrating the simulated with the observed hydrographs in Cabra river basin.

$$T_c = \frac{0.00013L^{0.77}}{S^{0.385}} \quad (4\text{-}19)$$

$$T_{lag} = 0.6 * T_c \quad (4\text{-}20)$$

| | | |
|---|---|---|
| $T_c$ | = Time of concentration | (hours) |
| L | = Length of the overland flow | (feet) |
| S | = Average overland flow in feet | (ft/ft) |
| $T_{lag}$ | = The time it takes a flood wave to move downstream | (hours) |

**Clark**

For Cabra river basin Clark transformation model requires estimation of the time of concentration $T_c$ using the equation 4-19 and the storage coefficient.

The time of concentration determines the maximum travel time in the subbasin; it is used in the development of the translation hydrograph, and the storage coefficient is used in the linear reservoir that accounts for storage affects across the subbasin (USACE, 2009).

#### 4.2.9. Baseflow method

Nonlinear boussinesq method is designed to approximate the behavior observed in catchments when channel flow recedes after an event, the method gives an exponentially decreasing baseflow from a single event, but the parameters can be estimated from measurable qualities of the catchment (USACE, 2000). For Cabra river parameters such as porosity, conductivity were obtained from soil texture and river length was obtained from the processed DEM.

#### 4.2.10. Loss method

Deficit and constant method was chosen. A loss /gain method represents losses from the channel, additions to the channel from groundwater, or bi-directional water movements, the method tracks the mean volume of water in natural storage in the watershed, it should be used in combination with a meteorologic model that computes evapotranspiration (USACE, 2000). For the Initial deficit values obtained during fieldwork were used as initial trials.

#### 4.2.11. HEC-HMS Limitations

Every simulation system has limitations due to the choices made in the design and development of the software. The limitations that arise in this program are the simplified model formulation and simplified flow representation (USACE, 2009). The software ignores the basin transfer processes, uses uncoupled water balance submodels in the different domains.

### 4.3. Calibration

Hydrologic models require adjustments of the values of model parameters, hydrologic influences and stresses in order to tune the model. By the fine-tunning of the input data, the reliability of the model will improve. The procedure of adjusting the model input (e.g. parameters, boundary values, stresses) is necessary to match model output with measured field data for the selected period and situation entered to the model. The ultimate modelling objective is to produce a model that can accurately and reliably simulate or predict (future) conditions for which no information is available (Rientjes, 2010).

For an optimal calibration, one must consider the overall shape of the hydrograph, high peaks and low flows. Calibration was performed mainly focused matching the highest peaks of the simulated to the observed hydrograph; initial calibration was performed manually using the initial values obtained from fieldwork, however a calibration optimization was performed using an automatically internal algorithm that evaluated all parameters simultaneously and defined the best set of parameters according to the data entered. Table 4-10 shows the initial values obtained from fieldwork entered as initial values to the model and the optimized final ones for the two methods used in HEC-HMS Clark and Snyder.

Table 4 - 10: Initial and final calibration parameters for Clark and Snyder transformation methods

| Methods | Parameter | Units | Initial value | Optimized value |
|---|---|---|---|---|
| Transform Clark | Clark Time of Concentration | hrs | 1.2 | 1.46 |
| Loss Deficit and Constant | Clark Storage Coefficient | hrs | 3 | 3.93 |
| Baseflow Nonlinear Bousinesq | Constant Rate | mm/hrs | 4.3 | 7.99 |
| | Initial Deficit | mm | 5 | 5.28 |
| | Maximum Deficit | mm | 300 | 300.57 |
| **Methods** | **Parameter** | **Units** | **Initial value** | **Optimized value** |
| Transform Snyder | Initial Deficit | mm | 5 | 5.05 |
| Loss Deficit and Constant | Maximum Deficit | mm | 100 | 100.12 |
| Baseflow Nonlinear Bousinesq | Constant Rate | mm/hrs | 4.3 | 4.43 |
| | Snyder Peaking Coefficient | | 0.32 | 0.32 |
| | Snyder Time to Peak | hrs | 0.72 | 0.69 |

# 5. RESULTS AND DISCUSSION

## 5.1. Methodology results

### 5.1.1. Rainfall data results

Figure 5-1 shows the annual accumulated rainfall for stations Utive, Loma Bonita, Altos de Pacora and Tocumen for the years 1980 to 1999, from high values of rainfall in Altos de Pacora, decreasing in the downstream station Tocumen.

For mountainous terrain, the number events and the quantity of rainfall per event generally increase with elevation (Haan, 1982).

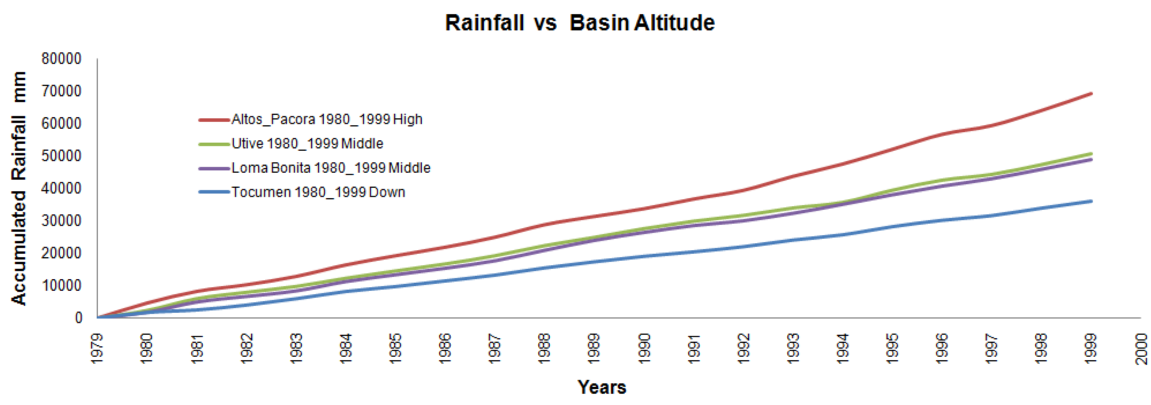


Figure 5 - 1: Annual accumulated rainfall Cabra river basin from 1980 to 1999.

### 5.1.2. Extreme frequency distribution results

- Table 5-1 shows the results of the return periods for rainfall stations located in Cabra river basin, as well as the results of the extreme frequency distributions applied to the rainfall stations data set. According to the statistical analysis performed, extreme events occur in the middle basin for the rain stations Utive and Loma Bonita followed by the Upper station Altos de Pacora and finally Tocumen station. It is observed that even that the rainfalls high volume happen upstream as shown in figure 5-1 the maximum extreme events were mainly recorded in the middle basin.
- Time series of four rainfall stations were evaluated with six extreme frequency distributions. Results of each distribution are graphed as shown in figures 5-2 to 5-5. Several distributions seem to fit for each of the stations, but in order to choose the appropriate distribution, for each of the stations a chi-square analysis was performed (See section 4.1.5 as reference). Values of chi-square < 1 are considered optimum. According to the chi-square analysis several distributions fit to one rainfall station (see table 4-3). In all the extreme distribution analysis using the chi-square and observing the distributions it can be inferred that Pareto and Gumbel prevail in all the analyzed rainfall stations.

- Extreme frequency analysis distributions are shown from figures 5-2 to 5-5 for rainfall stations Loma Bonita, Utive, Tocumen and Altos de Pacora in Cabra river basin. It is observed that the lognormal distribution does not give good results in any of the analyzed rainfall stations.
- The exponential distribution gave the highest values in all of the analysed rainfall stations for 100 years return period, but in any case this prediction remain uncertain considering the length of the series.

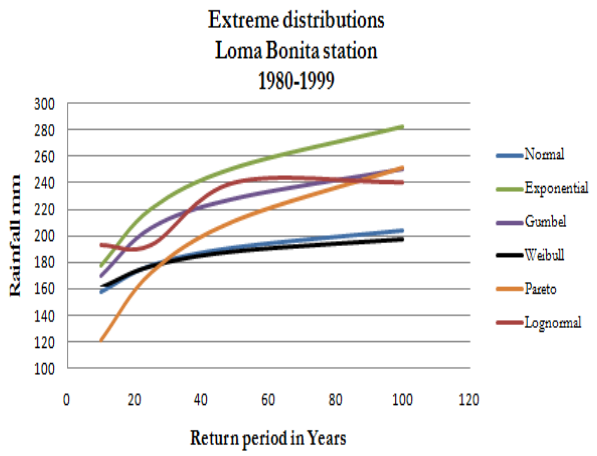


Figure 5 - 2: Extreme distributions Loma Bonita station.

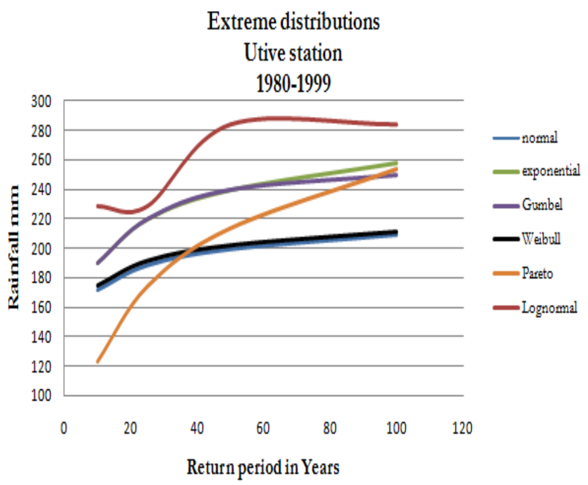


Figure 5 - 3: Extreme distributions Utive station.

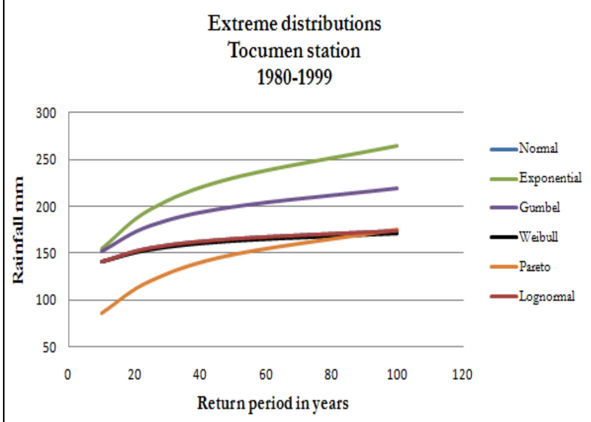


Figure 5 - 4: Extreme distributions Tocumen station.

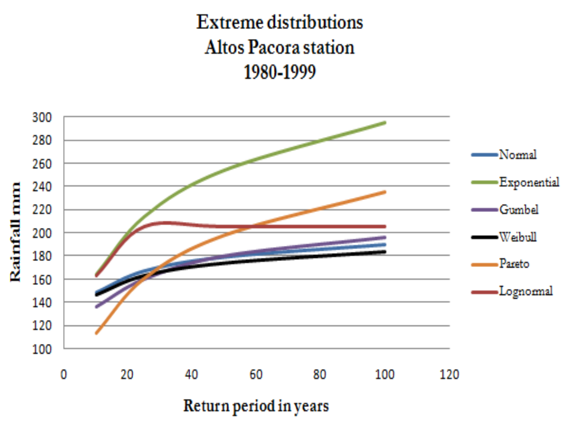


Figure 5 - 5: Extreme distributions Altos de Pacora

Table 5 - 1: Return periods of daily extreme rainfall events analysis on the upper Cabra river basin.

| **Rainfall station Utive** | **Tr Years** | **Normal mm** | **Exponential mm** | **Gumbel mm** | **Weibull mm** | **Pareto mm** |
|---|---|---|---|---|---|---|
| | 10 | 172 | 190 | 190 | 175 | 123 |
| | 25 | 188 | 220 | 220 | 191 | 174 |
| | 50 | 199 | 240 | 240 | 202 | 214 |
| | 100 | 209 | 258 | 250 | 211 | 254 |
| **Rainfall station Loma Bonita** | **Tr Years** | **Normal mm** | **Exponential mm** | **Gumbel mm** | **Weibull mm** | **Pareto mm** |
| | 10 | 158 | 178 | 170 | 161 | 121 |
| | 25 | 178 | 221 | 206 | 177 | 172 |
| | 50 | 191 | 252 | 228 | 188 | 211 |
| | 100 | 204 | 283 | 250 | 197 | 251 |
| **Rainfall station Altos de Pacora** | **Tr Years** | **Normal mm** | **Exponential mm** | **Gumbel mm** | **Weibull mm** | **Pareto mm** |
| | 10 | 148 | 164 | 136 | 146 | 114 |
| | 25 | 167 | 214 | 160 | 163 | 161 |
| | 50 | 179 | 254 | 180 | 174 | 198 |
| | 100 | 189 | 295 | 196 | 184 | 235 |
| **Rainfall station Tocumen** | **Tr Years** | **Normal mm** | **Exponential mm** | **Gumbel mm** | **Weibull mm** | **Pareto mm** |
| | 10 | 141 | 155 | 152 | 141 | 86 |
| | 25 | 155.7 | 197 | 180 | 154 | 121 |
| | 50 | 165.2 | 230 | 200 | 163 | 149 |
| | 100 | 173.8 | 264 | 220 | 171 | 176 |

Table 5-2 shows the final selected extreme distributions for the rainfall stations in Cabra river basin, according to the chi-square, the analysis made to table 4-3 and the figures 5-2 to 5-5.

Table 5 - 2: Selected extreme frequency distributions for Cabra river rainfall stations.

| **Function** | **Altos de Pacora Upper basin** | **Utive Middle basin** | **Loma Bonita Middle basin** | **Tocumen Downstream** |
|---|---|---|---|---|
| **Pareto** | X | X | X | X |
| **Weibull** | X | X | X | |
| **Gumbel** | X | X | X | X |
| **Exponencial** | | | | |
| **Normal** | | X | X | |
| **Lognormal** | | | | |

### 5.1.3. Results of the relation precipitation and discharge

An analysis of the amount of rainfall and discharge was performed based on the equation $\Delta P=P_t - P_{t-1}$; (See section 4.1.8), values of $\Delta P$ where $P_{t-1} = 0$ were chosen in order to determine the effective amount of rainfall that triggers the discharge in Cabra river. Variations of the discharge according to rainfall are shown in Table 5-3.

Table 5 - 3: Results of the relation precipitation and discharge.

| ΔP mm/day | Q mm/day | Q m3/s |
|---|---|---|
| 5.8 | 2.0 | 6.4 |
| 10.9 | 3.1 | 9.8 |
| 12.5 | 3.5 | 11.1 |
| 15.5 | 5.4 | 17.2 |
| 22.4 | 6.5 | 20.7 |
| 24.4 | 6.6 | 20.9 |
| 38.5 | 10.3 | 32.9 |
| 42.4 | 11.5 | 36.7 |
| 44.8 | 13.6 | 43.5 |
| 75.0 | 19.5 | 62.2 |
| 104.8 | 27.9 | 88.9 |

### 5.1.4. Evapotranspiration

Table 5 - 4: Daily Evapotranspiration Cabra river basin

| Months | Average Evapotranspiration mm |
|---|---|
| January | 3.0 |
| February | 5.1 |
| March | 4.1 |
| April | 3.4 |
| May | 5.4 |
| June | 5.1 |
| July | 5.6 |
| August | 5.1 |
| September | 4.7 |
| October | 4.7 |
| November | 3.6 |
| December | 4.1 |

Daily evapotranspiration for Cabra river basin was obtained using Thornthwaite's equation, results are shown in table 5-4, and the data was used in HBV and HEC-HMS models

### 5.1.5. Image processing results

Land cover classification Landsat TM images February 1984 and February 2010 of the upper Cabra river basin, using the maximum likelihood classifier algorithm. The classification was corroborated on pictures and fieldwork observations; the images were classified using two dominant land cover forest and grass. In the period of analysis the forest has increased 0.59 km$^2$, and it is observed that in the upper part the forest does not present high variation, while in the downstream part of the analyzed basin forest becomes grouped but in an erratic behavior, as shown in figures 5-6 and 5-7. The analysis was made mainly to the two types of landcover in order to fulfill data requirements for the HBV model. (See table 2-1 section 2.1.4)

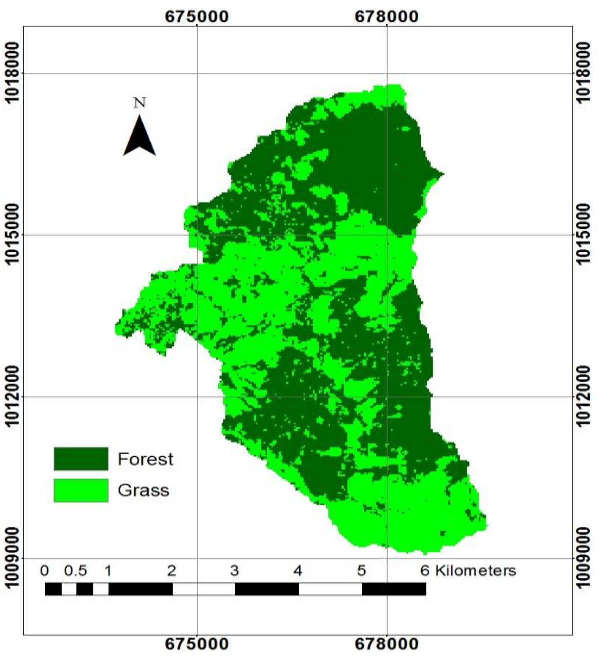


Figure 5 - 6: Land cover image Classification February 2010.

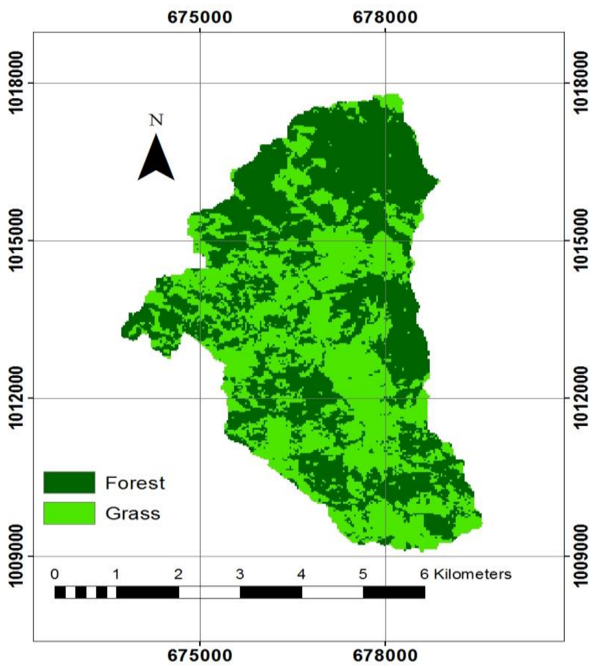


Figure 5 - 7: Land cover image Classification February 1984.

## 5.2. Modeling results (Final)

### 5.2.1. HBV-96 results

For model calibration several parameter simulations trials were performed, in order to achieve the best hydrographs matching the observed to the simulated hydrograph. The set of parameters used for calibration is shown in table 4-9, besides the correction of the stage was performed in section 2.2.4

A sensitivity analysis by trial and error was performed to the most susceptible parameters that influenced the shape of the hydrograph, in the peaks and in the baseflow.

Figure 5-8. Trial 1 Hydrograph calibration Simulated (black), observed (gray), rainfall (light gray) 1st January 2009 to 18 September 2010.

The observed hydrograph has a difference over the simulated; the shape of the hydrograph in the baseflow; and the peaks hardly match between the hydrographs.

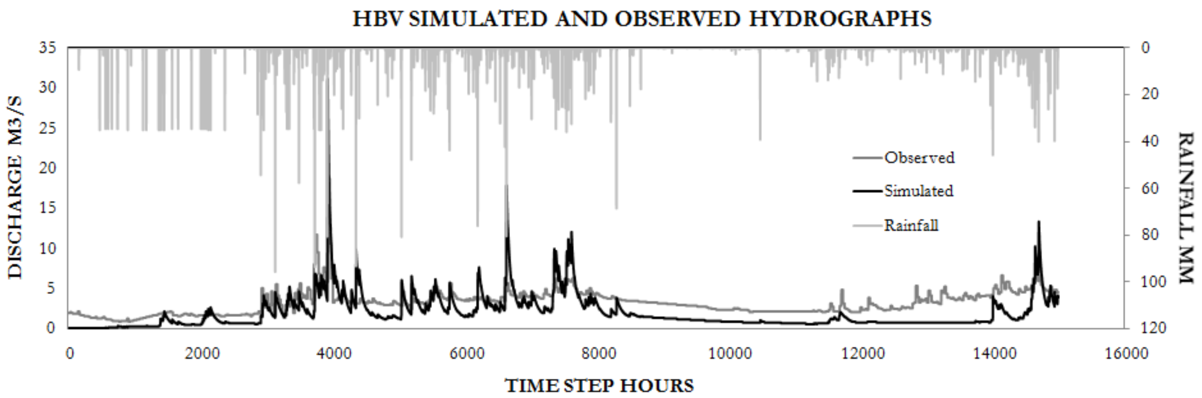


Figure 5 - 8: Trial 1 hydrograph calibration simulated (black), observed (gray) and rainfall (light gray).

In figure 5-9 it is observed that baseflow increases and peaks increase and decrease. There is a bias in simulated and observed baseflow.

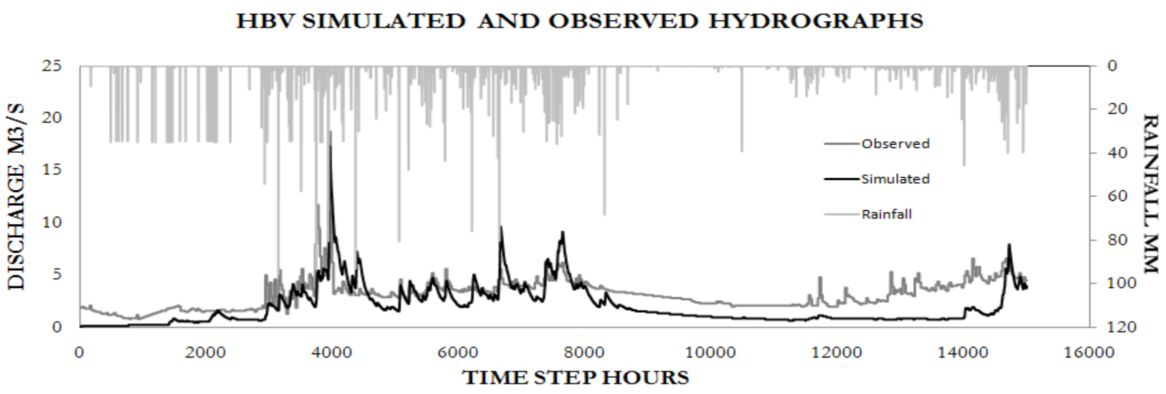


Figure 5 - 9: Trial 2 hydrograph calibration simulated (black), observed (gray) and rainfall (light gray).

After many more simulations and taking the most sensitive parameters to the edge of acceptable values (see table 4-9), it is concluded that, it was not possible to calibrate and match the simulated flow to the observed flow. The observed flow has approximately 2 $m^3/s$ of more baseflow, than the simulated flow in the overall hydrograph as shown in figure 5-10.

Figure 5-10. Trial 3 Hydrograph calibrations Simulated (black), observed (gray), rainfall (light gray) 1st January 2009 to 18 September 2010.

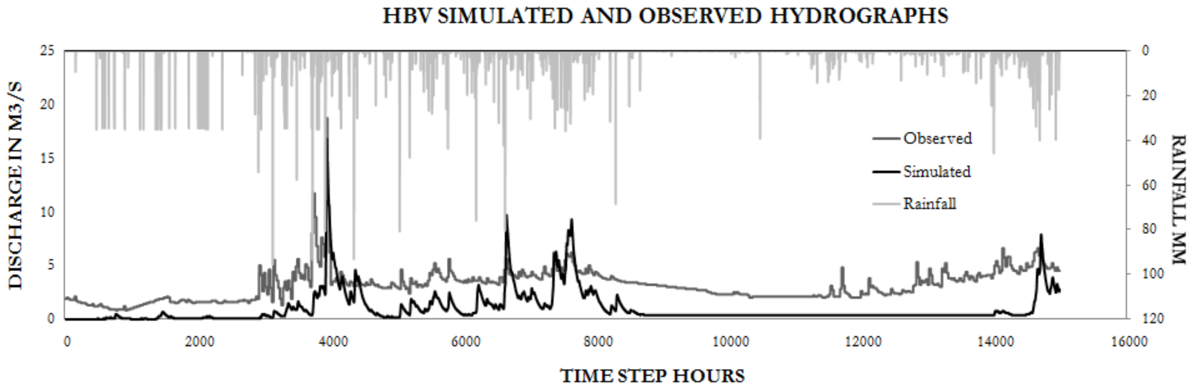


Figure 5 -10: Trial 3 hydrograph calibration simulated (black), observed (gray) and rainfall (light gray).

It was observed that the location of the stage was not proper; as it is located inside an eroded excavated pool that generates wrongly stage records. Refer to section 2.2.4 for stage datum correction performed.

#### Sensitivity analysis

After the datum correction (see section 2.2.4), the parameters Alfa, Beta, Khq, k4, Fc, Perc and Lp were submitted to a sensitivity analysis in order to gain a better understanding to calibrate the simulated with the observed hydrograph.

Alfa, Khq, Fc, and Perc showed the highest sensitivity in the results among the parameters analyzed. They are subject of analysis and discussion according to the observed tendency.

The Fc parameter was evaluated as shown in the figures 5-11 to 5-14 the parameter was evaluated ranging from 100 to 1500. Fc is the maximum soil moisture storage, characterizes to influence the total volume; it is observed in the encircled, that the higher the value of Fc the more rainfall the soil absorbs before runoff starts. For higher values of Fc make peaks to reduce as shown in figures 5-11 and 5-12. For Cabra river basin the value of Fc is 200 mm as shown in figure 5-14.

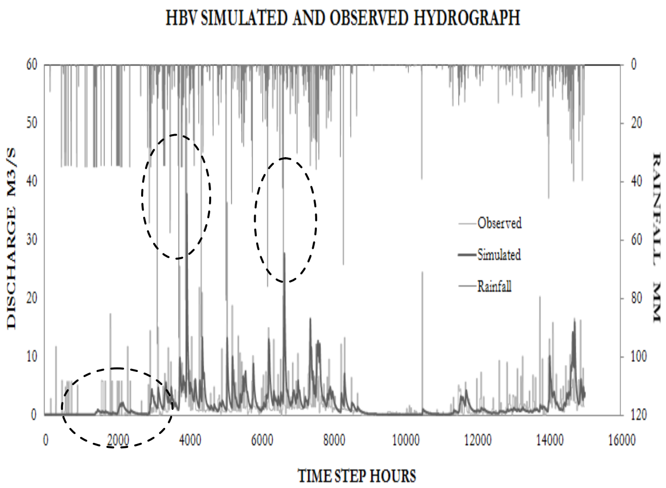


Figure 5 -11: Sensitivity analysis Fc 1500 mm

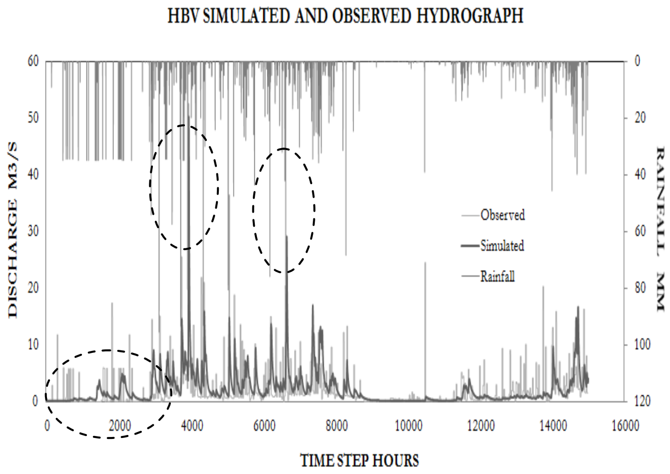


Figure 5 -12: Sensitivity Analysis Fc 900 mm

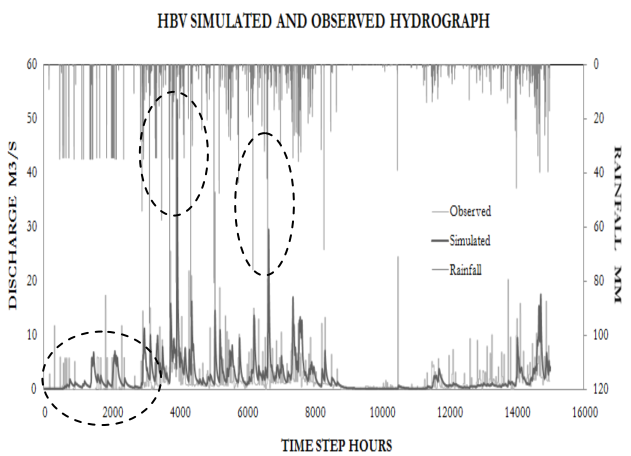


Figure 5 -13: Sensitivity analysis Fc 600 mm

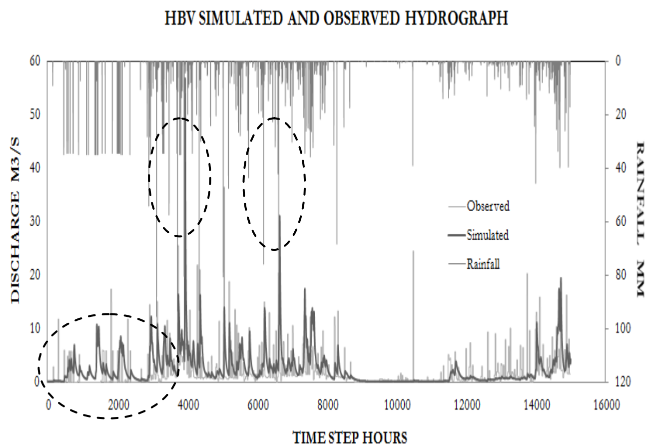


Figure 5 -14: Sensitivity analysis Fc 200 mm

The Perc parameter was evaluated in the range of 0.25 to 6 as shown in figures 5-15 to 5-18, it is considered the percolation from the upper to the lower response box in HBV-96 model; It is observed that the higher the percolation the more water remains in the system and in absence of rainfall and the longer the recession. Perc influences the shape of the hydrograph. For Cabra river basin the value of Perc is 0.25 mm/day as shown in figure 5-18.

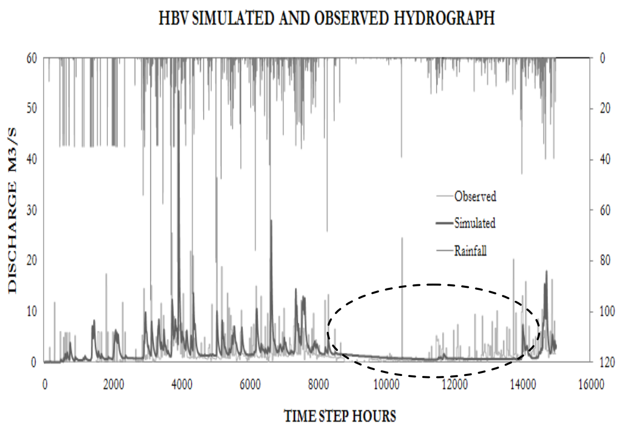


Figure 5 -15: Sensitivity analysis Perc 6 mm/day

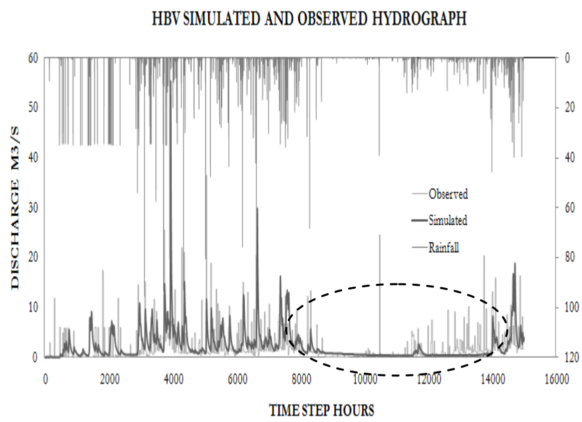


Figure 5 -16: Sensitivity analysis Perc 3 mm/day

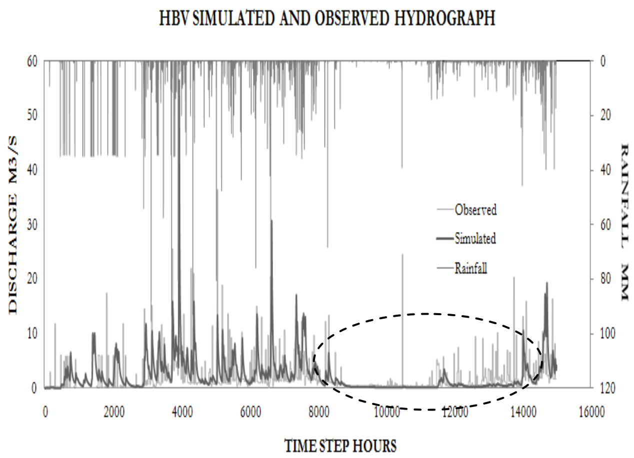


Figure 5 -17: Sensitivity analysis Perc 1 mm/day

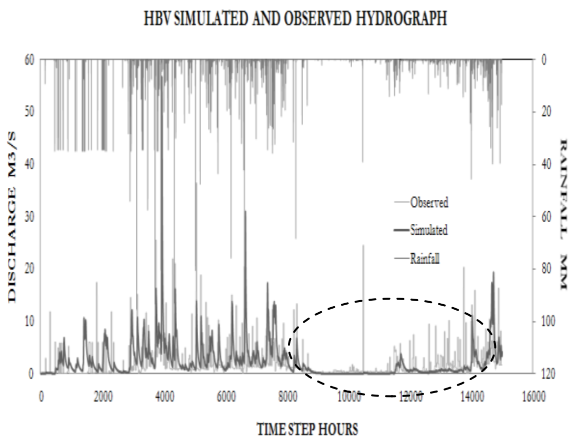


Figure 5 -18: Sensitivity analysis Perc 0.25 mm/day

The Khq parameter was evaluated in the range of 0.05 to 0.2 as shown in figures 5-19 to 5-22; it is considered the recession coefficient for the upper response box when the discharge is Hq. The parameters Khq, Hq and Alfa are involved in the equations of the outflow from the upper reservoir. It is observed that the lower the value for Khq the lower the response of the discharge to rainfall pulses; it influences the shape of the hydrograph. For Cabra river basin the value of Khq is 0.05 day $^{-1}$ as shown in figure 5-22.

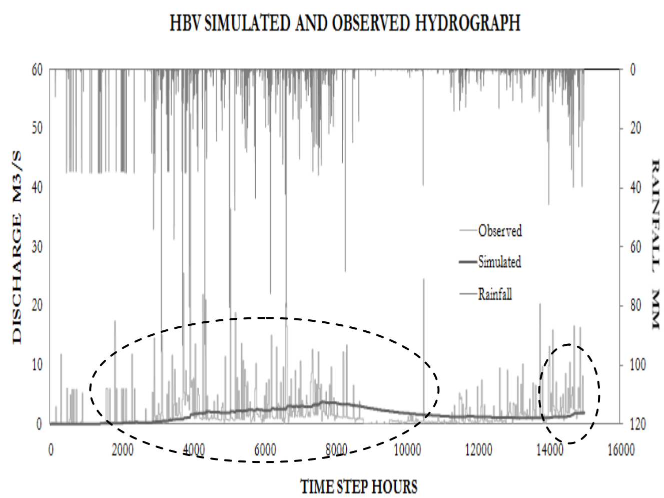


Figure 5 -19: Sensitivity analysis Khq 0.005 day $^{-1}$

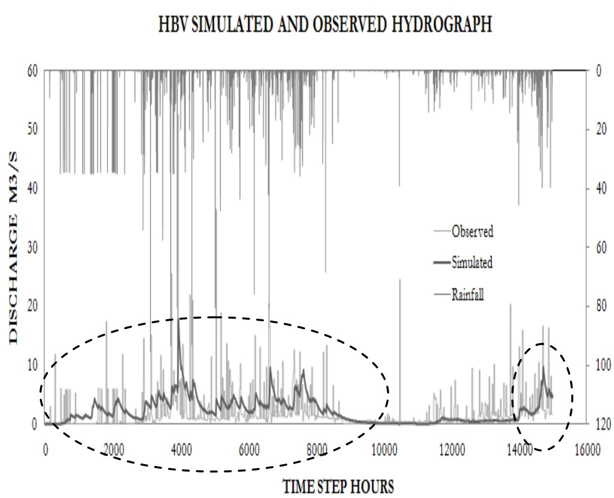


Figure 5 -20: Sensitivity analysis Khq 0.05 day $^{-1}$

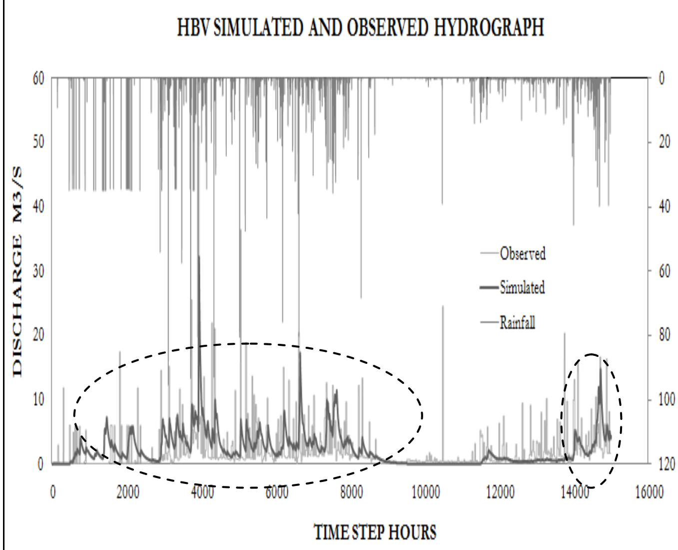


Figure 5 -21: Sensitivity analysis Khq 0.1 day $^{-1}$

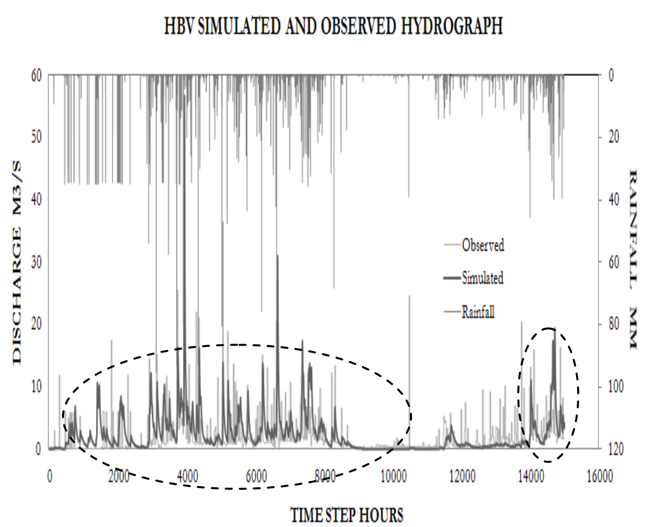


Figure 5 -22: Sensitivity analysis Khq 0.2 day $^{-1}$

The Alfa parameter was evaluated in the range of 0.5 to 1.1 as shown in figures 5-23 to 5-26.
Alfa is a measure of non-linearity, typically in order of 1 (SMHI, 2006). Alfa makes part of the equations of the outflow from the upper reservoir; in the analysis is observed that the lower the value the lower the peaks in the hydrographs, influencing the shape of the hydrograph rather than the volume. For Cabra river basin the value of Alfa is 1.1 as shown in figure 5-26.

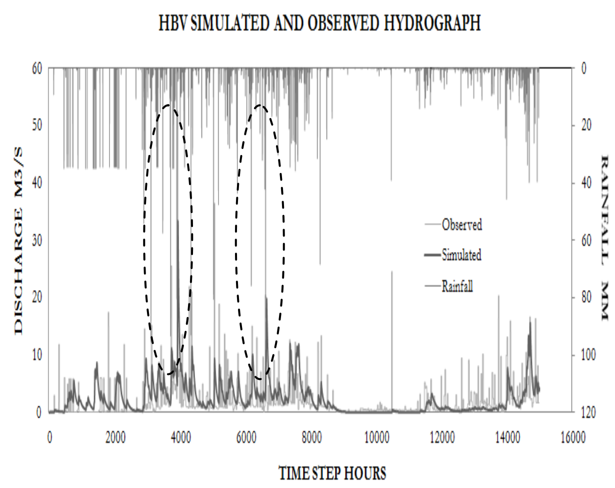


Figure 5 -23: Sensitivity analysis Alfa 0.5

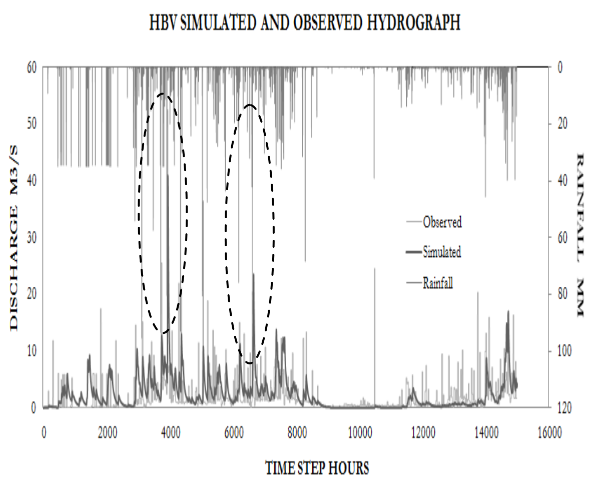


Figure 5 -24: Sensitivity analysis Alfa 0.7

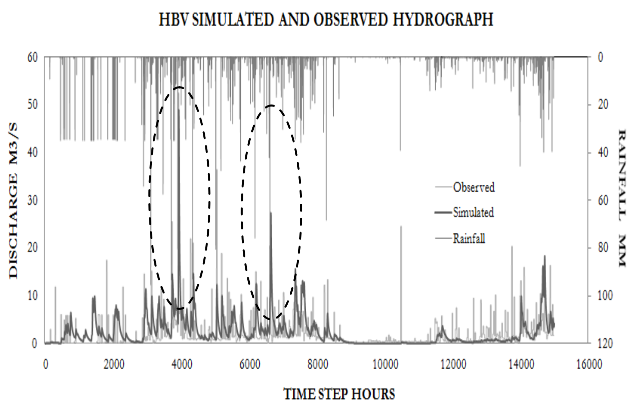


Figure 5 -25: Sensitivity analysis Alfa 0.9

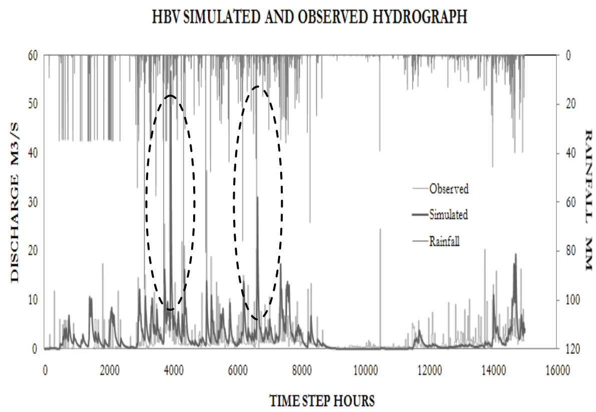


Figure 5 -26: Sensitivity analysis Alfa 1.1

Figure 5-27 shows the final attempt of the calibrated hydrograph with the corrected datum from section 2.2.4 and the final data set of parameters of table 4-9; It is observed that the simulated and the observed hydrographs both respond to rainfall pulses, despite that there is not a good agreement between the hydrographs, in general they match mostly in the peaks and baseflow in comparison with the previous trials. Sharp recessions mark the observed hydrograph while the simulated hydrographs shows soft falling limb in the recession, it should be noted that the observed hydrograph is given on a daily basis and the simulated hydrograph is on an hourly basis. This generates partial inconsistencies when trying to match both in the calibration phase.

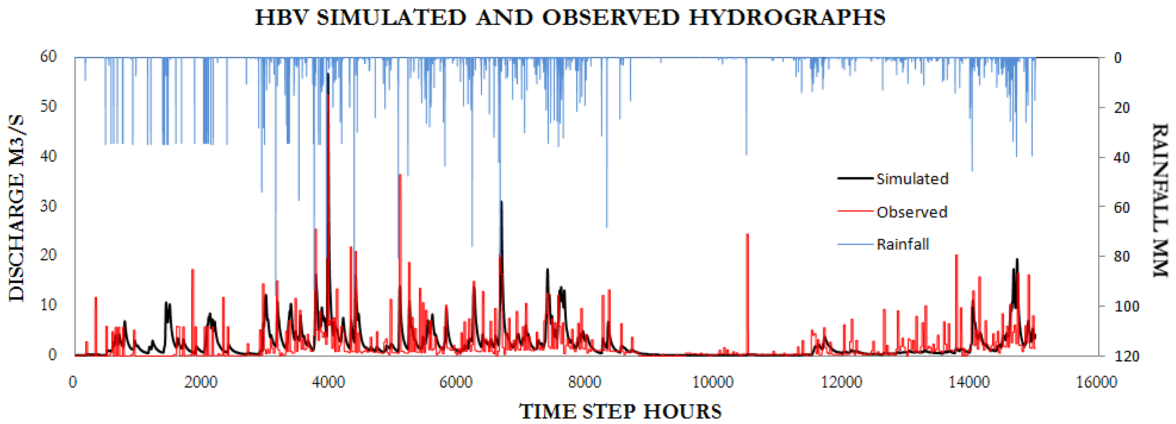


Figure 5 -27: Final hydrograph calibration simulated (black), observed (red) and rainfall (blue).

### 5.2.2. Observed hydrograph analysis

The daily mean discharges are estimated out of stages for the years 2009-2010; the black hydrograph is the simulated shown in figure 5-27. The highest peaks are observed from June to October 2009 (3600 to 7300 hour time step), and from August to September 2010 (13848 to 15000 hourly time step). The great irregularity shown by the sequence of daily mean flows during the wet months is indicative of a basin responding rapidly to rainfall. As example, there is 55 m3/s in the maximum peak presented on the 10 of June 2009 (hour time step 3854), shown in figure 5-27. The summer period From January to April 2010 (8760 to 11639 hour time step), shows a fast decline in the baseflow and the rain storms occurred in the dry season have produced few sharp peaks.

### 5.2.3. Simulated and observed hydrograph analysis

The rainfall-runoff model predicted the high peak discharges, fairly accurately from January 2009 to December 2009 (hour time step 1 to 8759), compared to the observed flow. For the year 2010 the observed and simulated flow hydrographs fairly coincide in the high peaks from August and September (hour time step 13848 to 15000).

There is a trend similar between the observed and simulated stream flow hydrographs, the peaks of the two hydrographs match reasonably for year 2009 than in 2010.

The simulated hydrograph seems to respond quite well to rainfall pulses and sharp recession in the baseflow; however the same process is not occurring to the observed flow. It is thought that the stage info

is not reliable or rainfall has biases or inconsistencies making the modelling calibration very difficult and thus reflecting in the results of the simulated and observed hydrographs.
Between February 10 and March 5 2009 (960 to 1535 hour time step) there was no recorded outflow to the rainfall, it might be the case of no stage observation for this period.
In the overall analysis of the simulated hydrographs it appears that, what triggers the highest peaks are rainfall intensities over a 100 mm in an hour preceded by short duration storms of less intensity.
For small and medium sized catchments, storms causing large river discharges vary in intensity in space as well as in time, and the consequent response is often affected by storm movement over the catchment area (Shaw, 1994). The amount of the rainfall stations seems insufficient.

#### Nash and Sutcliffe (NS)

The final model simulation was analyzed using the Nash and Sutcliffe (NS) efficiencies. NS value is related to the simulated and observed shapes of the hydrographs. The value obtained for Cabra's river basin hydrograph was 0.33. The simulated flow was performed with hourly data, while the observed flow was performed with daily data; furthermore the corrected discharges obtained from the stage went through a constricting procedure $|\Delta P|/\Delta Q$ to relate them to the rainfall pulses. Moreover the stage location is not the appropriate for taking measures; besides the rainfall data also had errors in their records. A combination of all these factors makes calibration cumbersome.

#### Relative Volume Error ($RV_E$)

The relative volume error $RV_E$ is related to the mass balance.
The $RV_E$ calculated was -1.65% indicating that the model performs well for Cabra river basin.

According to the results from NS and $RV_E$ during modeling calibration, it is observed that HBV reproduces the volumes, but the model could not reproduce the detailed pattern of the peaks overall the hydrograph.

#### Flow recession

For the hydrograph recession analysis a period between 31 July to 8 August 2009 was selected as shown in figure 5-27. An exponential tendency line was added and from the equation of the curve was found that $e^{-a} = e^{-0.022}$.

The term $e^{-a}$ is an indicator of the extent of baseflow, typical ranges of daily recession constants for stream flow components, namely runoff (0-2-0.8), interflow (0.7-0.94) and groundwater flow (0.93-0.995) do overlap; However, high recession constants (eg > 0.9) tend to indicate dominance of baseflow in stream flow (McMahon et al, 1998).

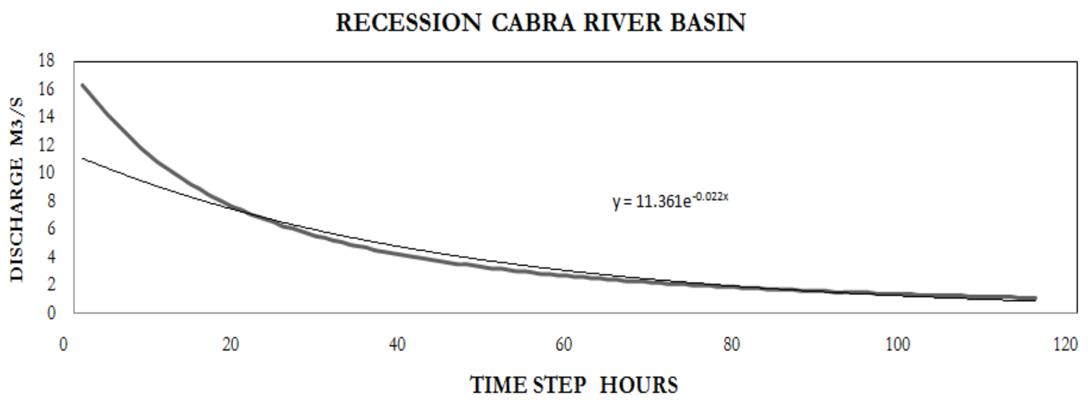


Figure 5 -28: Recession curve Cabra river

### 5.2.4. HEC-HMS results

#### Clark and Snyder

Figure 5-29 and 5-30 show the final simulated Clark and Snyder observed hydrographs after the optimized parameter calibration. It is established that the simulated and observed hydrographs respond to rainfall pulses, they match quite accurate in the peaks. In the recession is sharp in the simulated hydrograph similarly to the observed one. For the baseflow has an overall constant value of baseflow in the whole hydrograph.

The peaks simulate quite accurate and there is response to rainfall pulses but, due that the observed hydrograph has a daily value, there is a high error in the volume estimation.

The highest peak for both simulations with Clark and Snyder transform methods was observed on 13 June 2009 (hour time step 3912) with a discharge to the peak of 52 $m^3/s$

#### Nash and Sutcliffe (NS)

The HEC-HMS model Clark and Snyder Transform simulation were analyzed using the Nash and Sutcliffe efficiencies. NS value is related to the simulated and observed shapes of the hydrographs. The values obtained for Cabra's river basin hydrograph was for Clark 0.171 and Snyder 0.190; causes for this low values are attributed to the simulated flow was performed with hourly data, while the observed flow was performed with daily data. Other error mentioned in previous sections also affects the results here

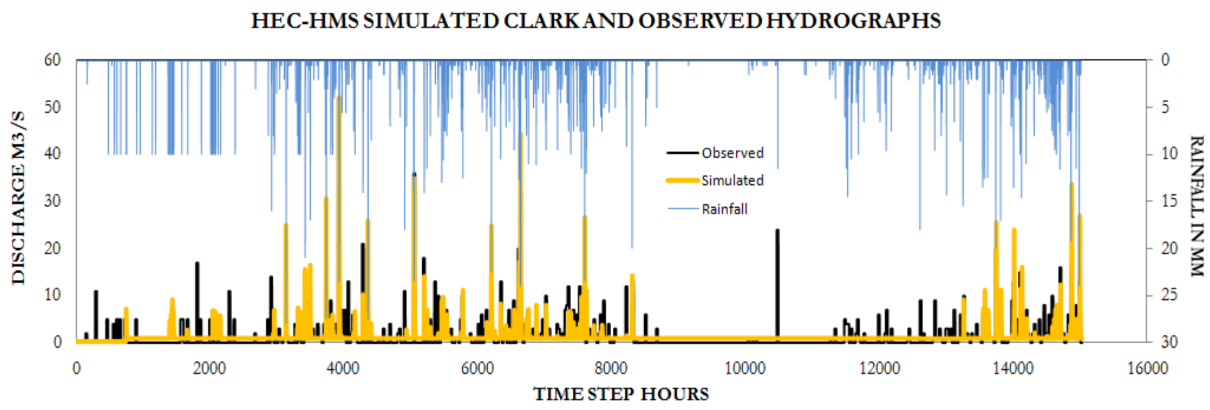


Figure 5 -29: Final hydrograph Clark simulated (yellow), observed (black), rainfall (blue).

Relative Volume Error ($RV_E$)
The relative volume error $RV_E$ calculated to the simulated and observed hydrographs for figures 5-29 and 5-30 was -47.56% for Clark and -44.38% for Snyder indicating not a good performance.

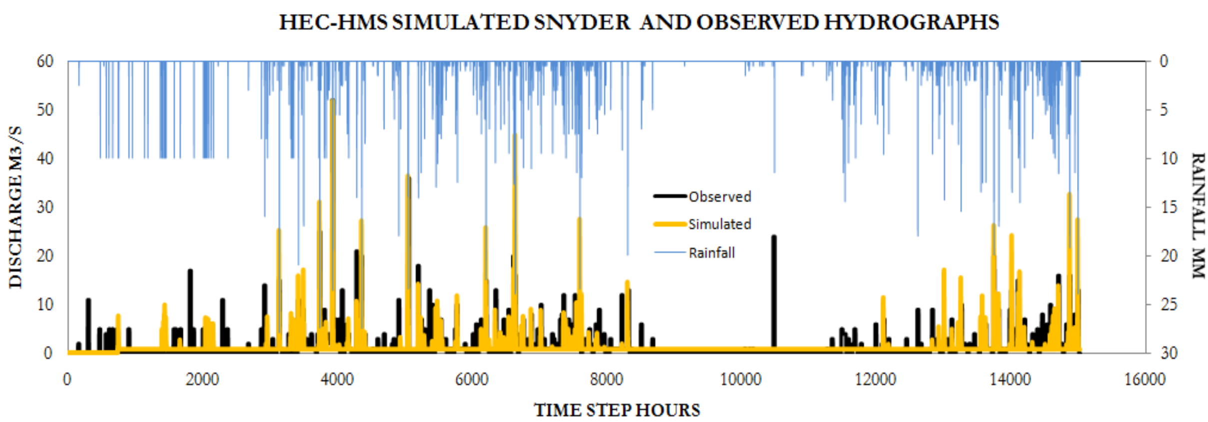


Figure 5 -30: Final hydrograph Snyder simulated (yellow), observed (black), rainfall (blue).

### 5.2.5. HBV and HEC-HMS results

Figure 5-31 shows the simulated hydrographs HBV (red), HEC-HMS (yellow), observed (black), HBV presents the results as a continuous hydrograph, HEC-HMS models the rainfall as a sharp successive rainfall events. From 21 January to 30 September 2009 (hour time step 480 to 8000), both models have highly response to rainfall peaks comparing it with the observed flow; baseflow into this period is modeled by HEC-HMS sharply and constant, while for HBV the hydrograph shows the typical bell-biased shape and recession. From 25 December 2009 to 9 April 2010 (hour time step 8600 to 11120 hours), both models hardly respond to any pulse of rain; From 18 April to 27 June 2010(hour time step 11339 to 13021), there are rainfall pulses between 10 and 15 mm hourly but there is a small answer from HBV hydrograph.

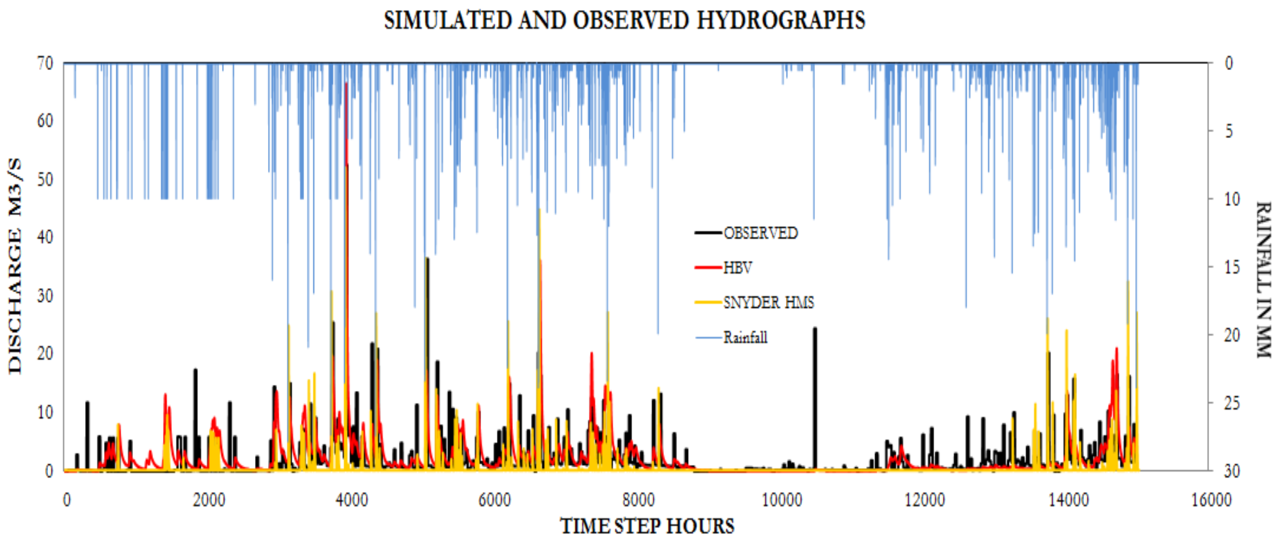


Figure 5 -31: Simulated hydrographs HBV (red), HEC-HMS (yellow), observed (black), rainfall (blue).

From 7 July to 30 July 2010 (hour time step 13254 to 13808), the models responds to rainfall events from 15 to 20 mm in an hour, the peaks overestimate the observed ones; from 5 August to 18 September 2010 (hour time step 13949 to 14988), the response of both models to rainfall pulses from 5mm to 25 mm is very similar compared with the observed hydrograph.

Table 5-5 shows the simulated and observed volumes calculated with HBV and HEC-HMS as well as $RV_E$ and NS. The HBV simulated and observed volumes are quite close, despite that observed data is in daily time step and the simulated in hourly time step.
Clark and Snyder transform methods give similar results in the simulated and the observed volumes, it is detected that while entering the discharge data to HEC-HMS, the model does not take into account the decimal digits, which speeds the calculations but generates underestimation of the volumes; this fact; does not permit to evaluate the best transform method performance of the model.

Table 5 - 5: HBV and HEC-HMS simulated and observed volumes.

| MODEL | SIMULATED VOLUMES M³ | OBSERVED VOLUMES M³ | RVE | NS |
|---|---|---|---|---|
| HBV | 130.251.240.00 | 132.442.560.00 | -1.655 | 0.332 |
| HEC-HMS Clark | 59.044.680.00 | 111.974.400.00 | -47.56 | 0.171 |
| HEC-HMS Snyder | 62.283.600.00 | 111.974.400.00 | -44.38 | 0.190 |

It is observed, that simulations result reflects more on the capability of the models to assess basin runoff responses; but the data does not allow making better modeling estimations to the observed hydrograph.

# 6. CONCLUSIONS AND RECOMMENDATIONS

## 6.1. Conclusion

For the Upper Cabra river basin study, satellite images and GIS were integrated to HBV (semi-distributed) and HEC-HMS (Lumped) hydrological models to evaluate the surface runoff of the upper basin. The use of GIS tools was very important for speeding the hydrology processing and data preparation for entering to the models.
The principal objective of this study is to simulate the rainfall-runoff in the upper Cabra river basin by using hydrological models, with ground data input, remote sensing and geographic information systems.

Rainfall data has many inconsistencies and the wrong values found in the data set for stations Rancho Cafe and Cerro Pelon were removed. The criteria for removing the values were based on records that showed unusual patterns such as two rainfall events with the same intensity in less than one hour, equal intensity during the same day, or a rainfall event of 30 mm or more in 15 minutes were considered not a natural pattern and erased from the rainfall time series. Even though after modeling with HBV and HEC-HMS it was difficult to establish an accurate relation between rainfall and response.

An analysis was performed to the stage data for the years 2009 and 2010, by analyzing the cross section located in Rancho Cafe station and the data records of the stages, two methods were used, the area velocity method with fieldwork data and by the stage evaluation using WinXSPRO software.
The discharges were mainly affected because the stage is located into one pool in the river, resulting in wrong measurements of the river stage and low quality results when discharges were calculated using the stage data.

A graphical data analysis was performed by comparing the amount of daily rainfall and the observed runoff for Cabra river basin. The runoff data quality for the year 2009 and 2010 is identified to be poor. To better understand the basin responses in terms of observed discharges, a relation is plotted between the change in rainfall and the change in runoff; several attempts in modelling were tried to improve simulated and observed hydrographs, but the results were not the expected ones, because the spatial representation of rainfall and runoff quality superseded all corrective measures.

Land cover analysis was performed to Landsat images from February 1984 and February 2010 using supervised classification, the maximum likelihood classifier, and the confusion matrix was performed to analyze the accuracy of classification, besides for the 2010 image the classification was corroborated with field pictures. The analysis of the images showed that land cover of the upper Cabra basin from 1984 to 2010 increased the forest in 0.59 $km^2$.

The calibration of HBV-96 model was performed by trial and error using the most sensitive parameters from table 4-9 and this method is time consuming; it was achieved successfully when evaluating the $RV_E$ and NS, the calibration was considered accepted in spite of all the data corrections made to the rainfall and discharge (see figure 5-11).

Calibration was done manually to determine the sensitivity of the hydrographs to the initial values, and finally a calibration optimization was performed using an automatic optimization trial that evaluates all selected parameters simultaneously and determines an optimized value. The shape of the hydrographs using Clark and Snyder showed a good match between simulated and observed hydrographs in the peaks, but the $RV_E$ results were not satisfactory, as well as Nash and Sutcliffe due to volumetric differences.

The HBV-96 and HEC-HMS models were selected based on the purpose and objectives of the study, also on the input data requirements and data availability for modelling.
It is not sure which model represents better the conditions of Cabra river basin, because there is still not reliable data, but for sure HBV-96 is better coupled between modeled storages and allows better hourly stream flow estimates in the upper Cabra river basin.

The analysis of the Chi-square and the extreme distributions figures allowed inferring which distributions represent best the extreme events in Cabra river basin.
According to the analysis made to the rainfall stations data set the best extreme distributions that fit Utive and Loma bonita stations are Pareto, Weibull, Gumbel and Normal distributions; for Altos de Pacora Pare to, Weibull and Gumbel and for Tocumen Station Pareto and Gumbel.

Pareto and Gumbel extreme distributions prove adequate for the Cabra basin; and could be used for future extreme rainfall analysis.

Analyzing the highest values of the extreme events obtained with Pareto distribution, it is observed that for Tr 10 is 123 mm and Tr 100 is 254 mm. for Utive station.

## 6.2. Recommendations

- Data collection has to be restructured completely. To improve it is advisable to change the location of the stage, select a location as much straight as possible to avoid future scouring or alteration from the river bed and river cross section and mainly avoiding pools or disturbances that could affect the stage measurements.
- For rainfall data compatibility, stage measurements must be taken on a regular basis of 15 minutes or less as well as the rainfall data, in order to perform a comparison and analysis of the basin runoff. The actual interval is not compatible with the concentration time of the small catchment.
- Rainfall data must be verified, the available data has errors that make the computations and calibration of the model very difficult.
- Despite of simulated hydrographs in HBV and HEC-HMS have similarities in the peaks when modeling the same data set, there is still much uncertainty on the data of the river stage and rainfall.
- To enhance rain data, is necessary to develop regular verification campaigns of rainfall and stage data; the process can be achieved going to the field with portable pluviometers, verifying the rainfall info sent by the radio rain station with the one collected in the field site, as well as checking any alteration in the gage due to temperature, wind or any climatic variation.
- For a better understanding of extreme rainfall events in the upper Cabra river basin, more years of data collection of 15 minutes or 10 minutes rainfall and stage data should be undertaken, in order to improve the data for calibrating and validating the models.
- It is recommended to install strategically an additional gage station in between Rancho Cafe and Cero Pelon stations, in order to represent the spatial variation of the rainfall in the Catchment.

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# ANNEX A

HEC-HMS successful modelling cases

- Puerto Rico Temporal Rainfall distribution in Puerto Rico a case study to determine the temporal rainfall distributions of extreme storms, and the impact of rainstorm sequences in Yaguez river watershed, the impact of rainstorm sequences on the response of a typical small watershed were evaluated using HEC-HMS (Gonzalez, 2005).
- Philippines Reconstructing the tropical storm Ketsana flood event in Marikina River for the year 2009, Peak flows and hydrographs were calculated using HEC-HMS for different areas along the Marikina River, for a extreme rainfall event and were compared with 8 stations along the river (Abon et al, 2010).
- Malaysia Runoff characteristics and application of HEC-HMS for modeling storm flow hydrograph in an oil palm catchment. In this case study Rainfall –runoff processes in a small oil palm catchment in Johor Malaysia were examined, the peak flow and storm flow volume were moderately correlated with rainfall, and the Hydrographs were satisfactorily modeled using HEC-HMS (Yusop et al, 2007).
- San Antonio Regional scale flood modeling using NEXRAD rainfall, GIS and HEC-HMS/RAS a case study for the San Antonio River Basin Summer 2002 storm event. Hydrographs were calculated for all the basin using HEC-HMS for the period from June 30 to July 9 (Knebla et al, 2004).
- Nepal Development of flood forecasting models for the Bagmati basin, HEC-HMS was used to convert the precipitation excess to overland flow and channel runoff. The simulation was done for a period of four months (June September) covering the whole rainy season of year 2004 (T. Kafle et al, 2004).
- India Simulation of HEC-HMS for simulating watershed runoff in the Upper Baitarrani River Basin of Eastern India using daily monsoon season (June October) rainfall and stream flow data from (1999-2005). In this case study annual and daily stream flows were simulated (Verma et al, 2010)

# ANNEX B

**Rainfall days in Cabra river basin**
**Period 1975-2004**

| Year | Days of rain in all Basin | Percentage Days of rainfall Per Year in All Basin |
|---|---|---|
| 1975 | 153 | 42 |
| 1976 | 44 | 12 |
| 1977 | 61 | 17 |
| 1978 | 119 | 33 |
| 1979 | 107 | 29 |
| 1980 | 117 | 32 |
| 1981 | 155 | 42 |
| 1982 | 108 | 30 |
| 1983 | 123 | 34 |
| 1984 | 140 | 38 |
| 1985 | 121 | 33 |
| 1986 | 100 | 27 |
| 1987 | 133 | 36 |
| 1988 | 170 | 47 |
| 1989 | 129 | 35 |
| 1990 | 135 | 37 |
| 1991 | 112 | 31 |
| 1992 | 114 | 31 |
| 1993 | 129 | 35 |
| 1994 | 126 | 35 |
| 1995 | 143 | 39 |
| 1996 | 116 | 32 |
| 1997 | 66 | 18 |
| 1998 | 127 | 35 |
| 1999 | 177 | 48 |
| 2000 | 99 | 27 |
| 2001 | 109 | 30 |
| 2004 | 118 | 32 |