Evaluating the Effects of LULC Changes and Climate Variability in the Hydrological Response of a Tropical Andean River Basin. The Case of the Boconó River Basin - Venezuela.

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To the memory of my Father

September, 2012

„*To rule the mountains is to rule the waters*“
(Ancient Chinese proverb)

„ *The connection between forest and rivers is like that between father and son. No forest, no rivers*“
(Gifford Pinchot).

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Content

List of Figures........ IV
List of Tables........ VII
List of Abbreviations........ IX
Abstract........ XI
Kurzfassung........ XV
Resumen........ XIX

Chapter 1.- Introduction........ 1
1.1.- Introduction........ 2
1.2.- Research Problem........ 5
1.3.- Research deficit........ 9
1.4.- The Research Targets........ 11
1.5.- The Study Area........ 12
1.6.- Methods and Dissertation structure........ 13
1.7.-Relevant concepts........ 16
1.7.1.- Integrated water resource management........ 16
1.7.2.- Spatial Analysis........ 17
1.7.3.- Spatial Changes........ 18
1.7.4.- Land Cover vs. Land Use........ 19
1.7.5.- Hydrological Modelling........ 20
1.7.6.- Climate Change........ 21

Chapter 2.- Methodological approach........ 23
2.1.- Introduction........ 24
2.2.- The General Approach........ 24
2.3.- The First methodological approach........ 25
2.3.1.- Build-up the spatial platform for the geographical data........ 27
2.3.1.1.- Brief overview of SRTM Data........ 28
2.3.1.2.- Digital Elevation Model (DEM) for the Boconó River Basin........ 29
2.3.1.3.- Delineating the River Basin........ 29
2.3.1.4.- Generation of basic topographic layers from the DEM........ 30
2.3.1.5.- Geomorphometric analysis........ 30
2.4.- The Second Methodological approach........ 30
2.4.1.- Ancillary remote sensing data used in the approach........ 34
2.4.2.- The LANDSAT Program. Overview........ 34
2.4.3.- The Land Use / Land Cover (LULC) Mapping Process........ 37
2.4.3.1.- The Pre – processing........ 37
2.4.3.2.- The LULC Classification / Analysis Process........ 40
2.4.3.3.- The Product Generation Process........ 42
2.4.4.- Multitemporal evaluation of LULC changes in the Boconó River Basin (Post Classification)........ 42
2.4.5.- Validation and Accuracy........ 45
2.4.6.- Generation of a LULC Map for 2028........ 47
2.5.- The Third Methodological Approach........ 49
2.5.1.- The Model J-2000g. Overview........ 50
2.5.2.- The Hydrological Response Units (HRUs), as the basic “Modelling Units” for the modelling process in J-2000g........ 53
2.5.3.- The Data Pre – processing........ 55
2.5.3.1.- The Spatial Context for the Modelling process........ 55

2.5.3.1.1.- Flow direction........ 57
2.5.3.1.2.- Flow accumulation & stream network........ 57
2.5.3.1.3.- Altitude........ 57
2.5.3.1.4.- Slope........ 58
2.5.3.1.5.- Aspect........ 58
2.5.3.1.6.- Basic Terrain Forms........ 58
2.5.3.1.7.- Land Use /Land Cover (LULC)........ 59
2.5.3.1.8.- Geology........ 59
2.5.3.1.9.- Soils........ 60
2.5.3.2.- The Temporal Context. Climatic and Hydrological raw metadata........ 60
A.- Precipitation data........ 64
B.- Temperature data........ 65
C.- Additional climatic raw data........ 66
D.- Runoff data........ 66
2.5.4.- The Hydrological Response Units as spatial platform for Modelling........ 66
2.5.5.- Parameterization Process........ 68
2.5.5.1.- Soil Parameters........ 69
2.5.5.2.-Vegetation and Land Use Parameters........ 71
2.5.5.2.1.- Albedo........ 71
2.5.5.2.2.- Stomatal Resistance........ 71
2.5.5.2.3.- Leaf Area Index (LAI)........ 72
2.5.5.2.4.- Geological Parameters........ 74
2.5.6.- Model Calibration & Validation........ 76
2.5.6.1.- Sensitivity Analysis........ 78
2.5.6.1.1.- Nash-Sutcliffe-Efficiency........ 79
2.5.6.1.2.- Logarithmic Nash-Sutcliffe-Efficiency........ 80
2.5.6.1.3.- Relative Percentage Volume Error (PBIAS)........ 80
2.5.6.1.4.- Coefficient of Determination (r^2)........ 81

Chapter 3.- The Boconó River Basin as a “water resource area”........ 82
3.1.- **Overview**........ 83
3.2.- **Origen and physical configuration**........ 85
3.3.- **Topographical configuration**........ 85
3.4.- **Topographical Orientation and Aspect dynamic**........ 86
3.5.- **Geological structure and framework**........ 86
3.6.- **Landforms**........ 90
3.7.- **Climatic controls**........ 92
3.8.- **Soils formation**........ 94
3.9.- **Hydrological patterns**........ 96
3.9.1.- Approximation to the hydrological landscapes in the Boconó River Basin........ 97
3.10.- **The role of the Land Cover in the dynamic of the FHLUs in the area**........ 104

Chapter 4.- Temporal & Spatial LULC Changes in the Boconó River Basin during the Period 1988 – 2008........ 108
4.1.- **Introduction**........ 109
4.2.- **LULC Categories identified in the Boconó River Basin**........ 109
4.3.- **LULC in T0 (1988), T1(1997) and T2(2008)**........ 112
4.4.- **LULC categorical dynamic and transitions between T0-T1-T2**........ 116
4.4.1.- LULC categorical changes and transitions for T0 – T1........ 116
4.4.1.1.- General quantification of the change........ 116

4.4.1.2.- Net change and Swapping.......... 118
4.4.1.3.- Systematic Inter-category transitions in the landscape system.......... 119
4.4.2.- LULC categorical changes and transitions for T1-T2.......... 124
4.4.2.1.- General quantification of the change.......... 124
4.4.2.2.- Net change and swapping.......... 124
4.4.2.3.- Systematic Inter-category transitions in the landscape system.......... 127
4.5.- **Comparison with other LULC studies conducted on tropical regions**.......... 130
4.6.- **Implications for Land Planning and Watershed Management**.......... 132

Chapter 5.- Temporal & Spatial analysis of the hydrological response in the Boconó River Basin.......... 138
5.1.- **Introduction.**.......... 139
5.2.- **Temporal Relationship between Rainfall and Runoff in the Boconó River Basin**.......... 139
5.3.- **Functional Hydrological Landscape in the Boconó River Basin. The HRUs System**.......... 142
5.4.- **Modelling the Hydrological Response through the Model J2000g**.......... 144
5.4.1.- Verification of the Modelling results.......... 154
5.5.- Spatial relationship of the water balance components in the Boconó River Basin..... 156

Chapter 6.- Spatial changes & hydrological response through specific scenarios in the Boconó River Basin.......... 164
6.1**.- Introduction**.......... 165
6.2.- **LULC projection for 2028. A basic map for the future scenarios simulated in J2000g**.......... 165
6.3.- **The scenarios for the simulation process**.......... 170
6.3.1.- Changes occurring in the LULC system at the river basin level.......... 170
6.3.2.- Changes occurring in the climatic system at the mesoscale level.......... 171
6.4.- **Hydrological response simulated under the specific scenarios**.......... 176
6.4.1.- Historical recent evolution of the seasonal flows (1989 – 2009).......... 176
6.4.2.- Hydrological response of the Boconó River Basin under different scenarios accounting for spatial changes in the catchment area.......... 185
6.4.3.- Level of uncertainty & significance of the changes.......... 194
6.4.4.- The role of the spatial changes (LULC changes and climatic changes) in the hydrological response of the river basin. Discussion of the results.......... 197

Chapter 7.- Summary, Conclusions & Further Research.......... 205
7.1.- **Summary**.......... 206
7.2.- **Conclusions**.......... 209
7.2.1.- Conclusions oriented to the Target Questions.......... 209
7.2.2.- Conclusions oriented to the Methods & Models used in the thesis.......... 213
7.3.- **Further Research**.......... 215
7.3.1.- In terms of LULC change.......... 215
7.3.2.- In terms of hydrological modelling.......... 215
References.......... 217
Appendix.......... 243

List of Figures

Figure 1.1.- Panoramic view of San Miguel Watershed, an important sector in the Boconó River Basin. (Source: Google Earth).. 8
Figure 1.2.- Location of the Study Area in a regional context... 13
Figure 1.3.- Basic theoretical approaches involved in the research process................... 15
Figure 2.1. - General Methodological approach defined and followed during the study 25
Figure 2.2.- Relationship between spatial resolution, temporal resolution and data sources in remote sensing. (Adapted from Cihlar, 2000).. 33
Figure 2.3.- Methodological approach followed in the LULC classification process......... 39
Figure 2.4.- Procedure followed for the Multitemporal evaluation.................................. 43
Figure 2.5.- Main structure and involved processes into the LCM Modeler. (Source: Clark Labs, 2009)………………………………………………………………………… 47
Figure 2.6.- Partial view of the main Window of the Transition Sub-Models within the LCM.. 49
Figure 2.7.- Process Structure of the Model J2000g. (Source: Adapted from JAMS Wiki, 2011).. 52
Figure 2.8.- Method to process the spatial information into the modelling system........... 56
Figure 2.9. - Spatial distribution of the climatic stations. (The numbers for the stations are identified on Table 2.8).. 63
Figure 2.10.- Methodological Process followed to delineate the HRUs………………… 68
Figure 2.11.- The calibration/validation process followed using the “split sample validation” method... 78
Figure 3.1.- Geographical Overview of the Study Area... 84
Figure 3.2.- Configuration of the Slope Gradient in the Study Area................................ 87
Figure 3.3.- Spatial pattern of the Aspect in the Study Area... 88
Figure 3.4.- Geological Framework for the Study Area... 89
Figure 3.5.- Mean annual monthly precipitation for three Gauge Stations in the Boconó River Basin.. 93
Figure 3.6.- Mean annual Temperature in the Boconó-Aeropuerto Station...................... 94
Figure 3.7.- Soil Types of the Boconó River Basin... 95
Figure 3.8. - General Overview of the Hydrological landscape system in mountain environments. (A) Generalized framework for mountainous terrain from Winter (2001). (B): The Winter´s framework adapted to the study area... 98
Figure 3.9. - Andine wetlands located in the Broad crest forming the FHLU 1 in the River Basin. (a) Páramo “Las Lajas”, in the south – west part of the catchment. (b) Páramo Guaramacal (Guaramacal National Park), in the south-east part of the catchment………………………………………………………………………………… 99
Figure 3.10. - Extensive convex hillside in the San Miguel Watershed, example of the FHLU 2 in the area……………………………………………………………………… 100
Figure 3.11. - Fluvial plain of the Boconó River, forming the FHLU 3 in the area……….. 101
Figure 3.12.- Main Terrain Forms in the Study Area... 103
Figure 3.13. Land use/land cover for the study Area in 2008... 105
Figure 4.1.- LULC in the Boconó River Basin for T0, T1 and T2.................................... 113
Figure 4.2.- Relative areal distribution of the different LULC categories during the period of study………………………………………………………………………… 115
Figure 4.3.- Persistence & changing area in Boconó River Basin for T0 – T1………… 117
Figure 4.4.- Persistence & changing area in Boconó River Basin for T1 – T2………… 125

Figure 4.5.- Transition-area for the Forested Categories in the period T0-T1………… 134

Figure 4.6.- Transition-area for the Forested Categories in the period T1-T2………… 134
Figure 4.7.- Transition area for the Land Use categories in the period T0-T1…………… 136
Figure 4.8.- Transition area for the Land Use categories in the period T1-T2…………… 136
Figure 5.1.- Annual precipitation and annual average runoff for the available period of observed runoff data……………………………………………………………………………… 140
Figure 5.2.- Average monthly and average monthly runoff for the Boconó River Basin 141
Figure 5.3. - The Boconó River at the outlet (La Cavita sector), during the low flow period, in January 2010……………………………………………………………………….. 141
Figure 5.4.- Hydrological Response Units (HRUs) delineated for the year 1988……… 143
Figure 5.5.- Main output of the modeling process in J-2000g for the Model B-1. (RunoffPlot), showing the Observed runoff (obsRunoff), the simulated runoff (simRunoff) and the precipitation……………………………………………………………. 145
Figure 5.6.- Main output of the modeling process in J-2000g for the Models B2 (A) and B-3 (B)………………………………………………………………………………………… 147
Figure 5.7.- Comparison between observed and simulated values produced by the models B-1, B-2 and B-3………………………………………………………………………… 148
Figure 5.8.- Comparison between the water balance components estimated by the Models B-1, B-2 y B-3……………………………………………………………………….. 149
Figure 5.9.- Comparison between simulated runoff, the observed data and the values founded in the Literature for 4 discharge events occurred in the Boconó river………….. 151
Figure 5.10. Hydrograph resulted from the Validation process, using the Model B-3… 154
Figure 5.11.- Mean average precipitation in mm/year, for the Boconó River Basin......... 157
Figure 5.12.- Mean average runoff in mm/year for the Boconó River Basin.................... 158
Figure 5.13.- Mean annual actual Evapotranspiration (actET) in mm/year, for the Boconó River Basin.. 160
Figure 5.14.- Mean average Direct Flow in mm/year, for the Boconó River Basin……… 162
Figure 5.15.- Mean average groundwater recharge in mm/year, for the Boconó River Basin……………………………………………………………………………………….. 163
Figure 6.1. - Main output of the LCM after the simulation of a specific LULC transition 166
Figure 6.2. - LULC Map for 2028 derived from the Land Change Modeler – LCCM……. 168
Figures 6.3.- Comparative distribution of the LULC for the three maps used to delineate the HRUs………………………………………………………………………… 169
Figure 6.4. - Areal distribution of the LULC for 1988, 2008 and 2028 in the Boconó River Basin……………………………………………………………………………….. 170
Figure 6.5.- Temporal distribution of the scenarios simulated and the main goals in each case……………………………………………………………………………….. 172
Figure 6.6.- LULC Maps and their corresponding HRUs maps delineated to simulate the different scenarios in J2000g Model.. 173
Figure 6.7.- Hydrographs corresponding to the “control” years to be used in the comparison of scenarios 1 and 2... 177
Figure 6.8.- total daily runoff simulated for the scenarios 1 and 2.................................. 178
Figure 6.9.- Average daily precipitation simulated on J2000g for the scenario 2 (year 2009).. 179
Figure 6.10.- Comparison between the simulated runoff for scenario 2 and the observed data for 1989... 179
Figure 6.11.- Oceanic Niño Index from 2000 to 2010 (Source: NOAA, 2010)…………… 181
Figure 6.12.- Comparison of total values of hydrological variables for the scenarios 1 and 2.. 182
Figure 6.13.- Comparison between the average, maximal and minimal temperatures measured for the scenarios 1 and 2... 183

Figure 6.14.- total annual runoff in m3/seg simulated for the scenarios, using the Model 3.. 186
Figure 6.15.- Trend followed by the RMSD across the different scenarios..................... 187
Figure 6.16.- Deviation of the Indicators from the “status quo” scenario (1).................... 189
Figure 6.17.- Percentage of change of the indicators from the “status quo”.................... 193
Figure 6.18.- Values of SNR for the Water Balance components.................................. 196
Figure 6.19. - Simulated Hydrographs corresponding to the scenarios 4, 8 and 9........... 198
Figure 6.20. - Suspended sediments of the Boconó River measured in La Cavita Station (Source: Macias, 2002)…………………………………………………………….. 202

List of Tables

Table 1.1.- Relation of water use of the country respect to the average in Latin America........ 6
Table 2.1.- Raw Data – Type compiled and used in the research project, according to Galati (2006)........ 26
Table 2.2.- Main results of the Shuttle Radar Topographic Mission (SRTM)........ 28
Table 2.3.- Main processes followed during the build up of the spatial platform for the geographical data........ 31
Table 2.4.- Main Characteristics of the LANDSAT Data used in the research project........ 36
Table 2.5.- LANDSAT Scenes compiled to be used in the project........ 38
Table 2.6.- General cross-tabulation matrix for comparing two maps from different points in time........ 44
Table 2.7.- Hydro meteorological Raw Data required for the Modelling process........ 61
Table 2.8.- List with the climate stations used in the Project........ 62
Table 2.9.- Target Variables reclassified for the HRUs delineation........ 67
Table 2.10.- Main characteristics of the soils in the Boconó River Basin........ 70
Table 2.11.- Field capacity Values derived from Saxton & Rawls (2006)........ 71
Table 2.12.- Values of Albedo for the LULC of the Boconó River Basin........ 72
Table 2.13.- Stomata Resistance Values for the LULC categories in the Boconó River Basin........ 73
Table 2.14.- Stomatal Resistance Values for “reference crops” in the Boconó River Basin........ 73
Table 2.16.- LAI values for the different LULC categories during the dry season in Boconó River Basin........ 74
Table 2.17.- LAI values for the different LULC categories during the rainy season in Boconó River Basin........ 75
Table 2.18.- Comparison between the LAI values estimated from RS and those measured “in situ” by Schwarzkopf et al (2011)........ 75
Table 2.19.- Maximal Percolation of the rocks present in the study area........ 76
Table 2.20.- J2000g Parameters considered for the Calibration process........ 79
Table 3.1- General outline of the Geological Framework in the Boconó River Basin, and its hydrological implications........ 91
Table 4.1.- Land Use / Land Cover (LULC) Categories identified in the Boconó River Basin........ 110
Table 4. 2. - Main results obtained in the Accuracy assessment for the T0, T1 and T2 classifications........ 112
Table 4.3.- General evolution of the LULC during the considered period........ 114
Table 4.4.- Landscape Dynamic in the Boconó River Basin for the Period T0 – T1 (1988 – 1997)…………… 118
Table 4.5.- The most systematic transitions occurred in T0-T1, in terms of Losses…….. 121
Table 4.6.- The most systematic transitions occurred in T0 – T1, in terms of Gain........ 123
Table 4.7.- Landscape Dynamic in the Boconó River Basin for the Period T1 – T2 (1997-2008)……………. 126
Table 4.8.- The most systematic transitions occurred in T1 – T2, in terms of Losses........ 128
Table 4.9.- The most systematic transitions occurred in T1 – T2, in terms of Gains........ 129
Table 5.1.- General information about the HRUs maps generated for the modelling process........ 142

Table 5.2.- Basic Efficiency Criteria obtained for the Model B-1 in J2000g...................... 146
Table 5.3.- Basic Efficiency Criteria obtained for the Model B-2 in J2000g...................... 150
Table 5.4.- Basic Efficiency Criteria obtained for the Model B-3 in J2000g...................... 150
Table 5.5.- Changes in the parameter values during the calibration process.................. 153
Table 5.6.- Water Balance components derived from the simulation for the period 1988 – 1990.. 155
Table 6.1. - Running Statistics from the Transition Sub-Models simulated in LCM…….. 167
Table 6.2.- General description of the scenarios to be simulated in J2000g.................... 175
Table 6.3.- Percentage of monthly rainfall anomalies for all events associated with ENSO and A-ENSO events in the Andean Region – Venezuela. (S= strong; M= moderate)... 180
Table 6.4.- Basic components of the hydrological balance for the scenarios 1 and 2...... 182
Table 6.5.- Total annual Runoff in m3/seg obtained for the different scenarios................ 186
Table 6.6.- Indicators for the evaluation of the simulated scenarios................................ 188
Table 6.7.- Percentage of deviation of the scenarios from the status quo scenario......... 192
Table 6.8.- Signal to Noise Ratio values obtained for the water balance components of the different scenarios (Model B-3)... 196
Table 6. 9.- Simplified water balance of the TMCF in comparison with Grassland in La Mucuy Sector, Mérida – Venezuela... 199

Abbreviations

Abbreviation	Description
ABF	Average Base Flow
A-ENSO	Anti-ENSO
Alb	Albedo
actET	Actual Evapotranspiration
APF	Average Peak Flow
AVE	Absolute Volume Error
CDB	Convention of Biological Diversity
DEM	Digital Elevation Model
DOD	Dry Out Day
ENSO	El Niño-Southern Oscillation
ET	Evapotranspiration
ETM+	Enhanced Thematic Mapper
FC	Field Capacity
FHLU	Fundamental Hydrological Landscape Unit
GIS	Geographic Information System
HRU	Hydrological Response Unit
HPD	Highest Peak Discharge
IPCC	Intergovernmental Panel on Climate Change
ITCZ	Intertropical Convergence Zone
JAMS	Jena Adaptable Modeling System
LAI	Leaf Area Index
LAT	Latitude
Log.NSE	Logarithmic Nash-Sutcliffe Efficiency
LON	Longitude
LC	Land Cover
LCC	Land Cover Category
LCM	Land Change Modeler for Ecological Sustainability
LUCHEM	Land Use Change on Hydrology by Ensemble Modeling
LULC	Land Use / Land Cover
LULCC	Land Use /Land cover Change
MARNR	Ministerio de Ambiente y Recursos Naturales de Venezuela (today: MINAMB)
MLP	Multi-Layer Perceptron
N	North
NASA	National Aeronautics and Space Administration
NE	North-East
NSC	Nash-Sutcliffe Coefficient
NSE	Nash-Sutcliffe Efficiency
NDVI	Normalized Difference Vegetation index
OM	Organic Matter
PBIAS	Relative Percentage Volume Error
PET	Potential Evapotranspiration
PLAPADA	Plant Parameter Database
RMSD	Root Mean Square Deviation
RMSE	Root Mean Square Error
SAGA	System for Automated Geoscientific Analysis
SNR	Signal to Noise Ratio
SRTM	Shuttle Radar Topography Mission

SW	South-West
TAR	Total Annual Runoff
TM	Thematic Mapper
TMCF	Tropical Montane Cloudy Forest
USGS	US Geological Survey
UTM	Universal Transverse Mercator
W	West
WBE	Water Balance Error
WFD	European Water Framework Directory

Abstract

Tropical river basins are constantly under growing pressure due to the population increase, the consequent changes in Land Use & Land Cover (LULC) and the effects derived from the climate change at regional scale The research study presented here, aimed to analyze the effect of the spatial changes, particularly inherent to the LULC changes in a tropical River Basin, and its possible impact in the water resources - response. The Boconó River Basin, located in the North Venezuelan Andean Region was selected as study area, being a very representative Andean catchment in which the biophysical and the socio-cultural systems are strongly interacting to generate a quite complex dynamic reflected in the form and intensity of the natural resources use.

Four main research targets were established as follows: (1) To analyze the spatial dynamic of the Boconó River Basin during the Period 1988 – 2008, in terms of changes occurring in LULC; (2) To analyze the dynamic of water resources within the River Basin, through the study of annual flows and seasonal flows; (3) To analyze the potential impact that such changes in LULC, in combination with climatic variability, could have in the future hydrological response; and (4) To discuss the possible relationships and its geographical implications between the spatial changes and the dynamic of water flows within the Boconó River Basin. The realization of such research targets rested in a conceived relevant methodological approach containing three main grouping and interacting Methods: Geoinformatic & GIS, Remote Sensing as well as Hydrological Modelling, which were continuously acting in an integrated form, so that the exchange of data, parametric and non-parametric information as well as maps between them were always needed.

At first, the study area was delineated from the SRTM data set (90 m spatial resolution), in order to build the Digital Elevation Model (DEM), and also to prepare the basic thematic maps (Topography, Slope, Aspect, and Drainage Network). Secondly, a set of LANDSAT TM imagery for 1988, 1997 and 2008 were compiled and classified through a semi – supervised approach, following a multi – level clustering for a multi – class segmentation of the scenes, using the “**hyperclustering method**”. After that, a multi-temporal analysis for the LULC changes was done, and the resulting cross-tabulation matrixes were used to determine important parameters like: net change, swapping, gross gain and gross losses. A more detailed analysis lead to estimate the most systematic “**inter-category**” transitions occurred in the landscape, which identify the specific trajectories that the LULC categories have been experienced in the River Basin. The “**inter-category**” transitions were a basic input into the Land Change modeller for ecologically sustainability, in order to project the changes 20 years in the future, generating a potential LULC map for 2028, which was a very important input for the modelling process.

Thirdly, an approach concerning the development of a simulation process using the **process-oriented model J2000g** was driven. Such model required a pre-processing for the climatic data, as well as the compilation and processing of information concerning to the basic parameters required to model the hydrological balance in J2000g. For a process-oriented estimation of the meso-scale soil water distribution in the catchment the concept of Hydrological Response Units (HRUs) was applied, being delineated from a perspective of the “**hydrological landscapes**” approach. Thus, the terrain landforms together with the geological framework and the LULC were the basic input for the delineation. Three HRUs maps were delineated for 1988, 2008 and 2028. Due to the limitations derived from the hydro climatic input data, three models were designed, with different methods to estimate the evapotranspiration. The models were calibrated and validated using the “**split-sample**” method, and the basic indicators for efficiencies were evaluated. Finally, nine scenarios were considered in order to simulate and to evaluate the hydrological response in both, the recent past, and the possible impact of the LULC changes and the climatic variability projected in the future.

A total of 12 LULC categories were identified and delineated in a landscape system where the persistence was found to be the predominant state. However, a very important dynamic was detected, in which the forested land covers showed a decreasing trend, while the human-induced types of land cover (Cropland, Grass-(anthropogenic) and Urban Areas), have been increasing progressively. The LULC categories: Successional Srhubland, Sub-montane Forest, Open-cleared Forest and Cropland were the most dynamic among the two considered periods, accounting for the highest total change value, as well as gains, losses, swapping and net change.

The results derived from the cross-tabulation matrix, revealed that the Tropical Montane

Cloudy Forest (TMCF) experimented a reduction of 12.8% (3530.43 ha) in the last 20 years. This is a considerable reduction taking into account the important role of the ecosystem in hydrological, ecological and biological terms. The study also demonstrated that the changes and the reduction showed by the TMCF in that area cannot be directly associated to the expansion of land use categories like Cropland or Grass-Anthropogenic. At least on the last 20 years, the TMCF have been systematically changing to an intermediate condition for LC, basically to Open-cleared Forest and Sucessional Srhubland. The systematic transition experimented by the category Fluvial Plain suggest an intense dynamic of the river, and the occurrence of high peak flows and important flooding events during the period, which have been affecting the urban expanding area, as well as croplands.

The results from the model J2000g showed that the hydrological response could be reasonable modeled, despite of the relatively scarce raw data basis referred to the hydro-meteorological variables. According to the historical data and also to the hydrographs simulated in J2000g, the Boconó river show a hydrological dynamic typically observed in tropical mountainous rivers, characterized by a well defined seasonality of the streamflows, and a rapid response to the convective and heavy precipitation events, which are very typical in that region. The highly variability of the convection processes reported in the literature and the influence of the anomalies El Nino-Southern Oscillation (ENSO) and (Anti-ENSO) A-ENSO suggest that the seasonal flows patterns can be highly variables among the years. The study revealed a high variability in the streamflows occurred in the last 20 years, derived from the variability of the meso-scale climatic processes, and the alternate sequence of ENSO and A-ENSO events. It is evident that the Boconó River is very sensitive to the variability imposed by the climatic processes.

The simulation for the different scenarios revealed that the future variability for the streamflows and the water yield in the area is mostly explained by the climatic conditions and patterns, as by the LULC alone. Thus, the possible intensification and more frequently recurrence of the anomalies ENSO and A-ENSO could be responsible for the intensification and seasonal variability of the streamflows. The scenarios accounting for LULC changes showed clearly a low impact of the LULC changes in the hydrological regimes. Those changes could only impact the water balance through the variation in the Evapotranspiration rates.

The results broadly suggest that the Boconó River is highly sensitive to the positive changes in the climatic variables precipitation and temperature. Thus, a relatively small positive change in the precipitation patterns could generate an important change in the hydrological response, as seen on the simulation for these scenarios.

Hopefully, all the results showed in this PhD Thesis Book can be a useful basis to promote more effective area-oriented policies within the watershed & river basin management in this important Region.

Kurzfassung

Wassereinzugsgebiete in den Tropen stehen unter steigendem Druck durch die wachsende Bevölkerung, die sich ergebenden Veränderungen in der Landnutzung und Landbedeckung und auch durch Auswirkungen des Klimawandels auf regionaler Ebene. Die hier vorgestellte Dissertation hat das Ziel, die Wirkung der räumlichen Veränderungen, insbesondere die Veränderungen in der Landnutzung/Landbedeckung, in einem tropischen Einzugsgebiet und seine möglichen Auswirkungen in der Wasserressourcendynamik zu analysieren. Das Einzugsgebiet des Boconó im Norden der venezolanischen Anden wurde als Untersuchungsgebiet gewählt, da das Einzugsgebiet die hydrologischen Systeme der Anden modellhaft repräsentiert. In diesen sind die biophysikalischen und soziokulturellen Systeme stark verflechtet und bilden eine sehr komplexe Dynamik, welche sich in der Form und Intensität der natürlichen Ressourcennutzung wiederspiegelt.

In der Arbeit wurden vier Forschungsschwerpunkte festgelegt: (1) Analyse der räumlichen Dynamik des Boconó Einzugsgebietes während des Zeitraumes 1988 - 2008 im Hinblick auf Veränderungen in der Landnutzung/Landbedeckung; (2) Analyse der Dynamik der Wasserverfügbarkeit durch die Auswertung des jährlichen und saisonalen Wasserabflusses; (3) Analyse der potenziellen Auswirkungen, die solche Veränderungen in der Landnutzung/Landbedeckung in Kombination mit dem Klimawandel auf die zukünftige hydrologische Dynamik haben können; sowie die (4) Analyse der möglichen Beziehungen und geographischen Auswirkungen zwischen den Veränderungen der Landnutzung/Landbedeckung und der Dynamik des Wasserabflusses innerhalb des Einzugsgebietes. Die Realisierung dieser Forschungsziele fundiert auf drei methodischen Ansätzen: Geoinformatik & Geographische Informationssysteme (GIS), Fernerkundung sowie Hydrologische Modellierung. Diese drei Gruppen stehen in kontinuierlicher Wechselwirkung, so dass der Austausch von Daten, parametrischen und nicht-parametrische Information, sowie Karten in ständigem Gebrauch war.

Zunächst wurde das Untersuchungsgebiet aus dem SRTM–Datensatz (90 m Auflösung) abgeleitet, um ein digitales Geländemodel zu generieren und daraus einige grundlegenden thematischen Karten (Topographie, Neigung, Exposition, Abflussnetzwerk) vorzubereiten. Weiter wurden eine Reihe von LANDSAT-TM Bilder für 1988, 1997 und 2008 zusammengestellt und dann durch einen semi-überwachten Ansatz, basierend auf einer multi-level Clusteranalyse für eine Segmentierung der Szenen, anhand der „**Hyperclustering-Methode**“ klassifiziert. Danach wurde eine multitemporale Analyse der

Änderungen in der Landnutzung/Landbedeckung vorgenommen, und die daraus resultierenden Matrizen wurden verwendet um wichtige Parameter wie die Nettoveränderung, den Austausch, die Zuwächse sowie Abnahmen zu bestimmen. Eine weiterführende Analyse bildet die systematischen Übergänge von der einen in die andere Landnutzungs-/Landbedeckungskategorien ab, die innerhalb des Untersuchungsraumes auftreten, und welche die spezifischen Tendenzen der Landnutzung/Landbedeckungskategorien im Einzugsgebiet abbilden. Diese Übergänge in eine andere Landnutzungs-/Landbedeckungskategorie sind wichtige Eingangsgrößen in den „Landnutzungswandelmodellierer für eine nachhaltige Ökologie“ um Änderungen 20 Jahre in die Zukunft zu projizieren Dabei wurde eine potentielle Landnutzungs-/Landbedeckungskarte für 2028 generiert, die ein weiterer, sehr wichtiger Input, für den Modellierungsprozess bildet.

Als dritten Schritt wurde, mit Hilfe des **prozess-orientierten Modells J2000g**, ein Simulationsprozess entwickelt. Ein solches Modell benötigt eine Vorprozessierung klimatischer Daten, sowie eine Zusammenstellung und Verarbeitung von Informationen über grundlegende Parameter, die für die Modellierung der Wasserbilanz in J2000g erforderlich sind. Das Konzept der HRUs (Hydrological Response Units) wurde für eine prozessorientierte Abschätzung der mesoskaligen Boden-Wasser-Verteilung im Einzugsgebiet angewendet, die mittels eines neuen Ansatzes „**hydrologischer Landschaften**“ abgegrenzt werden. Der Landschaftsformenschatz des Gebietes in Zusammenhang mit der Geologie und der Landnutzung/Landbedeckung sind daher die Basisdaten für die Ableitung der HRUs. Kartensätze der HRUs für die Jahre 1988, 2008 und 2028 wurden entsprechend erstellt. Aufgrund Einschränkungen der hydroklimatischen Ausgangsdaten wurden drei Modelle entworfen, die mittels verschiedener Methoden die Evapotranspiration berechnen. Die Modelle wurden kalibriert und durch die Anwendung der „**Split-sample**“ Methode validiert; des Weiteren wurden die grundlegenden Indikatoren für die Effizienz des Modelles beurteilt. Abschließend wurden neun Szenarien festgelegt, um die hydrologische Dynamik zu simulieren sowie zu evaluieren – für die jüngste Vergangenheit, sowie für zukünftige mögliche Auswirkungen der Landnutzungs-/Landbedeckungsveränderungen und Klimaschwankungen. Insgesamt wurden 12 Landnutzungs-/Landbedeckungskategorien abgegrenzt, wobei die Meisten über die Jahre hin stabil verortet sind. Ein wichtiger Trend jedoch konnte aufgezeigt werden: die bewaldeten Gebiete haben einen rückläufigen Trend während die anthropogen beeinflussten Landbedeckungskategorien (Ackerland, Grasflächen und Urbane Flächen) immer stärker angewachsen sind. Die Kategorien Sekundäre Verbuschung, Halbimmergrüner Bergwald, Wald mit lichter Kronenbedeckung und Ackerland verhielten sich am dynamischsten innerhalb den zwei betrachteten Zeiträumen; v.a. bei dem Werte Höchste

Gesamtveränderung, sowie bei den Zuwächsen, Verlusten, Wandel und der Nettoveränderung.

Die Ergebnisse decken auf, dass die Fläche des Bergnebelwaldes um 12,8 % (3530,43 ha) während den letzten 20 Jahren verringert wurde. Dies ist ein erheblicher Anteil, v.a. angesichts der wichtigen Rolle dieses Ökosystems in hydrologischer, ökologischer sowie biologischer Hinsicht. Die Ergebnisse zeigen zudem auf, dass die Veränderungen und Reduzierung des Bergnebelwaldes nicht im direkten Zusammenhang mit den Ausdehnungen der Landnutzungskategorien ‚Ackerland' oder ‚Grasflächen' stehen. Zumindest während den letzten 20 Jahren haben sich die Flächen von vormals Bergnebelwald hin zu ‚Wald mit lichter Kronenbedeckung' sowie ‚sekundäre Verbuschung' geändert. Die systematische Veränderung der Kategorie ‚Flussebene', zeigt eine deutliche und intensive Dynamik des Flusses auf, und das Vorkommen von Hochwässern und Überschwemmungsereignissen haben die expandierende urbanen Bereiche sowie die Ackerlandflächen stark betroffen.

Die Ergebnisse des Models J2000g zeigen auf, dass die hydrologische Dynamik gut erfasst und modelliert werden konnte, trotz der relativ geringen Datengrundlage der hydro-meteorologischen Eingangsparameter. Historische Daten sowie die simulierten Abflussganglinien in J2000g des Boconó zeigen eine typische hydrologische Dynamik des Abflusses und eine schnelle Reaktion auf die Starkregenereignisse der konvektionellen Niederschläge, welche für diese Region typisch sind. Die hohe Variabilität der konvektionellen Niederschlagsereignissen, aus der Literatur entnommen, und der Einfluss der El Niño-Southern Oscillation sowie des Anti-El Niño (La Niña), lassen vermuten, dass die saisonalen Abflussganglinien von Jahr zu Jahr sehr unterschiedlich ausfallen könnten. In dieser Arbeit wurde dies für die letzten 20 Jahre bestätigt, Einflussfaktoren waren v.a. meso-skalige Klimaprozesse und die wechselnden El-Niño und La-Niña Ereignisse. Zusammenfassend lässt sich sagen, dass der Boconó sehr sensibel auf klimatische Schwankungen reagiert.

Weiterhin zeigt die Analyse, dass, für verschiedene Zukunftsszenarien, die zukünftigen Schwankungen der Abflussganglinien und der Wassermengen v.a. durch klimatische Prozesse und Muster erklärt werden können, weniger durch die Landbedeckungs-/Landnutzungsveränderung allein. Mögliche Verstärkungen und ein häufigeres Auftreten von El-Niño bzw. La-Niña Ereignissen können auch die saisonalen Schwankungen der Abflussganglinie der Gewässer in diesen Regionen verstärken. Die Szenarien, welche Veränderungen in der Landbedeckung/Landnutzung beschreiben, verändern hingegen das hydrologische Abflussverhalten kaum. Einzig Änderungen der Evapotranspirationsraten können dabei den Wasserhaushalt stören.

Insgesamt zeigt die Studie, dass der Boconó empfindlich auf erhöhte Werte bei Niederschlägen und der Temperatur reagiert. Deshalb können schon relative kleine Intensivierungen in der Niederschlagsverteilung und –menge einen großen Einfluss im hydrologischen Abflussverhalten haben; wie man an den Szenariensimulationen sehen kann.

Die Hoffnung bleibt, dass die aufgezeigten Ergebnisse dieser Dissertation eine Basis bilden, um eine effektivere, Gebiets-orientierte Politik beim Management des Wasserhaushaltes in dieser Region zu forcieren.

Resumen

Las cuencas altas tropicales estan constantemente bajo una creciente presión antropogénica debido al crecimiento demográfico, los consecuentes cambios en el Uso y Cobertura del Terreno y los efectos derivados del cambio climático a escala regional. El presente trabajo de investigación tuvo como propósito analizar los efectos de los cambios espaciales, particularmente aquellos inherentes al uso/cobertura del terreno en una cuenca alta tropical, y su posible impacto en la dinámica de los recursos hídricos. Para tal fín fue seleccionada como área de estudio la cuenca alta del Río Boconó, localizada en la zona Norte de la Región Andina venezolana, siendo ésta una cuenca muy representativa de la zona andina en la cual los sistemas biofísico y socio-cultural se encuentran en estrecha y continua interacción para así generar una compleja dinámica reflejada en la forma e intensidad del uso de sus recursos naturales.

Para ello se establecieron cuatro objetivos trascendentales: (1) Analizar la dinámica espacial de la cuenca alta del Río Boconó durante el periodo 1988 – 2008, en términos de los cambios ocurridos en el Uso/Cobertura del terreno. (2) Analizar la dinámica hidrológica en la cuenca, a través del estudio de los caudales anuales y estacionales; (3) Analizar el impacto potencial que tales cambios en el Uso/Cobertura del terreno, en combinación con la variabilidad climática, podría tener a futuro en la respuesta hidrológica de la cuenca; y (4) Discutir las posibles interrelaciones e implicaciones geográficas entre los cambios espaciales y la dinámica de los recursos hídricos en la referida cuenca. Para el alcance de dichos objetivos fue concebido un enfoque metodológico relevante, el cual contiene 3 grupos básicos de métodos: Geoinformática y SIG, Sensores Remotos y Simulación Hidrológica, los cuales estuvieron en interacción continua y usados de manera integrada, de modo que el intercambio de datos, información paramétrica y no-paramétrica, al igual que mapas entre los grupos fue siempre necesaria.

En primer lugar, el área de estudio fue delineada a través del uso de una imágen SRTM (90 m de resolución), con el fín de construir un Modelo Digital de Elevación (MDE), y de preparar coberturas temáticas básicas como Topografía, Pendiente, Aspect, y Red de Drenaje. En segundo lugar, se compiló una grupo de Imágenes LANDSAT TM correspondientes a los años 1988, 1997 y 2008 para luego ser clasificadas a través del método semi-supervisado, siguiendo un proceso de agrupamiento multi-nivel para una segmentación múltiple de clases, usando el metodo de "**Hyperclustering**". Luego, se realizó una evaluación multitemporal de los cambios en el Uso/Cobertura del terreno y las matrices de tabulación cruzada fueron procesadas para determinar parametros importantes como: cambio neto, intercambio, asi como ganancia y pérdida netas. Un análisis aún más detallado permitió

determinar las transiciones sistemáticas "**inter-categoricas**" ocurridas en el sistema paisaje, las cuales identifican las trayectorias específicas que las categorias de Uso/Cobertura del terreno han estado experimentando en la cuenca. Las transiciones "**inter-categóricas**" fueron un criterio básico dentro del simulador de Cambio del Terreso (Land Change Modeller for ecological sustainability), con el fín de proyectar los cambios más importantes en el futuro, generando así un mapa potencial de Uso/Cobertura del terreno para el año 2028, el cual fue un elemento importante para el proceso de simulación hidrológica.

En tercer lugar, fue conducido el proceso de simulación hidrológica a través del uso del **modelo "orientado a procesos" J2000g**. Dicho modelo requirió de un pre-procesamiento de los datos climatológicos, así como de la compilación y procesamiento de información concerniente a parámetros básicos requeridos para simular el balance hidrico en J2000g. Para la estimación "**orientada a proceso**" de la distribución de agua en el suelo en la cuenca se aplicó el concepto de Unidades de Respuesta Hidrológica (HRUs), siendo éstas delineadas a partir del enfoque de los "**paisajes hidrológicos**". Así, las principales formas del terreno junto con las formaciones geológicas y el Uso/cobertura del terreno fueron los atributos básicos para la delineación de las Unidades de Respuesta Hidrológica (HRUs). Asi, se delinearon tres mapas de HRUs para los años 1988, 2008 y 2028. Debido a las limitaciones derivadas de la escasa información hidrológica, se diseñaron tres modelos de simulación, con diferentes métodos para la estimación de la Evapotranspiración. Los modelos fueron calibrados y validados a través del método "**split-sample**", y luego se evaluaron los distintos indicadores de eficiencia de los modelos. Finalmente, se consideraron nueve escenarios para simular y evaluar el comportamiento y la respuesta hidrológica tanto en el pasado reciente, como en el posible impacto futuro que los cambios en el Uso/Cobertura del terreno y la variabilidad climática pudiesen generar en el area.

Se identificaron y delinearon en total 12 categorias de Uso/cobertura del terreno en un sistema de paisajes donde la persistencia fue definida como la condición predominante. No obstante, se detectó un proceso dinámico importante, en el cual las coberturas boscosas del terreno mostraron una tendencia decreciente, mientras que los tipos de categorias de Uso inducidas por los humanos (cultivos agrícolas, pastos cultivados y uso urbano) se han ido incrementando progresivamente. Las categorias Arbustal secundario (S-Shr); Bosque sub-montano (Sm-F); Bosque clareado-abierto (Oc-F) y Agricultura (Cro-L) fueron las que mostraron mayor dinamismo en los dos periodos considerados, acusando los más altos valores de cambio total, al igual que ganancias, pérdidas, intercambio y cambio neto.

Los resultados derivados de la matriz de tabulación cruzada revelaron que el Bosque Tropical Nublado Montano (TMCF) experimentó una reducción de 12,8% (3530,43 ha) en los últimos 20 años. Esta es una reducción considerable teniendo en cuenta el rol importante de este ecosistema en términos hidrológicos, ecológicos y biológicos. El estudio también demostró que los cambios y la reducción experimentada por el Bosque Tropical Nublado Montano en el area, no pueden ser asociados directamente con la expansión de los Usos antropogénicos como Agricultura y Pastos cultivados. Al menos en los últimos 20 años este Bosque ha estado cambiando sistematicamente a un tipo intermedio de Cobertura del Terreno como (Oc-F) y (S-Shr). Las transiciones sistemáticas experimentadas por la categoria Planicie aluvial (Fl-P) durante el periodo, sugieren una intensa dinámica del Río Boconó, y la ocurrencia de picos de crecidas e importantes eventos de inundación durante el periodo, los cuales han estado afectando algunas areas de expansión urbana y zonas de cultivos.

Los resultados del Modelo J2000g mostraron que la respuesta hidrológica pudo ser razonablemente simulada, a pesar de la escasez relativa de datos correpsondientes a las variables climatológicas e hidrologicas. De acuerdo con los datos históricos y con los hidrogramas resultantes de la simulación, el Río Boconó muestra una dinámica hidrológica tipicamente observada en los ríos montañosos tropicales, caracterizada por una estacionalidad bien definida de los caudales, y una rápida respuesta a los procesos convectivos de precipitaciones intensas, típicas de esta región. La alta variabilidad de los procesos convectivos reportados en la literatura y la influencia de las anomalias ENOS y A-ENOS, sugieren que los patrones de caudales estacionales pueden ser altamente variables de un año a otro. El estudio reveló una alta variabilidad en los caudales en los últimos 20 años, derivada de la variabilidad de los procesos climáticos a meso-escala, y la secuencia alternada de eventos ENOS y A-ENOS. Es evidente que el Río Boconó es muy sensible a la variabilidad impuesta por los procesos climáticos.

Las simulaciones de los distintos escenarios revelaron que la variabilidad futura de los caudales y la producción de agua en la cuenca es más explicada por las condiciones climáticas y los patrones climáticos, que por los cambios en el Uso/Cobertura del terreno. La posible intensificación y una mayor recurrencia de las anomalias ENOS y A-ENOS podrian ser responsables de la intensificación y la variabilidad estacional de los caudales. Los escenarios evaluando solo los cambios de Uso/Cobertura del terreno mostraron claramente el bajo impacto que tales cambios tendrían en los regímenes hidrológicos. Dichos cambios solo podrían impactar el balance hídrico a través de la variación en las tasas de evapotranspiración.

Los resultados ampliamente sugieren que el Río Boconó es altamente sensible a los cambios positivos en las variables climáticas precipitación y temperatura. Así, un cambio positivo relativamente pequeno en los patrones de precipitación podria generar un cambio importante en la respuesta hidrológica, tal como se observó en los escenarios respectivos.

Se espera que los resultados mostrados en esta disertación doctoral puedan ser una base de gran utilidad para promover politicas más efectivas en términos de la realidad local enmarcadas dentro del manejo de cuencas en esta importante región.

Chapter 1

Introduction, Problem Description & Research Targets

1.1.- Introduction

The environmental crisis, joined to the increase of population and the economic growth appears to be the most concerning topics in the global scenario during the XXI century. The three processes are intimate linked, showing trend patterns which can be quite different in a geographical context. Despite of such differences, there is a common point to highlight: the demand for natural resources or environmental goods even tends to increase, especially in developing countries where the exploitation of natural resources is needed to support its expanding economies. Thus, the anthropogenic pressure over the natural systems tends to be constant or even to increase. In this context, the water is increasingly becoming a "**critical issue**", as a main "**multifunctional resource**" which has a paramount importance in a geological, biological, ecological, social, cultural and economical sense.

High-quality water suitable for human and animal consumption, and water of sufficient quality for irrigation, looms large on the screen of critical issues in the new millennium. Many are calling it **the most important factor for sustainable development and peace** (Bonell & Bruijnzel, 2004). Water is simply the most important "**environmental service**", being used in the exploitation of all other natural resources. But at the same time, the exploitation of other natural resources (e.g. forests, minerals, soils and land resources) could affect the water resources, whereby the water bodies and water sources (particularly freshwater) could be seriously threatened. As a consequence of overuse and/or misuse of water, problems related with a relatively water scarcity has been appearing at local and regional levels (the world-trade of virtual water can face and mask the scarcity at the national scale (Chapagain & Hoekstra, 2008)). All the estimates of future global population suggest continuing rising demand for water resources, and thus growing scarcity (Chenoweth, 2008).

On the other hand, the global warming appears to worse the scarcity, through the changes in important processes like the rainfall patterns, droughts and the intensification of anomalies like "El Niño" (ENSO) and „La Niña" (A-ENSO). On this subject, Dourojeani & Jouralev (1999) state that the water scarcity as environmental service will constantly increase with the time, so that the competence for water among users will be more drastic and merciless in the near future.

Recognizing the undeniable importance of water as environmental service, is logical to realize the leading role that the worlds mountain systems play, as the main source of fresh water that feeds the great rivers across the planet. According to Diouf (2002), one of each two persons in the world meets its requirements using water which comes from the mountain systems, that is, 3000 million people depend on fresh water coming directly from the mountains.

The previous statement makes clear the relevance and role of watersheds and/or river basins as capturing, channelling, regulating and storing fresh water for different anthropogenic uses. But at the same time, river basins also contain or are repositories of another important natural resources or environmental goods, as well as cultural resources. That is why watersheds and river basins constitute multifunctional units of hydrological, biophysical, socio-economic and socio-politic interest, closely related to natural resource planning and management, especially water resources (Dixon and Easter, 1991 quoted by Dawei and Jingsheng, 2001). The importance of watersheds or river basins have been highlighted by many authors like: Richter et al (1985); Hernandez (1987); Medina (1990); Reyes (1990); Barrios (1994); Faustino (1995); Dourojeani & Jouralev (1999); Broocks & Eckman (2000), Mejia (2000); Wagner et al (2002); Poudel (2003); BID (2005) and Dehnhardt & Petschow (2008).

River basins undoubtedly constitute extremely complex natural and cultural systems where many components constantly interact with one another. Therefore, the state of natural resources - quantity, quality and spatial distribution - is derived from the total addition of those interrelationships. Wagner et al. (2002) support the idea that the status of water resources in a river basin is not the result of only one cause, but it is the synthesis of a series of dependent relationships "multi-cause / multi-effect". Such relationships join various elements grouped in five main factors: biophysical, socio-cultural, economic, institutional and political. Thus, researchers, planners and managers must consider all this factors from a basin and its surrounding environment, in order to formulate a comprehensive and integrated development plan to achieve specific objectives (Poudel, 2003).

Having a definite boundary in a physical and a geographical sense, it makes easy and pragmatic to use this functional entity as a main environmental system for studying the natural resources in different perspectives: research, planning and resources management, etc. Despite of its clearly explicit boundary, river basins are undoubtedly open systems, which make the consanguineous contact and interchange with outside. Material and energy exist in the various scales, being in constant exchange with other systems in the outside, and the whole structure of the river basins has been made of each scale owing to those contacts (Deng et al, 2000).

Introduction

The interest for analyzing natural resources at river basin level has been gaining relevance in the contemporary world, since a river basin represent "**a reasonable and relevant demarcation on the landscape for land-use planning**" (Gordon, 1994). According to Wescoat and White (2003) the last decade of the twentieth century witnessed a revival and extension of watershed & river basin management in environmental planning worldwide. There have been also an important change into the paradigm and even into the approach for the river basin management, moving from a engineering to a more integrated or environmental perspective; from water development or water supply to management of water demand, and from top-down to bottom-up approach (Staudenrausch et al, 2000)(Dehnhardt & Petschow, 2008). According to BID (2005), watersheds & river basins as environmental units are very useful for the integrated resources management, especially in steep lands where the resources exploitation is going fast, and the anthropogenic uses are not developed according to the limits of the soil and other resources.

But the dynamic nature of these quite complex systems can be very different in a geographical or geospatial perspective. In a first approximation, a big differentiation between the watersheds and river basins in temperate regions and those of the tropical region must be done. Contrary to the temperate regions, where the upland catchments shows a relatively low level of settling or they are not heavily utilized by humans, with a sparse population using water and other resources, river basins in the tropical regions (where only developing and poorly countries are located), usually faces a more complex dynamic. Historically and because of geographical reasons, especially the existence of less harsh or "cooler" climates, the upland watersheds or catchments have been historically occupied by people whose have been cultivating the land, using water and forest resources, and in some cases, establishing towns and cities systems. In temperate regions the development of natural resources like: land, soils, water and forests is confined to the lowlands, meanwhile, the upland catchments and especially those with steep slopes are usually under forest cover, or even under a very low environmental stress.

Watersheds & river basins of the tropical regions and developing countries are in some cases relatively densely populated, with relatively high rates of population growth, which has serious implications in the relationships between people and environmental services. According to Templeton and Scherr (1999) (Quoted by Poudel (2003)), most of the empirical studies indicate that hills and mountains of the developing countries have high population growth and along with this the arable land area grows. In many cases, mostly poor people are settled in steep hillsides (slope above 15%), usually practicing a smallholder farming system with agricultural production in small parcels for subsistence purposes, as well as shifting cultivation, which represent a pressure over natural resources in areas which are ecologically fragile and environmentally sensitive. Thus, the dynamics of natural resources use in catchments across the mountain regions of the world are determined by three factors: environmental, social and economical conditions (Richter et al, 1985; Barrios, 1994; Mannion, 2002; Poudel, 2003; Bonell & Bruijnzel, 2004).

However, the base of environmental data or information in catchments or Upland watersheds of the tropical regions is usually weak. The lack of climatic, hydrological, ecological and even social and economical data represent a problem and a big challenge for researching and planning processes in many tropical mountain regions. This simply limits the watershed analysis and the river basin management, as two processes which intend to reach the sustainable use of the natural resources in local and regional perspectives. As a consequence, some technical actions or solutions created an implemented in temperate regions are not successful when applying it in tropical upland catchments; and some methodologies as well as models created to simulate environmental processes cannot be used or their applications in tropical river basins are simply limited. Thus, the lack of basic information has been highlighted as a serious problem that interferes with decision making of resource planning in developing countries mountain zones, being well documented for many authors (Richter et al., 1985; Hauck, 1985; Barrios, 1994; Dourojeani & Jouralev, 1999; Mejia, 2000; Thapa, 2001; Poudel, 2003; Shiklomanov & Rodda, 2003; Bonell and Bruijnzel, 2004; Hadgu, 2008).

1.2. - Research Problem

Rivers and river basins are subject to constant processes of change. The state and the structure of river landscapes and land resources are primarily determined by the type and intensity of the utilisation of the ecological, economic, social or cultural functions provided by the river systems (Dehnhardt & Petschow, 2008). It has been pointed out above how different can be the type and intensity of the resources use in catchments across the latitude; so, there is no doubt that particularly in Tropical regions, the river basins have undergone dramatic land use changes in the last few decades, and these changes are the effect of an equally large number of local causes and factors, highlighting a complexity that tends to defy easy generalizations (Bonell & Brujinzel, 2004).

In Venezuela, like in the rest of tropical regions worldwide, the upland river basins have been submitted to an **immense anthropogenic pressure** because their environmental conditions (climate, soils, biodiversity and landscapes) have been attractive for people to settle from times before the arrival of the Spaniards. During the last decades this pressure has become even more intense, generating important spatial changes derived from deforestation, farming system implementation and urban growth to mention just a few. Gonzalez (2000) considered this fact as a main problem in Venezuela, together with others like: seasonality of the rainfall, spatial distribution of the population, and higher rates of water consumption per capita (the highest in Latin America) (Table 1.1).

In a more regional perspective the Andean Region constitutes the most important water producer zone in the west part of the country. Within this important Region, the state of Trujillo constitutes a special case, as being one of the poorest states in the whole country.

With a high density of population, large proportion of poor people, a weak economic system, and also a weak institutional system, this part of the Andes faces a very complex problematic which can be easily perceptible across the upland watersheds and steep lands. There can be seen a very complex structure in the landscapes system, where the people settled in the steep hillsides practice agriculture for subsistence, shifting cultivation and extensive cattle, all developed in small parcels. They usually alter the surrounding forests in order to harvest diverse resources like timber (usually for local consumption only), firewood, as well as other non-wood resources (the harvesting of some plants species like mosses, tree fern, orchids, bromeliads and other ornamentals plants represent also a problem which is affecting some specific forested areas (Bonell & Brujinzel, 2004)). It should be noted here that many of these process are occurring within the Tropical Montane Cloudy Forest (TMCF), which is located in many hillside-slopes, especially in rainfed steep lands across the region.

The TMCF has a paramount importance, not only in terms of their ecological richness. These kinds of Forests are really important in terms of hydrological functioning, specifically for water yield. In such forest there is usually a net gain of water that comes from the "**horizontal precipitation**" or "**occult**" precipitation in form of wind-driven drizzle and fog.

Table 1.1- Relation of water use of the country respect to the average in Latin America.

Use of Freshwater	Domestic Uses	Irrigation
Latin America	200 l/person/day	0,24 l/sec/ha
Venezuela	424 l/person/day	1 l/sec/ha

Source: Gonzalez, 2000.

Additions of moisture for true cloud forest may reach hundreds of millimetres per year, with typical values ranging between 5 and 20% of vertical rainfall (in seasonally dry or dry areas it could be many times greater, over 100%), and in some areas all the moisture reaching the soils is captured by such trees. Reported net precipitation for montane forest no subjected to frequent low cloud and fog range from 55 to 80% (Bonell & Bruijnzeel, 2004).

Tropical Montane Cloudy Forests represents in many areas one of the last surviving sources of good quality surface water, in contrast to places downstream where the quality of the water in rivers and lakes is often degraded. Thus, TMCF are probably the most effective water suppliers of any tropical forest type (as well as a treasure house for biodiversity) (Bonell & Brujinzel, 2004). The clearing and destruction of TMCF constitutes an irreversible process, which has many negative effects in the environmental systems. Particularly important are the effects in water yield: dynamic of seasonal flows (especially dry seasonal base flow), peak flows and groundwater recharge.

In an intra-regional perspective, the Boconó River Basin could be a very good example or a reference to analyze the complex problematic exposed before, especially those related with the TMCF and all the environmental and hydrological implications. The Boconó River Basin constitutes a „**water resource-area**" which has a great importance in the State of Trujillo, because it is the river with the highest hydrological yield, estimated in: 2300 million m^3/year (Bone et al.,1985). For its reason the UN proposed the possibility that the water produced in this river were used economically (Ostos, 1975); in fact the Dam Boconó - Tucupido was built in the lowest part of the catchment area, in order to produce energy, and to irrigate the high plains of Barinas State.

In a biophysical perspective, the river basin is under a continuously high tectonic pressure, derived from the intense activity of the "Boconó Fault", which completely dissect it longitudinally, defining indeed the orientation of the river (NE-SW). The rocks formations are very jointed and fragile, the slopes are very steep, and the soils are young and fragile also. The density of population living in their hillsides, and using it for smallholder farming systems (cultivation and extensive cattle) made a constant pressure over the landscape and land resources; thus, problems like land degradation, soil erosion and water pollution are always present. The existence of a complex cross-road network made the hillsides easier to settle, and contributes to the intensification of erosive process (according to Chang (2003) as much as 90% of all sediment produced from forest highlands and steep lands could originate from roads and stream crossings) (Verburg et al. (2004), consider accessibility as one of the most important determinants of land use/land cover change). The Figure

1.1 display a panoramic of the San Miguel Watershed, an important Sector of the Boconó River Basin, where the constrains above mentioned can be clearly observed.

The area also possesses a valuable wealth referred to natural resources, especially biodiversity, including the Tropical Montane Cloudy Forest (TMCF), as well as scenic resources and typical Andean landscapes, with high economic and cultural value. The existence of two protected areas (Protective Zone of Boconó River Basin and the Guaramacal National Park), lead us to confirm it (Hidalgo (2007) proposed the creation of a new protected area in the Páramo La Cristalina, due to the richness of the natural resources located in this area and the fragility of the landscapes systems). In recent years, the anthropogenic pressure in the catchment has become even more intense, affecting the land cover, especially invaluable ecosystems like the Tropical Montane Cloudy Forest. Obviously, this has severe implications for the biodiversity, but also affects the dynamic of water resources, having impacts in runoff regimes, and producing higher rates of sediments. This could have serious effects both "**in situ**" and "**off site**" of the basin, affecting people, cultivated land, and civil structures (dams, bridges, roadways etc).

Figure 1.1.- Panoramic of the San Miguel Watershed, an important sector of the Boconó River Basin. (Source: Google Earth).

Gasperi (2006) determined that the yield of sediments in the whole catchment area, have increased by 914 % with respect of the estimated value in order to build the Dam. This could let to us to imagine how intense is the dynamic related with land cover/land use changes into the Boconó River Basin.

1.3. - Research Deficit

Spatial changes have just recently became a relevant issue in river basin & hydrology analysis, as some researches have been intending to identify and evaluate the effects of those changes in water regime (river flows, runoff dynamic, flooding, water depletion, etc). These researches have intended to establish the relationship between the Land Use / Land Cover changes and the dynamic of water resources, both in a spatial-temporal perspective. Some examples of these includes: Brown & Dee (2000), Steuer & Hunt (2001), Krause (2002), Legesse et al. (2003), Bäse et al. (2006), Pizarro et al. (2006), Siriwardena et al. (2006), Marshall & Randhir (2008), Bruns & Fetcher (2008) and Mialhe et al. (2008).

Such a complex task requires defining complex approaches in which different methods and skills must be combined. Skills such as Remote Sensing, GIS, hydrological and statistical modelling software, as well as methods like: multi-temporal evaluation, spatial analysis, geostatistical analysis and simulation appear to be quite useful in dealing with the task of studying different processes, many of which are not yet well understood by science. Precisely, these skills intend to simplify the complexity of the real world through models which let us to identify, characterize, relate, represent and visualize different variables and processes driving the evolution of the environmental system. Many authors have emphasized the kindness of using such tools in environmental studies. Some examples are: Lakhtakia et al. (1996), Brown & Dee (2000), Müschen et al. (2000), Staudenrausch et al. (2000), Siriwardena et al. (2006), Lang & Blaschke (2007), Marshall & Randhir (2008), Bruns & Fetcher (2008), and Strager et al. (2010).

The influence of the environmental factors in the dynamic of water resources is complex and still not well known. Water production depends not only in land cover, but in many other variables related to climate, geology, soils, slope, anthropogenic activities, etc. Some recent works like Legesse et al. (2003), Pizarro et al. (2006), Siriwardena et al. (2006), and Marshall & Randhir (2008), have intended to determine the relationship between changes in land cover and the watershed processes, especially water dynamic, with results that are quite different among themselves.

Legesse et al (2003) have demonstrated that the water dynamic, through the discharge as a hydrological response, was sensitive to the climate change, specifically changes in rainfall patterns. In the same way, land use changes could results in a decreasing in water production of about 8%. Pizarro et al (2006) evaluated the relationship between peak river flows and land vegetation cover (change from native forest to commercial plantation of Pinus Radiata), in central Chile, concluding that the migration from Forest to commercial plantation did not caused significant changes in flow peaks. Siriwardena et al. (2006) evaluated the impact of land use change in a watershed of Australia, founding that the change occurred in land cover caused an increase of approximately 40% in runoff. Through simulation, Marshall & Randhir (2008) discovered that changing land cover in the future could have severe impacts on water resources (quantity and quality) in Connecticut River Watershed – USA. A special case here is the research of Steuer & Hunt (2001), who analyzed the effects of Urbanization in the water dynamic in Midelton – Wisconsin (USA).

More recently, the project on “Assessing the impact of land use on hydrology by ensemble modelling (LUCHEM)”, aimed to investigate the envelope of predictions on changes in hydrological fluxes due to land use change in the low mountainous Dill Catchment – Germany (Breuer et al, 2009). In this project an ensemble of 10 hydrological models was applied using the same input data in order to evaluate both actual conditions and a set of land use scenarios (Breuer, 2009). Particularly the scenario predictions of the 10 hydrological models and the most promising deterministic ensemble method used in LUCHEM were analyzed by Huisman et al (2009).

Certainly, these are valuable experiences to deal with such a complex task, which means to try to explain the influence of the change in Land Use / Land Cover in the dynamic of water flows; however, there are still many gaps in this process to be solved, and many questions to be answered. Moreover, these experiences are all spatially confined to temperate regions, where biophysical as well as socioeconomic conditions are particular. Tropical ecosystems are very different from their counterparts in higher latitudes. They have different geological and evolutionary histories, and different climatic extremes and dynamics. The number of interacting species is typically much higher in tropical ecosystems, including streams, and the interactions are often more complex (Bonell & Brujinzel, 2004). However, the information about tropical streams is relatively sparse and very scattered.

In tropical regions, the climatologic factors (e.g.: rainfall) are more aggressive, which means that the erosivity levels tends to be higher as in the temperate regions. Social, economical and political conditions in tropical rural areas are also very complex; thus, the poverty, depressive local economies, instability and lack of plans and investment programs are always current and usually such complex realities and the collateral relationship has not been well studied so far.

In general, the state of knowledge about the environment and particularly about such kind of environmental research topics in many developing countries such as Venezuela, particularly related to upland catchments remain still weak and the lack of information as well as research projects specifically designed in function of local realities are remarkable. This constitutes a serious obstacle that limits the success of management tasks. The lack of basic information has been highlighted as a serious problem that interferes with decision making of resource planning in mountain regions of developing countries (Richter et al. (1985), Hauck (1985), Barrios (1994*),* Cornieles (1997) Mejia (2000), Thapa (2001), Hadgu, 2008).

Generally, most of the researches carried out in tropical upland river basins are focused on processes related to soil use and land deterioration. However, the incidence of spatial changes (land uses) on the quantity and quality of water resources is certainly a scarcely developed subject.

1.4. - The Research Targets

The context of the problematic characterizing the Boconó River Basin as well as many other parts of the Trujillo State and the Andean Region, as described above, lead to formulate the following research questions:

A. - What kind of changes in land use/land cover (LULC) have been occurring in the Boconó River Basin, during the last 20 years?
B. - How intense have been the changes experimented by the forest cover, and particularly the Tropical Montane Cloudy Forest in the area during the last 20 years?
C. - How was the dynamic of water, particularly seasonal flows and peak flows in the river basin during the same time- period?
D. - Is there a kind of correlation between the dynamic of seasonal flows, and the spatial changes that the river basin experimented during this time-period?
E. - Does the future LULC changes -according to the trends observed in the area- could have an impact in the streamflows patterns or in the water yield in the area?

These research questions were the basis for the definition of the main Research Targets, as follow:

1.- To analyze the spatial dynamic of the Boconó River Basin during the Period 1988 – 2008, in terms of changes occurring in Land use/ Land cover (LULC).

2. - To analyze the dynamic of water resources in the River Basin, through the study of annual and seasonal flows using a process oriented and spatially distributed hydrological model.

3. - To analyze the potential impact that such changes in LULC, in combination with climatic variability, could have in the future hydrological response and water yield.

4. - To discuss the possible relationships and its geographical implications between the spatial changes related with land uses/land cover dynamic, and the dynamic of water flows within the Boconó River Basin.

1.5. - The Study Area

Located in the northern part of the Venezuelan Andean region, the Boconó river basin can be considered as a representative case of the complex dynamics characterizing the Andean hydrological systems. Having a total surface area of 1580 km^2 and a wide altitudinal range, the river basin harbor many ecosystems ranging from the Sub-Andean Páramo in the upland areas, to the savanna ecosystem downstream in the upper plains of the Llanos region. With an annual yield of 2,300 million m^3 and a very acceptable chemical quality, the Boconó river was included into the regional planning policies in the Seventies, in order to develop the water resources in the lowlands region, so that the Boconó – Tucupido Dam systems were built in the Llanos region, in order to generate energy, flooding control and for irrigated cropping also.

The focus of this study is the upper part of the Basin (upland Boconó), which is located in the south-east part of the State of Trujillo, between the coordinates 09°11’40” - 09°31’50” N and 70°04’08” – 70°22’53” W, with a surface area of 537.62 km^2. The highest point is located 3400 m above sea level in the Páramo of Cendé, and the lowest point is the confluence between the Boconó and Burate rivers (1100 m above sea level) (Fig. 1.2).

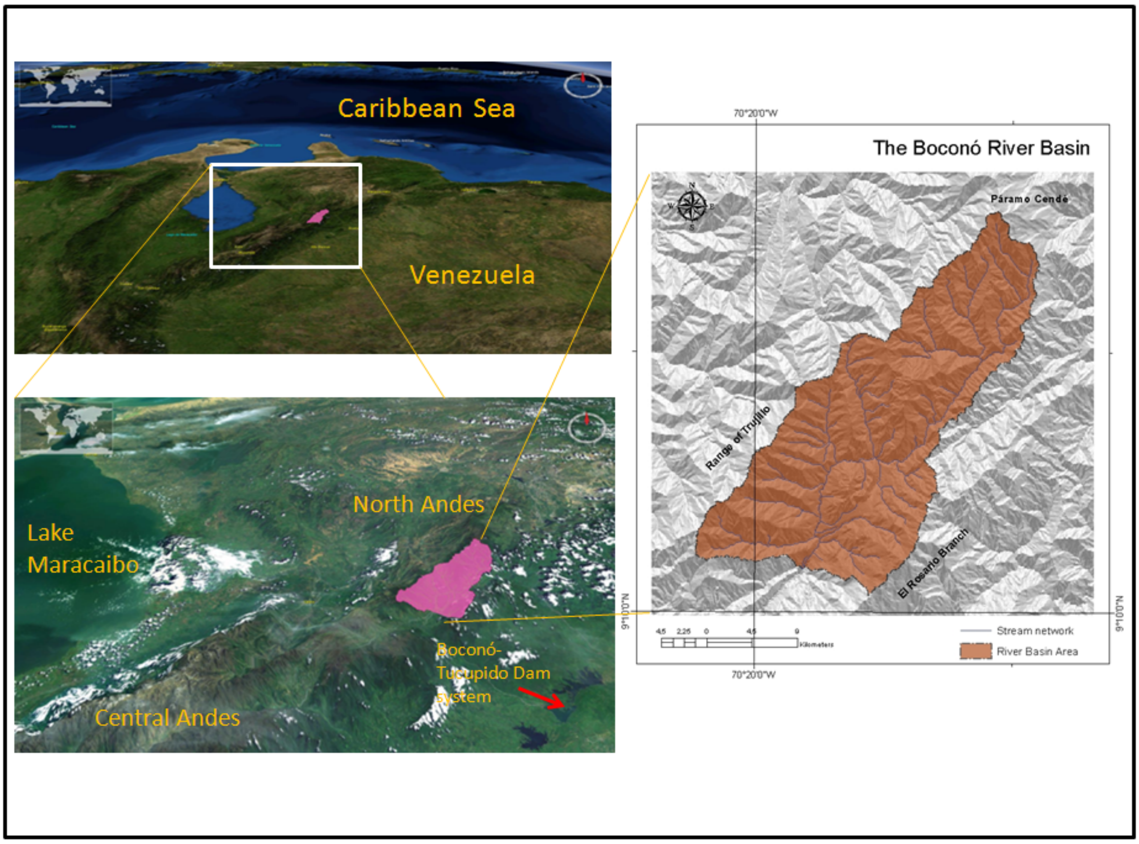


Figure 1.2. - Location of the Study area in a regional context.

The Boconó river drops from the north-east to the south-west, over a distance of approximately 57 km, and the mean runoff is about 15,55 m3/sec (Cornieles, 1997). It has a massive and strongly dissected topography, with highly jointed lithological framework as well as youth and relatively shallow soils, and the climate is defined as perhumid mesotermic with a single maximum in rainfall occurring between May and July (unimodal regime) (Andressen et al., 2000). Annual mean rainfall is about 1838 mm, and the annual mean temperature range from 19.7 °C to 21.5 °C (Macias, 2002). A more comprehensive description of the study area is developed in Chapter 3, focusing the discussion in the elements playing an important role in the configuration of the river basin as an important "**water resources area**" in the region.

1.6. - Methods & Dissertation Structure

In order to achieve the purpose of this project, a methodology containing 3 relevant grouping and interacting approaches were conceived, being derived from equal three relevant approaches which were used as conceptual frameworks in this study: the "***Ecosystem approach***" (Dehnhardt &

Petschow, 2008) and the "***Hydrological landscapes***" concept (Winter, 2001), closely linked to the "***Geographic visualization***" (Dodge et al, 2008).

The "***Ecosystem approach***" is essentially a relevant approach which integrate the ecosystems as a very important element affecting the dynamic of the water production and water development at the watershed level, been adopted in many river basin management projects, like those from the European Water Framework Directive (Dehnhardt & Petschow, 2008). Secondly, the "***Hydrological landscapes***" constitutes a new conceptual framework that considers the water dynamic as a result of the combination of topographic, geological, geomorphological and climatological conditions (Winter, 2001).

Both conceptual approaches are linked in this study to the "**geographical visualization**" approach, which is simply the whole raft of innovative means that the Geography as science have had, in order to represent information through the use of spatial visualization (Dodge et al., 2008). In essence, the geographic visualization provides a graphical ideation to render a place, a phenomenon or a process visible, thus enabling the most powerful human information-processing abilities, to be directly brought to bear (Dodge et al, 2008).

With the rapid growth and uptake of the GIS technologies, the geographic visualization have been living a digital transition, leading to introduce new methods and techniques or simply change the ones that previously existed for collecting, processing and representing spatial information. Those new GIS technologies were used here in diverse steps and for different purposes also, from the beginning to the end of the methodological approach. Different software were used to reach the desired purposes, which were interacting in the three methodological axis formed by the three approaches defined to develop the study. In this sense, the GIS techniques were the bridge between the approaches, exchanging data, and or information for specific purposes.

The Figure 1.3 illustrates the basic theoretical approaches in a systematic way. From these approaches the three methodological axis followed in the study were originated, which are going to be conveniently explained on Chapter 2.

In the first methodological axis the spatial platform to be used during the whole study was created from the use of a SRTM scene, and diverse geomorphometric and hydrological information were derived. In a second methodological approach, a multitemporal evaluation of LULC in the catchment

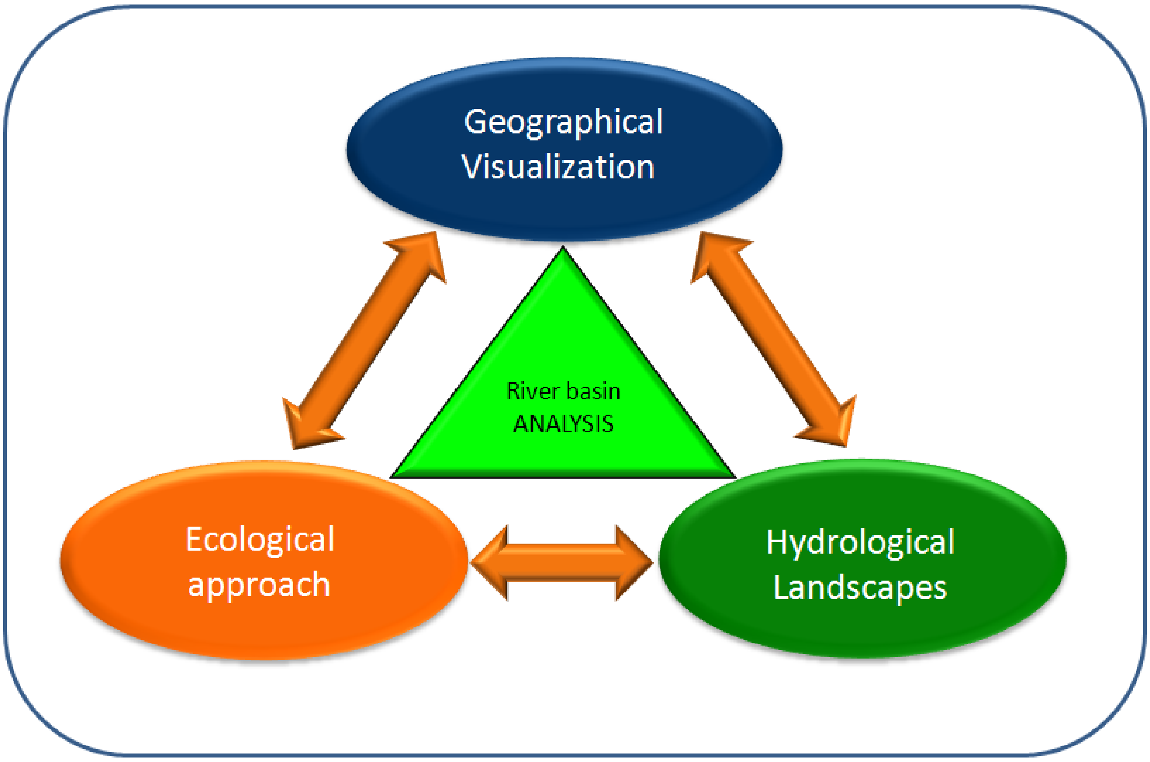


Figure 1.3. - Basic theoretical approaches involved in the research process.

was done, using LANDSAT TM. It leads to define the dynamic and recent evolution followed by the different LULC in the river basin. The study of the cross-tabulation matrixes for the period analyzed lead to identify the main transitions which are being occurring in the landscape system.

In a third methodological approach the hydrological response and water yield were analyzed through the use of a process oriented and distributed model designed to evaluate the impact of various combinations of precipitation, climate conditions and land use on variables such as streamflow, sediment yields, and general basin hydrology. For this process was necessary to collect basic daily data concerning to: precipitation, temperature, evaporation and runoff, as well as maps containing information about soils and geological characteristics. All the information was organized in a Data Base required for the model system.

At the end, the three approaches were combined to generate and to evaluate the future hydrological response projected into different scenarios that possibly could be expected to occur in the catchment, leading to evaluate the possible impact that such spatial changes could to generate in the water yield.

The dissertation has been structured in 7 Chapters. In the Chapter 2, the methodological approach with the correspondent methods, techniques and required software is conveniently explained. The Chapter 3 pretended to show how important is the Boconó River Basin as a "**Water resource-area**" in a regional context. A discussion about the relationships between the biophysical and socioeconomic conditions, and the state of the natural resources, especially the water resources, was done from a perspective of the **ecosystem-oriented management approach**, which is the most important approach being currently used in river basin management. This discussion is very important as spatial context to support the discussion and analysis of the results presented on the next chapters.

The Chapter 4 contains the results concerning to the temporal & spatial LULC changes in the Boconó River Basin during the period 1988 – 2008. The results of the multitemporal evaluation are presented here, and the spatial dynamic for the sub-periods T0 –T1 and T1 –T2 in terms of persistence, swapping, net change and inter-category transitions are presented and discussed. The results were compared with similar trends observed in other regions worldwide, and the implications for land use planning were also considered.

The temporal & spatial analysis of the hydrological response for the Boconó River was presented on Chapter 5, based on historical data available, coupled with the results produced by the model J2000g. In the Chapter 6 the impact of the spatial changes in the river basin in the hydrological response and water yield was intended, through the simulation of different scenarios especially defined for that. Finally, the Chapter 7 summarized the main processes and results obtained in the study, and after that the conclusions and further research are also presented.

1.7. - Relevant Concepts

1.7.1. - Integrated water resources management

Integrated water resources management involves the co-ordinated development, allocations, use and management of water, and related natural resources in order to meet present and future human needs whilst maintaining the functioning of vital ecological systems. (Mitchel, 1990)(Quoted by Akpabio et al, 2007). Common to these management attempts must be the recognition of the intricate linkages between water and land as well as among economic, social and environmental systems (Akpabio et al, 2007).

The concept has been used since early 1900s; however, it has attracted global attention in the last 20 years, being considered a key strategy for sustainable development and achievement of the millennium development goals (Watson et al., 2007). Although this is promoted as a new approach to resource management it is in many aspects a return to traditional values with recognition of the interconnectedness of hydrology, ecology and land management (Davie, 2008).

During the XX century, the continuing destruction of distinct environmental systems and natural resources, where the environmental policy, control structures and many actions were in many cases insufficient -in others simply inadequate- claimed for a new more effective approach. The situation had been even more dramatic in undeveloped and poor countries, in which the adoption of policies and control structures based on foreign experiences, not only failed in solving the problems, but in some cases created news ones. At the end of the century, a change in problem perception occurred, so scientists, planners and politics inclusive, realized that environmental problems required a new approach, which needs not only interdisciplinary but also transdisciplinary research approaches, reflecting a reinforcement of the relations between science and management (Dehnhardt & Petschow, 2008).

In this sense, the European Water Framework (WFD), created in 2000 as a main regulation framework for the management of water resources (Dehnhardt & Petschow, 2008), seeks to apply the integrated management approach, adopting the ecosystem approach of the Convention of Biological Diversity (CDB), as main basis. The ecosystem approach is a general framework for holistic decision-making acknowledges the dynamics and complexity of ecosystems, combines ecosystem functions with social needs and user interests, and refers to scale issues and institutions (Dehnhardt & Petschow, 2008). In this sense, the WFD is itself considered an "**Ecosystem-oriented-management approach**".

1.7.2. - Spatial analysis

Spatial analysis refers to a process in which spatial data are quantitatively analyzed. In a narrow sense, spatial analysis is a pre-GIS set of methods developed by geographers during the quantitative revolution of the 1960s, in order to describe geographic distributions, identify spatial patterns, and analyze geographic relationships and processes (Albrecht, 2007). Thus, the emphasis of Spatial analysis is to measure properties and relationships, taking into account the spatial localization of the phenomenon under study in a direct way, so the central idea is to incorporate the dimension "space" into the analysis to be done (Camara et al, 2004). Spatial analysis is not necessarily a complex process, but it implies reducing complex relationships to something simpler, possibly bringing to attention things that otherwise would have remained hidden to the user (Galati, 2006).

Spatial analysis emerged during the 1950s and 1960s largely from the advancement of quantitative methods in geography, geology and the earth sciences, as well as regional science and macro-economics. The development of the spatial statistics as well as locational analysis during the 1960s lead to enforce the role of the spatial analysis in the “quantitative revolution” that Geography lived in that time-period (Longley & Batty, 2003).

With the development of GIS and other digital techniques, the relevance and usefulness of spatial analysis have been growing fast. It is clear that the rapid growth of GIS has given a big boost to fundamental research in spatial analysis, and in many ways solidifies the future of the quantitative focus of the discipline (O`Kelly, 2002)(In: Fotheringham & Rogerson, 2002). The spatial analysis has been of interest in many fields and many disciplines like: ecology, archaeology, natural resources, landscape architecture, geodetic sciences, etc. They have for a long time used such techniques, but now they also use GIS as a creative tool to improve and also to optimize the spatial analysis.

Spatial analysis takes GIS as a major step forward, ranging from restricted representational forms to custom –made depictions of the world to critical interpretation of the assumptions that are invoked to represent it (Longley & Batty, 2003). However, is important to note that spatial analysis should be clearly distinguished from GIS operations, and from spatial modelling as well (O´Sullivan & Unwin, 2003). GIS constitutes only a platform for specific application analysis of location and feature attributes, or spatial analysis (Galati, 2006).

As above mentioned, the “**space**” constitutes a very important dimension in geographical studies. But a “**spatial entity**” or even a landscape never remains “**static**” or unchanged, but instead are dynamic. That’s why the temporal dimension comes to the spatial analysis, so that the next concept acquires paramount importance in the context of this study.

1.7.3. - Spatial changes

The main constituents of Geography are space, relations in space and changes in space (Morril, 1970). Changes particularly affect any phenomenon attribute (directly or indirectly) to the spatial dimension. Spatial changes are then referred to a single or more spatial phenomenon, their internal and external static or dynamic properties, life characteristics behaviour and quality (Kavouras, 2001) (In: Raper & Cheylan, 2001). The scientific studies of the spatial processes that induces or yield any kind of change is impossible without considering both space and time as basic dimensions (Peuquet, 1994).

Spatial changes are the result of a complex web of interaction between human and biophysical factors acting over a wide range of temporal and spatial scales, so that at different scales there will be also different factor or factors dominating or influencing the force which lead the change to occur (Moreira et al., 2008).

1.7.4. - Land Cover vs. Land Use

According to Mannion (2002), "**Land cover"** is a term used to describe the components or features characterizing the Earth´s surface. For the most part these components comprise plants, as units of vegetation or ecosystems, soils, sediments, water and the built environment. So the land cover describes the materials that are present on the surface, for example vegetation or rocks.

The Term "**Land Use**" differs from land cover in so far as it reflects the function of land units, notably the human use of land, which often has economic significance. In other words, the land use describes how a parcel or a land unit is used by humans (Sabins, 2000).

But both "**Land cover**" and "**Land use**" are not statics in a spatial-temporal perspective. On the contrary, both have been historically permanently subject to biophysical and anthropogenic forces which induce changes in different structure-levels and space-time scales, and modify the energy and water exchange of the soil-vegetation-atmosphere system; such modifications become globally significant through their accumulative effects, so it would be particularly hazardous for food production and food security (Verburg et al., 1999) (Krishna & Badarinth, 2004). Thus, Land use / land cover changes are simply the most conspicuous changes in cultural landscapes worldwide (Bormann et al, 2009).

Land cover and Land use assessment constitutes an important step in planning sustainable land management that can help to minimize agro-biodiversity losses and land degradation, especially in developing countries (Hadgu, 2008).

1.7.5. - Hydrological modelling

Experimental studies in catchments are usually very difficult to do, because they are costly, time consuming, weather dependent, and the results are also difficult to replicate. That's why the modelling became a very important research issue in hydrology and watershed analysis. Hydrologic simulation provides an alternative approach for rapidly assessing forest practices and other land managements in order to predict watershed response to various weather conditions and management strategies (Chang, 2003).

„A model is a simplified conceptualization of a complex, possibly chaotic system, which is often characterized by highly variable behaviour in space and time" (Viney et al., 2009). A model – whether mathematical, numerical or scale- is a simplification of reality (Davie, 2008). In constructing a computer model we are normally trying to build as good representation of hydrological reality as we can, given our understanding of the key hydrological processes and our ability to represent these as a series of equations (Davie, 2008).

In hydrology the models are classified in:

a) **Black box models**

   They are the simplest kind of models, which simulate streamflow as a direct relationship between it and another measured variable (e.g. annual rainfall) meanwhile all the other processes are all putted in a single regression relationship.

b) **Lumped conceptual models**

   These kinds of models reproduce different hydrological processes in a numerical form, so all the processes operate at one spatial scale, and there is no spatial discretisation.

c) **Physically based distributed models**

   In these models are processes operating within a catchment that are simulated as a series of physical equations at points distributed throughout the catchment.

d) **Hydrological modelling for specific needs**

   In last years there are even more tools available to the hydrologist to build their own computer model to simulate a particular situation of interest. This kind can be named **object-oriented simulation**, and it offers a future role for hydrological modelling.

Until today, there are a lot of hydrological models, which also have different levels of complexity, but all of them are a simplification of reality and aim to either make a prediction or improve our understanding of biophysical processes (Davie, 2008).

As considered before, the environmental systems, and particularly the water-resources systems are extremely complex, so that the modelling approaches have to deal with incorporating knowledge from a broad range of scientific disciplines. Thus, models can be developed for different purposes, and they should also require different levels of detail and comprehensiveness (Leavesley et al., 2002). In this sense, the "modular approach" could to provide a framework to focus those processes that are most important to simulate. The term "module" refers to the different structures such as subroutines or functions to simulate a process in a model. An example of such kind of approaches is the Modular Model System (MMS), developed by the US Geological Survey (USGS), which provides a framework in which to address collaboratively the many complex issues associated with the design, development, and application of distributed hydrological and environmental models (Leavesley et al., 2002).

The GIS tools have been playing an important role in Hydrological modelling, providing modellers with new platforms for data management and visualization, and also powerful capabilities to process Digital Elevation Models (DEM). Some hydrological modelling techniques have also enabled GIS users to go beyond the data inventory and management stage to conduct sophisticated modelling and simulation (Sui & Maggio, 1999).

The continuing advances in physical and biological sciences, as well as GIS technology, computer technology, data resources and other related software are going to improve the modelling processes through new system enhancements and capabilities which will to facilitate the model development, application and analysis. Hopefully, this will lead to reach an ever better representation of the reality.

1.7.6. - Climate Change

According to the IPCC (Intergovermental Pannel on Climate Change), the term "**climate change**" is referred to a change in the state of the climate that can be identified (through the use of statistical tests) by changes in the mean and/or the variability of its properties, persisting for an extended period, typically decades or even longer. Under this concept, the change refers to any change in climate over time, whether due to natural variability or as a result of human activity (IPCC, 2007). The concept above presented is quite different from the definition adopted by the United Nations Framework Convention on Climate Change (UNFCCC), in which the climate change refers basically to any change in the climate system that can be attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods (UN, 1992).

In some cases, the term “**climate change**” has been used synonymously with the term “**global warming**”, specifically referred to a process produced by the effect of the greenhouse gases concentration in the atmosphere. However, the scientist tends to use the term climate change in the wider sense to also include natural changes in climate (NASA, 2012).

However, the changes not necessarily imply only negative effects or the standards of living will fall. For example, the increased CO2 concentrations in the atmosphere may be beneficial for plant growth, thus enhancing agricultural production in some regions, which could have economic and social consequences. This partly explains the different degrees of willingness of some governments to take actions against the climate change (Van Dam, 1999).

Climate can change due to diverse and complex factors like: changes in solar activity; long-period changes in the Earth´s orbital elements (eccentricity, obliquity of the ecliptic, precession of equinoxes), natural internal processes of the climate system, or anthropogenic forcing (increasing concentrations of carbon dioxide) (NSIDC, 2012).

The ocean is a fundamental part of the climate system at global level, so the changes and fluctuations occurring in the oceans could have also effects in the climate system at global and regional scales. However, some of the fluctuations occur in short-term (years or few decades), like the ENSO /AENSO oscillations, the Pacific decadal oscillation, the Arctic Oscillation and the NAO (North Atlantic Oscillation). So they represent climate variability rather than climate change.

Chapter 2

The Methodological Approach

2.1- Introduction

On Chapter 1 was presented an overview of the conceptual approaches taken into account in order to reach the research targets defined for this study. These targets leaded to conceive a big approach formed by three main methodological axes which were acting in an integrated form, so that the exchange of data, parametric and non-parametric information as well as maps was always needed. This is logic, considering that the geographic information products are "often interactive software applications used to help people make decisions" (Galati, 2006). The "**digital transition**" that have been living Geography (particularly), lead to the technologies like GIS and remote sensing to play a paramount role in the **Geographical Visualization** (Dodge et al., 2008). Obviously, those technologies are the "heart" of the methodological approach defined in this case; thus, the Method was structured in three big interdependent and stretch related approaches, to be explained below.

2.2. - The general approach

The Figure 2.1 display the general approach conceived in the study in order to reach the established relevant goals. Three important methodological axes were derived from the conceptual approaches explained on Chapter 1, and showed in the Figure 1.3. The first Axis is derived from the Geographic visualization, with GIS as main approach to operationalize the processes for exploration, analysis, synthesis and representation of the issues concerning to the problem here studied. The second axis came into account from the ecosystem approach in which the multitemporal analysis of the LULC in the catchment could be done, using the Remote Sensing approach as the basic method to deal with such important task. The third Axis was derived from the hydrological landscapes to develop a methodological approach for the analysis of the streamflows dynamic, using the hydromodelling as a basic method. For each approach specific processes and task were developed, through the use of specific tools and software.

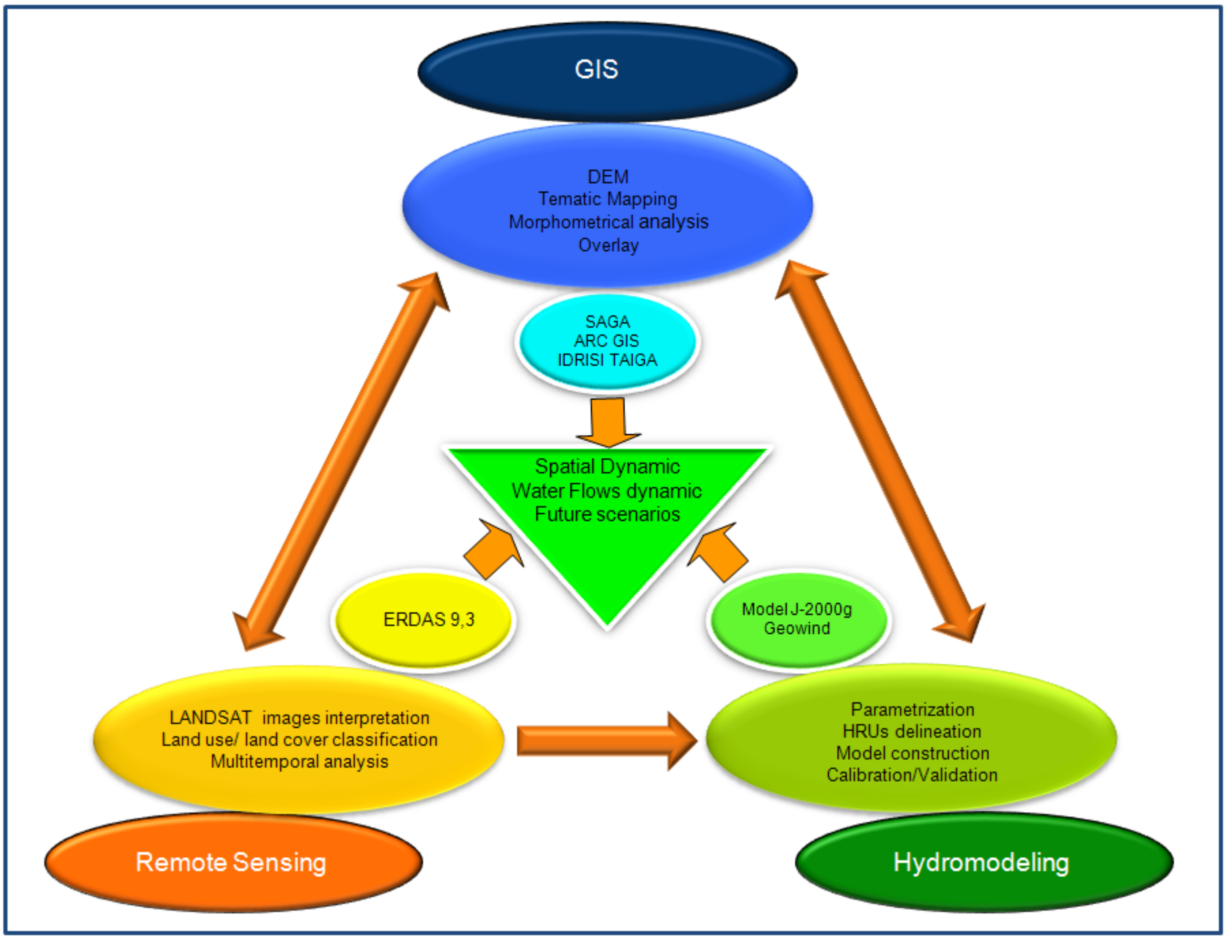


Figure 2.1. - General Methodological approach defined and followed during the study.

2.3. - The first methodological approach

This "introductory" step sought to establish the basis support for all the spatial information which had to be generated, processed and used during the whole research process. It obviously required that all the raw data considered necessary to reach the research targets had to be compiled from different sources. The Table 2.1 shows the different types of raw data –according to Galati (2006) - which were compiled in this case. It is important to highlight that most of the information available compiled was founded in a nondigital format, which means that the digitalization had to be the main form to introduce raw data into the methodological process. The process to transform nondigital data into digital data is often laborious (Liu, 2002), so that considerable time and effort were necessary to transfer the raw

Table 2.1. - Raw Data – Type compiled and used in the research project, according to Galati (2006).

Raw data type	Name	Year /Age	Basic features	Available Format	Source
Satellite / GPS	Shuttle Radar Topographic Mission (SRTM) Image	2007	Raster format, 90 m resolution	Digital	Geographical Institute of Venezuela " Simón Bolivar"
	LANDSAT TM Images	1987 – 2008 (different time-points)	Raster format, 30 m resolution	Digital	Institute of Geography – ULA USGS LANDSAT Archive
Transformed maps	Soil Units	1984	1:100.000 Old hardcopy map	Nondigital	MARNR
	Geological framework	1984	1:100.000 Old hardcopy map	Nondigital	MARNR
	Geological framework	1999	1:100.000 Old hardcopy map	Scanned	Centro de Ecologia de Boconó
	Stream network	1984	1:100.000 Old hardcopy map	Nondigital	MARNR
	Rainfall erosivity	1984	1:100.000 Old hardcopy map	Nondigital	MARNR
	Slope units	1984	1:100.000 Old hardcopy map	Nondigital	MARNR
	Land use/land cover	1980	1:100.000 Old hardcopy map	Nondigital	Centro de Ecologia de Boconó
User data development	Thesis, Research projects, publications	Different years	Information about different topics/attributes spatially referred to the study-area	Nondigital / digital	Different sources (Libraries, web – sites, journals)
Other attribute tables	Climatological Data	Period-time different among the gauge-stations	Daily and monthly data about: rainfall, temperature, wind speed, humidity, evaporation	Nondigital /Digital	MARNR / Centro de Ecología de Boconó INAMEH Meteored.com Tutiempo.net ARGUS – Portal Hidroclimático
	Hydrological Data	Period-time different	Daily and monthly data about: runoff, volume, sediments	Nondigital	MARNR INAMEH

data into a digital format. Only the Satellite/GPS raw data type (one of the most important primary data source, according to Lang & Blaschke (2007)), was available in digital format; however, some adjustments had to be done during the pre-processing, in order to make the data able to be adequately processed.

2.3.1- Build-up the spatial platform for the geographical data

In a strictly cartographic sense, the spatial platform seems to be the basic element necessary to build the spatial data inherent to the study area. Nowadays the Digital Elevation Model (DEM) represent the most conspicuous way to build such kind of spatial platforms, as the DEM provide a spatial representation containing the basic geographical location qualities: latitude, longitude and altitude.

A Digital Elevation Model is simply a quantitative model of a part of the earth´s surface in a digital form, formed from a interpolation of the continuous surface that have many uses in GIS (Burrough & Mc. Donnell, 2006). In those models the properties of the earth surface are described by the expressions of morphographic and topographic features (Bolch, 2006). The DEMs were originally created as a precursor of the orthophotomap, but today they have many other applications, so actually they are the basis for modelling physiographical processes (Ebner, 1992 (Quoted by Schmullius et al, 2000)). Particularly, they play an important role in hydrological modelling, as they can provide (when converted into a Digital Terrain Model – DTM), two important derivatives: **Slope** and **Aspect**; both are basic parameters to consider in the process of simulating the water drop through the surface (Albrecht, 2007). The 3 – Dimensional display in hydrological modelling provide also a more effective way to communicate the results, through a more familiar view of the real world (Dodge et al., 2008). This will be more detailed discussed later in this chapter.

The Data sources for a DEM are diverse: from direct measures in the field with theodolite or GPS, through stereo aerial photographs, digitizing of contour lines on paper maps, until the use of scanner systems in aeroplanes and satellites (Burrough & Mc. Donnell, 2006). In this case the data source for the DEM came from the use of one image from the Shuttle Radar Topographic Mission – SRTM.

2.3.1.1. - Brief Overview of SRTM Data:

The Shuttle Radar Topographic Mission flew in February 2000 promoted by NASA, the National Geospatial – Intelligence Agency, and the German and Italian Space Agencies. Previous missions occurred in 1994, in which the potential use of the multi-frequency multi-polarization radars was successfully tested (Schmullius et al, 2000). The main goal was to acquire a digital elevation model of all land between about 60° north latitude and 56° south latitude, that is, the 80% of Earth´s land surface (Farr, et al., 2007).

The Mission used two kind of aperture radars: the C-band system (5.6 cm; C-RADAR), had to generate contiguous mapping coverage as called for by the mission objectives. The X-band system (3.1 cm; X-RADAR) generated data along discrete swaths 50 km wide, which offered contiguous coverage at higher latitudes. The X-RADAR had a slightly higher resolution and better signal to noise ratio (SNR), than the other one (Farr, et al., 2007). The Table 2.2 shows the results of the Mission, in which 99, 58% of the targeted land coverage have actually been successfully mapped (Werninghaus, 2001).

Table 2.2. - Main results of the Shuttle Radar Topographic Mission (SRTM).

Data Takes	**X- SAR**	**C-RADAR**
	367	764
Resolution	30	30 m (90m)
Coverage (Total)	112 Mio Km2	__
Coverage (Land)	64 Mio km2	119 Mio km2
Playback	49	104
Raw Data	3660 G bytes	8590 G bytes

Source: Werninghaus (2001); Bolch (2006).

A detailed description of the SRTM Mission was done by Van Zyl (2001), Rabus et al., (2003), and Farr et al, (2007); meanwhile Werninghaus (2001) considered the implications of the Mission for the German Radar Programme. Schmullius et al. (2000) showed the first applications of the SRTM images in Europe and Africa. Rodriguez et al., (2005) made a general assessment of the SRTM topographic products. Nikolakopoulos et al (2006) compared the quality of the SRTM elevation products vs. those derived from ASTER images. Some examples of real applications of the SRTM products for hydrological purposes are: Bolch (2006); Ludwig & Schneider (2006); Valeriano et al., (2006); Sanders (2007); Schumann et al., (2008), and Le Coz et al., (2009).

2.3.1.2. - Digital Elevation Model (DEM) for the Boconó River Basin:

The Digital Elevation Model required for the Study Area was built using the SRTM Image identified as: SRTM3NO9W071, acquired on February 2002 with 3-ARC and 90 m resolution. The Image was imported into the "**Open Source GIS**" Software SAGA (System for Automated Geoscientific Analysis), a very versatile GIS Software which combines a powerful geographical analysis engine with an intuitive and user-friendly GUI (Olaya, 2004).

At first the Image had to be subjected to a first pre-processing, in order to remove the negative elevation values for the water bodies. Then, the Image was subset to define the "**Area of interest**", where the river basin is effectively located.

2.3.1.3. - Delineating the river basin:

SAGA has been developed specially to deal with aspects and operations inherent to hydrology and geomorphology (Cimmery, 2010). In this sense, the Software was very appropriately used to delineate the River Basin, following the procedure:

A second pre-processing was necessary to remove the depressions (pits or sink) in order to fill them and level off, to be relative to surrounding terrain. Then the catchment area was calculated through the Hydrology/Parallel Processing Module. The next stage was the delineation of the **stream network**, produced in both format´s types: raster and vector; and the channel direction were also generated in this process. The river basin was finally delineated using the Watershed Basins Module.

2.3.1.4. - Generation of basic topographic layers from the DEM:

The basic topographical characteristics: Slope, Aspect and Contour lines for the hypsometry, were created from the DEM through SAGA, Using the Local Morphometry Module. The Method Fit 2 Degree Polynom (Zevenbergen & Thorne, 1987) was used to define Slope and Aspect. The contour lines for the hypsometric map were defined through a module which creates “isopleths” lines, connecting points with the same altitude value.

2.3.1.5. - Geomorphometric Analysis:

The versatility of the Software lets to calculate some parameters which have important implications in geomorphologic and hydrological processes. One of the basic parameters is the determination of the terrain forms, calculated with the Peucker & Douglas Method, which considers the slope gradients to all lower and higher neighbours for the cell being processed in order to identify the predominant form. This lead to determine the predominant form, making a differentiation between concave and convex hill-slopes and considering also the position across the landscape; this relation has very important hydrological implications, particularly for the identification and delineation of the hydrological landscapes system, being thus an important element to be considered into the modelling process for the delineation of the Hydrological Response Units (HRUs). Other parameters like: Convergence and divergence of water flow, plane curvature and profile curvature were also easily determined.

The processes above described lead to define the “**digital platform**” from which the two following methodological approaches were developed to reach the research targets defined for the project. The Table 2.3 resume the processing followed in this step, and the main products which were obtained.

2.4. - The second Methodological approach

The second approach was conceived in order to analyze the spatial dynamic occurring within the Boconó river basin in the recent past, according to the first research target pointed out in

Table 2.3. - Main processes followed during the build up of the spatial platform for the geographical data.

Variable	Method	Product
Elevation	Linear interpolation	DEM
Network	Conrad (2001)	Channel network
Catchment Area	Linear flow distribution D8	Water Divide
Isohypses	Contour lines from Grid (Conrad, 2001)	Isohypses map
Aspect	Fit 2.Degree Polynom (Zevenbergen & Thorne 1987)	Aspect map
Sloping	Fit 2.Degree Polynom (Zevenbergen & Thorne 1987)	Slope map
Wetness	TWI (Topographic Wetness Index) (Conrad & Boehner, 2001)	Wetness Index map
Morphometry	Strahler Order	Morphometric structure
Convergence/divergence	Convergence Index	Convergence of flux
Terrain classification	Peucker & Douglas (1975)	Terrain Forms

the Chapter 1. This analysis intended to identify and to study the spatial relationship of the diverse Land Cover and Land Use (LULC), as main external spatial properties playing a vital role in the geographical configuration of the river basin and in the environmental evolution, being also assumed to cause changes in the hydrological response and water yield.

The LULC system is very complex and very dynamic, particularly in the tropical regions, as mentioned on Chapter 1. Thus, it was considered important to analyze the changes, whose has been recently occurring in the river basin, in a quantitative and qualitative way. The study and particularly the mapping of the LULC system worldwide became possible with the development of remote sensing technologies, at first through the aerial photography, and more intensive, with the development of the satellite data, especially with the development of the LANDSAT Program in the seventies. The remote sensing technologies has always played a very important role in the evaluation of the land uses system across the earth, so the use of spectral information in order to separate different land cover types is very effective and thus became by far the most popular way to classify the Land Cover (Wieslaw, 1993) (Cihlar, 2000). Thus, diverse categories of LULC can be mapped at different scales and resolution which range from worldwide to local municipalities (Sabins, 2000).

The big success of the remote sensing lies in the multiple applications that can be done using the different tools (photos, images and so on), through a multiple-view approach to data collection, in a multistage form, using multispectral information and possibly in a multitemporal way (Lillesand & Kiefer, 1994). Hence, the multitemporal sensing represents the best form to detect changes occurring in any spatial phenomena; this involves the use of multitemporal data sets to discriminate areas of LULC change between dates of imaging (Lillesand & Kiefer, 1994).

The multitemporal evaluation represent a very useful approach to deal with such a complex task, allowing to identify quantitative and qualitatively the changes occurred in a spatial-temporal perspective. The multitemporal evaluation is a process for an automated detection of Land Cover change from digital data through the comparison of two or more images in raster, vector or other data format (Wieslaw, 1993). Since the arrival of the remote sensing “era”, the change detection and the multitemporal evaluation have become even more attractive in the context of multiple purposes in the environmental sciences. Some examples of this are: Byrne et al. (1980), Conese & Maselli (1991), Wieslaw (1993), Lambin & Strahler (1994), Bruzzone et al. (2004), Soakodan (2007), Carrao et al. (2008), Waske & Braun (2009), Xian et al. (2009), and Mendoza et al, (2011).

Cihlar (2000), highlighted 5 factors as determinant in the land cover analysis: (1) **the Purpose**, which help to define the classes to be delineated and analyzed; (2) **Thematic content**, useful to enforce both the classification and evaluation processes; (3) **Scale**, which is determinant in the choice of the remote sensing data source appropriate to the mapping problem; (4) **Data**, simply the type of remote sensing available or required; and (5) **Processing and analysis algorithms**, affecting the classification and evaluation processes, and of course, the quality of final products.

Obviously, in the change detection process there are two critical dimensions in choosing the appropriate data type: space and time. It means that the scale is then defined through the combination of spatial and temporal resolution for the satellite data sources. The Figure 2.2 shows the basic relationships existing between spatial resolution, temporal resolution and data sources, as illustrated by Cihlar (2000). There are four main domains ranging from extremes: coarse resolution and fine resolution; both are relative and covers a range of resolutions.

The Domain “A” represents the coarse resolution area appropriate for mapping at global scale and short time intervals. The Domain “B”, clearly highlighted in the Figure, includes the fine spatial resolution with data relatively infrequent obtained. This domain includes the mapping processes spatially referred to a regional or even, national level, using data that can be

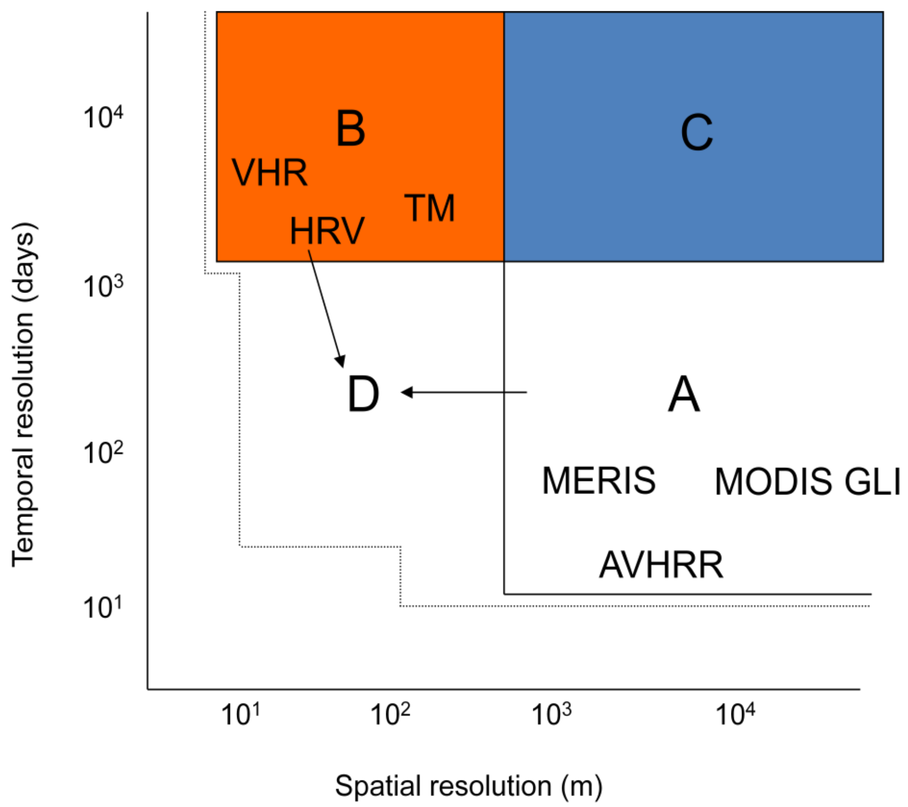


Figure 2.2. - Relationship between spatial resolution, temporal resolution and data sources in remote sensing. (Adapted from Cihlar, 2000).

compiled over long time periods. The projects studying small areas and regions using LANDSAT TM scenes are mostly included here. In fact, this is the Domain of spatial and temporal resolution in which this study is included. The Domain C can combine methods from the domains A and B, and the Domain D requires data at highest level of fine resolution and very frequently obtained.

2.4.1. - Ancillary remote sensing data used in the approach

The multitemporal evaluation was done using images from LANDSAT TM program, which are able to study regions through combining fine spatial resolution and coarse temporal resolution. The LANDSAT TM program offers today´s most important source of optical satellite data, mainly due to the high temporal persistence of the program (since 1972), the higher spectral resolution of TM satellite and the well distributed ground and receiving stations all over the world (Lang & Blaschke, 2007). The last point is simply a critical factor in remote regions such as the case of study, where the data and information are clearly scarce.

2.4.2. - The LANDSAT Program. Overview

Definitively the LANDSAT Program created by NASA almost 40 years ago revolutionized the scientific world, introducing the remote sensing into a new technological age for capturing terrestrial information for scientific purposes. This program has been the major contributor to the growth and acceptance of remote sensing as a scientific discipline (Sabins, 2000). The LANDSAT earth resources satellite system was the first designed to provide near global coverage of the earth´s on a regular and predictable basis (Richards & Jia, 1999). It simply have been providing a very good repetitive (the first in the world´s history) worldwide database of the earth cover, which has an adequate spatial as well spectral resolution, being useful in many scientific applications.

Each LANDSAT satellite produce an image of the earth´s surface along the satellite´s ground track in a 185 kilometer-wide swath as the satellite moves in a descending orbit from north to south over the sunlit side of the earth. Thus, the satellite crosses every point on the Earth at nearly the same time once every 16 or 18 days (USGS - NASA, 2010).

Until today, the LANDSAT Program has been developed through 7 missions in whom 3 generations of satellite have been launched. The first generation correspond to LANDSAT 1 (1972), LANDSAT 2 (1975) and LANDSAT 3 (1978). They worked using a Multispectral scanner (MSS), and they all already ceased operation (Sabins, 2000). The second generation correspond to LANDSAT 4 and 5, launched on 1982 and 1984 respectively, using an improved imaging system called: Thematic Mapper (TM). The third generation correspond to LANDSAT 6 and 7. The first one was launched on 1993 but failed to reach orbit, so it couldn't operate. The LANDSAT 7 was launched on April 15, 1999, carrying a new sensor: the Enhanced Thematic Mapper (ETM+) demonstrating significant progress in precise numerical radiometry, spectral differentiation and seasonally repetitive monitoring (Goward et al., 2001) The next generation correspond to the LANDSAT Data Continuity Mission (LANDSAT 8 – LDCM), which is intended to ensure continuity of LANDSAT data well beyond the Mission 7 (USGS – NASA, 2010).

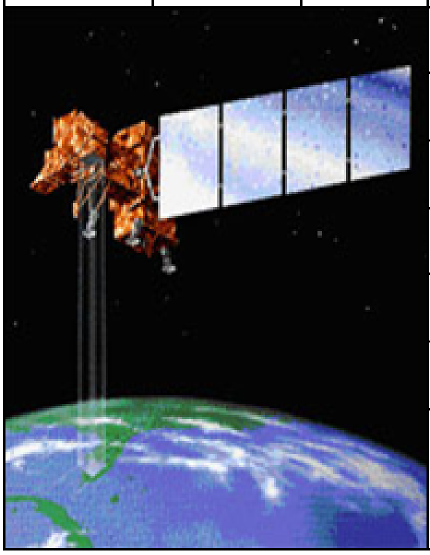
Due to the relevance of the LANDSAT Program for the Remote Sensing, as well as the usefulness the LANDSAT scenes in multiple applications in research, planning, development and so forth, it's nowadays a very well documented theme. Many authors like: Lintz & Simonett (1976); Curran (1985); Harris (1987); Lillesand & Kiefer (1994); Richards & Jia (1999); Sabins (2000); USGS – NASA (2010), described the LANDSAT program, the history, the main technical specifications, and the applicability also. Detailed info can also be founded in NASA and USGS web sites (http://landsat.gsfc.nasa.gov/ and http://landsat.usgs.gov/, respectively). More detailed and complementary analysis of the LANDSAT Program, technological issues and its potential for multiple uses can be found in: Goward et al. (2001); Masek et al. (2001); Ardvidson et al. (2001); Wulder et al. (2008), and Loveland et al. (2008).

The scenes collected and classified for this study correspond to the second and third generation (missions 4, 5 and 7 respectively), which were considered suitable to the research´s requirements. The main characteristics of the used data like: channels, spectral range, light type and resolution are gentle resumed in the Table 2.4. The criteria followed for the selection of the scenes was based on the following targets:

A. - Correspondence with the hydro-climatic raw data and the thematic content.

Based on the assumptions expressed in the research targets (Chapter 1), the period to be considered for the change detection, had to be similar to the period to be simulated in the hydrological analysis.

Table 2.4. - Main Characteristics of the LANDSAT Data used in the research process.

Sensor	Mission	Time-period	Channel	Spectral range	Name	Resolution
TM	4, 5	Since 1982	Band 1	0,45 – 0,52	VIS (visible light: blue)	Ca. 30 m
			Band 2	0,52 – 0,60	VIS (visible light: green)	Ca. 30 m
			Band 3	0,63 – 0,69	VIS (visible light: red)	Ca. 30 m
			Band 4	0,76 – 0,90	NIR (near infrared)	Ca. 30 m
			Band 5	1,55 – 1,75	SWIR (shortwave radiation)	Ca. 30 m
			Band 6	10,4 – 12,5	TIR (thermal infrared)	Ca. 120 m
			Band 7	2,08 – 2,35	SWIR (shortwave radiation)	Ca. 30 m
ETM +	7	Since 1999	Band 1	0,45 – 0,52	VIS (visible light: blue)	Ca. 30m
			Band 2	0,52 – 0,61	VIS (visible light: green)	Ca. 30 m
			Band 3	0,63 – 0,69	VIS (visible light: red)	Ca. 30 m
			Band 4	0,78 – 0.90	NIR (near infrared)	Ca. 30 m
			Band 5	1,55 – 1,75	SWIR (shortwave radiation)	Ca. 30 m
			Band 6	10,4 – 12,5	TIR (thermal infrared)	Ca. 60 m
			Band 7	2,09 – 2,35	SWIR (shortwave radiation)	Ca. 30 m
			Band 8	0,52 – 0,90	PAN (visible light)	Ca. 15 m

Source: Adapted from Bolch (2006). Images Courtesy of NASA and USGS.

B. - Lower interference of Cloudiness & Fog.

Due to the climatological behaviour derived from the global and regional patterns, the study area is always prone to be cloudy, particularly during the rainy season. For that reason was also important to select images having less than 30% cloudiness covering the effective area for interpreting, which were certainly not easy to find. It means that the cloudiness and fog remained as a problem in the classification process, leading to compile additional scenes and special treatments which will be explained below.

According to the research targets highlighted on chapter 1, together with the criteria above mentioned, three time-point were identified for the LULC classification and analysis: 1988 (T0); 1997 (T1) and 2008 (T2). This sequence was considered appropriate in terms of the LULC dynamic, in terms of the available data, and adequate to the period to be considered in the hydrological modelling.

The Table 2.5 contain all the scenes compiled to be used in the research, from the sources mentioned on Table 2.1. It show the sequence of paired scenes (Rows 053 and 054) covering the study area. Two image types can be distinguished in this case: "**pilot**" scenes and "**control**" scenes. The first group contain the scenes to be classified for each time-point to be considered in the multitemporal evaluation. These scenes correspond to 1988, 1997 and 2008. The remainder scenes form the second group, and were used as control images for the classification of the first group in order to improve the clustering of the areas covered by cloud, fog and shadows.

2.4.3. - The Land Use / Land Cover (LULC) Mapping Process.

Based on the structure pointed out by Cihlar (2000), the mapping process was done in three main straightforward steps, clearly highlighted in the Figure 2.3. Within each step, specific methods and technical exercises were necessarily done. The whole process was developed through the use of software ERDAS 9.3 as the basic technological tool.

2.4.3.1. - The Pre - processing

All the scenes compiled were at first individually prepared for the classification, through the radiometric correction, as well as the enhancement of some elements like brightness, contrast, haze reduction and equalization in order to improve the quality of the scenes. All these processes were carried out interactively.

As above mentioned, the Boconó river basin is located spread across two scenes (Rows 053 and 054). For this study, the process was developed processing each scene separately; this procedure is considered highly flexible and can also cope with various limitations of the input

Table 2.5. - LANDSAT Scenes compiled to be used in the study.

LANDSAT Scene Identifier	Date Acquired	WRS - Path	WRS - Row	WRS - Type	Cloud Cover	Sun Elevation	Sun Azimuth	Source
LT40060531988020XXX10	1988/01/20	006	053	2	0	42.42750	129.67467	USGS
LT40060541988020XXX11	1988/01/20	006	054	2	0	43.16463	128.48357	ULA-IGCRN
LT40060541987305XXX03	1987/11/01	006	054	2	10	51.25637	126.28082	USGS
LT50060531991244XXX02	1991/09/01	006	053	2	10	55.86258	90.061633	ULA-IGCRN
LT50060541991244XXX01	1991/09/01	006	054	2	30	55.62257	87.927412	USGS
LT50060531996226XXX02	1996/08/13	006	053	2	0	52.97759	79.350190	USGS
LT50060541996226XXX02	1996/08/13	006	054	2	0	52.47973	77.526007	USGS
LT50060541997292XXX00	1997/10/19	006	054	2	10	55.89318	122.88033	USGS
LT50060531997292XXX00	1997/10/19	006	053	2	0	55.27345	124.82833	USGS
LE70060542000325EDC00	2000/11/20	006	054	-	20.53	52.60611	139.93803	ULA-IGCRN
LT50060532001031XXX01	2001/01/31	006	053	2	0	46.77914	129.031968	ULA-IGCRN
LT50060532008163CHM00	2008/06/11	006	053	2	18	59.87668	60.812181	USGS
LT50060542008163CHM00	2008/06/11	006	054	2	29	58.97029	58.8619998	USGS

data. This procedure has been used extensively in the past and good results have been reported (Cihlar, 2000). Both scenes were subset in order to process only the region where the river basin is effectively located. Thus, the time required for the processing was largely optimized.

Due the location of the study area within a massive mountain range, it was necessary to make adjustments in order to correct the effect produced by the topography (topographic correction or topographic normalization). The relief can severely affect the reflectance due to the oblique angle of the sunlight and the angle of the satellite when the image is produced. Thus, the areas facing the sun shines through, while the remote areas are usually shaded (topographic shadow).

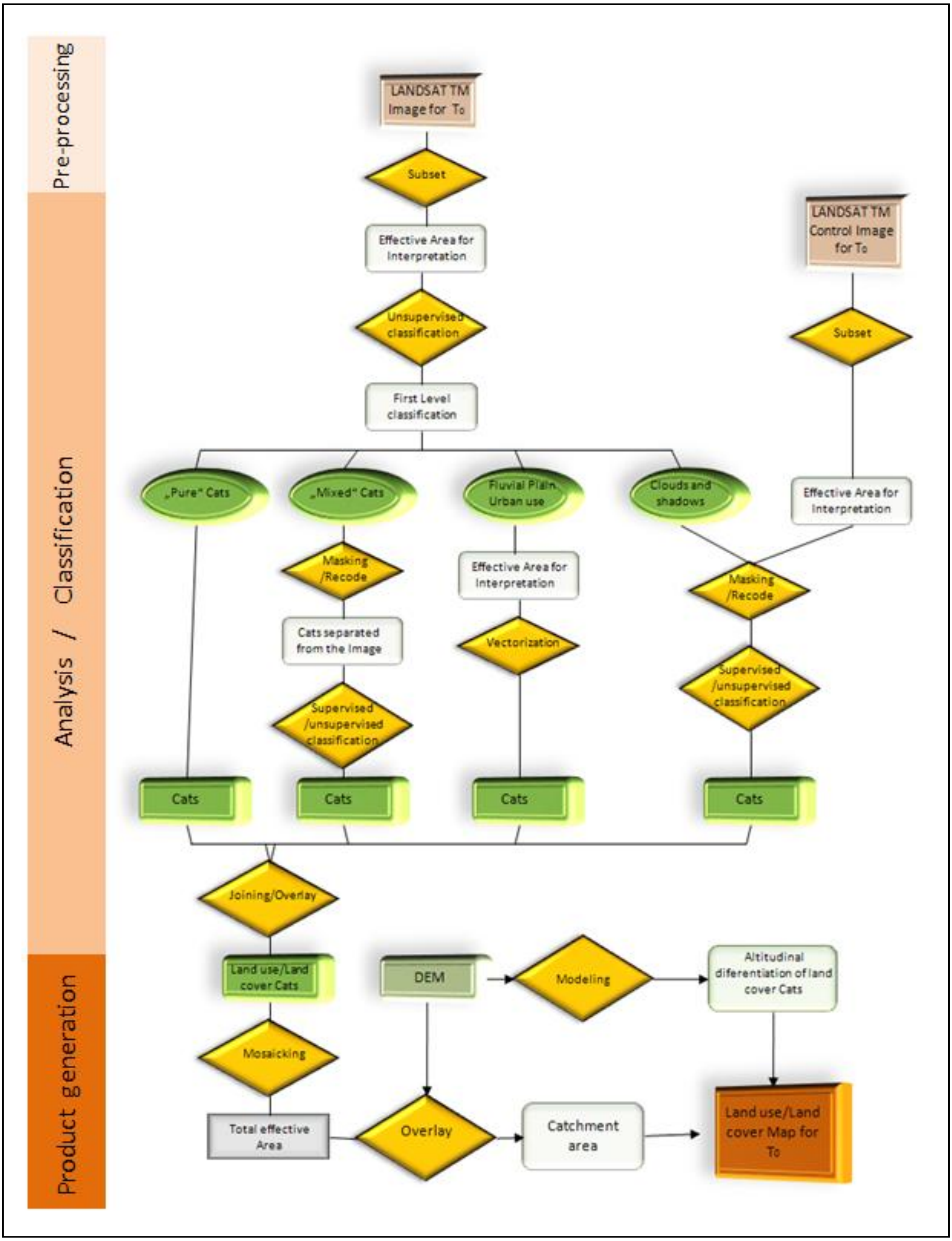


Figure 2.3. - Methodological approach followed in the LULC classification process

Bolch (2006) explains the problems derived from the existing methods to correct the topographic effect. Some problems founded trying to correct this effect includes: strong reductions in the image contrast, the site structure is not clearly visible after the corrections, and the darkest shades always remains, so it cannot be removed. Richter et al. (2009), concluded that there is currently no technique with the best ranking, and that the best ranking of method can also even change from one sub-scene to another within a large scene.

In this case, the corrections were intended through the topographic normalization module in ERDAS 9.3., in which some algorithms for this purpose are available. The correction was done using the algorithm corresponding to the Lambertian method of topographic normalization; however the results were not satisfying, as the problems mentioned by Bolch (2006) also remained in this case.

2.4.3.2. - The LULC Classification /Analysis Process

As can be clearly seen in Figure 2.3, the classification process was developed through a semi – supervised method, following a multi – level clustering for multi – class segmentation. Previous classification tests were made using the supervised method, based on the priori local knowledge of the study area and the possible categories to be founded. Thus, signatures for the well known LULC categories of interest were defined and tested. However, the first results were considered not satisfying, due two reasons: (1) the complex and strong fragmented LULC in the middle – low part of the river basin caused a not really effective differentiation of the signatures in this sector; and (2) the topographic shadows made also difficult to separate the LULC classes in the dissected sloping areas. For those reasons the unsupervised classification strategies were considerate more adequate to make a better clustering in a first level of classification. According to Cihlar (2000), the unsupervised method provides more comprehensive information on the spectral characteristics of the area, present clusters which are spectrally pure for the labelling step, and give also the opportunity to the analyst to group similar clusters into a smaller number of LULC classes.

In order to avoid and /or minimize the limitations founded in the previous testing above mentioned, the unsupervised classification at the first level was followed using the "**hyper clustering approach**", a simple and relatively common approach to classify multiple scene

LANDSAT mosaics.

This classification approach generate many hyperclusters from the image data available by testing for within – cluster heterogeneity; then the hypercluster can be merged into a smaller number of more reasonable groups which may resemble homogeneous classes, and finally label the resulting classes as spatial features of interest according to a pre-determined map legend or class hierarchy (Wulder et. al, 2004).

The process was done in ERDAS 9, 3 using a simple algorithm called K-means. In this case, the method was applied using 50 clusters to be classified after 24 iterations through the unsupervised approach (previous tests using 80 and 100 clusters, showed not many differences in the effective separation of the classes). The amount was then though reasonable to manage by the interpreter, and appropriate to differentiate 8 or 10 LULC classes in the study area.

The 50 clusters obtained in the first – level classification were interactively tested using the Land Cover map of the area (1980), together with the use of Quick Bird high resolution images from the open source software GOOGLE EARTH as well as local knowledge. After the test process, two groups of clusters could be then identified:

a) **“Pure” clusters**, including the clusters containing classes defined as unique in the area. That is, the classes which shows a clear spectral behaviour, making it clearly easy to distinguish from the others. Classes representing Forests and Grass were used to be included in this kind of clusters.

b) **“Mixed” clusters**, including those clusters in which two or more classes with similar spectral behaviour were joined. Categories like agriculture, anthropogenic grass, urban use, bare soil, fluvial plain, clouds and shadows were usually included in this kind of clusters.

The “**pure**” clusters remained unchanged until the final merging process. On the other hand, the “mixed” clusters were prone to a second - level classification process. At first, they were separated from the scene through masking process in ERDAS, and after that they were submitted into a second clustering process, using supervised and unsupervised methods. Thus, the classes were correctly separated from the others.

The spectral classes representing the urban use and the fluvial plain are usually diverse. For its reason, both were digitalized and vectorized, to be incorporated in the final merging as “**pure**” classes.

During the second – level classification, the clouds, fog and shadows were appropriately separated from other classes. They were used as mask scenes in order to cut the control images through spatial analysis, and finally they were processed like the “mixed” classes, in the same way above described.

Once the separation of mixed cluster in both scenes was already done, all the clusters were merged to form twelve final classes using the grouping tool in ERDAS 9, 3. The classes corresponding to urban use and fluvial plain were joined to the others through spatial analysis processes.

2.4.3.3. - The Product Generation Process

In this step the two classified scenes for each considered time-point were joined through mosaicking process, and then using spatial analysis in ERDAS 9, 3, the river basin was finally delineated. A modelling process in ERDAS was then done in order to make the altitudinal differentiation of the LC categories in the river basin. For this purpose the SRTM image before mentioned was used and the ecological criteria from Sarmiento & Ataroff (in: Burga et al (Edit), 2004) was used to differentiate the following LC classes: Tropical Montane Cloudy Forest, Sub montane Forest, Sub-Andine Páramo and Schrub. After that, the scene was filtered and a final generalization process was necessary, in order to eliminate the isolated pixels as well as smallest polygons.

The scenes were finally exported to the GIS software ARC GIS 10.0 for the mapping creation, and display processes.

2.4.4. - Multitemporal evaluation of LULC changes in the Boconó River Basin. (Post Classification).

The multitemporal evaluation process was guided using the tools for spatial analysis in the

GIS Analysis menu in ERDAS 9, 3. Hence, paired overlay was done in order to detect the changes occurred during the period – time considered. The Figure 2.4 illustrates the process followed in this case. The spatial analysis process was followed using the tool "MATRIX" analysis. The Matrix operation allows two thematic images or vector files of different years to be compared (ERDAS, 2008). This tool let to cross two different maps corresponding to the same area, in order to differentiate the changes occurred between the time-period. The resulting class values of a matrix operation are thus unique for each coincidence of two input class values described by rows (input layer 1) and columns (input layer 2) (Ramoelo, 2007); hence, the process produce two type of results: Maps which can illustrate the changes in a spatial context (LULC change map); and a cross tab Matrix containing the differences in area for the different classes.

The **cross-tabulation matrix**, also denominated "**transition matrix**" follows the format displayed on Table 2.6. The rows display the categories of time 1, and the columns display the categories of time 2. Entries on the diagonal indicate persistence in the landscape between the time-period, meanwhile the entries off the diagonal indicate a transition from category "*i*" to a different category "*j*" (Pontius et al, 2004).

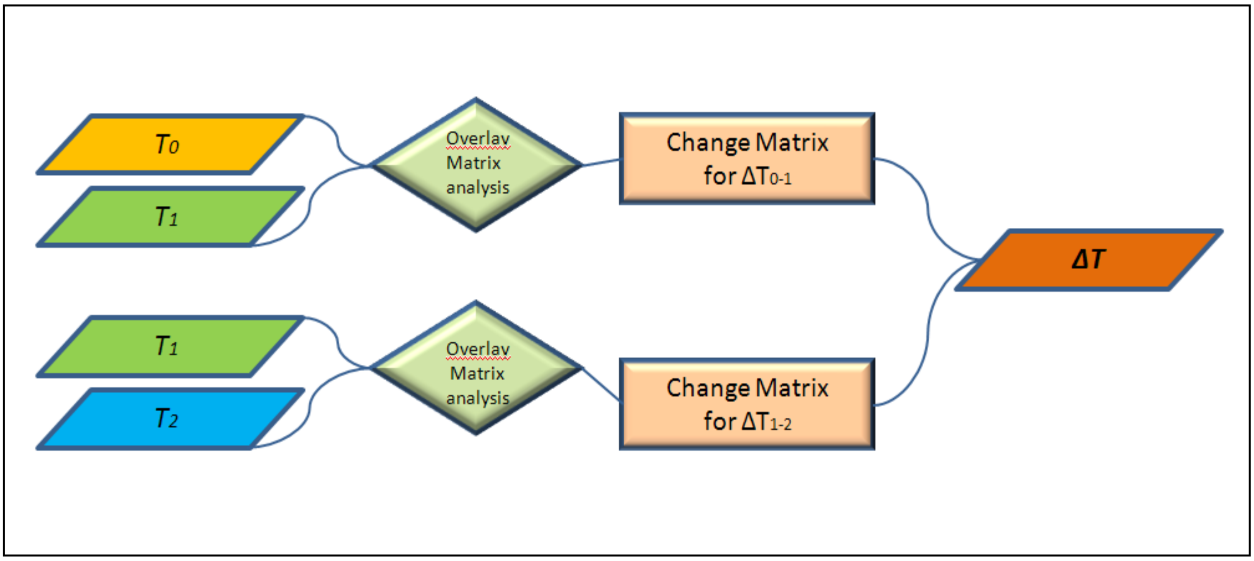


Figure 2.4. - Procedure followed for the multitemporal evaluation.

Table 2.6. - General cross-tabulation matrix for comparing two maps from different points in time.

	Time 2				**Total Time 1**	**Loss**
Time 1	Category 1	Category 2	Category 3	Category 4		
Category 1	P_{11}	P_{12}	P_{13}	P_{14}	P_{1+}	$P_{1+} - P_{11}$
Category 2	P_{21}	P_{22}	P_{23}	P_{24}	P_{2+}	$P_{2+} - P_{22}$
Category 3	P_{31}	P_{32}	P_{33}	P_{34}	P_{3+}	$P_{3+} - P_{33}$
Category 4	P_{41}	P_{42}	P_{43}	P_{44}	P_{4+}	$P_{4+} - P_{44}$
Total Time 2	P_{+1}	P_{+2}	P_{+3}	P_{+4}	*1*	
Gain	$P_{+1} – P_{11}$	$P_{+2} – P_{22}$	$P_{+3} – P_{33}$	$P_{+4} – P_{44}$	-	-

Starting from the matrix-values, the Gain (G_{ij}) was calculated through the difference between the total value for time 2 (P_{+j}) and the persistence (P_{ij}), using the Equation 2-1:

$$G_{ij} = P_{+j} – P_{jj} \qquad \text{(Equation 2-1)}$$

On the other hand, the Loss (L_{ij}) was the difference between the total value for the time 1 file (P_{j+}) and the persistence, using the Equation 2-2:

$$L_{ij} = P_{j+} - P_{jj} \qquad \text{(Equation 2-2)}$$

The swapping (S_j) between the categories was calculated as two times the minimum value of the gains and losses, through the Equation 2-3:

$$S_j = 2 \times \text{MIN} (Pj_{+} - P_{jj} , P_{+j} – P_{jj}) \qquad \text{(Equation 2-3)}$$

The total change for each category (C_j) was the sum of net change (D_j) and the swapping (S_j), or the sum of gain and loss (Equation 2-4):

$C_j = (D_j + S_j)$ (Equation 2-4)

In order to intend a more detailed analysis of the LULC changes, particularly the systematic inter-category transitions, the methodology proposed by Pontius et al. (2004) was applied, which analyze the off-diagonal entries to identify systematic transitions of land change for a given landscape´s degree of persistence. For that, the transitions must be interpreted relative to the sizes of the categories, leading to define the gain/loss that would be expected if the gain/loss in each category were to occur randomly (Pontius et al., 2004). The randomly expected gains for each category were calculated using the Equation 2-5:

$$Gij = \frac{(P+j-Pjj)x\ Pi+}{1-Pj+}$$ (Equation 2-5)

In this case, the gain as well as the proportion for each category at time 2 is considered fixed, distributing the gain across the other categories according the relative proportion of the other categories in time 1. The procedure to calculate the randomly expected losses for each category is quite similar to those explained above, using the Eq 6:

$$Lij = \frac{(Pi+\ -Pii)x\ P+j}{1-\ P+i}$$ (Equation 2-6)

As in the gain, the equation assumes that the loss of each category is fixed, and then distributes the loss across the other categories according to the relative proportion of the other categories in time 2.

Finally, the systematic transitions were identified trough a comparison between the observed and expected values for gain and loss, for each category.

2.4.5. - Validation and Accuracy.

The accuracy assessment has a paramount importance in remote sensing, as a process which let to evaluate and to validate the resulting LULC classification. This is commonly done through the preparation of a classification error matrix (also called confusion matrix or contingency table), in order to compare the relationship between known reference data (ground truth) with the corresponding results of the automated classification, on a category-by-category basis (Lillesand & Kiefer, 1994). Hence, the overall accuracy is simply the ratio of total correct pixels and the total number of pixels (Hadgu, 2008).

The validation was done following conventional methods, depending on the availability of the reference data. For the T0 classification, only a Land Use reference map for 1980 was available in a non digital format (Table 3.1). It was digitalized through a scanning process, and also georeferenced in ERDAS 9.3. This map was then used as a reference source for the validation, which was developed following the respective tool in ERDAS. A total of 255 validation points corresponding to reference pixels were randomly selected using the "**stratified random**" sampling method. They were interactively compared with the digital reference map, and the results were stored in the Accuracy Assessment CellArray, which is simply a list of class values for the pixels in the classified image file and the class values for the corresponding reference pixels (LEICA GEOSYSTEMS, 2007). The tool finally calculated the error matrix and the corresponding basic statistics, listed in the Accuracy report. The Kappa Coefficient is calculated, and expresses the proportionate reduction in error generated by a classification process compared with the error of a completely random classification (LEICA GEOSYSTEMS, 2007).

For the T2 classification, the validation was done using a combining method. On one hand, a field validation was done through a set of validation points randomly defined, which was previously identified on the image. During the validation process, some other validation points, whose were considered important for the validation process, were interactively incorporated into the process. All the information was used to manually calculate the error matrix. On the other hand, a second validation was done in office, through the process above described for the T0 scenes. A total of 250 reference pixels were randomly selected, and interactively compared with the **QuickBird** high resolution images available on the "open source" software GOOGLE EARTH. Finally, the T1 Classification was validated using the maps for T0 and T2, defining validation points basically in areas considered persistent across the time-period. After that, the Accuracy report with the Kappa Coefficient was also calculated.

2.4.6. - Generation of a LULC Map for 2028

Once the Multitemporal analysis was done, a complementary process was driven in order to project the inter-category transitions resulted in the future for the generation of a future LULC map for 2028, to be used later in the simulation process. The process to generate the LULC map for 2028 was conducted using the Land Change Modeller (LCM) for ecological sustainability from IDRISI TAIGA. This is a software solution designed to address the pressing problem of accelerated land conversion and the very specific analytical needs of biodiversity conservation (Clark Labs, 2009).

The LCM allows for determining the transition potential of the land use from one category to a different one, taking into consideration the static or dynamic variables, which will be the ones explaining the change. For predicting the land use, planning elements that can stimulate or limit the changes are included (Oñate & Bosque, 2010). The Figure 2.5 show the main processes involved into the structure of LCM and its respective implications.

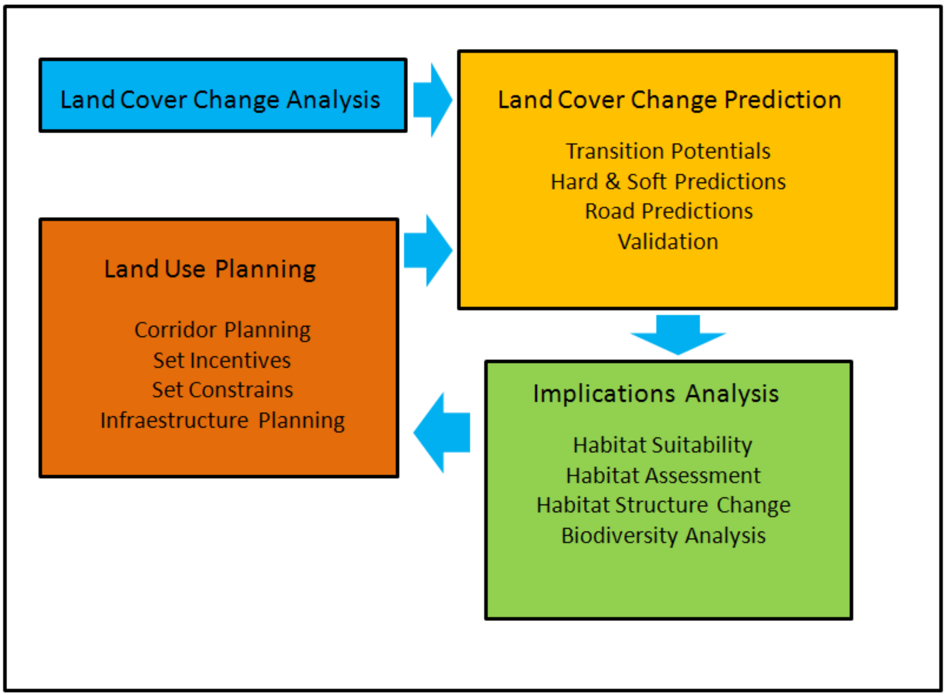


Figure 2.5. - Main structure and involved processes into the LCM Modeler. (Source: Clark Labs, 2009).

Into the Model, the prediction process is done essentially in two major stages: the transition potential sub-model stage and the change prediction model stage. In the first stage, the users specifies the particular transitions of interest for the sub-model and specifies the variables which drive the type of transition(s) taking place. After that, in the second stage, the model will predict, for the specified future date the allocation of land cover change (Clark Labs, 2009). The change is modelled empirically by using the past changes to develop a mathematical model and a GIS data layer expression of potential transition. The transitions can be grouped into a set of sub-models and the potential power of explanatory variables can be also explored. Variables can be added to the model as either static or dynamic components. Once model variables have been selected, each transition is modelled using either a Multi-Layer Perceptron neural network or Logistic Regression. Thus, the result for either model is a potential map for each transition, which is an expression of time-specific potential for change (Clark Labs, 2009).

After that the multitemporal analysis was done, and the transition matrixes were processed using the method from Pontius et al. (2004), the systematic transitions derived from the cross-tabulation matrix were analyzed, in order to select those that could have more relevance for the hydrological response. It´s important to quote here, that the purpose of the map was exclusively to be used in the simulation process, as input target layer to delineate the Hydrological Response Units – HRUs, as will explained below in this chapter. The map was not derived to be compared with those produced in the LULC classification, because this exercise could require a higher level of detail that could be not possible in this case, being also out of scope of the goals defined for the thesis.

A total of 14 systematic inter-category transitions were selected, which once grouped accounted by the main changes in the following LULC: Tropical Montane Cloudy Forest, Sub-montane Forest, Shrubland, Cropland and Urban use. Qualitative explanatory variables were required for the model, which can to affect the development of any particular transition in the landscape. In his case, it was assumed that the potential changes of the LULC categories are mainly governed by 3 biophysical variables: elevation, slope and aspect. Thus, the post-processed DEM provided the layers for the variables selected.

The Figure 2.6 Show the main window of the transition sub-model, displaying the two first steps: the first screen list all the possible systematic transitions derived from the multitemporal

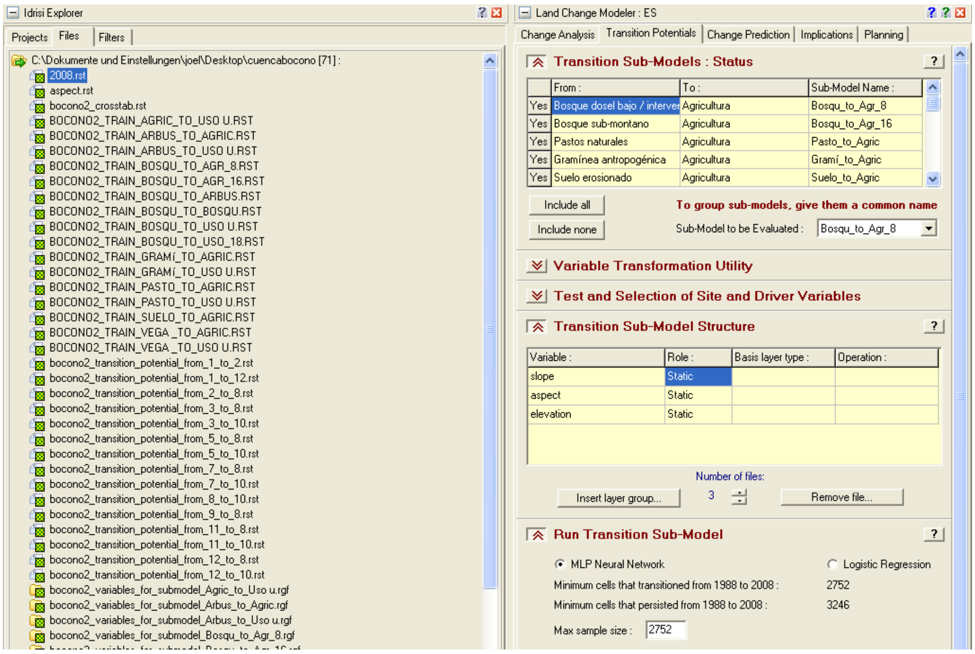


Figure 2.6. - Partial view of the main Window of the Transition Sub-Models within the LCM.

analysis. The second screen show the explicative variables selected in this case to determine the potential transitions. Into the model, each transition is simulated separately through the MLP Neural Network method, so that the model will generate a map showing the probabilities for the simulated transition to occur in the future. As target criteria, the probabilities > 75% for a change in a transition was considered possible to occur in the future LULC map. Once the transitions were simulated, the maps were post-processed in GIS software in order to derive the potential area to change according with the criteria above mentioned. All the change areas were finally merged to form the future map of LULC.

2.5. - The Third Methodological Approach

As mentioned on Chapter 1, the Boconó River Basin plays a very important role as a "**water resource area**" in a local and regional context in the Andean region. It means that the hydrological behaviour through characteristics like the flows regime, seasonal flows and peak flows, represent a big concern in the scope of this study. Hence, the third methodological approach pretended to cover the analysis of the water dynamic in the river basin using a process oriented model to make an abstract representation of the real dynamic and to consider the impact of the biophysical dynamic in the behaviour and configuration of the flow-regime in the spatial entity.

2.5.1. - The Model J-2000g. Overview.

The Model J-2000g constitutes a derivation or a simplified adaptation from the Model J2000, which is a kind of process oriented hydrological modelling system developed to evaluate the impacts of various combinations of precipitation, climate conditions and land use on variables such as streamflow, sediment yields, and general basin hydrology (Krause, 2002). In the J2000g version, some modifications were done in order to simplify many of the complex hydrological relationships within J2000, reducing the number of calibration parameters while maintaining, as much as possible, the characteristics of the seasonal hydrological variability of the water balance (Donmez et al, 2009). Another important difference among the models is related to the scale: the Model J2000 is applicable to large river basins of more than 1000 Km^2; meanwhile, the J2000g Version can be applicable at the mesoscale level, in order to simulate processes in river basins < 1000 Km2. The adaptation was done using the framework system JAMS (Jena Adaptable Modelling System), created in order to make the modelling process more flexible and to make easy the integration of the components required for the modelling process (Kralisch & Krause, 2006) (Fischer et. al, 2009).

According to Donmez et.al (2009), he model was philosophically based on the following rules:

1. - to make continuous and distributed simulations of important hydrological characteristics and processes in monthly and daily time steps.

2. - the applicability of the model is oriented to large areas (several 1000 km^2) but also applicable to selected individual mesoscale river basins.

3. - The model is essentially process oriented and spatially distributed.

4. - The model has a robust predictive ability with a small number of calibration parameters.

Until today, the models have been used under different conditions and in different geographical contexts, to simulate the hydrological processes. The Model J2000 was formally described by Krause (2001). It has been used in some projects like: Krause (2002); Bäse et al., (2006); Krause et al (2006); Fink et al, (2007); Pfannschmidt (2008); Scheffler (2008); Wolf et. al, (2009b); Krause & Hanisch (2009). A comparative analysis between the J2000 and the PRMS hydrological models was done by Bugan et. al (2009). The Model J2000g was implemented to be used in: Donmez et al (2009); Behrawan (2010), Krause (2010), and Becker (2012). The J2000g is widely described on JAMSWIKI (2011).

As usual in this kind of models, the J2000g has 3 basic characteristics: (1) require input information (raw data) inherent to biophysical processes, particularly those related with: climate, topography, soils, geology and LULC; (2) the model posses a specific structure defined by the existence of modules, which describe and calculate the different processes inherent to the hydrological cycle; and (3) the processes are arranged in a logical sequence, to produce the required outputs. These characteristics are illustrated on the Figure 2.7.

Being a spatially distributed model, the spatial dimension is very important for two basic reasons. On the one hand, the model describes, analyze and predict processes which are physically set and distributed, so that the model require as basic input information which is spatially distributed. Even the climatic information, which is punctually recorded in the stations, has to be spatially distributed into the model. On the other hand, as the processes occur in a physically concrete spatial platform (the catchment), it is very important that the spatial platform can be correctly delineated and the internal structure of the biophysical factors contributing to the hydrological dynamic appropriately identified and logically differentiated, leading to the concept of “**modelling unit**”. The “**modelling unit**” can be identified as a raster cell, a process unit or a sub basin provided, so that the spatial information is available for each attribute within each unit (Donmez et.al, 2009) (Behrawan, 2010). Hence, the spatial information about the biophysical factors lead to the delineation of the “**modelling units**”, and also are used into the different modules to calculate the hydrological processes using different methods.

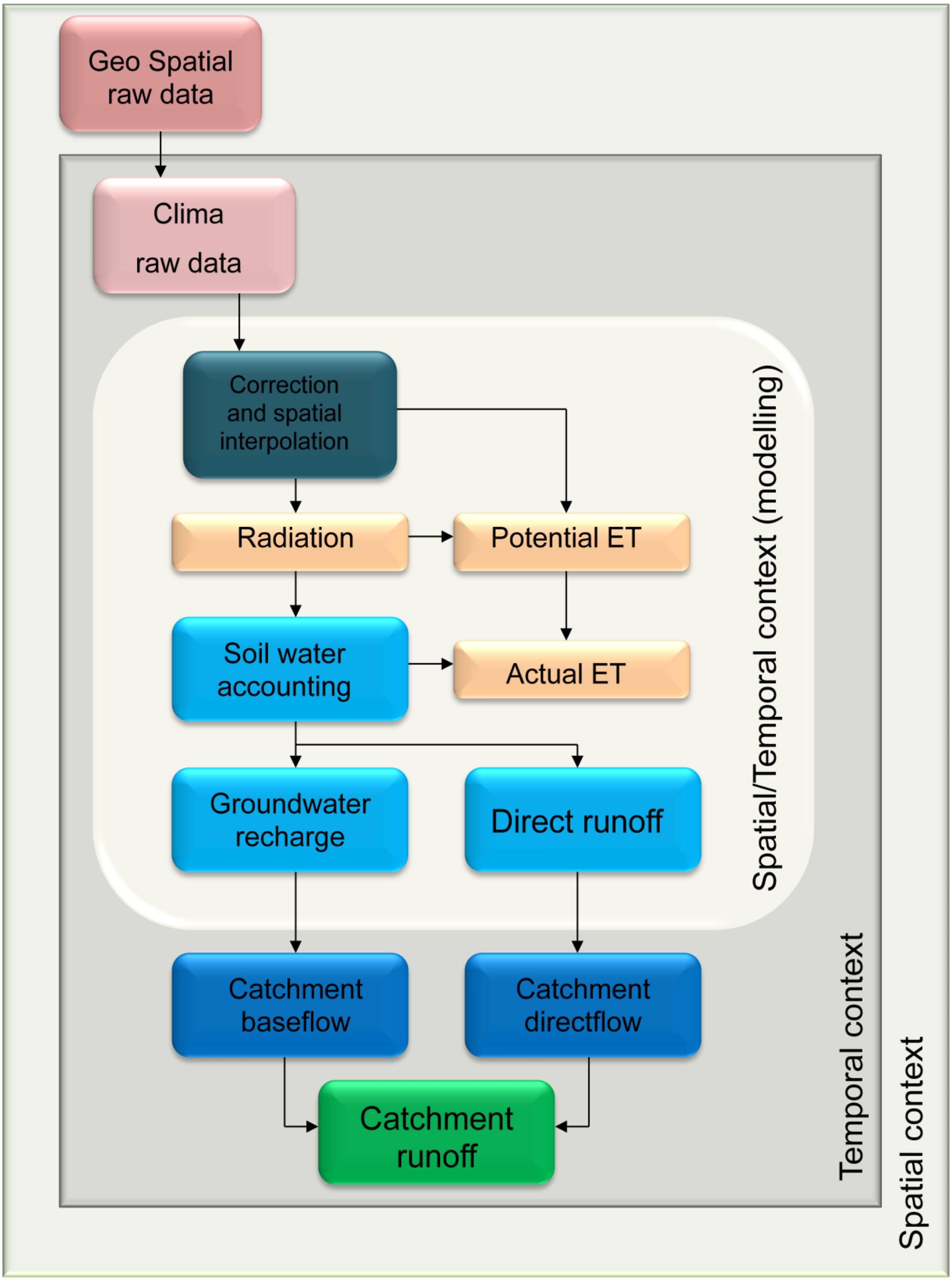


Figure 2.7. - Process Structure of the Model J2000g. (Source: Adapted from JAMS Wiki,

According to the first rule above mentioned, the temporal context is based in the fact that the climatic and hydrological processes occur in a specific time-scale. Thus, the different input variables inherent to the climatic as well as hydrological processes have to be temporally distributed in the model. The climate raw data is basically referred to: precipitation, temperature (minimum, maximum and average), sunshine duration, wind speed and relative humidity, collected in the observation stations located within or close to the basin. The calibration process also requires input of temporally distributed runoff data, but it will be considered later in the chapter.

2.5.2. - The Hydrological Response Units (HRUs), as the basic "Modelling Units" for the modelling process in J2000g.

As above mentioned, the behaviour of the hydrological processes, particularly the relationship between the rainfall and the runoff occurring within a catchment area is always depending on the form in which the different biophysical elements are spatially configured, structured and distributed across the landscape system. Through this conception, a river basin can be seen as "a heterogeneous assembly of distributed entities having a group of specific physiographic properties each of which has a specific response to the precipitation input and therefore contribute differently to the basin´s output" (Flügel, 1997). Thus, the heterogeneity showed by the physiographic properties across the landscape, integrated through a process logically managed, lead to delineate entities having homogeneity conditions in terms of the hydrological response, so that the river basin is partitioned through a discretisation process for modelling purposes. This process was described by Leavesley et al (1983), assuming that the watershed can be partitioned through the combination of the characteristics like slope, aspect, elevation, vegetation type and soil type. The resulting units were considered by these authors as "**homogeneous**" in terms of these characteristics, leading to provide the ability to account for spatial and temporal variations of the physical and hydrological conditions, providing also the ability to impose land use or climatic changes on parts or in the whole watershed. This approach was later complemented by Flügel (1995; 1996; 1997), who incorporated the notion of the topographic position into the landscape system, as a basic criteria to differentiate the slope, soil type and geological type in an integrated form. Thus, a Hydrological Response Unit can be defined as "**a distributed, heterogeneously structured**

entity having a common climate, land use and underlying pedo-topo-geological associations which control its hydrological transport dynamic" (Flügel, 1996).

This approach has been used in some process oriented and distributed models like: PREHVAH (Precipitation – Runoff – Evapotranspiration – HRU Model); SWAT (Soil and Water Assessment Tool); PRMS (Precipitation Runoff Modelling System), and of course in J2000 and J2000g – JAMS. (Schlegel, 2008).

The HRUs are usually derived from a regionalisation process operationalized through the intersection or combination of data layers containing the different landscape parameters or biogeophysical components above mentioned, using geographical information systems operations (GIS). Some different methodological approaches have been used until today, in order to deal with such a complex task.

The method regularly used is the conventional spatial analysis through an overlay, also called the "**intersection method**", which simply consider the intersection of the corresponding GIS layers of the several landscape components and their derivations or reclassifications, resulting in small common geometries or polygons as process entities (Wolf et al, 2009a). This method has been widely used in many simulation processes like: Flügel (1995) (1997); Krause (2002); Legesse et al (2003); Bäse et al (2006); Domnez et al (2009) and Behrawan (2010). A variation of this method is the "**grid cells method**", in which the catchment (through the different layers) is divided in grid cells having a specific area, and a specific configuration for the geobiophysical parameters; the HRUs are also obtained from overlay processes. This variation was used by Battaglin et al (1996). With the fast progress reached by the technologies of SIG and Remote Sensing, some alternative and variations to these conventional approaches already exist. Kahn et al (2009) presented a new approach for the delineation of HRUs in large river basins, based in the combined use of the area-aggregated slope system defined from the major landforms, and some specific indicators like the Compound Topographic Index (CTI), the Multi Resolution Valley Bottom Flatness (MRVBF), and the Surface Curvature Index.

Another innovative method recently developed by Wolf et al (2009a and 2009b) is the so-called "**Clustering Approach**", which integrates different relief parameters like Topographic Wetness Index, the Mass Balance Index, the Annual Solar Radiation Index and various curvature parameters, all of them closely related to hydrological processes. In this case, the parameters can be selected according to the significance of the processes in different landscapes and relief units. More information and methodological descriptions about the HRUs delineation process can be founded in Schlegel (2008) and Pfannschmidt (2008). The methodology used in this project for the delineation of the HRUs will be explained below.

According to the rules expressed on 2.5.1, the model has requirements of information and raw data from the two basic contexts: spatial and temporal. They are clearly correlated, so they are progressively related across the development of the model (see Figure 2.7). This is going to be explained across the different processes as follow.

2.4.3. - The Data Pre-processing

All the raw data required inherent to the spatially distributed variables useful to the modelling process have to be prepared and organized according to the conception of the approach into the model, and the corresponding requirements. Two types of information are essentially required into the model: spatial information and temporal information (Figure 2.7).

2.4.3.1. - The Spatial Context for the Modelling process

This context includes the spatial information corresponding to the different variables relevant to the hydrological processes, which were already above mentioned. This information leads to define the "**spatial static parameters**" to be used into the model to simulate the hydrological regime for the river Basin, and some of them are the basic input for the delineation of the HRUs. The Figure 2.8 illustrates the process followed in this case to produce the thematic layers containing the spatial information required for the model. The raw data used was already specified on Table 3.1, so basically Satellite/GPS data (SRTM data set and LANDSAT TM scenes) as well as transformed maps were the basic inputs used to derive the spatial context data.

The process for constructing the DEM from the SRTM data set, as well as the procedures followed to derive the different layers from it correspond to the first methodological approach which was already explained at the beginning of this Chapter. The DEM was used to produce

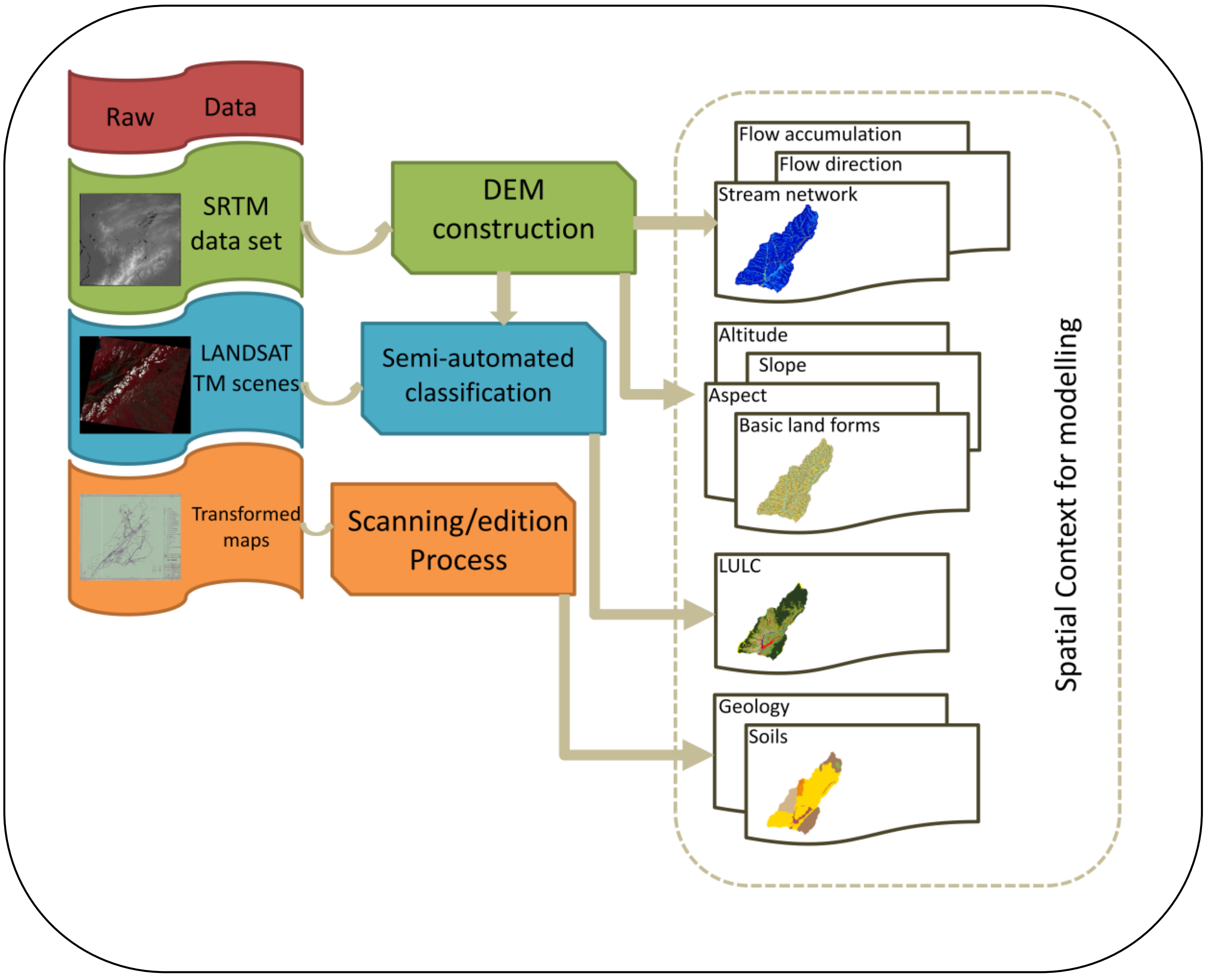


Figure 2.8. - Method to process the spatial information into the modelling system.

two types of spatial information: (a) basic layers containing linear data corresponding to the stream network, the flow direction and the flow accumulation; and (b) layers containing topographic and morphometric information like: altitude, slope, aspect and basic forms. As seen in the Figure 2.8, the DEM with altitude values was also used in the LULC classification process to differentiate the LC categories across the area.

LANDSAT TM scenes were used to derive the LULC layers in the river basin, following the procedure described on the second methodological approach. The original LULC classification maps were additionally reclassified, in order to join classes with similar hydrological behaviour, making the process to derive the HRUs even more simple.

The geology and soils layers for the river basin were taken directly from Transformed maps available for the study area from the sources mentioned on Table 3.1. They were scanned and edited using the ARC GIS 10 software, and some corrections were made from the LANDSAT TM interpretation.

All the layers generated constitute intermediate products, which will be required in the subsequent procedures for modelling. They are going to be gently described now:

2.4.3.1.1. - Flow direction

It simply represents the direction that the water follows across each raster cell in the area, being the basis for the calculation of the flow accumulation, the stream network and it is also essential to delineate the river basin from the water divide (Pfannschmidt, 2008).

2.4.3.1.2. - Flow accumulation & stream network

The flow accumulation in one particular raster cell is the sum of the flow coming from the cells above located, and this is the basic principle to define the stream network. Thus, the higher values indicates a concentrate flow, meanwhile the cero values are confined to the sloping areas across the river basin (Pfannschmidt, 2008).

2.4.3.1.3. - Altitude

The altitude reflect the hypsometric change occurring within the river basin, being a very important parameter, as influencing the behaviour of the different climatic parameters: temperature, wind, air pressure and precipitation regimes across the catchment (Pfannschmidt, 2008). Obviously, it affects the type, structure as well as the phenological seasonal cycle of the vegetation, and consequently defines the spatial distribution of the LC types across the area. Through the interaction with the slope and aspect, the altitude can produce a differentiated form of moisture conditions across the area, which can have ecological implications, affecting also the soil formation (Schlegel, 2008).

The altitude values were also essential in the regionalization of the different climatological variables. The DEM was also used in the parameterization of the HRUs in order to estimate the mean altitude of each polygon; this will be explained below in this Chapter.

2.4.3.1.4. - Slope

The slope has a paramount importance in the hydrological processes, as the angle of inclination determines the velocity of surface runoff, the quantification of solute transport processes and the interrelation between infiltration and runoff (Wolf, 2009a). The slope also affects the rainfall erosivity through the angle of incidence of the rain drops, influencing also the retention and budged of water in depressions. Hence, the slope has a strong influence in the process for soil formation. Through the angle of the sunlight the slope can also to influence the potential evapotranspiration.

2.4.3.1.5. - Aspect

The aspect defines at first the runoff direction. The hydrological relevance of this parameter lies on its direct influence in the radiation incidence and budget; solar radiation tends to be higher in south facing sloping areas, so that the evaporation is often more intense there. The aspect affects also the direction and intensity of winds, which could affect the rainfall intensity and consequently its erosivity (Schlegel, 2008). According to Chang (2003), the north facing sloping areas mostly have more dense vegetation and deeper soils; consequently the transpiration process is usually higher than those facing to the south. Even though, Krause (2001) consider that this parameter has a little direct influence on the runoff and in the separation of the runoff components into the modelling process.

2.4.3.1.6. - Basic terrain forms

As mentioned on 2.5.2, the concept of HRUs introduced by Flügel (1996) consider the landscape position as a very important element to express the hydrological dynamic through the association of the different process using the so called topo-pedo-geological model, which integrates the topography, the soils systems and the geological framework, in order to explain the hydrological behaviour across a river basin. Moore et al (1992) (Quoted by Wolf et al., 2009) consider the topography of the catchment as a crucial factor not only for the hydrological processes in the landscape, but for geomorphologic ad biological also. A simple way to represent the model cartographically is delineating the Basic terrain forms, through the method exposed on 2.3.1.5. The Basic forms delineated through the Peucker & Douglas Method, lead to delineate the basic forms across the landscape from a topographic perspective: peaks and narrow ridge crests, break-slopes (concave and convex), Pits, Pass and channel surface. These land forms describes the landscape in terms of local position, as they have a specific location through the mountainous landscape system, so they are interconnected by the flux or the movement of water and sediments coming from the top units (peaks, crests, pass), until the bottom units (channel surface). That's why they can represent topo-pedo-geological associations which can to describe the hydrological dynamic at the meso-scale level, in which this study was developed.

2.4.3.1.7. - Land Use / Land Cover (LULC)

It is well known that Land Cover plays a very important role in the processes inherent to the water cycle at the watershed level. Particularly the processes inherent to the quantitative and the spatial-temporal behavior of the interception, throughfall, evapotranspiration, infiltration rate, surface and subsurface runoff, and erosion/sedimentation are essentially governed by the type and condition of the land cover. All these hydrological implications that come from the Land Cover types, and particularly from the forest types, were widely discussed by Chang (2003). The relationship between the LULC and hydrological behavior in tropical regions are conveniently discussed by Bonell & Bruijnzel (2004).

The changes in LC and particularly the conversion of the forest areas into rangeland or cropland, usually have a big impact in all the ecological and hydrological processes. The most relevant are related with the increased runoff, decreasingly infiltration rates, and erosion/sediment yield also increased. This is more widely discussed by Mannion (2002), Chang (2003) and Bonell & Bruijnzel (2004). The implications of this parameter are the central scope of this research, so it will be more widely discussed on Chapters 4 and 6.

2.4.3.1.8. - Geology

The dynamics of the water inside the soil, and the underground water movement are closely related to the geological framework. The permeability of the rocks define how intense will be the water movement in the impervious zone. This is measured through the parameter hydraulic conductivity "Kf", and it considers the condition in which the water can circulate through the bedrock, being a function of: the flowing properties of water (density and viscosity), the porosity of the rock material and the gravity effect (Schlegel, 2008). A general rule said that with the increasing the coarseness or the porosity also increases the Kf Coefficient (Balke et al, 2000). Thus, the geological framework, through the permeability of the rock types, governs the groundwater recharge process, and also the time for the concentration of the baseflow.

2.4.3.1.9. - Soils

A significant percentage of most precipitation infiltrates to become stored soil water, which is either returned to the atmosphere by plant transpiration and evaporation or is conducted to lower levels and groundwater (Saxton & Rawls, 2006). This statement reveals the important role of the soil in the hydrological process, as water holder, water transmitter and water regulator. Obviously, the infiltration is largely governed by the soil configuration and its pedological characteristics like: texture grain size ratios, pore distribution and OM content. Saxton & Rawls (2006) consider the soil texture and the OM as primary variables affecting the soil water content. But the water quantity and its condition (viscosity), as well as the gravity gradient and the moisture are also determinants in the infiltration process (Pfannschmidt, 2008). The soil divides the precipitation into surface and underground water components, which gives rise to a particular relevance in the modeling process. More details about the relevance of the soil as a parameter for modeling can be founded in Schlegel (2008) and Pfannschmidt (2008).

2.5.3.2. - The Temporal Context. Climatic and Hydrological raw meta data.

Besides the spatially distributed data above described, the model require also data temporally distributed (See Figure 2.7), corresponding to hydro meteorological time series containing parameters which are relevant to calculate the different components of the model. In the model J2000g the hydrological processes can be simulated in a monthly or in a daily temporal context. In this case, the data series were collected in a daily temporal resolution, although the data availability was not really optimal, and the information was very sparse among the different sources mentioned on Table 2.1. The Table 2.7 shows the different hydrometerorological raw data required for the model. Some parameters like absolute humidity and sunshine duration were not available for the stations in the region, which means that they had to be calculated into the model. The meteorological raw data series were

Table 2.7. - Hydrometeorological Raw Data required for the Modelling process.

Data parameter	Units	**Availability for the study area**
Absolute Humidity	**g. cm-3**	-
Relative Humidity	**%**	X
Observed Rainfall	**mm**	X
Sunshine Duration	**H**	-
Maximum Daily Temperature	**°C**	X
Minimum Daily Temperature	**°C**	X
Mean Daily Temperature	**°C**	X
Wind Speed	**m.sec-1**	X
Evaporation	**mm**	X
Observed Runoff	m3/seg	X

compiled for 12 climate stations scattered throughout the region, some of them located within the river basin. The hydro-raw data corresponding to observed runoff were obtained from the Boconó – La Cavita Station, located at the outlet of the river Basin. The climate stations for which the raw data series were compiled are listed on the Table 2.8, and the spatial localization of the stations is displayed on Figure 2.9.

Only two of the stations considered (Boconó – Aeropuerto and Valera – Aeropuerto) records data inherent to the variables: temperature, wind speed, evaporation and humidity. The rest of the stations records only precipitation data. Some Stations were closed during the period considered, meanwhile others were recently installed.

The temporally distributed raw metadata constituted a critical issue into the project. Although there are enough synoptic stations covering the river basin and its surrounding areas, the information usually doesn't have optimal condition. Almost 60 % of the synoptic stations were installed on the Fifties (two of them were installed during the Forties). However, the daily data or even monthly data from some stations was very difficult to access, specially the older

Table 2.8. - Basic information of the climate stations used in the modelling process.

Name	Type	Serial number	Latitude	Longitude	Altitude	Start Record	End Record
Valle de Río Negro (1)	PR	7154	09 22 15	70 08 45	1720	1991	2009
Campo Elías (2)	PR	2190	09 23 48	70 03 37	1033	1957	2009
El Jarillo (3)	PR	2166	09 22 07	70 16 27	1890	1957	2008
Tostós (4)	PR	2187	09 11 44	70 19 39	2187	1957	2009
Las Mesitas (5)	PR	2196	09 03 37	70 27 58	2200	1957	2009
Páramo de Guaramacal (6)	PR	7153	09 11 25	70 08 45	1230	1991	2009
Niquitao (7)	PR	2199	09 06 58	70 24 03	1900	1957	2009
Boconó MOP (8)	PR	2176	09 15 13	70 16 38	1200	1945	2009
Boconó – Aeropuerto (9)	C2	7146	09 16 30	70 13 30	1560	1991	2009
Hacienda San Giusto (10)	C2	7142	09 17 43	70 12 43	1499	1972	1990
Páramo La Cristalina (11)	PR	2167	09 19 25	70 21 00	2070	1942	2006
Valera-Aeropuerto (12)	SP	7164	09 21 00	70 37 00	582	1983	2009

records. The raw data was very sparse across the sources listed on Table 3.1, and in some cases it was not easy to access. The time series were mostly deficient, having many gaps with missing values as well as encompassed values, which is considered a usual problem for the synoptic data (Boissonnade et al, 2002). It means that a "**data cleaning**" process to remove missing values and to replace erroneous values through the use of some methods to estimate pseudo data or surrogate data to complete the datasets were necessary to apply. The missing values has been reported by many authors as a critical issue, some examples are: Kemp et.al (1983); Eischeid et. al (1995); De Gaetano et al (1995); Xia et al (1999);

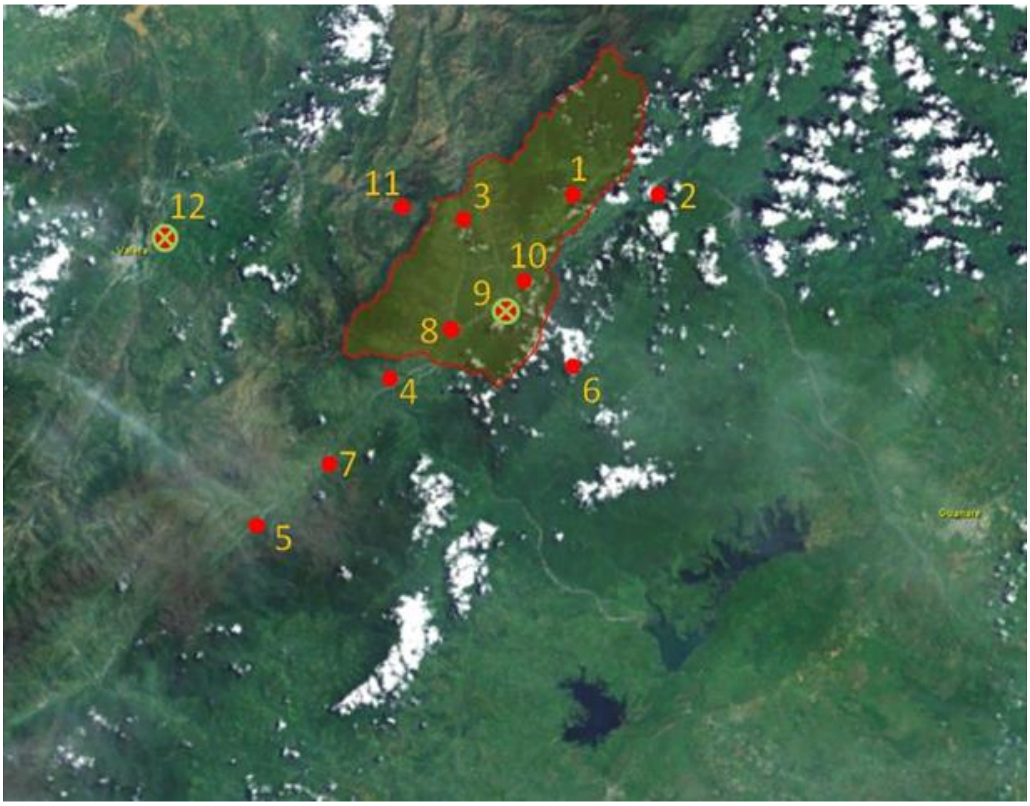


Figure 2.9. - Spatial distribution of the climatic stations. (The numbers for the stations are identified on Table 2.8).

Schneider (2001); Boissonnade et al (2002); Lo Presti et al (2010); and Kim & Pachepsky (2010).

The replacement of one missing daily value is fairly easy. However, the problem becomes much more complicated if there are blocks of daily missing values, a common problem, particularly for the data from some decades ago (Boissonnade et al, 2002). It was particularly the case in this project, in which all the considered stations had blocks of daily missing values across the series.

As seen on Table 2.1, a big portion of the raw data was supplied in a non digital format, so prior to the pre processing was necessary to convert the data into a digital format. Once the data was already in digital format, the next step was to complete and to homogenize the datasets for all the stations in the "**data cleaning**" process, following the methods described below:

A. - Precipitation data

Rainfall is so far the most fundamental data input for most of the simulation models; however, one of the major constrains for process-oriented models as in this case, is the difficulty of obtaining the required data sets in terms of format, quantity and quality also (Mzirai et al, 2005). The precipitation data sets used to have the largest problems related with missing data and encompassed data for all the stations considered in the project. For these reasons, some methods from the available methods set were used to solve the problem in this case. In some cases, the estimation was done using the data of the same problem – station (**within station methods**). In other cases a target or neighbour station had to be used (**between stations methods**). Thus, for missing values the surrogate data were estimated from the use of three methods in an alternate way: (1) Using a simple interpolation between available data or their derivatives, using a mean value of the data series, and in some cases using data from several days before and several days after the date of missing values in a non - linear regression to fill the 1 day data gap (Kim & Pachepsky, 2010). This method was used for cases in which an isolated missing value was founded in the data set. (2) Using the Normal Ratio Method (NR) or Normal Proportion, in which the estimated surrogate data value is considered as a combination of variables with different weights estimated using one or more surrounding stations (Eischeid et al, 1995) (Xia et al, 1999). The weights are thus estimated according to the Equation 2-7:

$$Wi = \frac{r^2 i(ni-2)}{1-r^2 i} \qquad \text{(Equation 2-7)}$$

Where: r is the correlation coefficient for each monthly time series between the target station and the i th surrounding stations; n is the number of points use to derive the correlation coefficient, and W is the resultant weight.

Finally, the surrogate data value is calculated from the Equation 2-8:

$$Vo = \frac{\sum_{i=1}^{n} WixVi}{\sum_{i=1}^{n} Wi}$$ (Equation 2-8)

Where Wi is weight of the surrounding stations and Vi is the observational data of the ith surrounding station.

(3) Correlative procedures, in this case simple linear regression between stations was used, considering the nearest station, and also regression within station could be applied, using the simple linear expression (Kemp et al, 1983):

$$Y = (a + b X)$$ (Equation 2.9)

Correlative procedures and particularly Regression techniques tends to produce more accurate results, when compared with other methods (Kemp et al, 1983) (Xia et al, 1999).

The encompassed data values were separated and temporal distributed according a method suggested by Barrios (2010) (pers. Com). For this method, the closest station had to be selected as a target station, having the similar temporal pattern trends in the occurrence of rainfall. Thus, the encompassed value could be disengaged, and also be temporally distributed within the time serie, using the same proportion showed by the target station during the same period.

B. - Temperature data

As above mentioned, only two stations in the Region accounted for climate variables like: temperature, wind speed, humidity and evaporation. The values for maximal, average und minimal temperature for the Station Boconó – Aeropuerto were adjusted, using the data set from Station Valera – Aeropuerto, which was more completed. The surrogated data were estimated through linear regression between stations techniques, which is according to Kemp et al (1983) the most adequate method for the estimation of surrogate or pseudo data for temperature.

C. - Additional climatic raw data

Data sets for the climatic variables: wind speed, relative humidity, evaporation were also available for the Station Boconó – Aeropuerto. However, the data sets contained many gaps, which were not possible to fill, due to the absence of another Station to use as a pattern station in order to estimate the surrogated data.

D. - Runoff Data

The available runoff data set correspond to the Station La Cavita, located at the outlet site of the river Basin. The Station was closed on 1996, after a flooding event, so after that time no more observed data for the river can be found. Some of the data supplied was referred to water level of the river. These values were used to estimate the runoff values using the calibrated equations for the level – runoff curve defined for the Boconó river Basin by Macias (2002).

2.5.4. - The Hydrological Response Units as spatial platform for modelling.

The Hydrological Response Units were finally delineated following an alternative multi – level spatial analysis procedure, in which the biophysical variables were organized in two groups to be overlaid in two different aggregation levels. The first group is referred to the **target variables**, those which define and determine geometrically the dynamic related to the hydrological landscapes in the river Basin. In this group were included: (1) Landforms; (2) Geological framework, and (3) Land Use / Land Cover (LULC). The second group includes the **complementary variables**, those which are also important to characterize the hydrological behavior across the different landscape units. In this group are included: (1) Altitude; (2) Slope; (3) Aspect, and (4): Soil type.

The target variables were reclassified before the overlay process, in order to optimize the merging process to obtain the genuine representative HRUs in the area. The Table 2.9 shows the target variables after they were reclassified for the HRUs delineation process. The complementary variables were not discretized for the overlay process, so they were used as continuous variables, so that the average values from each variable for each polygon were calculated.

Figure 2.10 illustrate the process to delineate the HRUs for the Boconó River Basin. In the first level multi-overlay the target variables were combined to geometrically generate the HRUs. After each overlay process, reclassification and generalization were necessary to eliminate the smallest polygons and to join categories having a reduced spatial presence. Thus, a map containing diverse polygons categorizing different HRUs types were obtained.

Table 2.9. - Target Variables reclassified for the HRUs delineation.

Target Variable	Category	Description
Land Forms	1	Channel
	2	Concave break
	3	Ridge
	4	Convex Break
Land Use / Land Cover (LULC)	1	Tropical Montane Cloudy Forest
	2	Sub-Montane Forest
	3	Schrub
	4	Grass
	5	Agriculture
	6	Fluvial plain & eroded soil
	7	Urban Area
Geological framework	1	Recent Alluvium
	2	Mucuchachi – Carboniferous
	3	Sabaneta – Carboniferous
	4	Palmarito – Permic
	5	Sierra Nevada – Cretaceous
	6	Terraces – Pleistocene

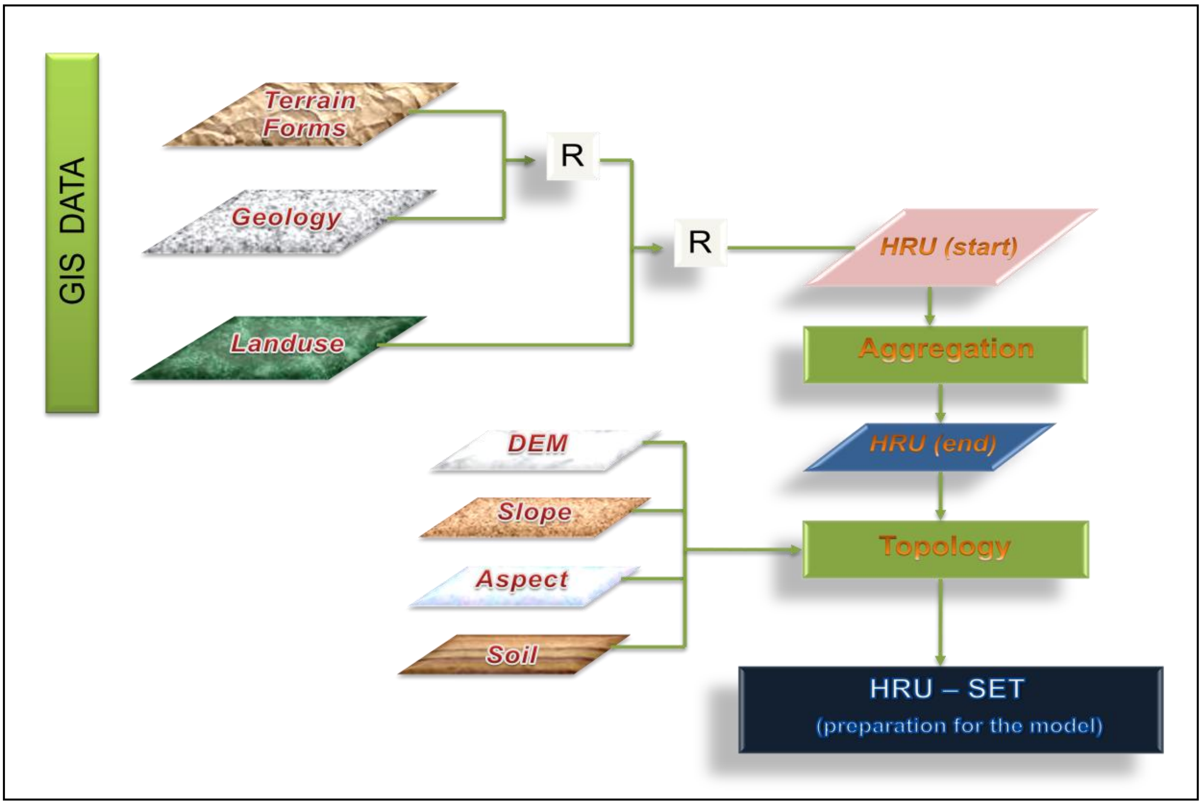


Figure 2.10.- Methodological Process followed to delineate the HRUs

In the second level multi overlay process, the HRUs map delineated in the first level process was progressively combined with the complementary variables, in order to define the metrics and the value of the parameters for each HRU type. According to the target goals of the project, it was necessary to simulate the hydrological dynamic under different spatial conditions (different LULC scenarios). For this reason, three HRUs maps were created through this approach. The first one was generated considering the LULC map for 1988. The second one was generated considering the LULC map for 2008, and the third one was derived for the LULC projection until 2028.

2.5.5. - Parameterisation process

As usual in this kind of models, the J2000g model has some requirements for input data referred to parameters noticeably affecting the hydrological processes, so they are of paramount importance to estimate the water balance within the simulation process. These parameters include information about soil, vegetation and geology. The parameterisation is simply the process of defining the spatial pattern of parameter values into the model construction (Refgsgaard and Storm, 1996).

The parameterisation is a very important process in the model construction, so that Refgsgaard and Storm (1996), consider crucial to develop a rigorous parameterisation in order to avoid some methodological problems at the subsequent phases of calibration and validation. They highlight the following points as critical to be considered for the parameterisation:

1. - The parameter classes (soil types, vegetation types, climatological zones, geological layers, etc), should be selected so that it becomes easy, in an objective way, to associate parameter values.

2. - It should explicitly be evaluated which parameters can be assessed from field data alone and which need some kind of calibration.

3. - The number of real calibration parameters should be kept low, both for practical and methodological points of view.

Particularly the last condition facilitates the subsequent calibration process, makes it more robust, and also ensures a higher degree of credibility to the subsequent model predictions as the model is not overparameterised (Andersen et al, 2001).

The last principles were completely adopted in the parameterisation procedure, and the parameters are gently described below:

2.5.5.1. - Soil Parameters

For this important environmental factor, the model requires information about the structure and depth of the profile, as well as the value of field capacity for each horizon that constitutes the profile. Unfortunately, there is a lack of detailed information about the soils in the area, and only general information was founded in the literature, basically those published by: Nuñez (1984) and Bone et al., (1985). The Table 2.10 contains the basic information about the soils in the river Basin. The field capacity was determined in two ways:

a. - Direct extraction of values from estimates made by Saxton & Rawls (2006)
b. - Direct calculation of the value of FC, depending on soil information available, using the Rawls equation (Rawls et al, 2002):

$$FC = 0{,}2576 - 0{,}0020\ \%S + 0{,}0036\ \%C + 0{,}0299\ OM \qquad \text{(Equation 2-10)}$$

The Table 2.11 shows the field capacity values for the different soil types in the Boconó river Basin.

Table 2.10. - Main characteristics of the soils in the Boconó river basin.

Category	USDA Taxonomy Soil Type		Texture	Structure	Permeability	Organic carbon %
	Order	Sub order				
I	Ultisol	Tropohumults Tropudults	Clayed	Blocky	Moderate to slow	3,64
II	Entisol	Troporthent	Sandy loam	Blocky	Rapid	3,57
III	Ultisol	Tropohumults	Silty Loam	Blocky	Moderate	5,52
IV	Ultisol	Tropohumults	Loam	Blocky	Moderate	5,59
V	Inseptisol	Humitropepts	Sandy clay loam	Blocky	Moderate	3,97
VI	Inseptisol	Humitropepts Distropepts Eutropepts	Sandy loam	Blocky	Rapid	3,64

Source: Nuñez (1984); Bone et al., (1985).

Table 2.11. - Field capacity Values derived from Saxton & Rawls (2006).

Soil Class	Texture	Depth (cm)	Field capacity %	Field Capacity (mm)
I	Clayed	50 – 200	42	420,0
II	Sandy loam	100 - 200	18	360,0
III	Silty loam	150	31	465,0
IV	Loam	>200	28	560,0
V	Sandy clay loam	>200	27	540,0
VI	Sandy loam	100 – 180	18	324,0

Source: Nuñez (1984); Bone et al., (1985); Saxton & Rawls (2006).

2.5.5.2. - Vegetation and Land use Parameters

These parameters are an important input for the estimation of evapotranspiration using methods like the Penman - Monteith, and include some indicators expressing the level of energy and moisture absorption by vegetation and / or different categories of land use. Three parameters are included here: Albedo, Stomatal Resistance and Leaf Area Index (LAI).

2.5.5.2.1. - Albedo

The albedo values for the LULC categories were extracted directly from the literature, specifically from Mattheß & Ubell (1983), and PLAPADA website - Plant Parameter Database (http://www.uni-giessen.de/~ gh1461/plapada/plapada.html). The Table 2.12 shows the albedo values for each category of use and land cover in the Boconó river Basin.

2.5.5.2.2. - Stomatal Resistance

Stomatal resistance values of the plants were estimated directly from the stomatal conductivity values, which are usually available in the literature. Stomatal Conductivity values were obtained from Motzer et al (2005) and also from the

Table 2.12. - Values of Albedo for the LULC of the Boconó river basin.

LULC Category	Albedo (%)
Dense Forest	3 – 10
Prairie	5 – 10
Humid Grass	33 – 37
Dry Grass	15 – 25
Bed river	9 – 18
Bare soil	10 – 20
Crops	24 – 25
Urban areas	10 – 12

Source: Mattheß & Ubell, (1983); PlaPaDa – Plant Parameter Database (http://www.uni-giessen.de/~gh1461/plapada/plapada.html).

PLAPADA website - Plant Parameter Database (http://www.uni-giessen.de/ ~ gh1461/plapada/plapada.html); these values were then converted to stomatal resistance values.

Table 2.13 shows the stomatal resistance values derived according to the types of vegetation present in the Boconó River Basin. The average value for the category "Agriculture" was estimated using the reference crops, that is, the most common crops developed in the study area. The Table 2.14 contains the stomatal resistance for the reference crops in the river Basin

2.5.5.2.3. - Leaf Area Index (LAI)

The Leaf Area Index (LAI) was estimated from remote sensing methods. LANDSAT scenes for the study area with the least possible amount of cloud were chosen, for the two seasonal periods of the year (dry and rainy seasons). They were processed in ERDAS for the estimation of NDVI (Normalized Difference Vegetation Index), so that two NDVI values were

Table 2.13.- Stomatal Resistance Values for the LULC categories in the Boconó river Basin

LULC Category	Stomatal conductance (gs) (mm/s)	Stomatal Resistance (Rs) (s/m) ***
Tropical Montane Cloudy Forest	4.024 (Canopy trees)* 2.195 (Understory)*	248.509 (Canopy trees) 455.581 (Understory)
Sub-montane Forest	3.75**	266.667
Grass	6.23**	160.514
Schrubland	5.31**	188.323
Agriculture	6.118***	168.817
Urban use	---	---
Fluvial plain & eroded soil	---	---

Source: * Motzer et. al (2005) . ** PlaPaDa – Plant Parameter Database (http://www.uni-giessen.de/~gh1461/plapada/plapada.html). *** The author

Table 2.14. - Stomatal Resistance Values for "reference crops" in the Boconó river Basin

Crop Type	Stomatal conductance (gs) (mm/s) *	Stomatal Resistance (Rs) (s/m) **
Beet	7.10	140.845
Tomato	5.85	170.940
Common Bean	7.70	129.870
Potato	5.00	200.000
Maize	4.94	202.429
Average	6.118	168.817

Source: *PlaPaDa – Plant Parameter

Database (http://www.uni-giessen.de/~gh1461/plapada/plapada.html). ** The author obtained: the one for the dry season, and the other one for the rainy season. Then, NDVI maps were processed in ERDAS using the methodology proposed by Hochschild (2001), for the ultimate derivation of LAI for each seasonal period. Additionally, LAI values for the Tropical Montane Cloudy Forest (TMCF) were compared with LAI values measured "in situ" in some plots of Venezuelan TMCF by Schwarzkopf et al (2011).

Table 2.16 shows the estimated LAI values for the different LULC categories during the dry season in the Boconó River Basin. The estimated values for the rainy season are displayed on Table 3.15. Table 3.16 shows the comparison between the estimated LAI values for the Tropical Montane Cloudy Forest, and those measured by Schwarzkopf et al (2011).

2.5.5.2.4. - Geological parameters

The J2000g model requires geological information concerning to the maximal percolation rate for the different rock types. This parameter is determined directly from the permeability values that can be founded in the literature. The permeability values for the rock types existing in the study area were taken from Gregory & Walling (1973) and Spitz & Moreno (1996). The tabulated values of hydraulic conductivity and the subsequent percolation rate values for the rock types in the study area are showed on Table 2.19.

Table 2.16. - LAI values for the different LULC categories during the dry season in Boconó river basin.

LULC category	Min value	Max value	Range	Mean	Std Dev
Tropical Montane Cloudy Forest	-0,621582	2,87572	3,497299	2,05374	0,399383
Sub-Montane Forest	-0,944871	2,71228	3,65715	1,6818	0,44979
Grass	-0,569881	2,66365	3,23353	1,28538	0,461903
Schrubland	-0,631456	2,851249	3,4827	1,78577	0,44696
Agriculture	-0,768016	2,776649	3,54467	1,378469	0,460137
Urban use	-0,923968	2,538039	3,461999	0,578626	0,674099
Fluvial plain /eroded soil	-0,967167	2,769	3,73617	0,337603	0,796145

Table 2.17.- LAI values for the different LULC categories during the rainy season in Boconó river basin.

LULC category	Min value	Max value	Range	Mean	Std Dev
Tropical Montane Cloudy Forest	0,000	2,962069	2,962069	2,155649	0,287261
Sub-Montane Forest	0,000	2,93101	2,93101	2,094919	0,374574
Grass	0,000	2,86227	2,86227	1,785989	0,396095
Schrubland	0,000	2,97861	2,97861	2,05766	0,359584
Agriculture	0,000	2,918309	2,918309	1,855839	0,447456
Urban use	0,000	2,80623	2,80623	1,030249	0,80923
Fluvial plain /eroded soil	0,000	2,72074	2,72074	0,745927	0,84106

Table 2.18. - Comparison between the LAI values estimated from RS and those measured “in situ” by Schwarzkopf et al (2011).

LULC Category	LAI Values estimated from Remote Sensing		LAI values measured “in situ” by Schwarzkopf et al (2011)		
	dry season	rainy season	MZ	LM	LC
TMCF	2,054 (0,40)	2,156 (0,29)	2,4 (0,4)	2,1 (0,5)	2,3 (0,3)

Note: Numbers in parenthesis are standard deviations. (MZ: Monte Zerpa; LM: La Mucuy; LC: La Carbonera).

Table 2.19. - Maximal Percolation of the rocks present in the study area.

Identity code	Rock Type	Max Percolation (m/day)	Max Percolation (mm/day)
1	Unconsolidated (Sand & Gravel)	10^4	10^7
2	Silty slates	10^{-6}	0,001
3	Marine Shale /Phyllites	10	1000
4	Shales	10^{-2}	10
5	Gneiss / Schist	10^{-6}	0,001
6	Gravel	10^6	10^9

Source: Gregory & Walling (1973); Spitz & Moreno (1996)

2.5.6. - Model Calibration & Validation

Normally the Hydrological models drag different errors which come from different sources of uncertainty. Refsgaard & Storm (1996) identify 4 basic types of sources of uncertainty:

1. - Random or systematic errors in the input data (i.e. precipitation, temperature, evapotranspiration, etc), used to represent the input conditions in time and space over the catchment.

2. - Random or systematic errors in the recorded data (i.e., river water levels, groundwater heads, discharge data).

3. - Errors due to non-optimal parameter values.

4. - Errors due to an incomplete or biased model structure.

All these kind of errors can to affect the results, producing a difference between the simulated variables and the observed or recorded data. Thus, the calibration & validation processes must be necessarily considered, in order to guarantee that the results can be properly useful to represent the real condition, and to solve practical problems. The calibration process means the estimation of values for the model “**parameters**” in order to enable the model towards a closely match to explain the behaviour of the real system that the model intends to represent (Gupta et al, 1998).

The validation, meanwhile, is simply the process of demonstrating that a given specific model is capable of making sufficiently accurate predictions (Refsgaard, 1997). This implies the application of the model with the calibrated values of the parameters, in order to simulate the hydrological response for a different period to those used for the calibration. Thus, the model is said to be validated if its accuracy and predictive capability in the validation period have been proved to lie within acceptable limits (Refsgaard, 1997).

Three kinds of methods are available to develop the calibration process:

a. - Trial-and-error, manual parameter adjustment.

b. - Automatic, numerical parameter optimization.

c. - A combination of “a” and “b”.

These methods are conveniently described by Refsgaard & Storm (1996), highlighting the advantages and disadvantages of using each one.

In this research project, the calibration was conducted using the “c” method, in which were carried out sensitivity tests by automatic optimization, in order to identify the relevant parameters, and after that, they were additionally calibrated through trial-and-error method.

The runoff data available for La Cavita Station contain only sectioned data from 1988 – 1990, 1991 – 1992 and 1995-1996, respectively. For that reason, two sections were selected for the calibration-validation process: the calibration was done using the first section (1988 – 1990), meanwhile the third section (1995-1996) was considered for the validation. Thus, the so-called “**Split sample validation**” method was followed in this case. The Figure 2.11 simplifies the process followed for the calibration/validation using the “**Split sample**” method. The year 1989 was selected as a control year, in order to make the comparisons between the different scenarios defined for the simulation process.

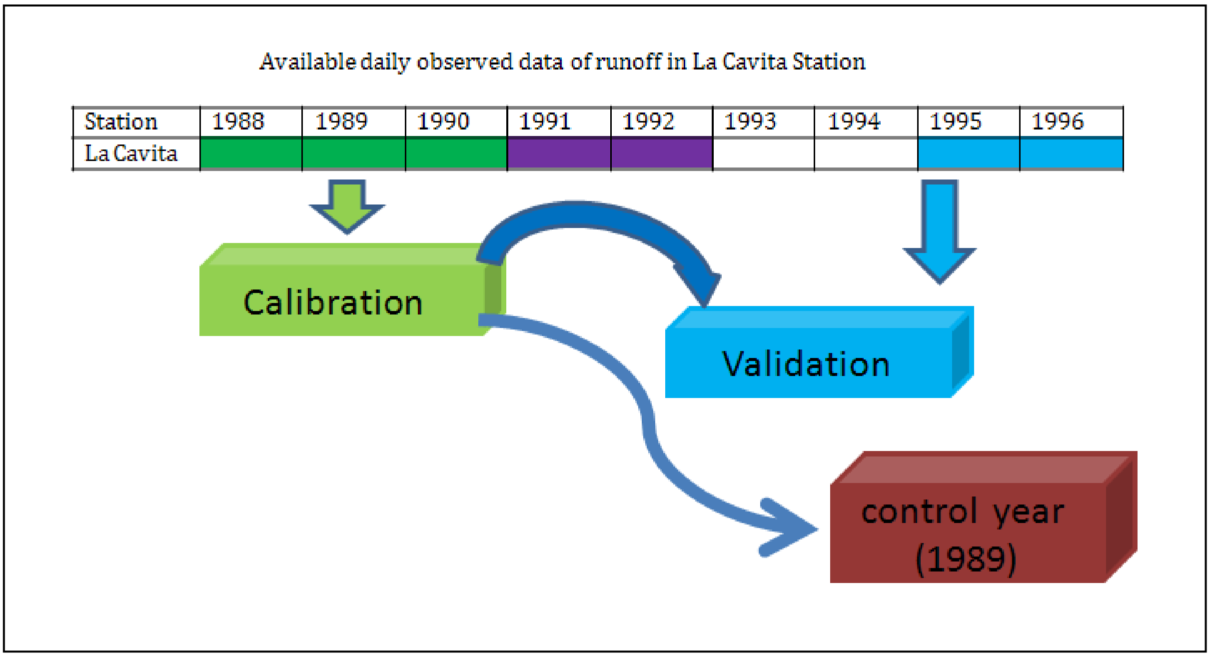


Figure 2.11.- The calibration/validation process followed using the “split sample validation” method.

2.5.6.1. Sensitivity Analysis

During the model calibration is very important to verify the correspondence between the quality of the data used for the simulation and the potential accuracy of the predictions becoming from the results. Thus, the sensitivity analysis can to deal with this task, letting to determine the value of the sensibility of one parameter, so that the modeller can to find the parameters, which have to be considered for the optimization process (Bäse, 2005). The process allows the identification of such parameters being sensitive and influencing the model output (Bahremand & De Smedt, 2008) (quoted by Scheffler, 2008). The parameters to be evaluated in this case are those kinds of parameters directly contained in the model, related to: groundwater recharge, soil – water and snow – module parameters (not considered in this case). The Table 2.20 list the parameters included into the model J2000g, and considered feasible to be evaluated in this case.

The process to determine sensitive parameters in this project was done using the single and

Table 2.20. - J2000g Parameters considered for the Calibration process.

Identity name	Descriptor	Process	Range value
FCA	Adaptation factor for maximun soil moisture storage	Soil & water	0 - 20
LatVertDist	Distribution of runoff to lateral and vertical component	Soil & water	0 - 100
linETRed	ET reduction coefficient	Soil & water	0 - 1
petMult	ET adaptation factor	Soil & water	0 - 10
maxPercAd	Adaptation for maximum percolation rates	Soil & water	0 - 100
DFk	Recession coefficient for direct flow	Water	1 - 1000
BFk	Recession coefficient for base flow	Water	1 - 1000

multi parameter Monte Carlo Analysis method, available within the Model J2000g. Exercises were done based on 1000 Monte Carlo runs, which were after analyzed through visual inspection. The reactions to the model performance were evaluated using the following functions for efficiency criteria: The Nash-Sutcliffe-Efficiency (NSE); the logarithmic Nash-Sutcliffe-Efficiency (log.NSE); the coefficient of determination (r2); and the relative percentage volume error (PBIAS).

2.5.6.1.1. Nash-Sutcliffe-Efficiency

The efficiency NSE is defined as one minus the sum of the absolute squared differences between the predicted and observed values normalized by the variance of the observed values during the period under investigation (Krause et al, 2005). It is calculated trough the following equation:

$$NSE = 1 - \frac{\sum_{i=1}^{n}((Qobs)i-(Qsim)i)^2}{\sum_{i=1}^{n}((Qobs)i-(\breve{Q}\ obs)i)^2} \quad \text{(Equation 2-11)}$$

With Q_{obs} representing the observed runoff value and Q_{sim} the modelled runoff value at time i, Q_{obs} defines the observed mean runoff for the given time period. The range of NSE lies between 1.0 (perfect fit) and $-\infty$. Values lower than zero indicates that the mean value of the observed time series would have been a better predictor than the model (Krause et al, 2005).

With this method, the differences between observed and predicted values are calculated as squared values. Thus, larger values in time series are strongly overestimated whereas lower values are neglected. This is, according to Krause et al, (2005), a main disadvantage of the method, leading to an overestimation of the model performance during peak flows, and an underestimation during low flow conditions.

2.5.6.1.2. - Logarithmic Nash Sutcliffe Efficiency

This is simply a variation of the NSE where the logarithmic values of Qobs and Qsim are calculated, which reduces the problem above mentioned respect to the sensitivity to the extreme values. Through the logarithmic transformation of the runoff values the peaks are flattened and the low flows are kept more or less at the same level (Krause et al, 2005).

2.5.6.1.3. - Relative percentage volume error (PBIAS).

According to Behrawan (2010), the percent bias (PBIAS), is a measure of the average tendency of the modeled flows to be larger or smaller than their observed values, that is, PBIAS is simply the deviation of streamflow discharge, expressed as a percent. PBIAS is calculated using the expression:

$$PBIAS = \frac{\sum_{i=1}^{n}(Qi,obs - Qi,sim)(100)}{\sum_{i=1}^{n}(Qi,obs)}$$ (Equation 2-12)

Where:

Qi,obs: observed streamflow

Qi, sim: simulated streamflow

The optimal PBIAS value is zero (0.0); a positive value indicates a model bias toward underestimation, whereas a negative value indicates a bias toward overestimation (Gupta et al, 1999) (Quoted by Behrawan, 2010).

2.5.6.1.4. - Coefficient of determination (r^2)

The coefficient of determination r^2 is defined as the squared value of the coefficient of correlation according to Bravais – Pearson, being calculated as follow:

$$r^2 = \left[\frac{\sum_{i=1}^{n}(Oi - \bar{O})(Pi - \bar{P})}{\sqrt{\sum_{i=1}^{n}(Oi - \bar{O})^2} \sqrt{\sum_{i=1}^{n}(Pi - \bar{P})^2}} \right]^2 \qquad \text{(Equation 2-13)}$$

with O observed and P predicted values.

In this case, r^2 can be expressed as the squared ratio between the covariance and the multiplied standard deviations of the observed and predicted values; therefore, the r^2 basically estimates the combined dispersion against the single dispersion of the observed and predicted series (Krause et al, 2005). The range of r^2 lies between 0 and 1, where zero means no correlation, meanwhile 1 means that the dispersion of predicted series are equal to the observed series.

Chapter 3

The Boconó River Basin as a "Water Resource Area"

3.1. - Overview

Nowadays are river basins widely recognized as a complex, ecological and interactive systems, in which the water production is a result from a very complex combination of dynamic forces, continuously in advance, having an uncertainty concerning cause-and-effect relation. Many aspects concerning those relations are not well understood, and many questions cannot be answered yet. However, different concepts, theories and methodological approaches have been developed in order to characterize such biophysical systems in a simplified way.

This Chapter pretends to describe and to characterize the study area from a geographical perspective, taking account of the main geobiophysical factors as “controlling factors” for the dynamic of water yield within the river Basin. The three basic theoretical approaches explained on Chapter 1 were combined for this purpose, and particularly a characterization of the hydrological landscapes in the study area was intended, linking the conceptual idea proposed by Winter (2001) with the main terrain forms mapped from the DEM.
The Figure 3.1 shows a geographical overview of the Boconó River Basin, basically the water divide and the stream network. This basin is located in the North part of the Andean mountain range, specifically between the Ranges: “Sierra de Trujillo”, “Sierra de Barbacoas” and a mountain branch called „Ramal de El Rosario”; presents the typical features of a tropical upland river basin, having a relatively elongated form, and a drainage pattern being dendritic with a tendency to be rectangular, product of the intense tectonic activity (Ostos, 1975).
The mainstream is about 56, 5 km long, showing an average slope of 2, 4%, and the runoff coefficient is about 0,70 (Cornieles, 1997).

The Boconó river, together with the Burate river, are the most important stream systems as tributaries flowing to the Boconó – Tucupido Dam System, which is located downstream in the region called “The Llanos Occidentales”, between the cities: Guanare and Barinas (Bone et al., 1985) (Macias, 2002).

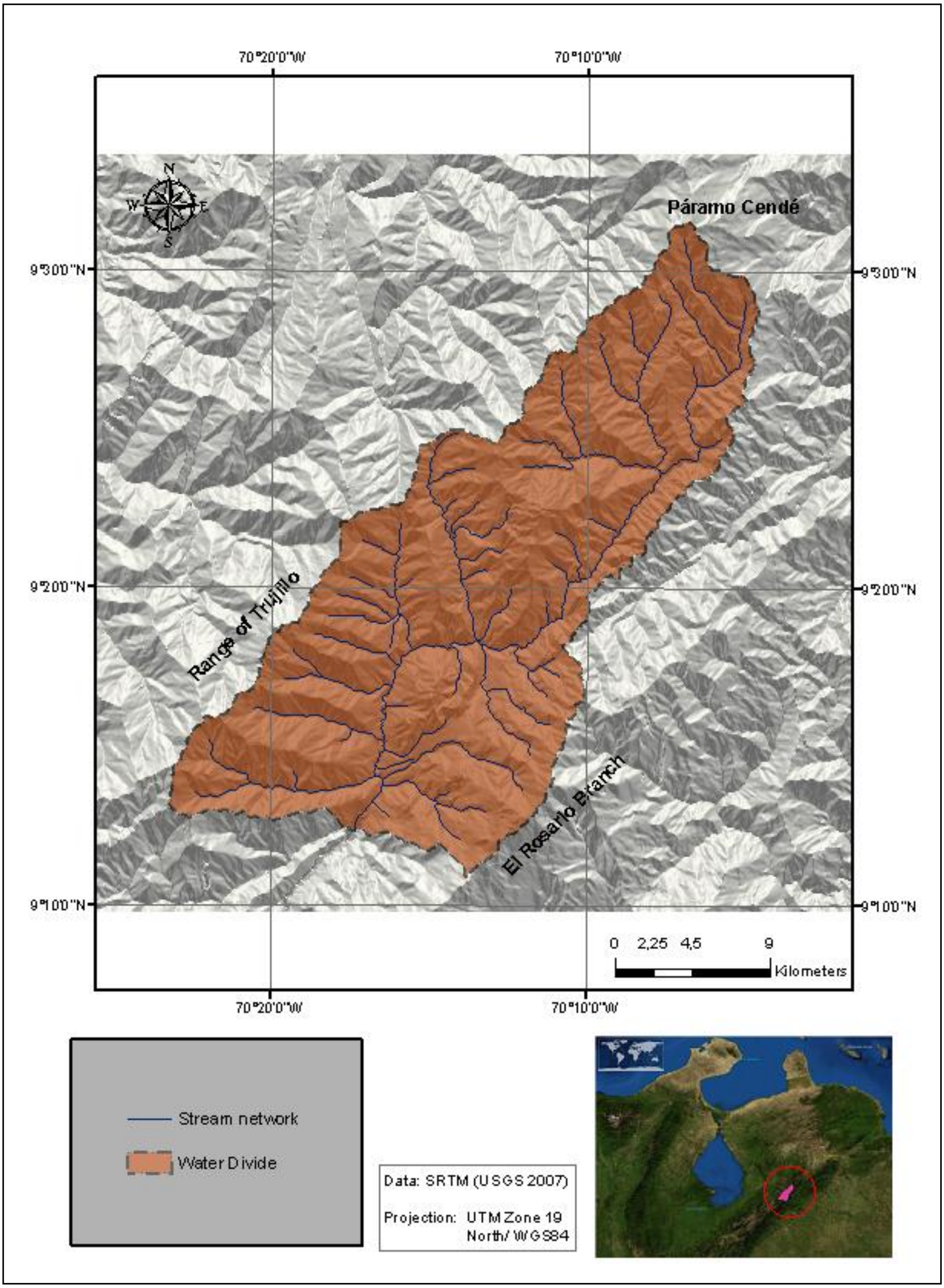


Figure 3.1. - Geographical Overview of the Study Area.

3.2. - Origen and physical configuration

The Venezuelan Andes experimented a first lifting process at the end of the Paleozoic Era, and prevailed until the beginning of the Mesozoic, when this ancient range was eroded and then subject to marine transgressions during the Cretaceous (Cárdenas, 1964). Finally, the definitive lifting occurred between the Eocene and Oligocene (the maximum level of lifting probably occurred 2,5 million years ago, during the Pliocene (Vivas, 1992)), and since this period a combination of successive lifting, intense tectonic activity and geological erosion has been happening. For this reason is expected to find in the study-area rock- formations almost corresponding to the whole ages, from the Pre-Cambric until the Quaternary, containing the three main rock-types.

The catchment is located within the Tectonic axis formed by the Boconó Fault Zone, which is the most important structural feature of the Venezuelan Andes (Ostos, 1975) (Vivas, 1992). The Fault runs slightly oblique to the Merida Andes chain axis from The Táchira Depression at the border between Colombia and Venezuela, until Morón on the Caribbean coast (Audemard & Audemard, 2002). In fact, the Fault cross longitudinally the river basin, separating the metamorphosed crystalline rocks in the north portion, from those less metamorphosed in the south part, and defining the direction of the river´s course (Cornieles, 1997).

3.3. - Topographical configuration

The relief is characterized by its massive form and vigor, and it has been strongly influenced by two factors: the type of rocks, which define the resistance to the denudation, and the tectonic activity, which has strongly determined the form of the mountains and the orientation of the stream networks. As above mentioned, the river basin is well delimited by three systems: The mountain chain: “Sierra de Trujillo”, dividing the catchment area in the north-west part; The Branch called “Ramal de El Rosario”, which made the water divide in the south-east side (see Figure 2.1). Both systems finally converge in the Páramo Cendé (3,652 m.a.s.l) where the mountain Chain “Sierra de Barbacoas” begin. Between the massive chains the ancient tectonic lead to form a kind of depression called “The Depression of Boconó” (Vivas, 1992), in which the Quaternary deposits, as well as the erosive activity of the river helped to built a relatively extensive upland river valley.

The elevation ranges from 3652 m.a.s.l in the Páramo Cendé, and 1100 m.a.s.l. in the confluence between the Boconó and Burate rivers, thus making a gradient of 2552 m.a.s.l.

This elevation gradient has a paramount importance in topographical, climatological and geoecological terms, because it defines differences across the landscape which has many implications in the dynamic of water resources. Particularly topographical and morphological conditions are then complex and varied, leading to the existence of deep and extensive hillsides, in contrast with another forms like risks, escarpments and alluviums; thus, the slopes are quite varied across the landscape system. The Figure 2.2 shows the configuration of slopes in the area.

Only a 3,6% of the total surface seems to have slope range between 0° - 8°, spatially confined to the fluvial plains and, in some cases, to the eroded ridge crests. On the other side, a 43, 9% of the surface is in the range of 30 – 50°, that is, the area has a predominant dissected landscape. 22,4 % of surface ranges between 15 – 30°, and finally the 23,9 % of the surface area has slope > 50°. This slope – patterns has serious implications in processes like denudation, erosion, pedogenesis, and also in the dynamic of water, particularly the overland flow across the landscape system.

3.4. - Topographical Orientation and Aspect dynamic

Obviously, the catchment has the same orientation as the whole mountain range, that is, from SW to NE; this simply determines the Aspect for the incidence of the sun radiation. The Figure 3.3 shows the spatial pattern for the Aspect across the catchment.

The 51,4 % of the total surface and specially the hillsides facing to the north-east, receiving more solar radiation than the hillsides facing to the south-west (48,6%). The spatial pattern for the Aspect is very important in the distribution of the sun energy into the catchment area, which has climatic implications and hence made a control in the land cover patterns. In the Area the hillsides facing to Southwest (48,6% of surface) receives always less radiation, so they are more humid and hence have a more dense land cover (specially the Tropical Montane Cloudy Forest - TMCF). Obviously this has hydrological implications, having a strong spatial influence in the spatial distribution of the overland flows and the water yield.

3.5 Geological Structure and framework

The Figure 3.4 shows the spatial distribution of the main lithological types within the catchment. The area rest over a diverse lithology consisting of: crystalline rocks of deep origin formed during the Precambrian Era, as well as metamorphic and sedimentary rocks formed during the Paleozoic era (Cornieles, 1997). Deposits of the Tertiary, as well as recent

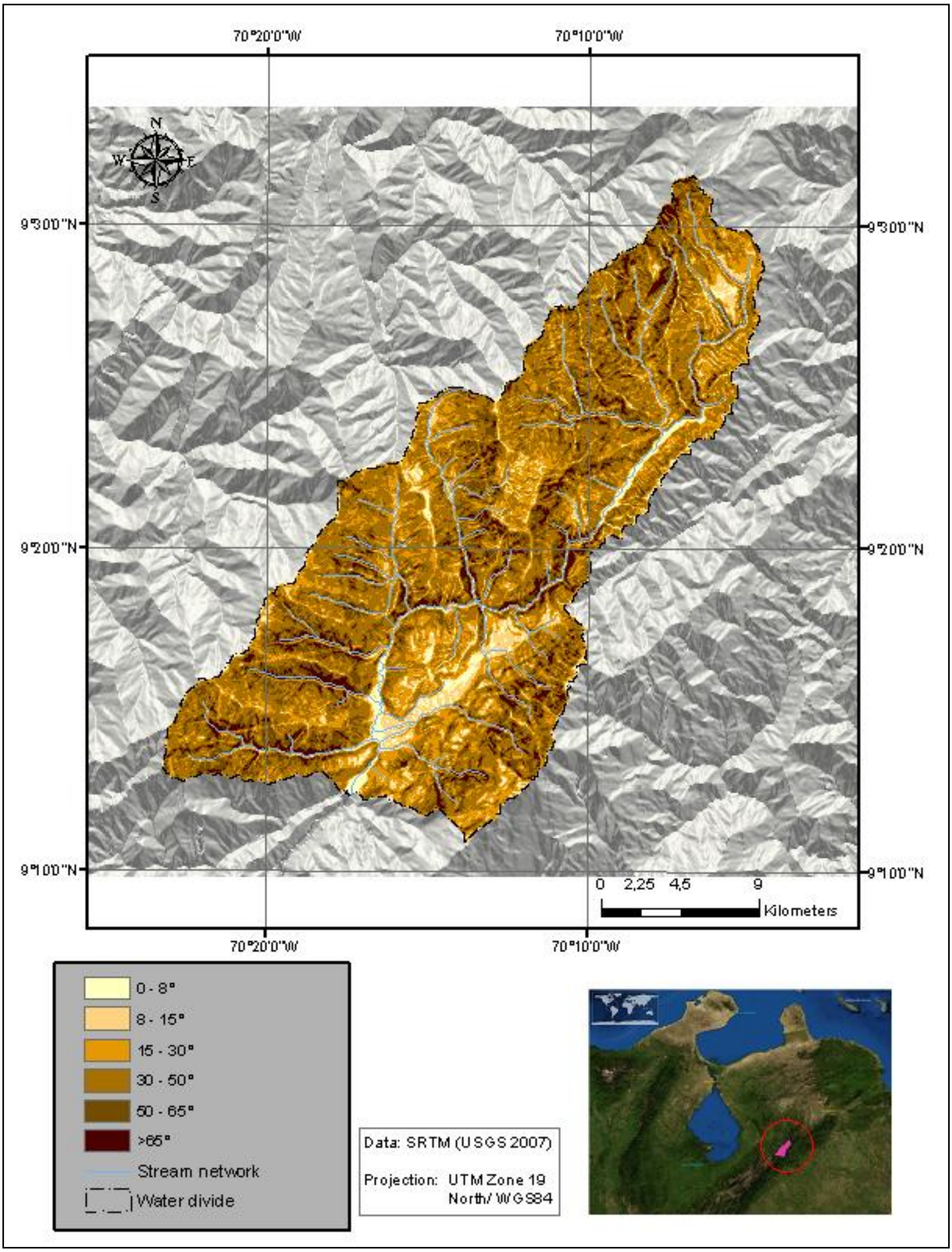


Figure 3.2. - Configuration of the Slope Gradient in the Study Area.

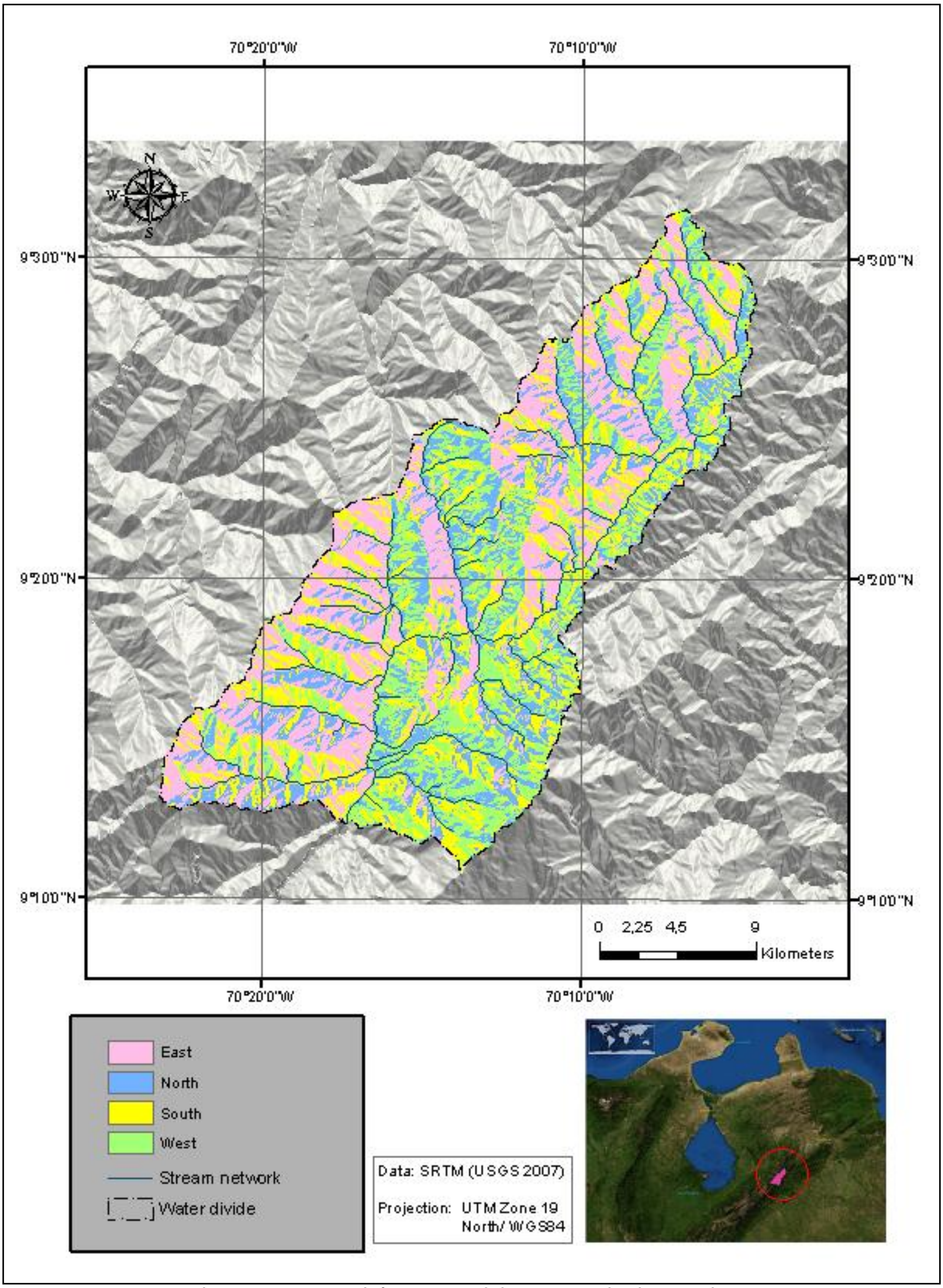


Figure 3.3. - Spatial pattern of the Aspect in the Study Area.

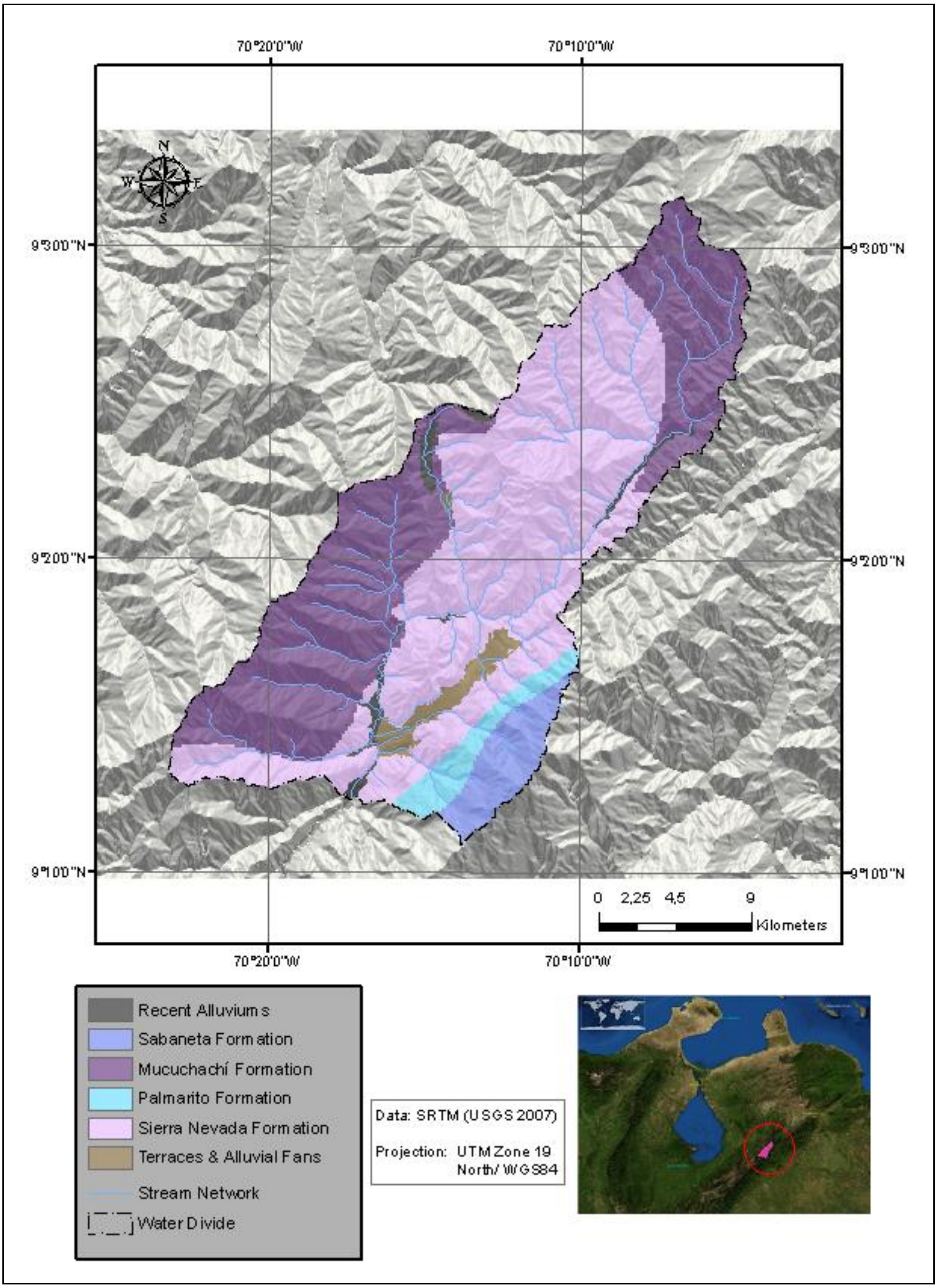


Figure 3.4. - Geological Framework for the Study Area.

alluviums are also present. The rock formations and its main characteristics are synthesized in Table 3.1.
The very intense tectonic activity occurred during the Tertiary and Quaternary periods are traduced in well developed quaternary landforms like alluvial-colluvial fans and terraces (Fig 2.4), as well as the particular highly smoothed ridge crests in places like Loma de Mitimbís and Loma de Pabellón (Ostos, 1975).

As seen in Table 3.1, the area posses igneous crystalline rocks like Granit, metamorphic rocks like gneiss, schist, slate and phyllite, and sedimentary ones like conglomerate, sandstone, siltstone, limestone and shale (Ministerio de Minas e Hidrocarburos, 1969). All these types are basically indurate material (Gregory & Walling, 1973), except the sediments contained within the alluviums, which are usually unconsolidated material. Obviously, all of them have different physical and chemical properties, showing differences in mechanical behavior as well as hydrological response.

Due to the intense tectonic activity, all the rocks formations are severely jointed, so that they are highly prone to the weathering, disintegration and the subsequent transport through colluvial and alluvial processes (Gil, 2000). The climatic and ecological conditions also promote the rapid decay of many rock-types (Goudie, 1985). This have had a paramount importance in terms of denudation, geomorphic processes, soil formation, so that the water dynamic is also seriously affected through changes in the relation surface flow vs. infiltration, changes in intensity of erosion, transport and deposition, suspended sediments, as well as the chemical composition of the water. This will be more detailed discussed later in this chapter.

2.6. - Land forms

The factors above discussed particularly the topographic and geological conditions and framework, have been working together in an integrated way to sculpt the relief, producing different landforms, which are typical in this kind of environments. Thus, a landscape system composed by: structural risks, erosion risks, structural escarpments, hillsides, alluvial accumulations and two relatively extensive upland fluvial plains are present in the area. The complex of geobiophysical relationships occurring in such landscape system has played an important role in the distribution of the natural resources, influencing directly the patterns of the human settlements in the area.

Table 3.1- General outline of the Geological Framework in the Boconó River Basin, and its hydrological implications.

Era	Period	Epoch	Lithological Unit Formation	Lithological composition	General characteristics	Hydrological implications
Cenozoic	Quaternary	Holocene	Recent alluvions	Deposits of alluvial sediments and unconsolidated alluvium	Conglomerates, sand, silt and clay. Material heterometric	High porosity High permeability
		Pleistocene	Terraces - alluvial fans	Continental deposits of consolidated sediments, rubble material	Variable heterometry High content of clay and silt	Moderate to high porosity Moderate permeability
Paleozoic	Permian	-	Palmarito	Marine shale, siltstone, shale and sand silt loam. In some cases gray limestone	Mechanically weak High erodability	Moderate porosity Low permeability Drainage density tends to be moderate to high High producer of sediments
	Carboniferous-Permian	-	Sabaneta	A thick sequence of sandstone pebbles, gray to brown, as well as metalimolite phyllites, schists and metaconglomerates. In southeastern part of the Boconó river there are conglomerates and blue-gray slate	Steep slopes High erodability Well-drained soils	Moderate porosity Moderate permeability Tends to produce low drainage density under dense forest cover Water production tends to be high High producer of sediments
	Carboniferous-Permian	-	Mucuchachí	Laminated silty slates and gray black to green slate, and partly carbonaceous phyllite	Jointing Middle height hills Drainage tends to be abundant High erodability and mass movements High degree of weathering	Low porosity Low permeability Drainage tends to be abundant
Precambrian	Precambrian	-	Sierra Nevada	Granit, Gneiss and schist	Tectonic jointing. Soils with low fertility Stony soils	moderate porosity low permeability Drainage density tends to be low Water production tends to be high Alkalinity Suspended material: feldspar and biotite mica and moscovite

Source: MMH (1969); Strahler (1969); Gregory & Walling (1973); Vivas (1992); Brigg & Smithson(1993); Cornieles (1997); Gil (2000).

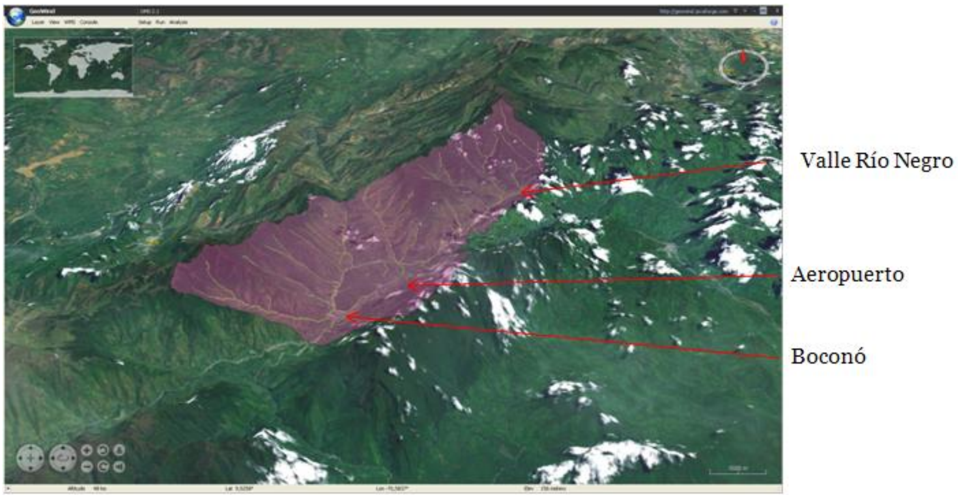
3.7. - Climatic controls

The Boconó river Basin is located in the Andean sector which forms the upland region of the Orinoco river basin, which means that the area is directly influenced by the climatic factors controlling the precipitation patterns in the region of the west plains called "Llanos Occidentales" (Andressen et al, 2000).

The tropical Americas have no major monsoon system because of the geographical configuration, so that the march of the precipitation in the region is quite different as those in the "monsoon areas" (Pulwarty et. al, 1998). Climate in the Llanos region is strongly governed by the action of the Intertropical Convergence Zone (ITCZ), having a unimodal rainfall regime with a July-August maximum over the whole region.

Climate of the catchment area is established as a succession of per humid mesothermic climates of tropical mountains, with a unique maximum value for rainfalls occurring between May/June/July (Andressen et. al, 2000). However, the combined action of the altitude and latitude lead to establish important differences in mesoclimates and microclimates within the river basin. The complex configuration of the topography makes these differences even more diverse.

Latitudinal situation permit to the sun radiation received to be more intense with the altitude, because the dry and less dense air deep into the mountain system cannot absorb the sunbeam. However, the clouds formation derived from the orographic effect, diminish the insolation, influencing the rainfall patterns and the average temperatures across the area (Ostos, 1975). The aspect patterns above discussed makes the process even more complex across the area. This can be observed in the Figure 3.5, which shows a spatial-temporal approximation of the rainfall patterns within the river basin. The observed differences among the rain gauge stations: Boconó (1200 m.a.s.l), Boconó-Aeropuerto (1560 m.a.s.l) and Valle de Río Negro (1720 m.a.s.l) are due the latitudinal-altitudinal, as well as the Aspect effect.
Cornieles (1997) defined two "rainfall penetration areas" in the river basin: the first one is located in the extreme south-east (Branch El Rosario), where the air mass discharges the humidity across the hillside, receiving heavy precipitation. The second one is located in the north-east part of the catchment, the upland sector of the river basin, where the Boconó River begins, and where the rain gauge station "Valle de Río Negro" is located (see Figure 3.5).
The constant presence of clouds in mountainous areas may also increase precipitation levels



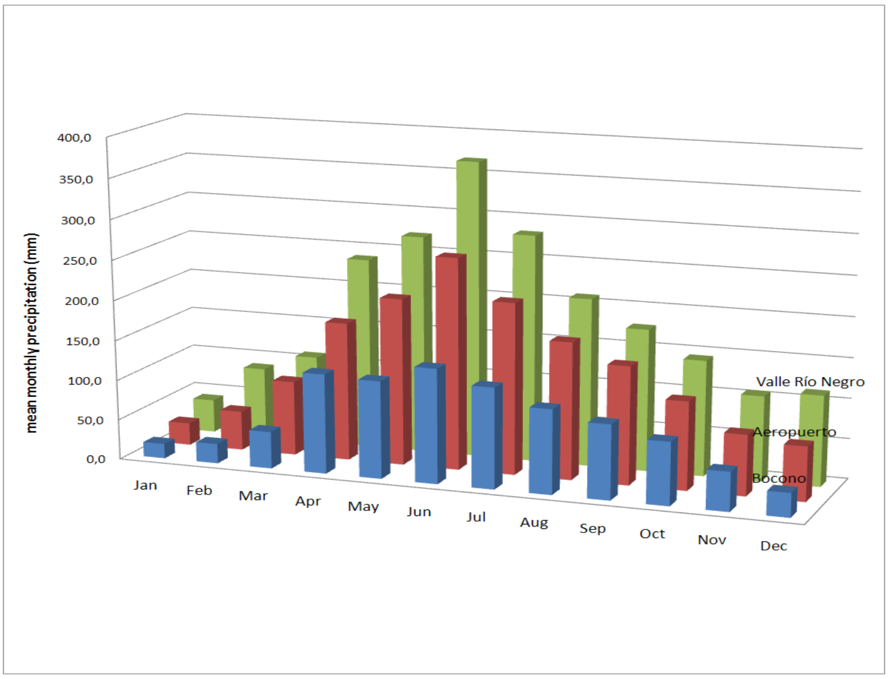


Figure 3.5. - Mean annual monthly precipitation for three Gauge Stations in the Boconó river basin.

through the fog drip produced when the water droplets from clouds are caught by trees (Goudie, 1985). In the area this is expected to occur into the Tropical Montane Cloudy Forest (TMCF), which is present in many sectors, having a very important contribution to moisture conditions, water regulation, and water production. This will be more detailed discussed later.

The temperature is also affected by the factors above mentioned. Figure 2.6 shows the annual distribution of the temperatures measured in the Station: Boconó-Aeropuerto. This is a typical isothermal regime characteristic of the tropical climates, with a very little variation across the year. The lowest values of temperature are expected to occur between December and January, when the whole region is influenced by the polar fronts during the winter in the north hemisphere. However, a little inflexion in the mean and minimal temperature occurs in July, probably explained by the effect of the cloudiness during the rainy season. This effect is even more intense for the average maximum temperature, which suggests that the effect produced by the cloudiness could be more intense during the afternoon, when the maximum temperature is expected to occur.

3.8. - Soils formation

All the processes above described and discussed act together as controlling factors in the processes related to the soils formation and evolution. The hydrological dynamic also affect the pedological processes, through the processes of denudation, meteorization, erosion, transport and deposition of diverse materials. Unfortunately, the available information concerning to soil types and characteristics in the basin is quite scarce, and detailed surveys have not been yet conduced (Nuñez, 1984) (Cornieles, 1997). The spatial pattern of soil types in the area is showed in Figure 2.7. The most important taxonomic categories in the area are: Ultisol, Inceptisol and Entisol (Cuesta, 1984).

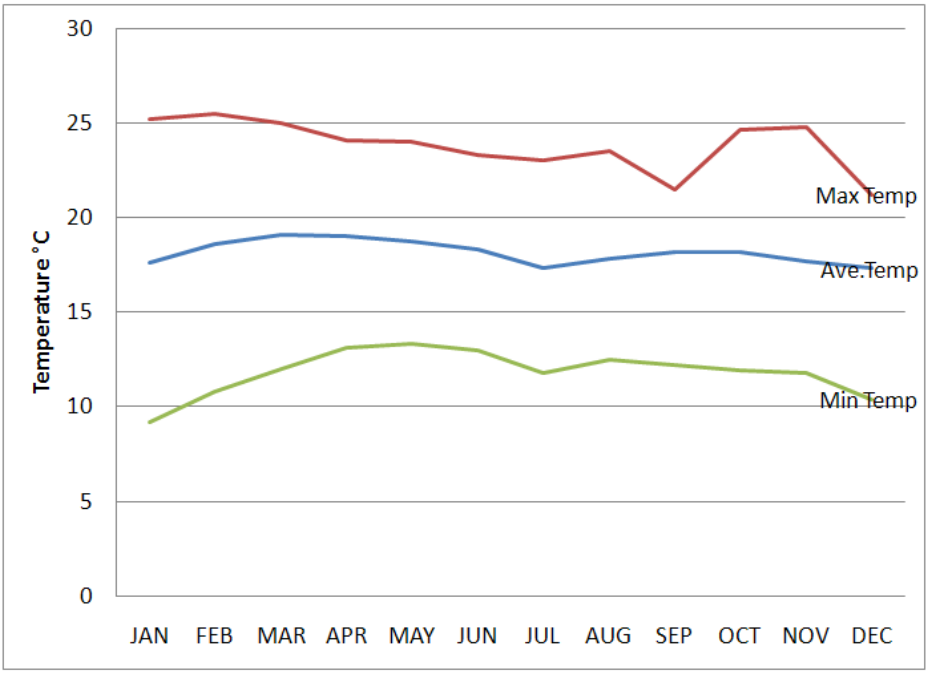


Figure 3.6. - Mean annual Temperature in the Boconó-Aeropuerto Station.

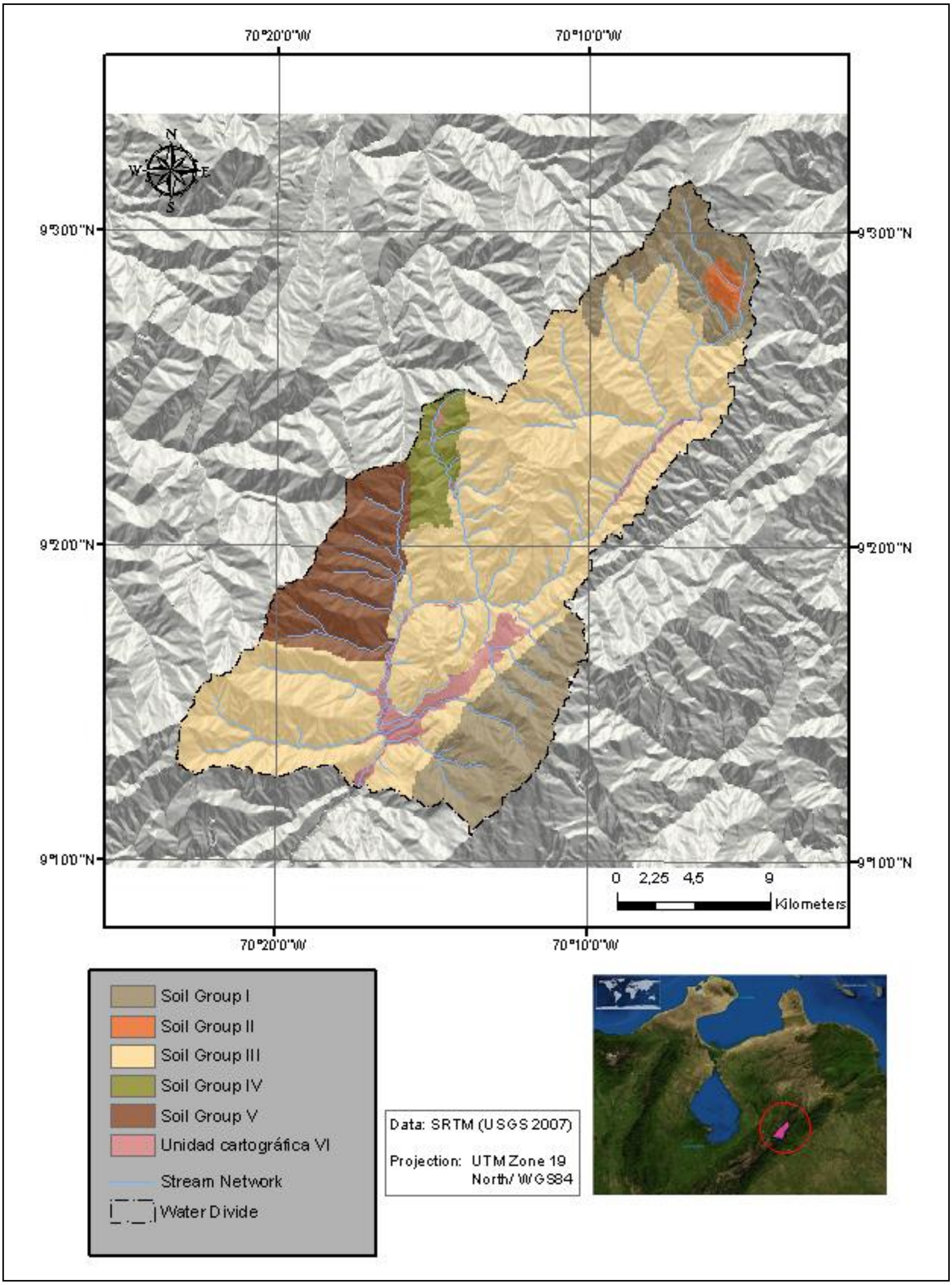


Figure 3.7. - Main Soil types in the Boconó river Basin.

(Bizarro, 1985). Mollisols and Alfisols are also present but they are restricted to small areas like toe slopes and alluvial plains in the upland valley.

Soils of the Group I are derived from the metamorphic and sedimentary rocks of the Mucuchachí, Sabaneta and Palmarito Formations. Basically Tropohumults and Tropudults are present, which generally have a clayed texture; consequently they are moderate to poorly drained soils (Nuñez, 1984) (Bone et al, 1985). Soils of the Group II are formed from silty slates (Mucuchachí) in a low sloping zone, having a moderate structure, a sandy loam texture which implies a high permeability.

Soils of the Group III are derived from the Sierra Nevada formation, with Granit, Gneiss and Schist as parent material (Table 2.1). They are Ultisols, basically Tropohumults, showing silty loam and clayed textures; thus, the permeability is moderate to low. In some cases can be also founded Humitropepts and Dystropepts in this Group (Guerrero, 1984).

The Groups IV and V are derived from materials of the Mucuchachí Formation (Table 2.1). For the Group IV are the Ultisols (Tropohumults) the dominant type. The soil texture is Loamy, having a moderate permeability. The soils of the Group V are Inceptisols, where the humitropepts are the dominating type. They have a sandy clay loam texture, which lead to have a moderate permeability.

The last soil group (VI) is formed from the Cuaternary forms and processes. In the alluvial terraces and fans the types Haplustulsts and Haplustalfs were formed, having sandy loam and sandy clay loam textures. In the recent alluviums can be found soils of the types: Troporthents and Tropofluvents; they have a sandy loam and loamy sand textures, and a moderate to rapid permeability.

In general, all the soil types have a common element: the pH condition. The acidity is normally moderate to high, because of the geologic framework.

3.9. - Hydrological patterns.

All the characteristics above mentioned and discussed act joined as main factors controlling the hydrological configuration of the area, as well as the hydrological processes. As a typical mountainous river basin, the Boconó have a dendritic-rectangular stream network system flowing from mountain ridges to the down part of a relatively extensive upland valley. It is naturally a middle order system (fourth-order according to Strahler, 1969), in which the first-order streams widely dominate the landscape, being the head of the stream system, and also the primary conduits for water, sediment and also vegetative material routed from hillslopes to higher- order channels. There are 52 first-order streams in the basin; 13 second-order streams and only 3 third-order streams. The fourth-order is reached in the confluence between the Boconó and San Miguel rivers.

According to Naiman (1992), first and second order streams are naturally prone to catastrophic erosion because steep slopes adjacent to steep channels favor landslides and debris flows. The study area is not an exception in this case, and the erosive processes are very intensive in some areas due to the combination of the biophysical factors above discussed, and the anthropogenic dynamic. Particularly the sub-watersheds of San Miguel and San Rafael show a complex dynamic, with many evidences of strong erosion processes (Nuñez, 1984; Bone et al., 1985; Cornieles, 1997; Caraballo, 2011). The catchment has a drainage density of 6 km. ha^{-1} (Cornieles, 1997); controlled by the rocks formations and a dense forest cover in the areas where the first-order streams are present.

In the area are present five of the 7 basic channel types defined by Montgomery & Buffington (1997) (In: Ward & Trimble, 2004): Cascade channels, step-pool channels and colluvial channels are usually found in the hillsides; meanwhile, a combination of pool-riffle channels and plane-bed channels dominate in the lowest part, where the upland valleys have been developing during the recent past.

3.9.1. - Approximation to the hydrological landscapes in the Boconó River Basin.

According to the conceptual model for hydrological landscapes presented by Winter (2000) and Winter (2001), the study area corresponds to a mountainous valley landscape system. The Figure 3.8a shows a generalized visualization of the hydrological landscape of narrow uplands and lowlands separated by a large steep valley, according to Winter (2001). Figure 3.8b presents an adaptation of the concept to the river basin. There can be seen the landscapes system in a simplified form, in which the system is composed by 3 main Fundamental Hydrological Landscape Units (FHLU), to be described:

A) FHLU 1: this unit corresponds to the broad ridge crests located in the highest parts of the basin, where the ecosystem Páramo exist. In these units the ancient periglacial processes modeled a very typical landscape, identified by Winter (2001) as “Hummocky terrain”. This landscape is quite complex consisting of a succession of small hills and depressions, which in some

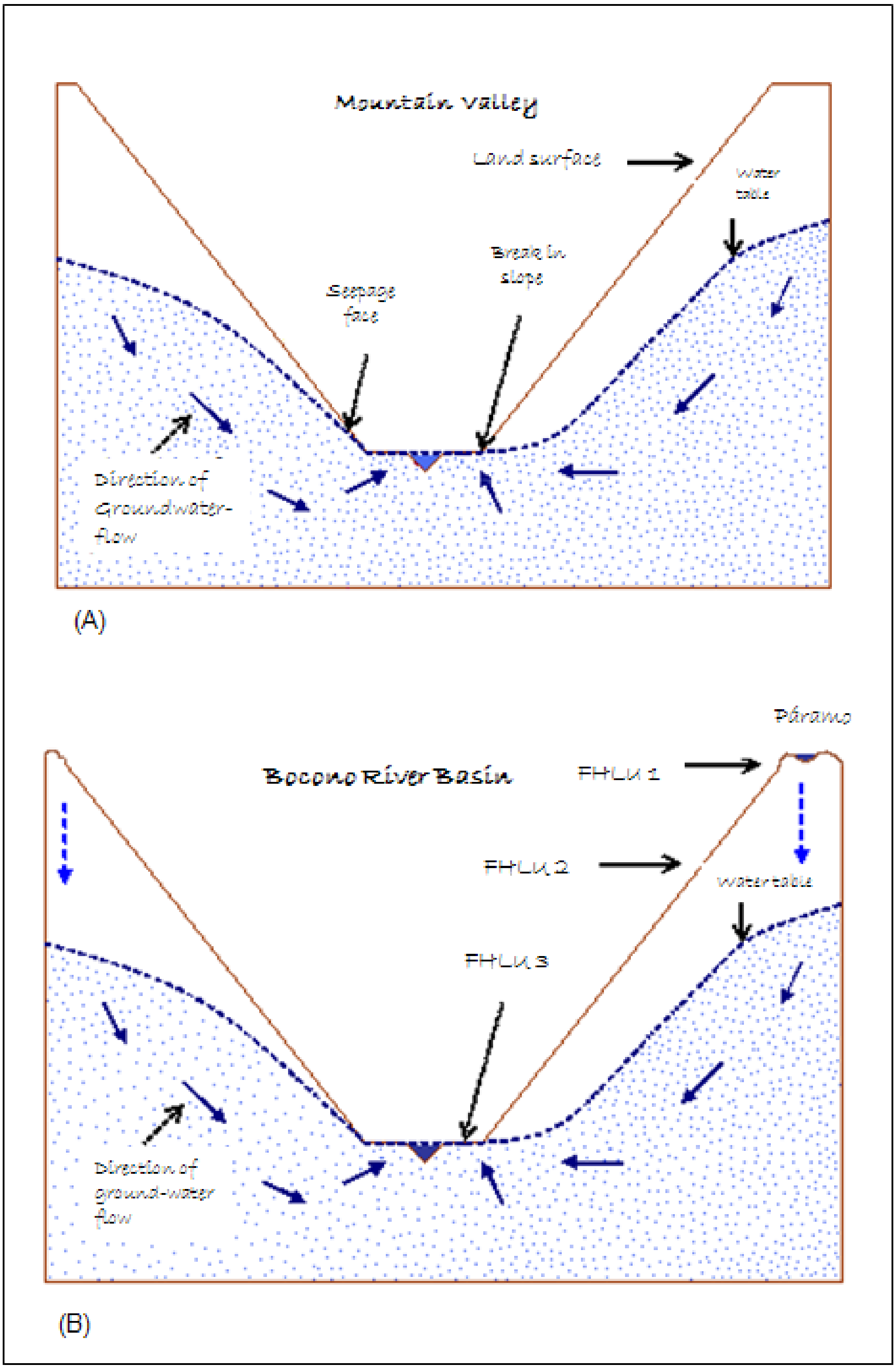


Figure 3.8. - General Overview of the Hydrological landscape system in mountain environments. (A) Generalized framework for mountainous terrain from Winter (2001). (B): The Winter´s framework adapted to the study area.

cases let the water to be dammed in little pounds, lakes or swamps. In many cases this kind of "andine wetlands" are the beginning of some first-order streams.

The dynamic of water flows is very complex, due to a wide variety of interactions between wetlands and ground water (Winter, 2000). Here there is any integrated stream drainage network, so streamflow is not the main source of water for the wetlands; they depend primarily on interaction with groundwater and with atmospheric water also. For this reason, these kinds of wetlands are usually highly vulnerable to the climatic change (Winter, 2000). Infiltration and groundwater recharge are both very important processes to occur in this kind of units (Park & Van de Giesen, 2004). The Figure 3.9 shows a view of "Las Lajas" sector in the south – west part of the river basin. In the broad ridge crest like those located in this area, some "andine wetlands" like little pounds, lakes or swamps currently exist.

B) FHLU 2: this type of landscape corresponds to the more extensive unit in this kind of landscape systems. Is formed by the extensive hillsides and intervening steeper slopes across the river basin. In these areas the surface runoff (overland flow) tends to be more important than the groundwater dynamic (Winter, 2001) (Park & Van de Giesen, 2004);

(a) (b)

Figure 3.9. - Andine wetlands located in the Broad crest forming the FHLU 1 in the River Basin. (a) Páramo "Las Lajas", in the south – west part of the catchment. (b) Páramo Guaramacal (Guaramacal National Park), in the south-east part of the catchment.

and the recharge of the ground water is highly depending on the geologic framework. The nature and intensity of the surface runoff depends on the atmospheric water (intensity of precipitations), the slope, as well as the geological framework. In this units begin the stream network, and the first-order and second-order streams are always present. Because of the dominating steep slopes, the following kinds of channels are found: cascade channels, step-pool channels colluvial channels and bedrock channels. (Montgomery & Buffington,1997) (In: Ward & Trimble, 2004).

Erosion and sediment transport are also very important in these FHLUs, also they can receive sediments from the dissected hillsides and transport it until the valley. This largely depends on the geologic framework, the soil types and the land cover. In the area the cleared and cultivated lands lying over sandy loam soils of the Sierra Nevada Formation are surely highly prone to be eroded. Hillsides lying over shale, limestone or phyllites of Sabaneta and Palmarito Formations are prone to landslides, consequently they tends to be source-areas of sediments.

The Figure 3.10 show a partial view of an extensive convex hillside in the San Miguel Watershed, under different categories of LULC, affecting the production and intensity of the overland flow, which is very important in this type of FHLU.

Figure 3.10. - Extensive convex hillside in the San Miguel Watershed, example of the FHLU 2 in the area.

The river basin is well connected through an intensive road network (Quevedo, 1997). Particularly the watersheds of San Miguel and San Rafael have a very extensive road network. Rural roads and trails in hillsides are one the most important sources of sediments in mountainous areas (Chang, 2003) (Verburg, 2004), affecting also the water quality.

C) FHLU 3: this unit is restricted to the bottom of the valley, which correspond to the lowlands in the river basin. The slopes are gently and flat, letting to the middle-order streams (third and fourth-order streams) to be well developed. The flatter slopes leads to the ground water recharge to be important here, and the stream drainage networks coming from the last unit play a very important role in the surface runoff. According to Park & Van de Giesen (2004), the saturation excess overland flow and channel flow are the dominant processes in this landscape unit. The atmospheric water is in turn not important in this area or its role in the surface runoff is simply limited. Plane-bed channels as well as pool-riffle channels are present, being characteristics in this kind of landscapes units. Transport and deposition of sediments are two relevant processes to occur in this kind of FHLUs, as the slope let to the water to leave the charge of sediments across the fluvial plain. The Figure 3.11 shows a part of the fluvial plain of the Boconó River, forming the FHLU 3.

Figure 3.11. - Fluvial plain of the Boconó River, forming the FHLU 3 in the area.

The Figure 3.12 shows the distribution of the main terrain forms in the river basin, which are highly coincident with the FHLU defining the hydrological landscapes in the area. The ridge crest match with the FHLU 1 and are relative extensive in the area, occupying 163,1 km² (30,3 %); this is explained by the geologic framework. The jointed materials and the tectonic dynamic result in such kind of forms of the crests, many of them are showing a hilly form in the top part of the massive mountains. This is more evident in the sector Loma Pabellón and Mitimbís, where the gneiss from Sierra Nevada is strongly jointed, showing very hilly ridges (Ostos, 1975). However, must be noted here that the typical “Hummocky terrain” forms are spatially confined to the higher ridge crests, located above 2900 m.a.s.l., which were affected by the ancient glacial processes (Vivas, 1992). The peaks and narrow ridge crest represent only 0,7% of the total surface (3,8 Km²).

The concave-convex breaks are the most representative terrain form, extending across 195,3 Km², that is, the 36,3% of the total surface. They match with the FHLU 2, including the hillsides and slopes which capture and transport the surface runoff until the channel´s system. The slope gradient, as well as the geological framework governs the ability of the breaks to generate surface runoff. The land cover can also affect this dynamic, so the existence of a dense forest implies that the hydrological processes are strongly regulated. In the case of the Tropical Montane Cloudy Forest (TMCF), the regulation is further accompanied with an additional production of moisture from the cloudiness, the horizontal precipitation and the augmented condensation. This effect will be more discussed below. This means that the land cover is also very important to consider in the differentiation of FHLU, particularly in this kind of environments.

The channel surface in the river basin cover 153,9 Km², that is, the 28,6% of the total surface. This category match with the FHLU 3, covering the bottom of the valley where the main stream flows. Is important to note, that in this case the extension of the channels seems to be exaggerated, which could be because of the type of method used for the calculation here. Many channels located in upland areas, close to the basis of the first-order streams are really part of the FHLU 2. The slope and the dissection of the land surface don’t let to develop a channel-valley wide enough to be considered part of the FHLU 3. So the FHLU 3 is strictly confined to the channels where the middle-order streams (third and fourth-order) flows through the landscape. Nevertheless, the magnitude of the channel system, as resulted from the model, can be used as evidence of the high suitability observed in the Boconó river basin to concentrate and lead water flows down streams.

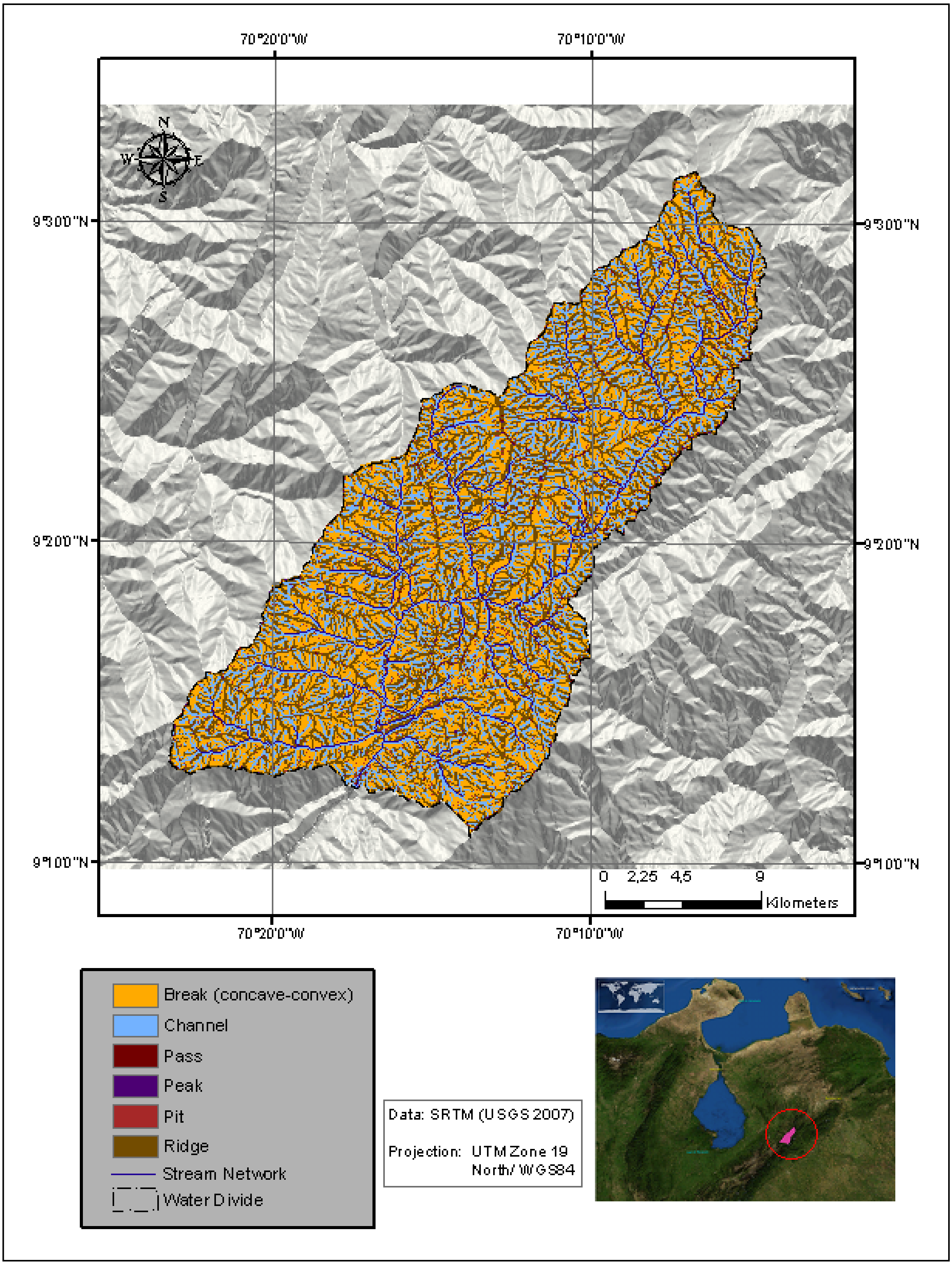


Figure 3.12. - Main Terrain Forms in the Study Area.

In the area only the 1,8% (9,5 Km²) are included as Pass form, being not much important in terms of the dynamic of the water across the landscape. Finally the Pits cover 11,9 km² (2,2% of the total surface). These include the ondulations and depressions in the landscape, which in many cases can retain and dam the water flows.

3.10. - The role of the Land cover in the dynamic of the FHLUs in the area

The ecological conditions, and particularly the type and density of the land cover play a very important role in the hydrological behavior and the hydrological response of the landscape. In last years many authors like: Naiman (1992), Hutjes et al. (1998), Chang (2003), Ward & Trimble (2004), Bonnel & Bruijnzeel (2004), Davie (2008) and Dehnhardt & Petschow (2008), have been highlighting the importance of the vegetation, and particularly the forest ecosystem in the hydrological patterns. In fact, the forests play a very important role in different ways like: hydrological, climatic, mechanic, biologic and social (Chang, 2003); all these functions are intimately related with water production and water quality. Although this aspect will be widely consider in Chapter 4, is important to note here the role of the land cover across the different hydrological landscapes in Boconó River Basin.

The Figure 3.13 shows the land cover and land uses existing in the river basin in 2008. Can be clearly noted the extension of the forest cover in the area. The 44, 6% of the total area is under the Tropical Montane Cloudy Forest (TMCF), a very relevant forest type and ecosystem, which has many important ecological as well as hydrological implications (Bonnel & Bruijnzeel, 2004). This kind of forest is considered particular respect the other types of forest cover, because they can receive substantial additional amounts of "occult" precipitation in form of wind-driven drizzle and fog. The horizontal precipitation coming from the drizzle and fog represent a net gain of water and humidity, which in some cases may reach hundreds of millimeters per year, with typical values ranging between 5 and 20% of vertical rainfall. Reported net precipitation for montane forest subjected to frequent low cloud and fog range from 55 to 80% (Bonnel & Bruijnzeel, 2004).

The last reasons seem to confirm that the TMCF tends to produce more water than other forest types. Moreover, the flows coming from TMCF tends to be more stable during the dry season or periods of lower rainfall. These constitute additional advantages to those well known properties related to the forest in terms of: control of the interception, infiltration, runoff and erosion, and so on.

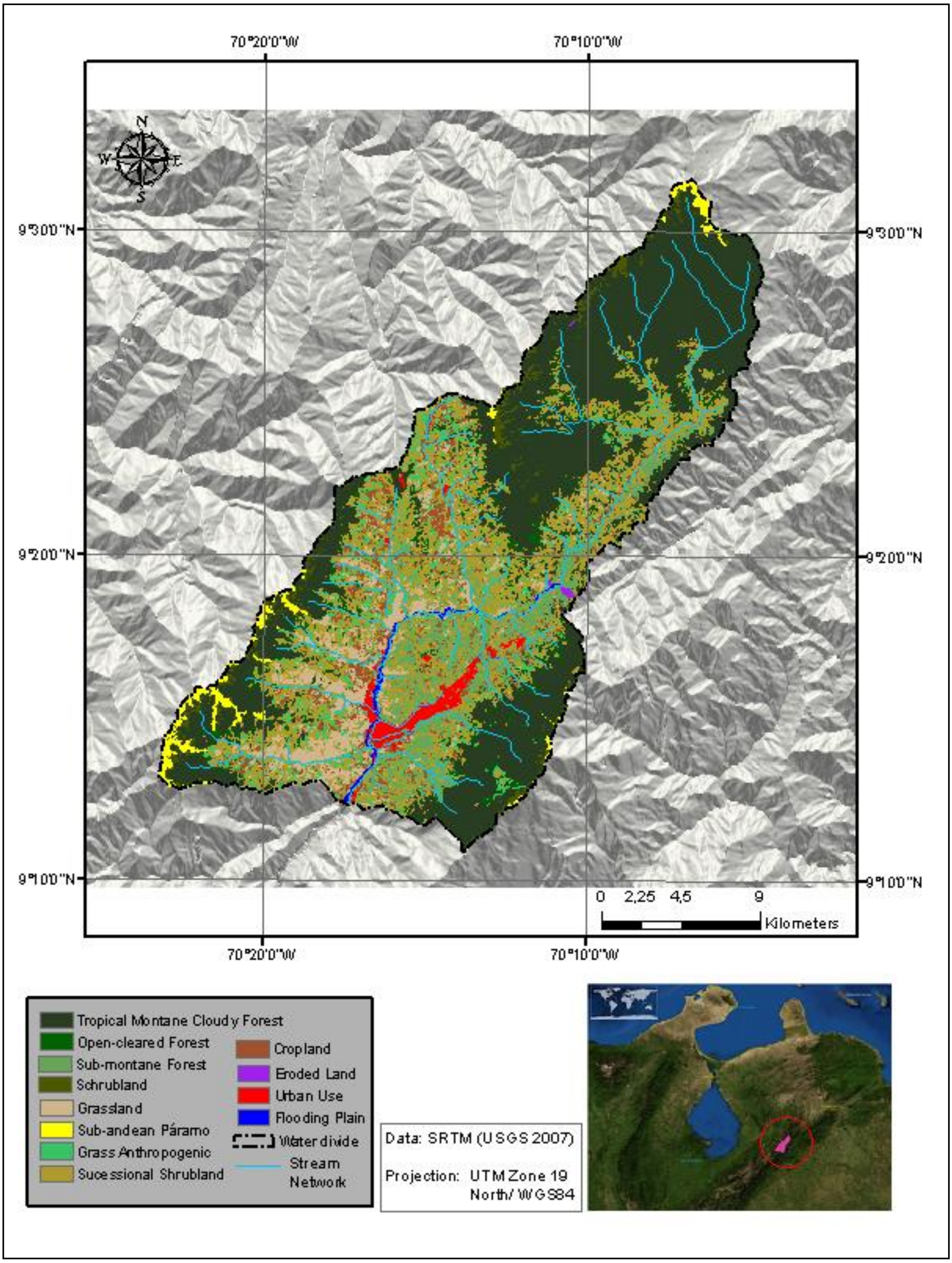


Figure 3.13. - Land use/land cover for the study Area in 2008.

For these reasons it is possible to assert that the FHLUs, and particularly those covered by this ecosystem has to be considered as “**water producer units**”. The location of the TCMF in the river basin can to confirm the asseveration. This ecosystem usually covers the top part and highest sectors of the hillsides or FHLUs 2, where the first-order streams begin. Many of these freshwater streams have being used as a source of water supply for housing and irrigation across the area. In fact, the 9 aqueduct systems existing in the river basin depend on first-order freshwater streams (Bone et al, 1985).

This facts together with the construction of the Boconó – Tucupido Dam system, lead to the Governmental institutions to consider the importance of the water production in this area, promoting the declaration of the Boconó river Basin as a “Protected Area” on 26-05-1974 (Mendez et al, 2004). This declaration was seeking to achieve the following goals:

- to preserve the natural resources of the river basin
- to assure the lifetime of the Boconó – Tucupido Dam system
- to preserve the natural and cultural diversity

In addition, the Guaramacal National Park was declared in 1988, in order to preserve the ecosystems and the biodiversity existing in the flank south-east of the river basin (Muñoz et al, 2006). Hidalgo (2007) evaluated the geographical conditions of the natural resources in the sector “Páramo La Cristalina”, in the flank south-west of the watershed, concluding that the area is susceptible enough to establish a new “Protected Area”, because of the richness that present the biodiversity and other natural resources, as well as the vulnerability of the landscapes in the area.

On the other hand, the sub-montane forest cover only 8 % of the total area, but this ecosystem has been progressively replaced by coffee plantations and little agroforestry systems, so the original forest is really restricted to small areas. Other important ecosystems in the area are: grass, schrubland (successional vegetation), scrub and sub-alpine Páramo, which will be appropriately characterized in Chapter 4.

These categories of land cover coexist also with specific land use types, which are very importance not only in economical terms, but in social and cultural perspectives also. Shifting agriculture is located mostly in upland areas, using clear-cut and burning as usual tasks. Conventional agriculture is also developed in low parts and quaternary landforms, in some cases under irrigation. Coffee plantations are very usual between 800 and 2000 m above sea level, occupying an important portion of the sub-montane forest (Gil, 2000). In a small proportion, the extensive cattle show a moderate development, being spatially confined to the low parts and the quaternary landforms (Macias, 2002). Finally, the 1,6 % of total surface is occupied by urban use, being the Boconó city the most important urban system within the river basin. The land uses will be also presented and detailed discussed in the Chapter 4.

The Boconó river basin posses a geographical configuration that lead to declare it as a “**Water Resource Area**” in a local and regional context. The topographical structure, the geological framework, the climatic controls and the ecological conditions made possible that the area can produce enough freshwater for diverse human purposes. The flows produced are also of great importance to maintain the Boconó-Tucupido Dam system, so the lifetime of this important system largely depend on the water quantity, as well as the quality expressed in the volume of sediments, coming directly from the Boconó and Burate rivers. Naturally, the water production of this river basin, as well as the future of the dam system, are subject to the dynamic related to land cover/land uses occurring upstream into the catchment, the behavior of the annual and seasonal flows, and the possible variations derived of climatic anomalies (ENSO / A-ENSO) or simply the climate change. These are aspects to be considered and discussed in the following chapters.

Chapter 4

Temporal & Spatial LULC Changes in the Boconó River Basin during the Period 1988 – 2008.

4.1- Introduction

On chapter 3 was briefly discussed the role of the LULC categories existing in the river Basin (particularly the TMCF), and the possible implications for the hydrological dynamic in the Boconó river Basin. The rest of the categories existing in the area were mentioned and only gentle explained, being also considered in terms of the hydrological dynamic. This Chapter present the results obtained from the application of the methods included in the so-called Second Methodological Approach. At first, the LULC categories finally identified and characterized are formally presented and displayed. After that, the inter- temporal variation of the categories for the period considered in the multi-temporal analysis will be presented and explained in terms of the persistence, swapping, as well as the main systematic inter-category transitions. The dynamic as well as the trends for the main LULC processes in the area were also considered and compared with trends observed in other tropical regions around the world. Finally, the main implications of the LULC dynamic in the river Basin for the land use planning are conveniently discussed.

4.2. - LULC Categories identified in the Boconó River Basin

Based on the classification processes developed within the Second Methodological Approach explained on last Chapter, twelve (12) Land Use /Land Cover categories were identified in the Boconó River Basin. All the categories were identified and delineated for the 3 time periods evaluated, so all of them remained considered during the whole process inherent to the Second Methodological Approach. The Table 4.1 display the LULC categories, each with the corresponding identity-code, designation, a brief description and finally the surface area in ha and % that each category was showing in 2008. A view of the different LULC categories identified is presented on Appendix A.

As seen on Table 4.1, the Tropical Montane Cloudy Forest (Tmc-F) dominates widely the landscape system in the river basin, covering 22493,97 ha (41,8 % of the total area). This is followed by the Successional Shrubland (S-Shr), which covers 12840,75 ha (23,9 % of the area). The cultivated land (Cropping area (Cro-L)) + Anthropogenic Grassland (Gr-An) are

Table 4.1.- Land Use / Land Cover (LULC) Categories identified in the Boconó River Basin.

Category	Identity-Code	Designation	Description	Surface area (ha) (2008)	Surface area % (2008)
1	Tmc-F	Tropical Montane Cloudy Forest	Multilayered forest with a very complex structure. The vegetation is dominated by evergreen Trees whose crowns may rise up to 35 m height, bearing a large number of different epiphytes (> 100 species). The forest may have accounted for an average of 100 tree species per hectare.	22493,97	41,8
2	Oc-F	Open – Cleared Forest	In fact this category corresponds to the lower sector of the Tropical Montane Cloudy Forest, which is undergoing a clear-cutting process. There are evidences of selective clear cutting of tree species, so that the forest presents a less dense and more open canopy, as well as the presence of successional vegetation.	1522,89	2,8
3	Sm-F	Sub-Montane Forest	Multilayered forest with a complex structure. During the short dry season (1 – 3 months), the upper – canopy trees throw a lot of its leaves, having a reduced foliage; although the lower trees and shrubs are mostly evergreen. The canopy reaches up from 20 to 30 m height; however some individuals trees can reach up to > 40 meters. The coffee plantations, specially the coffee planted under shadow belong also to this category.	4278,51	8,0
4	Schr	Schrub	Open forest with dense vegetation, which can reach a height of 3 – 6 meters. Corresponds to the transitional zone between the High Montane Cloudy Forest and the Sub-andean Paramo.	1277,73	2,4
5	Gr-L	Grasland	Areas with natural mixed herbaceous vegetation ad grass. The vegetation is generally dense and can reach 2 meters height.	3335,76	6,2
6	Cro-L	Cropping area	Area under crop systems typologies diverse as horticulture and coffee without shadow.	2867,4	5,3
7	Sa-P	Sub-andean Páramo	Special ecosystem existing in the whole Andean region, consisting mainly of grass, ground rosettes, dwarf shrubs cushion plants and conspicuos giant rosettes like Espeletia and Puya. However, the vegetation vary greatly depending on the altitude, humidity and other environmental factors.	1114,47	2,1
8	Gr-An	Grasland (anthropogenic)	Areas of cultivated grasses and / or pastures established for extensive grazing and cattle	2832,03	5,3
9	S-Shr	Successional shrubland	Areas with successional vegetation being in regeneration process after the clear cutting, or after they were cultivated. The vegetation usually has low hight and variable density.	12840,75	23,9
10	Ero-L	Eroded Soil	Bare soil surface, prone to the direct action of erosion agents.	39,87	0,1
11	Fl-P	Fluvial Plain	Area occupied by the river bed, usually having low slope where the river can be horizontally expanded.	293,76	0,5
12	Ur-U	Urban Use	Area occupied by the Boconó city, as well as the towns San Miguel and San Rafael. Basically corresponds to a residential, commercial use and associated services.	865,26	1,6

together the third dominant category in the area, covering 5699,43 ha (10,6% of the area) in 2008. The Sub-montane Forest (Sm-F) covers 4278,51 ha (8 % of the area), meanwhile the natural Grassland (Gr-L) spread over 3335,76 ha (6,2%). The altitudinal range where the Sub-montane Forest (Sm-F) is located in the whole Andean region is also coincident with the altitudinal range suited for the coffee plantations. In fact, this ecosystem has been severely reduced because the implementation of coffee plantations (Sarmiento & Ataroff (2004) In: La Marca & Soriano, 2004)). Due to the similar spectral signal showed by the coffee plantations respect to the Sub-montane forest (particularly shade coffee plantations), it was not possible to separate them with an adequate level of accuracy. For this reason the coffee plantations are included in this category.

The Open-cleared Forest (Oc-F) cover 1522,89 ha (2,8%); this category correspond to the lower sectors of the Tmc-F which are prone to a clearing process for logging and wood extraction, as well as non-wood products and plants extraction. The Schrub (Schr) (pre-Páramo) cover 1277,73 (2,4%), and the Sub-andean Páramo (Sa-P), which is a very important andean ecosystem spread over 1114,47 ha (2,1%) across the area. The Urban use (Ur-U) is actually covering 865,26 ha (1,6%) in the river Basin; basically correspond to the urban area of Boconó city, as well as the towns: San Miguel and San Rafael. The Flooding plain (Fl-P) and the Eroded Soil (Ero-L) can be considered as spatially remanent categories, as they only represent 0,5 (293,76 ha) and 0,1 % (865,26 ha) of the surface area, respectively. However, both are very important in terms of the geobiophysical and anthropogenic dynamic; the Flooding plain is not only a basic hydrological landscape unit, but a very important unit for anthropogenic purposes. In fact, the Urban Use in the study area has been expanding among the fluvial plain as the only suitable surface land for such land use. This will be discussed later on this chapter.

The Table 4.2 display the results obtained for the accuracy assessment, applied to the T0, T1 and T2 classifications. The correspondent error matrices for each classification are displayed on Appendix B.

As seen on Table 4.2 and on Appendix B, the best values for accuracy were obtained for T2, and the lowest values were founded for T1. In general, the producer´s and user´s accuracy was greater than 70% for almost all the categories, except for Oc-F, Cro-L, S-Shr and Gr-An, which showed lower values in both cases for T0 and T1. For T0, only Oc-F (50%) and Cro-L

Table 4. 2. - Main results obtained in the Accuracy assessment for the T0, T1 and T2 classifications.

Indicator	T0 (1988)	T1 (1997)	T2 (2008)
Producers Accuracy	87,46	85,02	**91,53**
Users Accuracy	87,62	82,90	**91,67**
Total Accuracy	87,35	82,59	**88,80**
Kappa Coefficient	**0,79**	**0,79**	**0,87**

(63 %) showed lower values for producer´s accuracy, meanwhile all the values were greater than 70% for user´s accuracy (See Appendix B). For T1 the producer´s accuracy was lower for Gr-An (50 %), S-Shr (57,81 %), Cro-L (63,16 %), and Oc-F (66,67 %). For user´s accuracy the Oc-F, Gr-An and Cro-L remained with lower values, showing 53,33 %, 57,14% and 66,67% respectively (See Appendix B). For T2 all the categories showed greater values for both producer´s and user´s accuracy.

4.3.- LULC in T0 (1988), T1 (1997) and T2 (2008)

The Figure 4.1 shows the geographical visualization of the main Land Use / Land Cover (LULC) categories in the river Basin, for T0, T1 and T2, respectively. As above mentioned, the Tmc-F dominates the landscape, respect to the rest of the categories, leading to identify two main sub-systems: (1) Landscape sub-system with homogeneous matrix, which correspond to the surface area covered by the Tmc-F, being spatially confined to the upland sectors within the river basin, usually having a very dissected and sloping relief. (2) Landscape subsystem with a very heterogeneous matrix. The excessive tessellation of the LULC originates the so-called "**chessboard effect**" or "**chessboard landscape**" (Lang & Blaschke, 2007), which is typical of landscapes where the categories are highly fragmented, which suggest a intensive dynamic in the processes of land use/ land cover evolution. This subsystem is confined to the middle-lower part of the river Basin, where the rest of the LULC categories coexist in a very intricate way, showing a very complex and strong patching effect. The corresponding surface values for the Time-points analyzed (T0, T1 and T2), are gentle resumed on Table 4.3. An overview of the differences among the period, lead us to set up a basic differentiation between the LULC categories in three main groups as follow:

a) LULC categories loosing surface: basically the natural LC like forest (Tmc-F, Oc-F, Sm-F) and Grass (Gr-L) are including here. All of them show a decreasing trend

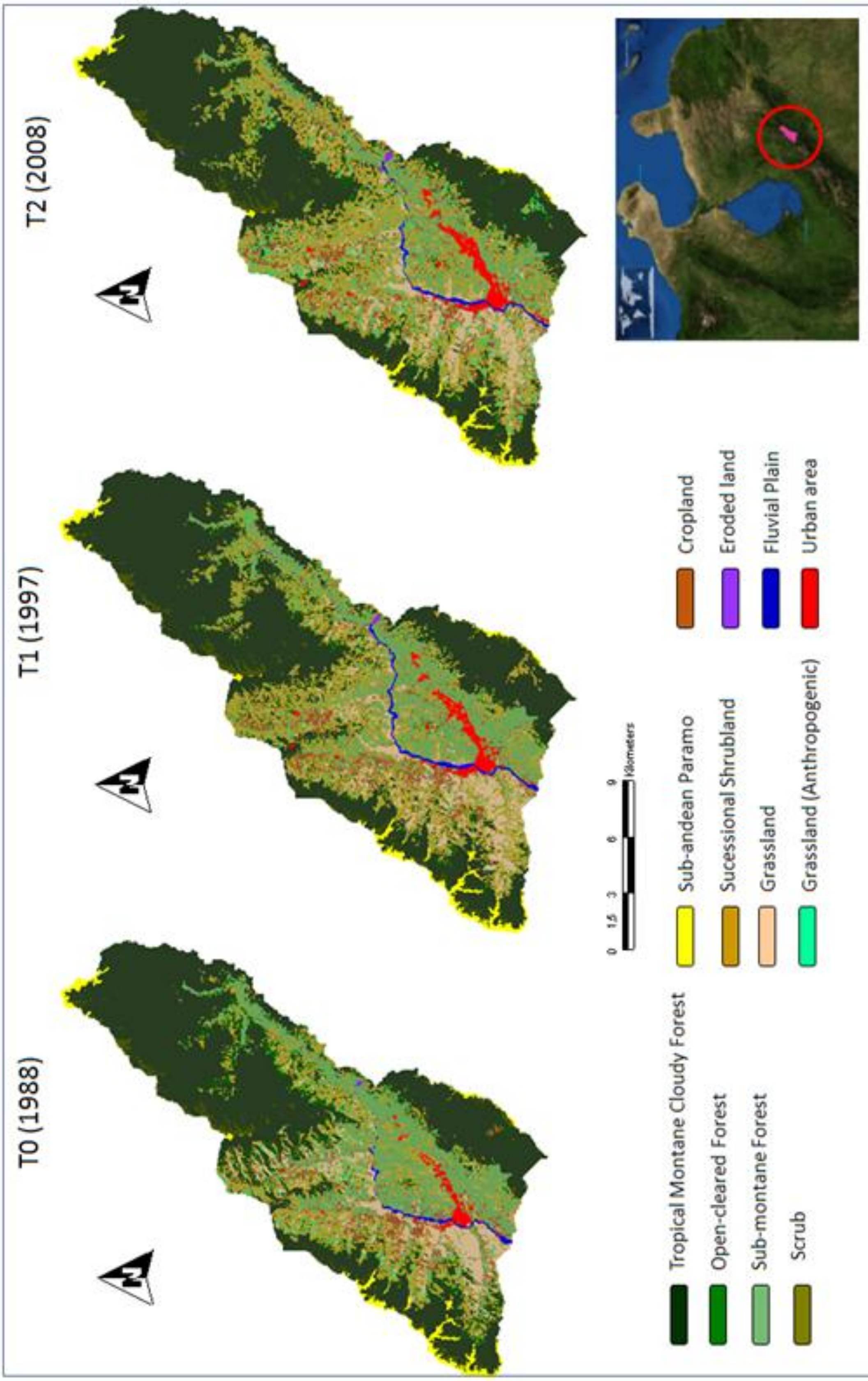


Figure 4.1.- LULC in the Boconó River Basin for T0, T1 and T2

c

between T0 and T2 (except Gr-L, which experienced a light increase between T1 – T2). The Tmc-F and Oc-F had a reduction of 3530,43 ha between T0 – T2, representing the 12,8 % of the total for the two categories combined in 1988. The reduction of the Sm-F in the river basin was more dramatic, losing the 43,1% of the surface area respect to 1988, that is, 3244,59 ha. On the other hand, Gr-L loosed 412,11 ha between T0-T1, and slightly recovered 85,05 ha in the next period, losing a total of 327,06 ha (9 % of the total in 1988).

b) LULC categories gaining surface: they are basically the human-induced types of land cover categories (Gr-An, Cro-L and Ur-U), as well as the categories: Schr and S-Shr. They increased progressively during the period, except Gr-An, which experienced a decrease in T0 – T1; however, the evident increase experienced during T1-T2 justify the inclusion of the category in this group. Gr-An and Cro-L combined, gained 2216,25 ha, representing an increase of 63,6 % of the agriculture dynamic in the river Basin respect 1988. The Urban use (Ur-U) experienced a dramatic increase during the whole period, gaining 99,36 % (431,28 ha) of the surface area that the category occupied in T0. Meanwhile, the LC category S-Shr experienced a big change, gaining almost 50% (49,5%) of the surface area for T0; so the LCC gained a total of 4249,08 ha., respect 1988. During the period Schr category gained 135,36 ha (12%) respect to T0.

Table 4.3.- General evolution of the LULC during the considered period

LULC Categories	1988 (T0)	1997 (T1)	2008 (T2)	Dif T1-T0	Dif T2-T1	Dif total T2-T0
	Area (ha)	**Area (ha)**	**Area (ha)**			
Tmc-F	**24573,78**	**23676,12**	**22493,97**	**-897,66**	**-1182,15**	**-2079,81**
Oc-F	**2973,51**	**1648,8**	**1522,89**	**-1324,71**	**-125,91**	**-1450,62**
Sm-F	**7523,1**	**6224,13**	**4278,51**	**-1298,97**	**-1945,62**	**-3244,59**
Schr	**1142,37**	**1199,88**	**1277,73**	**57,51**	**77,85**	**135,36**
Gr-L	**3662,82**	**3250,71**	**3335,76**	**-412,11**	**85,05**	**-327,06**
Sa-P	**1114,2**	**1117,71**	**1114,47**	**3,51**	**-3,24**	**0,27**
Gr-An	**1280,34**	**1181,16**	**2832,03**	**-99,18**	**1650,87**	**1551,69**
Cro-L	**2202,84**	**2330,46**	**2867,4**	**127,62**	**536,94**	**664,56**
Ero-L	**28,62**	**27,27**	**39,87**	**-1,35**	**12,6**	**11,25**
Ur-U	**433,98**	**729,18**	**865,26**	**295,2**	**136,08**	**431,28**
Fl-P	**234,9**	**391,95**	**293,76**	**157,05**	**-98,19**	**58,86**
S-Shr	**8591,67**	**11984,76**	**12840,75**	**3393,09**	**855,99**	**4249,08**
Total	**53762,13**	**53762,13**	**53762,13**	**-**	**-**	**-**

c) Relatively stable LULC categories: here are included the rest of the LC categories: Sa-P, Ero-L and Fl-P. These categories showed a similar pattern during the whole period, in which they loosed and gained surface, but maintaining its proportionality respect the rest of the LULC categories. The Fl-P gained 157,05 ha (67%) because of the flooding events occurred during the T0-T1. But in the second time-period it loosed 98,19 ha to other categories.

The Figure 4.2 display the relative differences in percentage for the LULC categories between T0 and T2, where the three basic trend can be also observed. These basic groups illustrate the general trends for the recent evolution of the LULCC in the river basin. However, they are only the initial framework to understand the spatial dynamic in the river basin, so they cannot reflect conveniently the spatial changes in a quantitative/qualitative way. The next section provides a more comprehensive and detailed description of the LULC categorical changes for the two time-periods, in terms of quantification, net change, swapping as well as inter-category transitions, using the approach proposed by Pontius et al.(2004).

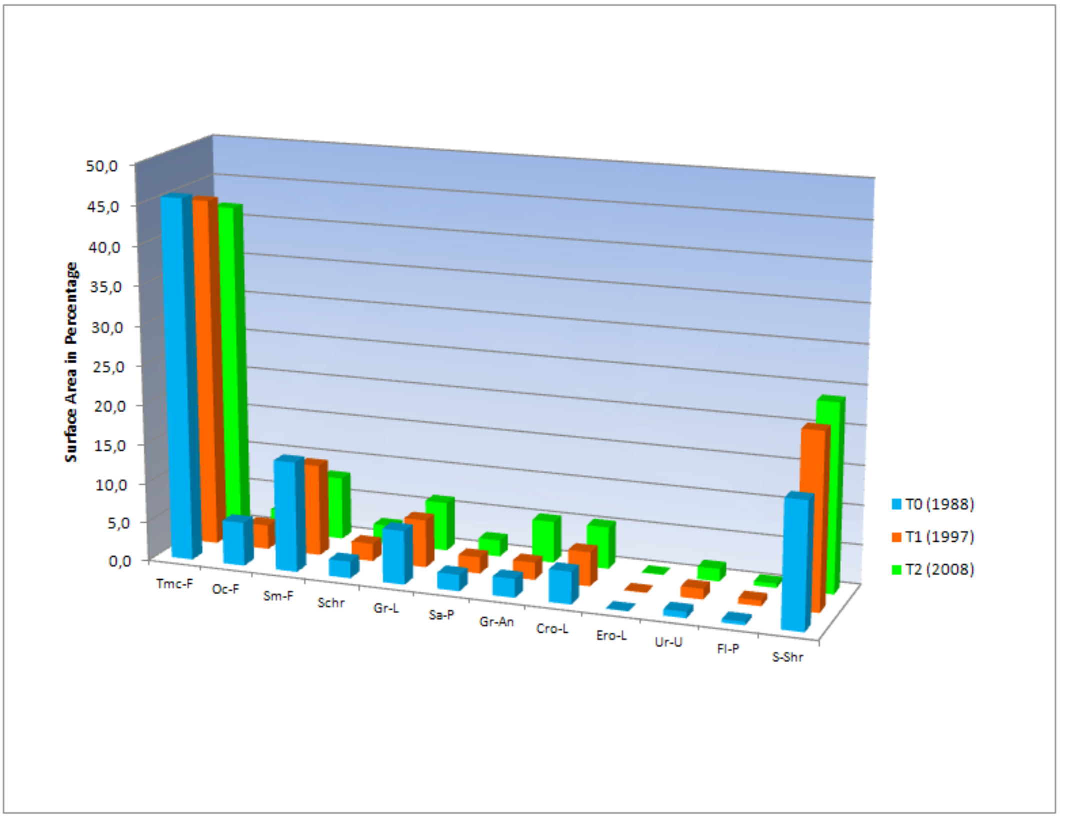


Figure 4.2.- Relative areal distribution of the different LULC categories during the period of study.

4.4. - LULC categorical dynamic and transitions between T0 – T1 – T2.

The values displayed on Table 4.3, show clearly differences among the time-periods for the categorical dynamic, suggesting differences accounted for intensity, diversity and extension of the LULC changes in the study area. For that reason it was considered necessary to drive this analysis separating the time period in two sub-periods, which are going to be explained below:

4.4.1. - LULC categorical changes and transitions for T0 – T1

4.4.1.1. - General quantification of the Change

The Figure 4.3 show the spatial distribution of the changes in the Boconó River Basin, which occurred within the time-period T0-T1. In this period can be observed that the river basin experienced a total change of 30,34%, which means that 16309,89 ha were affected by a kind of spatial change processes, meanwhile the 69,66% of the surface area (37452,24 ha) was accounted as persistent landscape or simply persistence. Thus, persistence dominates widely the landscape system of the river basin, which is considered normal, because the persistence usually dominates most landscapes, including those where authors claim that the change is important and / or large (Pontius et al, 2004).

Velasquez et al (2002) accounted 92% of persistence for natural land covers in Mexico; in the Atlanta metropolitan area (one of the USA´s fastest growing metropolises), there have been 75% persistence over the last 3 decades (Yang & Lo, 2002) (quoted by Pontius et a, 2004). Plata (2007) determined a persistence of 94,2% in the community of Madrid – Spain. Finally, Pineda et al, (2009) accounted 93,3% of landscape persistence in the State of Mexico – Mexico. Finally, Oñate & Bosque (2010), also detected a persistence of 80, 5% in the Catamayo-Chira Basin (Ecuador – Peru).

Although the persistence dominates the landscape, as usual, the persistence value of the Boconó river Basin can be considered slightly lower in comparison with those values above mentioned. This fact is important to highlight, considering that the whole river basin is defined as “**Protected Area**”, with a portion of the surface area belonging to the Guaramacal National Park.

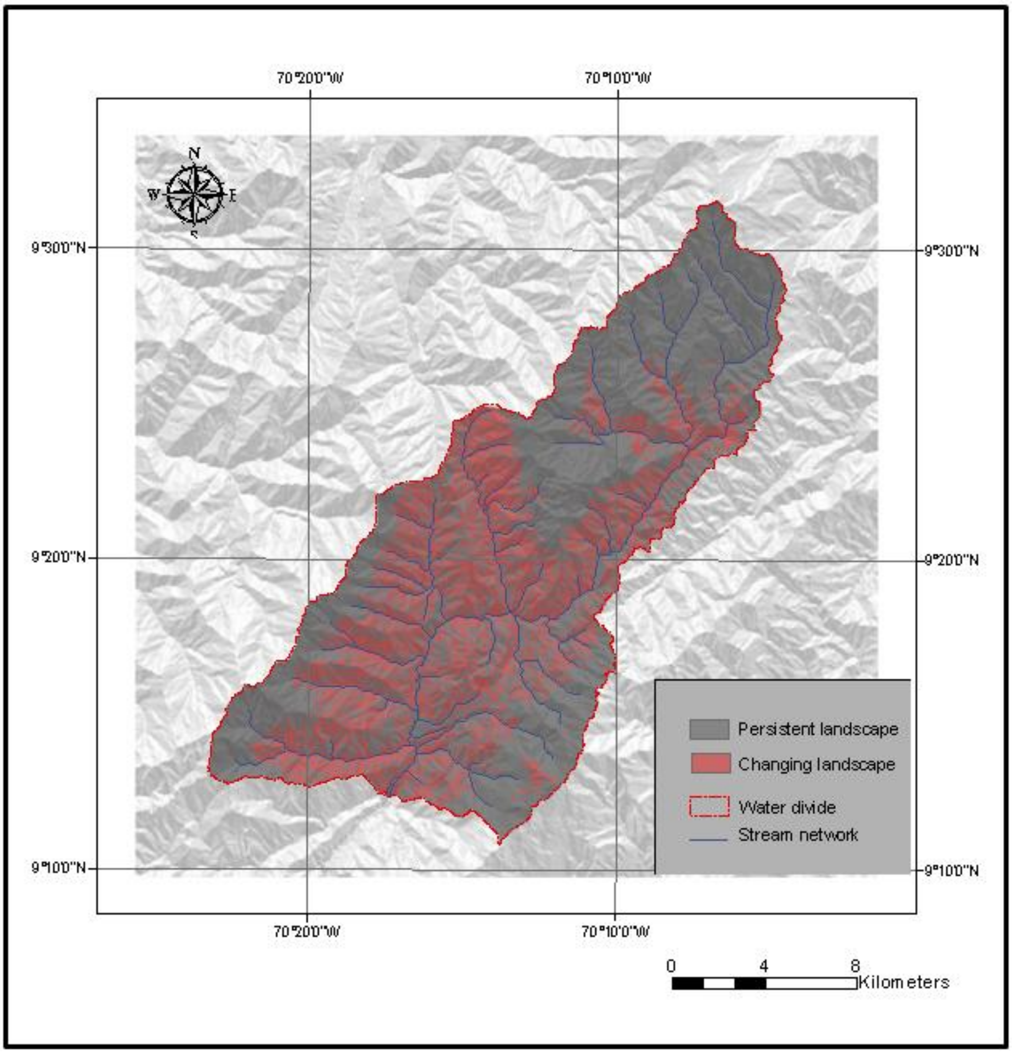


Figure 4.3.- Persistence & changing area in Boconó River Basin for T0 – T1.

The change have been occurring in the middle – lower part of the river basin, basically across the sloping dissected areas, the river valley and some extensive quaternary landforms located in the lowest part; they are coincident with the Fundamental Hydrological Landscape Units (FHLU) number 2 and 3, being consistent with the so – called "**chessboard landscape**".

A more detailed analysis of the transition Matrix derived for the period T0-T1, using the approach proposed by Pontius et al. (2004), lead to interpret the changes in a more detailed perspective, as follows:

4.4.1.2. - Net Change and Swapping

The Table 4.4 resume the landscape dynamic observed for the period T0 – T1. S-Shr was the most dynamic category in the river basin during this period, having a total change which represent the 22,4 % (12037,6 ha), of the total surface. It showed also the highest values for gain and losses respect the rest of LULC. During the period, S-Shr gained 14, 35% of surface area, losing at the same time 8 % to other categories. This category has also the highest value for swapping (16,1 % of the surface area), which means that this LCC constantly experienced changes during the period, losing surface area to other categories and gaining at the same time area from other categories whose changed to this one. Thus, 72% of the change for this category occurred as swapping-change dynamic.

The second more dynamic category in the area was Sm-F, which experienced a total change of 4485, 51 ha, representing the 8, 3% of the total surface area. In this period Sm-F gained 1593, 27 ha (third highest value), which in many cases could represent an expansion of the coffee plantations in the area (included in this category). However, it lost 2892, 24 ha (second highest value) to other categories, representing an important reduction of the forested cover in the area. The category has the third highest value of swapping (3186, 54 ha), which suggest that the Sub-montane Forest also experienced a swapping-change dynamic.

The third category experiencing important changes in the period is the Oc-F, with a total change value of 3721, 41 ha, (7 % of the total area). The Open-cleared Forest gained the fifth biggest portion of surface: 1198, 35 ha, suggesting that the clearcutting and logging in the

Table 4.4.- Landscape Dynamic in the Boconó River Basin for the Period T0 – T1 (1988 – 1997).

LULC Category	Gain		Loss		Total Change		Swap		Absolute value of net change	
	ha	%	ha	%	ha	%	ha	%	ha	%
Tmc-F	792,45	1,474	1690,11	3,143	2482,56	4,617	1584,9	2,948	947,66	1,669
Oc-F	1198,35	2,229	2523,06	4,693	3721,41	6,922	2396,7	4,458	1324,71	2,464
Sm-F	1593,27	2,963	2892,24	5,380	4485,51	8,343	3186,54	5,926	1298,97	2,417
Schr	58,86	0,109	1,35	0,003	60,21	0,112	2,7	0,006	57,51	0,106
Gr-L	1565,1	2,911	1977,21	3,678	3542,31	6,589	3130,2	5,822	412,11	0,767
Sa-P	7,29	0,014	3,78	0,007	11,07	0,021	7,56	0,024	3,51	0,003
Gr-An	1085,49	2,019	1184,67	2,204	2270,16	4,223	2170,98	4,038	99,18	0,185
Cro-L	1789,2	3,328	1661,58	3,091	3450,78	6,419	3323,16	6,180	127,62	0,237
Ero-L	13,59	0,025	14,94	0,028	28,53	0,053	27,18	0,052	1,35	0,003
Ur-U	295,92	0,550	0,72	0,001	296,64	0,551	1,44	0,004	295,2	0,549
Fl-P	195,03	0,363	37,98	0,071	233,01	0,434	75,96	0,142	157,05	0,292
S-Shr	7715,34	14,350	4322,25	8,040	12037,6	22,390	8644,5	16,080	3393,09	6,310
Total	16309,89	30,335	16309,89	30,339	16309,89	30,337	12275,91	22,84	4058,98	7,501

lowest part of Tmc-F was intense during the period. However, it lost 2523, 06 ha (third biggest amount) to other categories, showing that the clearcutting and logging was also intense within the category. A total of 2396, 7 ha (fifth highest value) were swapping-change dynamic for this category.

The fourth position in terms of total change (3542, 31 ha), gain (1565, 1 ha), loses (1977, 21 ha) and swapping (3130, 2 ha), is for Grassland; the balance between gain and losses, as well the swapping value, suggest that this category has a strong interaction with other LULCC. The fifth changing category with a total change of 3450, 78 ha (6, 4 % of the total area) is Cro-L, suggesting that the cropping areas also experienced important changes during the period. The category gained 1789, 2 ha, which is the second highest value for the period, losing also 1661, 58 ha (sixth value). With the second highest value (3323, 16 ha), Cro-L experienced also a swapping-change dynamic in the area.

Tcm-F is located in the sixth position of total changes, with a total value of 2482, 56 ha (4, 6 % of the total). The category gained 792, 45 ha (seventh value), but lost 1690, 11 ha; meanwhile, 1584, 9 ha were accounted as swapping-change. Finally, Gr-An showed the seventh highest change, with 2270, 16 ha (4, 2 % of the total area). It gained 1085, 49 ha and lost 1184, 67 ha, with a swapping value of 2170, 98 ha.

Despite of the dynamic above described the values for net change shows some differences among the positions between categories. Having the highest net value of 3393, 09 ha, the S-Shr remains as the most dynamic category for the period. The Oc-F had the second highest net change value (1324, 71 ha), and the third position is for Sm-F (1298, 97 ha). The Tropical Montane Cloudy Forest had the fourth highest net change value (947, 66 ha), followed by Gr-L (412, 11 ha), and the sixth position is for the category Ur-U, with a net change value of 295, 2 ha (most of the change in this category is net change, as usual), and a swapping value which tends to be cero. These values lead to affirm that the LCC and particularly the Forested LCC experienced the most important net changes in the river basin during this period.

4.4.1.3. - Systematic Inter-category transitions in the landscape system.

Now is possible to derive the categorical trajectory of the changes which have been occurring in the river basin during the studied period. The Table 4.5 accounts for the most important inter-category transitions for T0-T1 in terms of Losses. The magnitude of the ratio (fifth column) indicates in all cases the strength of the systematic transition between categories (Pontius et al., 2004).

The first thirteen rows on Table 4.5 indicate spatial processes or transitions affecting the Forested Land Covers in the River Basin: Tmc-F, Oc-F and Sm-F. These transitions indicate changes associated with deterioration, decrease or disappearance of the Forested areas, depending on the LULC category for which the forested categories have been migrating during the period. For example, the first transition process: Tmc-F – Oc-F indicate that the Tropical Montane Cloudy Forest changed to Open-cleared Forest in 3,764 times more than would be expected if the change were to occur randomly, losing 348,65 ha more than the expected value. This transition, together with the second one, indicate that the TMCF is changing systematically to an intermediate stage (Open-cleared Forest and / or Successional Shrubland), before it can finally change or migrate to any human-induced type of Land Use category (Gr-An or Cro-L). No transitions from Tmc-F to Land Use categories were observed. Similar transitional trends were observed in the Highlands of Chiapas – Mexico by Ochoa-Gaona (2001) and Cayuela et al (2006), being also described in two different regions in Chile (Schulz et al., 2010) (Echeverria et al., 2012).

The processes driving the transitions of the Tmc-F are basically associated with: clearcutting, logging, wood extraction and also plants and non-wood extraction. These processes could have been occurring in a successive way, and particularly the logging is probably occurring in a selective form, as checked in field. The selective extraction or harvesting of non-wood products (like Orchids and Bromeliads), has been also reported as a critical problem occurring in this ecosystem (Bonell & Brujinzel, 2004)

Another example is the transition Sm-F – Ero-L, indicating that in this portion of the surface area, the clearcutting/ logging processes derived in severe land degradation processes like erosion in 6,428 times more than expected, affecting 12,33 ha. The rest of transitions contribute to explain the other change processes occurring in the rest of categories, particularly in the human-induced types of Land Cover.

As seen on Table 4.5, Gr-L is basically migrating to Gr-An (174, 33 ha), Cro-L (316, 53 ha) and S-Shr (1224, 45 ha), and with less importance, to Fl-P (31, 32 ha) and Ur-U (31, 32 ha), respectively. Gr-An is basically migrating to Gr-L in 2,146 times more than expected (230, 4 ha). This contributes to explain the high swapping value observed for Gr-L during the period.

Table 4.5.- The most systematic transitions occurred in T0-T1, in terms of Losses

Sistematic Transition T0 »»»» T1	Ov	Ev	Ov-Ev	Ov-Ev/ Ev	Interpretation of the Transition
Tmc-F »»»» Oc-F	441,27	92,62	348,65	3,764	When Tropical Montane Cloudy Forest loses, Open-cleared Forest replaces it
Tmc-F »»»» S-Shr	1041,12	673,26	367,86	0,546	When Tropical Montane Cloudy Forest loses, Sucessional Shrubland replaces it
Oc-F »»»» Gr-An	168,93	57,19	111,74	1,954	When Open-cleared Forest loses, Grass Anthropogenic replaces it
Oc-F »»»» Cro-L	176,76	112,83	63,93	0,567	When Open-cleared Forest loses, Cropland replaces it
Oc-F »»»» S-Shr	1863,45	580,24	1283,21	2,212	When Open-cleared Forest loses, Sucessional Shrubland replaces it
Sm-F »»»» Oc-F	124,29	100,31	23,98	0,239	When Sub-montane Forest loses, Open-cleared Forest replaces it
Sm-F »»»» Gr-An	124,65	71,86	52,79	0,735	When Sub-montane Forest loses, Grass Anthropogenic replaces it.
Sm-F »»»» Cro-L	339,48	141,79	197,69	1,394	When Sub-montane Forest loses, Cropland replaces it. Cropland gains.
Sm-F »»»» Ero-L	12,33	1,66	10,67	6,428	When Sub-montane Forest loses, Eroded Land replaces it.
Sm-F »»»» Ur-U	61,92	44,37	17,55	0,396	When Sub-montane Forest loses, Urban Use replaces it. Urban Use gains.
Sm-F »»»» Fl-P	83,7	23,85	59,85	2,509	When Sub-montane Forest loses, Flooding Plain replaces it.
Sm-F »»»» S-Shr	2013,39	729,16	1284,23	1,761	When Sub-montane Forest loses, Sucessional Shrubland replaces it.
Schr »»»» S-Shr	1,35	0,31	1,04	3,355	When Schrubland loses, Sucessional Shrubland replaces it.
Gr-L »»»» Gr-An	174,33	46,24	128,09	2,770	When Grassland loses, Grass Anthropogenic replaces it.
Gr-L »»»» Cro-L	316,53	91,22	225,31	2,470	When Grassland loses, Cropland replaces it.
Gr-L »»»» Ur-U	31,32	28,54	2,78	0,097	When Grassland loses, Urban Use replaces it. Urban Use gains.
Gr-L »»»» Fl-P	31,32	15,34	15,98	1,042	When Grassland loses, Flooding Plain replaces it.
Gr-L »»»» S-Shr	1224,45	469,13	755,32	1,610	When Grassland loses, Sucessional Shrubland replaces it.
Sa-P »»»» S-Shr	3,78	0,86	2,92	3,395	When Sub Andean Páramo loses, sucessional Shrubland replaces it
Gr-An »»»» Oc-F	51,39	37,15	14,24	0,383	When Grass Anthropogenic loses, Open-cleared Forest replaces it.
Gr-An »»»» Gr-L	230,4	73,24	157,16	2,146	When Grass Anthropogenic loses, Grassland replaces it
Gr-An »»»» Cro-L	100,89	52,51	48,38	0,921	When Grass Anthropogenic loses, Cropland replaces it.
Gr-An »»»» S-Shr	706,68	270,02	436,66	1,617	When Grass Anthropogenic loses, Sucessional Shrubland replaces it.
Cro-L »»»» Sm-F	283,32	201,08	82,24	0,409	When Cropland loses, Sub-montane Forest replaces it.
Cro-L »»»» Gr-L	221,85	105,02	116,83	1,112	When Cropland loses, Grassland replaces it.
Cro-L »»»» Gr-An	70,11	38,16	31,95	0,837	When Cropland loses, Grass Anthropogenic replaces it.
Cro-L »»»» Ur-U	98,1	23,56	74,54	3,164	When Cropland loses, Urban Use replaces it.
Cro-L »»»» Fl-P	49,05	12,66	36,39	2,874	When Cropland loses, Flooding Plain replaces it
Cro-L »»»» S-Shr	846,63	387,19	459,44	1,187	When Cropland loses, Sucessional Shrubland replaces it.
Ero-L »»»» Tmc-f	7,74	6,58	1,16	0,176	When Eroded Land loses, Tropical Montane Cloudy Forest replaces it.
Ero-L »»»» Cro-L	1,35	0,65	0,70	1,077	When Eroded Land loses, Cropland replaces it.
Ero-L »»»» Fl-P	1,35	0,11	1,24	11,273	When Eroded Land loses, Fluvial Plain replaces it.
Ur-U »»»» Fl-P	0,72	0,01	0,71	71,000	When Urban Use loses, Flooding Plain replaces it.
Fl-P »»»» Gr-L	2,7	2,31	0,39	0,169	When Flooding Plain loses, Grassland replaces it.
Fl-P »»»» Cro-L	14,31	1,66	12,65	7,620	When Flooding Plain loses, Cropland replaces it.
Fl-P »»»» Ur-U	6,57	0,52	6,05	11,635	When Flooding Plain loses, Urban Use replaces it.
Fl-P »»»» S-Shr	11,43	8,53	2,90	0,340	When Flooding Plain loses, Sucessional Shrubland replaces it.
S-Shr »»»» Oc-F	513,0	170,58	342,42	2,007	When Sucessional Shrubland loses, Open-cleared Forest replaces it.
S-Shr »»»» Sm-F	984,69	643,94	340,75	0,529	When Sucessional Shrubland loses, Sub-montane Forest replaces it.
S-Shr »»»» Gr-L	811,44	336,32	475,12	1,413	When Sucessional Shrubland loses, Grassland replaces it.
S-Shr »»»» Gr-An	497,34	122,20	375,14	3,070	When Sucessional Shrubland loses, Grass Anthropogenic replaces it.
S-Shr »»»» Cro-L	766,53	241,11	525,42	2,179	When Sucessional Shrubland loses, Cropland replaces it.
S-Shr »»»» Ur-U	84,06	75,44	8,62	0,114	When Sucessional Shrubland loses, Urban Use replaces it.

Ov: Observed Value / Ev: Expected Value

The category Cro-L migrated to Ur-U in 3,164 times more than expected (98, 1 ha); to Fl-P in 2,874 (49, 05 ha), and to S-Shr in 1,187 times more than expected (846, 63 ha). Particularly the transition Cro-L – Fl-P indicates that the hydrological dynamic of the river, especially the peak flows or flooding events, affected cropping areas. The transition Ero-L – Fl-P suggests an intense hydrological dynamic during the period, which augmented the sediments emission of the river.

The transition Ur-U – Fl-P also suggest that the hydrological events occurred during the period, affected the urban area of Boconó city, which had been expanding across the fluvial plain of the River; this can be corroborated some rows below, with the transition Fl-P – Ur-U, in which the urban area growth across the flooding plain 11,625 times more than expected (6,57 ha). Finally, the transitions for the category S-Shr suggest a trend for the category to migrate to the Land Use categories Gr-An (3,070 times more than expected); Cro-L (2,179 times more than expected) and to Ur-U (0,114 times more than expected). The rest of the transitions suggest a regeneration process.

The Table 4.6 shows the most systematic inter-category transitions occurred in the period T0 – T1 in terms of gain. The first twelve transitions are associated to changes in the Forested Land Covers. Particularly the transition Sm-F – Ero-L indicate erosion processes occurring after the clearcutting of the Sub-montane Forest, in 5,489 times more than expected, affecting a total of 12,33 ha. On the other hand, the transitions Gr-An – Gr-l (4,760); Gr-An – S-Shr (2,231), and Gr-An - Sm-F (0,232) suggest a regeneration/revegetation process.

As seen on Table 4.6, the cropland area in the river basin is growing at the expense of the categories: Oc-F (176, 76 ha), Sm-F (339, 48 ha), Gr-L (316, 53 ha), Gr-An (100, 89 ha), and S-Shr (766, 53 ha). On the other hand, the Gr-An gained surface area migrating basically from: Oc-F (168, 93 ha), Gr-L (174, 33 ha), Cro-L (70, 11 ha), and from S-Shr (497, 34 ha).
The transition Cro-L – Sm-F could to indicate regeneration, or perhaps a change to coffee plantation, or a combination of both scenarios. The transition Cro-L – Gr-L could be explained by the type of cultivation usually practiced in the area, above mentioned.

The fact that the urban areas have been growing at the expense of croplands is corroborated again with the transition Cro-L – Ur-U, which indicates that the urban areas grew up from Cropland in 7,028 times more than expected (98,1 ha). The urban areas also grew up at the expense of other categories: Sm-F (61, 92 ha), Gr-L (31, 31 ha), S-Shr (84, 06 ha) and Gr-An

Table 4.6.- The most systematic transitions occurred in T0 – T1, in terms of Gains

Sistematic Transition T0 »»»» T1	Ov	Ev	Ov - Ev	Ov–Ev / Ev	Interpretation of the Transition
Tmc-F »»»» Schr	58,32	27,49	30,83	1,121	When Schrub gains, it replaces the Tropical Montane Cloudy Forest
Tmc-F »»»» Sa-P	6,93	3,40	3,53	1,038	When Sub Andean Páramo gains, it replaces the Tropical Montane Cloudy Forest
Oc-F »»»» Sm-F	130,32	102,46	27,86	0,272	When the Sub-montane Forest gains, it replaces the Open-cleared Forest.
Oc-F »»»» Gr-L	149,31	92,90	56,41	0,607	When the Grassland gains, it replaces the Open-cleared Forest
Oc-F »»»» Gr-An	168,93	61,50	107,43	1,747	When Grass Anthropogenic gains, it replaces Open-cleared Forest
Oc-F »»»» Cro-L	176,76	103,19	73,57	0,713	When Cropland gains, it replaces the Open-cleared Forest
Oc-F »»»» S-Shr	1863,45	507,89	1355,56	2,669	When Sucessional Shrub gains, it replaces Open-cleared Forest
Sm-F »»»» Cro-L	339,48	261,07	78,41	0,300	When Cropland gains, it replaces the Sub-montane Forest
Sm-F »»»» Ero-L	12,33	1,90	10,43	5,489	When Eroded Land gains, it replaces the Sub-montane Forest
Sm-F »»»» Ur-U	61,92	41,75	20,17	0,483	When Urban Use gains, it replaces the Sub-montane Forest
Sm-F »»»» Fl-P	83,7	27,41	56,29	2,054	When Flooding Plain gains, it replaces the Sub-montane Forest
Sm-F »»»» S-Shr	2013,39	1284,98	728,41	0,567	When Sucessional Shrubland gains, it replaces the Sub-montane Forest
Gr-L »»»» Sm-F	136,08	126,21	9,87	0,078	When Sub-montane Forest gains, it replaces the Grassland
Gr-L »»»» Gr-An	174,33	75,76	98,57	1,301	When Grass Anthropogenic gains, it replaces Grassland
Gr-L »»»» Cro-L	316,53	127,11	189,42	1,490	When Cropland gains, it replaces Grassland
Gr-L »»»» Ur-U	31,32	20,33	10,99	0,541	When Urban use gains, it replaces Grassland
Gr-L »»»» Fl-P	31,32	13,35	17,97	1,346	When Flooding Plain gains, it replaces Grassland
Gr-L »»»» S-Shr	1224,45	625,63	598,82	0,957	When Sucessional Shrubland gains, it replaces Grassland
Gr-An »»»» Oc-F	51,39	30,21	21,18	0,701	When Open- cleared Forest gains, it replaces Grass Anthropogenic
Gr-An »»»» Sm-F	54,36	44,12	10,24	0,232	When Sub-montane Forest gains, it replaces Grass Anthropogenic
Gr-An »»»» Gr-L	230,4	40,00	190,40	4,760	When Grassland gains, it replaces Grass Anthropogenic
Gr-An »»»» Cro-L	100,89	44,43	56,46	1,271	When Cropland gains, it replaces Grass Anthropogenic
Gr-An »»»» Ur-U	9,72	7,10	2,62	0,369	When Urban Use gains, it replaces Grass Anthropogenic
Gr-An »»»» S-Shr	706,68	218,69	487,99	2,231	When Sucessional Srhubland gains, it replaces Grass Anthropogenic
Cro-L »»»» Sm-F	283,32	75,90	207,42	2,733	When Sub-montane Forest gains, it replaces Cropland
Cro-L »»»» Gr-L	221,85	68,82	153,03	2,224	When Grassland gains, it replaces Cropland
Cro-L »»»» Gr-An	70,11	45,56	24,55	0,539	When Grass Anthropogenic gains, it replaces Cropland
Cro-L »»»» Ur-U	98,1	12,22	85,88	7,028	When Urban Use gains, it replaces Cropland
Cro-L »»»» Fl-P	49,05	8,03	41,02	5,108	When Flooding Plain gains, it replaces Cropland
Cro-L »»»» S-Shr	846,63	376,26	470,37	1,250	When Sucessional Shrubland gains, it replaces Cropland
Ero-L »»»» Tmc-F	7,74	0,78	6,96	8,923	When Tropical Montane Cloudy Forest gains, it replaces Eroded Land
Ero-L »»»» Cro-L	1,35	0,99	0,36	0,364	When Cropland gains, it replaces Eroded Land
Ero-L »»»» Fl-P	1,35	0,10	1,25	12,500	When Flooding Plain gains, it replaces Eroded Land
Fl-P »»»» Cro-L	14,31	8,15	6,16	0,756	When Cropland gains, it replaces Flooding Plain
Fl-P »»»» Ur-U	6,57	1,30	5,27	4,054	When Urban Use gains, it replaces Flooding Plain
S-Shr »»»» Tmc-F	638,01	233,26	404,75	1,735	When Tropical Montane Cloudy Forest gains, it replaces Sucessional Shrubland
S-Shr »»»» Oc-F	513	202,72	310,28	1,531	When Open cleared Forest gains, it replaces Sucessional Shrubland
S-Shr »»»» Sm-F	984,69	296,05	688,64	2,326	When Sub-montane Forest gains, it replaces Sucessional Shrubland
S-Shr »»»» Gr-L	811,44	268,40	543,04	2,023	When Grassland gains, it replaces Sucessional Shrubland
S-Shr »»»» Gr-An	497,34	177,70	319,64	1,799	When Grass Anthropogenic gains, it replaces Sucessional Shrubland
S-Shr »»»» Cro-L	766,53	298,15	468,38	1,571	When Cropland gains, it replaces Sucessional Shrubland
S-Shr »»»» Ur-U	84,06	47,68	36,38	0,763	When Urban Use gains, it replaces Sucessional Shrubland

Ov: Observed Value / Ev: Expected Value

(9, 72 ha). On the other hand, the Fl-P grew up at the expense of Cro-L in 5,108 times more than expected, affecting 49,05 ha.

The transition Ero-L – Tmc-F suggest a regeneration/revegetation process, showing a high level of resilience for the TMCF to be regenerated after such disturbances like landslides, as in this case. The transition Ero-L - Fl-P focuses a source of sediments which were transported by the river during the period. On the other hand, the transition Fl-P – Ur-U confirms the fact that the urban areas (in this case, the urban area of Boconó city) is expanding through the Flooding plain. The last transitions help to confirm the higher swapping-change dynamic associated to the category S-Shr. The Appendix C1 and C2 contain the Cross-tabulated matrixes of the period T0-T1 for losses and gains, respectively.

4.4.2. - LULC categorical changes and transitions for T1 – T2

4.4.2.1. - General quantification of the Change

The Figure 4.4 show the spatial distribution of the changes in the Boconó river basin, which occurred within the period: T1 – T2. In the second period the total changes were slight higher, with 18464, 7 ha affected by a type of change, representing the 34, 35% of the total area, and the persistence value descended to 65, 65 % of the total surface (35297, 46 ha). This fact suggests that during the second period, the intensity of changes in the area tended to be slight greater as in the first one.

4.4.2.2. - Net Change and Swapping

The Table 4.7 resume the landscape dynamic for the second period T1 – T2. Some light differences can be observed respect to the last period. S-Shr remains as the most dynamic category, with a total change value of 11750, 85 ha (22 % of the total area). It gained 6303, 42 ha and lost 5447, 43 ha. The 93% of the total value for this category (10894, 86 ha), occurred as swapping-change dynamic. Sm-F remains in the second position, with a total change of 3638, 88 ha (7 % of the total area). It gained less surface than in the last period (846, 99 ha), which is the seventh observed value for the period. Meanwhile, the losses remained high, having the second highest value for the period (2791, 89 ha). A total of 1693, 98 ha changed in a swapping-change form.

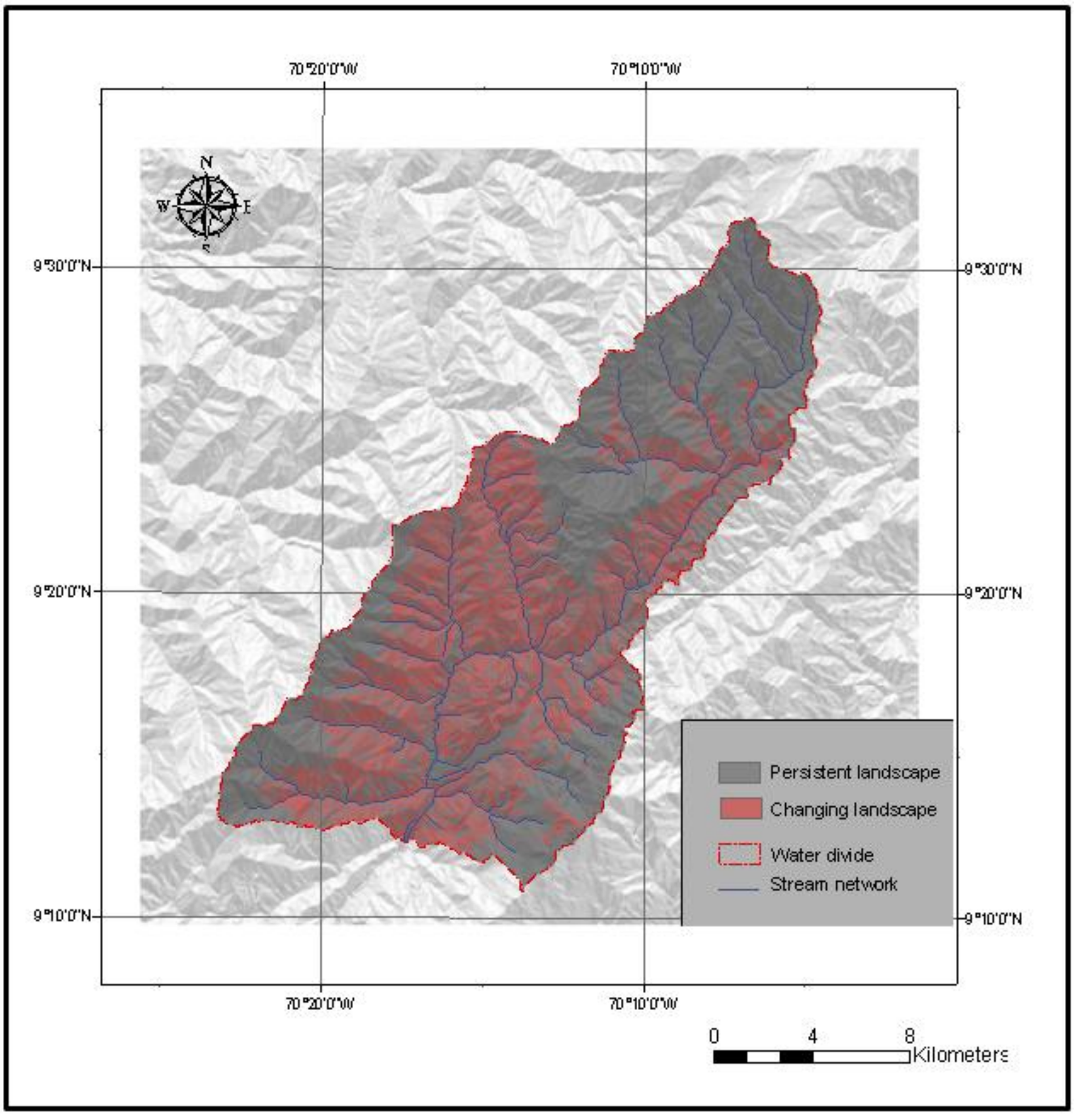


Figure 4.4.- Persistence & changing area in Boconó River Basin for T1 – T2.

The third category experiencing changes in the period was Gr-An, with a value of 3526, 83 ha (6, 6% of total area) for total change. It had the second higher value for gains in the period (2588, 85 ha), meanwhile the losses (937, 98 ha), were lower in comparison to the last period. Of the total value, 1875, 96 ha changed in a swapping-change form. The fourth position in this period is for Cro-L, having a value of 3463, 56 ha (6, 4% of the total area). Cropland gained 2000, 25 ha (the 3rd highest value) during the period, losing 1463, 31 ha (5th value), which can be explained for the type of agriculture applied in the area (shifting cultivation). This could explain the high value for swapping (2926, 62 ha) which is the third highest value for the period.

Table 4.7.- Landscape Dynamic in the Boconó River Basin for the Period T1 – T2 (1997-2008)

LULC Category	Gain		Loss		Total Change		Swap		Absolute value of net change	
	ha	%	ha	%	ha	%	ha	%	ha	%
Tmc-F	877,5	1,632	2023,74	3,764	2901,24	5,396	1755,0	3,266	1146,24	2,132
Oc_F	990,63	1,843	1113,21	2,071	2103,84	3,914	1981,26	3,686	122,58	0,228
Sm-F	846,99	1,575	2791,89	5,193	3638,88	6,768	1693,98	3,152	1944,9	3,618
Schr	29,25	0,054	1,35	0,003	30,6	0,057	2,7	0,006	27,9	0,051
Gr-L	1731,78	3,221	1646,73	3,063	3378,51	6,284	3293,46	6,126	85,05	0,158
Sa-P	7,11	0,013	0,63	0,001	7,74	0,014	1,26	0,002	6,48	0,012
Gr-An	2588,85	4,815	937,98	1,745	3526,83	6,560	1875,96	3,490	1650,87	3,070
Cro-L	2000,25	3,721	1463,31	2,722	3463,56	6,443	2926,62	5,444	536,94	0,999
Ero-L	17,46	0,032	4,86	0,009	22,32	0,041	9,72	0,018	12,6	0,023
Ur-U	138,24	0,257	2,16	0,004	140,4	0,261	4,32	0,008	136,08	0,253
Fl-P	36,54	0,068	134,73	0,251	171,27	0,319	73,08	0,136	98,19	0,183
S-Shr	6303,42	11,725	5447,43	10,132	11750,85	21,857	10894,86	20,264	855,99	1,593
Total	15568	28,956	15568	28,958	15568,02	28,957	12256,11	22,799	3311,91	6,16

The Gr-L had a total change of 3378, 51 ha (6, 3% of total area), as the fifth changing category. It maintained the same trend as in the last period, gaining 1731, 78 ha, losing 1646, 73 ha, with 3293, 46 ha as swapping-change value. The sixth position in this period was for the Tmc-F, which showed a total change of 2901, 24 ha (5, 4% of the total area). It showed the same trend for gain as in the last period (877, 5 ha), but the losses were quite higher (2023, 74 ha), with 1755, 0 ha as swapping-change value.

Finally, the Oc-F descended to the seventh position in the period, showing a total change of 2103, 84 ha (3, 9% of the total area). It gained 990, 63 ha, and loosed 1113, 21 ha, with a swapping value of 1981, 26 ha for the period.

The dynamic showed by the net change values changed slightly respect the last period. The category with the highest net change value was Sm-F (1944, 9 ha), followed by Gr-An (1650, 87 ha); and the Tmc-F reached the third position, with a net change of 1146 ha. S-Shr descended to the fourth position with 855, 99 ha, followed by Cro-L (536, 94 ha) and Ur-U in the sixth position, with a net change value of 136, 08 ha (most of the change occurring as net change).

4.4.2.3. - Systematic Inter-category transitions in the landscape system

The Tables 4.8 and 4.9 resume the most systematic transitions occurred in the second period (T1 – T2) in terms of losses and gains, respectively. As seen on Table 4.8, the number of rows accounting for changes in the Forested LC was reduced to 9, because of a light reduction in the transitions of Sm-F, which explains the reduction in the swapping value in the category for this period.

The same trend in the transitions for the Tmc-F can be observed in this period, but additionally 5,31 ha of the area covered by the category was affected by erosion processes, particularly landslides. An incipient transition process for the Sa-P occurred during the period, suggesting that some changes derived by anthropogenic pressure have been occurring in the Páramo ecosystems of the river basin. The growing anthropogenic pressure over the Sub-Andean Páramo in the study area was reported by Hidalgo (2007).

The categories Gr-L, Gr-An and Cro-L show the same transitional trends as in the last period. The Urban use continued to growing up at the expense of Cropland and the Flooding plain, and at the same time, the urban area continued being affected by peak flows or flooding processes. Finally, the S-Shr showed migrating trends to Gr-An (3,168), Cro-L (1,719), to Gr-L (1,507) and to Oc-F (0,910) also. Respect to the Gains in this period, the Table 4.9 illustrates the trend, where the first ten rows show the changes affecting the Forested LCC. In general, the trends and patterns for the transitions observed on last period remain during the second period.

The category Gr-L showed less intensity in the swapping, meanwhile Cro-L gained surface at the expense from Oc-F (66, 78 ha), Sm-F (269, 37 ha), Gr-L (361, 17 ha), Gr-An (172, 44 ha), Fl-P (36, 9 ha) and S-Shr (1037, 97 ha). Gr-An gained surface migrating from Gr-L in 2,142 times more than expected (502, 83 ha), and also from Cro-L (213, 39 ha), and from S-Shr (1571, 40 ha).

The urban areas continued to growing up in the period, gaining surface area basically from Sm-F (43, 38 ha), Gr-An (3, 78 ha), Cro-L (46, 08 ha), Fl-P (5, 85 ha) and S-Shr (31, 95 ha). Particularly the urban area growing close or into the category Fl-P is vulnerable to the river dynamic. During this period the category S-Shr reported systematic transitions with all the

Table 4.8.- The most systematic transitions occurred in T1 – T2, in terms of Losses

Systematic Transition T1 »»»» T2	Ov	Ev	Ov - Ev	Ov–Ev / Ev	Interpretation of the Transition
Tmc-F »»»» Oc-F	470,07	98,89	371,18	3,753	When Tropical Montane Cloudy Forest loses, Open-cleared Forest replaces it.
Tmc-F »»»» Ero-L	5,31	2,58	2,73	1,058	When Tropical Montane Cloudy Forest loses, Eroded Land replaces it.
Tmc-F »»»» S-Shr	1335,15	832,04	503,11	0,605	When Tropical Montane Cloudy Forest loses, Sucessional Shrubland replaces it.
Oc-F »»»» Gr-An	77,13	60,35	16,78	0,278	When Open-cleared Forest loses, Grass Anthropogenic replaces it.
Oc-F »»»» Cro-L	66,78	61,11	5,67	0,093	When Open-cleared Forest loses, Cropland replaces it.
Oc-F »»»» S-Shr	900,0	273,65	626,35	2,289	When Open-cleared Forest loses, Sucessional Srhubland replaces it.
Sm-F »»»» Cro-L	269,37	161,78	107,59	0,665	When Sub-montane Forest loses, Cropland replaces it.
Sm-F »»»» Ero-L	3,15	2,25	0,90	0,400	When Sub-montane Forest loses, Eroded Land replaces it.
Sm-F »»»» S-Shr	2122,38	724,49	1397,89	1,929	When Sub-montane Forest loses, Sucessional Shrubland replaces it.
Schr »»»» Gr-An	0,18	0,07	0,11	1,571	When Schrubland loses, Grass Anthropogenic replaces it.
Schr »»»» Ero-L	0,72	0,001	0,72	719,000	When Schrubland loses, Eroded Land replaces it.
Schr »»»» S-Shr	0,45	0,33	0,12	0,364	When Schrubland loses, Sucessional Shrubland replaces it.
Gr-L »»»» Gr-An	502,83	92,48	410,35	4,437	When Grassland loses, Grass Anthropogenic replaces it.
Gr-L »»»» Cro-L	361,17	93,64	267,53	2,857	When Grassland loses, Cropland replaces it.
Gr-L »»»» S-Shr	696,15	419,33	276,82	0,660	When Grassland loses, Sucessional Shrubland replaces it.
Sa-P »»»» Schr	0,36	0,01	0,35	35,000	When Sub-andean Páramo loses, Schrubland replaces it.
Sa-P »»»» Gr-An	0,18	0,03	0,15	5,000	When Sub-andean Páramo loses, Grass Anthropogenic replaces it.
Gr-An »»»» Gr-L	124,29	61,43	62,86	1,023	When Grass Anthropogenic loses, Grassland replaces it.
Gr-An »»»» Cro-L	172,44	52,81	119,63	2,265	When Grass Anthropogenic loses, Cropland replaces it.
Gr-An »»»» S-Shr	557,19	236,49	320,70	1,356	When Grass Anthropogenic loses, Sucessional Shrubland replaces it.
Cro-L »»»» Sm-F	161,73	123,04	38,69	0,314	When Cropland loses, Sub-montane Forest replaces it.
Cro-L »»»» Gr-L	266,58	95,91	170,67	1,779	When Cropland loses, Grassland replaces it.
Cro-L »»»» Gr-An	213,39	81,43	131,96	1,621	When Cropland loses, Grass Anthropogenic replaces it.
Cro-L »»»» Ero-L	1,89	1,15	0,74	0,643	When Cropland loses, Eroded Land replaces it.
Cro-L »»»» Ur-U	46,08	24,88	21,20	0,852	When Cropland loses, Urban Use replaces it.
Cro-L »»»» Fl-P	10,08	8,45	1,63	0,193	When Cropland loses, Flooding Plain replaces it.
Cro-L »»»» S-Shr	656,55	369,19	287,36	0,778	When Cropland loses, Sucessional Shrubland replaces it.
Ero-L »»»» Sm-F	1,89	0,39	1,50	3,846	When Eroded Land loses, Sub-montane Forest replaces it.
Ero-L »»»» Cro-L	0,9	0,26	0,64	2,462	When Eroded Land loses, Cropland replaces it.
Ero-L »»»» Fl-P	0,45	0,03	0,42	14,000	When Eroded Land loses, Flooding Plain replaces it.
Ero-L »»»» S-Shr	1,53	1,16	0,37	0,319	When Eroded Land loses, Sucessional Shrubland replaces it.
Ur-U »»»» Fl-P	2,16	0,01	2,15	215,000	When Urban Use loses, Flooding Plain replaces it.
Fl-P »»»» Sm-F	41,31	10,78	30,53	2,832	When Flooding Plain loses, Sub-montane Forest replaces it.
Fl-P »»»» Gr-L	11,16	8,41	2,75	0,327	When Flooding Plain loses, Grassland replaces it.
Fl-P »»»» Cro-L	36,9	7,23	29,67	4,104	When Flooding Plain loses, Cropland replaces it.
Fl-P »»»» Ero-L	0,18	0,10	0,08	0,800	When Flooding Plain loses, Eroded Land replaces it.
Fl-P »»»» Ur-U	5,85	2,18	3,67	1,683	When Flooding Plain loses, Urban Use replaces it.
Fl-P »»»» S-Shr	33,93	32,36	1,57	0,049	When Flooding Plain loses, Sucessional Shrubland replaces it.
S-Shr »»»» Oc-F	387,99	203,17	184,82	0,910	When Sucessional Shrubland loses, Open-cleared Forest replaces it.
S-Shr »»»» Gr-L	1113,21	444,05	669,16	1,507	When Sucessional Shrubland loses, Grassland replaces it.
S-Shr »»»» Gr-An	1571,4	377,00	1194,40	3,168	When Sucessional Shrubland loses, Grass Anthropogenic replaces it.
S-Shr »»»» Cro-L	1037,97	381,71	656,26	1,719	When Sucessional Shrubland loses, Cropland replaces it.
S-Shr »»»» Ero-L	6,12	5,31	0,81	0,153	When Sucessional Shrubland loses, Eroded Land replaces it.

Ov: Observed Value / Ev: Expected Value

Table 4.9.- The most systematic transitions occurred in T1 – T2, in terms of Gains

Sistematic Transition T1 »»»» T2	Ov	Ev	Ov - Ev	Ov–Ev / Ev	Interpretation of the Transition
Tmc-F »»»» Oc-F	470,07	450,06	20,01	0,044	When Open-cleared Forest gains, it replaces Tropical Montane Cloudy Forest.
Tmc-F »»»» Schr	14,67	13,18	1,49	0,113	When Schrubland gains, it replaces Tropical Montane Cloudy Forest.
Tmc-F »»»» Sa-P	3,33	3,20	0,13	0,041	When Sub-andean Páramo gains, it replaces Tropical Montane Cloudy Forest.
Oc-F »»»» Cro-L	66,78	64,12	2,66	0,041	When Croppland gains, it replaces Open-cleared Forest.
Oc-F »»»» S-Shr	900,0	248,77	651,23	2,618	When Sucessional Shrubland gains, it replaces Open-cleared Forest.
Sm-F »»»» Cro-L	269,37	242,07	27,30	0,113	When Cropland gains, it replaces Sub-montane Forest.
Sm-F »»»» Ero-L	3,15	2,02	1,13	0,559	When Eroded Land gains, it replaces Sub-montane Forest.
Sm-F »»»» Ur-U	43,38	16,22	27,16	1,674	When Urban Use gains, it replaces Sub-montane Forest.
Sm-F »»»» Fl-P	6,39	4,26	2,13	0,500	When Flooding Plain gains, it replaces Sub-montane Forest.
Sm-F »»»» S-Shr	2122,38	939,10	1183,28	1,260	When Sucessional Shrubland gains, it replaces Sub-montane Forest.
Schr »»»» Ero-L	0,72	0,39	0,33	0,846	When Eroded Land gains, it replaces Schrubland
Gr-L »»»» Gr-An	502,83	160,05	342,78	2,142	When Grass Anthropogenic gains, it replaces Grassland.
Gr-L »»»» Cro-L	361,17	126,42	234,75	1,857	When Cropland gains, it replaces Grassland.
Gr-L »»»» Fl-P	3,6	2,23	1,37	0,614	When Flooding Plain gains, it replaces Grassland.
Gr-L »»»» S-Shr	696,15	490,47	205,68	0,419	When Sucessional Shrubland gains, it replaces Grassland.
Gr-An »»»» Tmc-F	40,5	34,45	6,05	0,176	When Tropical Montane Cloudy Forest gains, it replaces Grass Anthropogenic
Gr-An »»»» Sm-F	23,85	21,04	2,81	0,134	When Sub-montane Forest gains, it replaces Grass Anthropogenic
Gr-An »»»» Gr-L	124,29	40,50	83,79	2,069	When Grassland gains, it replaces Grass Anthropogenic
Gr-An »»»» Cro-L	172,44	45,94	126,50	2,754	When Cropland gains, it replaces Grass Anthropogenic
Gr-An »»»» Ur-U	3,78	3,08	0,70	0,227	When Urban Use gains, it replaces Grass Anthropogenic
Gr-An »»»» S-Shr	557,19	178,21	378,98	2,127	When Sucessional Shrubland gains, it replaces Grass Anthropogenic
Cro-L »»»» Tmc-F	78,03	67,97	10,06	0,148	When Tropical Montane Cloudy Forest gains, it replaces Cropland
Cro-L »»»» Sm-F	161,73	41,52	120,21	2,895	When Sub-montane Forest gains, it replaces Cropland
Cro-L »»»» Gr-L	266,58	79,90	186,68	2,336	When Grassland gains, it replaces Cropland
Cro-L »»»» Gr-An	213,39	114,74	98,65	0,860	When Grass Anthropogenic gains, it replaces Cropland
Cro-L »»»» Ero-L	1,89	0,76	1,13	1,487	When Eroded Land gains, it replaces Cropland
Cro-L »»»» Ur-U	46,08	6,07	40,01	6,591	When Urban Use gains, it replaces Cropland
Cro-L »»»» Fl-P	10,08	1,60	8,48	5,300	When Flooding Plain gains, it replaces Cropland
Cro-L »»»» S-Shr	656,55	351,62	304,93	0,867	When Sucessional Shrubland gains, it replaces Cropland
Ero-L »»»» Sm-F	1,89	0,49	1,40	2,857	When Sub-montane Forest gains, it replaces Eroded Land.
Ero-L »»»» Fl-P	0,45	0,02	0,43	21,500	When Flooding Plain gains, it replaces Eroded Land.
Ur-U »»»» Fl-P	2,16	0,50	1,66	3,320	When Flooding Plain Gains, it replaces Urban Use.
Fl-P »»»» Sm-F	41,31	6,98	34,33	4,918	When Sub-montane Forest gains, it replaces Flooding Plain.
Fl-P »»»» Cro-L	36,9	15,24	21,66	1,421	When Cropland gains, it replaces Flooding Plain.
Fl-P »»»» Ero-L	0,18	0,13	0,05	0,385	When Eroded Land gains, it replaces Flooding Plain.
Fl-P »»»» Ur-U	5,85	1,02	4,83	4,735	When Urban Use gains, it replaces Flooding Plain.
S-Shr »»»» Tmc-F	705,42	349,55	355,87	1,018	When Tropical Montane Cloudy Forest gains, it replaces Sucessional Shrubland.
S-Shr »»»» Oc-F	387,99	227,82	160,17	0,703	When Open-cleared Forest gains, it replaces Sucessional Shrubland.
S-Shr »»»» Sm-F	562,95	213,53	349,42	1,636	When Sub-montane Forest gains, it replaces Sucessional Shrubland.
S-Shr »»»» Schr	13,59	6,67	6,92	1,037	When Schrubland gains, it replaces Sucessional Shrubland.
S-Shr »»»» Gr-L	1113,21	410,90	702,31	1,709	When Grassland gains, it replaces Sucessional Shrubland.
S-Shr »»»» Sa-P	3,78	1,62	2,16	1,333	When Sub-andean Páramo gains, it replaces Sucessional Shrubland.
S-Shr »»»» Gr-An	1571,4	590,08	981,32	1,663	When Grass Anthropogenic gains, it replaces Sucessional Shrubland.
S-Shr »»»» Cro-L	1037,97	466,10	571,87	1,227	When Cropland gains, it replaces Sucessional Shrubland.
S-Shr »»»» Ero-L	6,12	3,95	2,17	0,549	When Eroded Land gains, it replaces Sucessional Shrubland.
S-Shr »»»» Ur-U	31,95	31,24	0,71	0,023	When Urban Use gains, it replaces Sucessional Shrubland.
S-Shr »»»» Fl-P	13,05	10,66	2,39	0,224	When Flooding Plain gains, it replaces Sucessional Shrubland.

Ov: Observed Value / Ev: Expected Value

rest of the categories, which explain the high value for swapping-change for the category in this period. The corresponding Cross-tabulated Matrixes for losses and gains during this period are displayed on Appendix C-3 and C-4.

4.5. - Comparison with other LULC studies conducted on tropical regions

The LULC change has been a subject prone to be researched in some tropical regions worldwide; however, the experiences in mountainous regions and upland watersheds and river basins remains still relatively scarce. Mostly the studies that have been done in the past were based only in the simple comparison of surface area changing between time-points. An important proportion of such similar evaluations have been conducted in Africa tropical, but they are almost spatially confined to lowlands or in regions having sub-humid or semi-arid climates. Some examples of these experiences are: Tekle & Hedlund (2000) in Kalu District, Ethiopia; Reid et al (2000) in southwestern Ethiopia; Petit et al (2001) in the southern of Zambia; Braimoh & Vlek (2005) in northern Ghana; Baldyga et al (2007) in Kenya; Hadgu (2008) in Ethiopia; and Kiage et al (2009) in Kenya. Particularly the experiences of Braimoh & Vlek (2005) and Hadgu (2008) are valuable, as both of them evaluated the LULC changes linked to spatially explicit driving forces, founding the accessibility to be a determinant force driving the LULC changes in the respective regions studied.

In the case of Tropical Asia, Walsh et al (2001) analyzed the LULC based on the NDVI patterns at multiscale level in northern Thailand. They observed that the social variables were more definitive at finer spatial scales for explaining the variation in LC, meanwhile the environmental variables were more important at coarser spatial scales. Rao & Pant (2001) studied the LULC changes in tropical Himalayas, accounting for reduction in forest and expansion of the agriculture. Gautam et al (2003) studied the LULC between 1976 and 2000 in Nepal in order to demonstrate forest improvement and agriculture expansion. Bhattarai & Conway (2008) analyzed the LU dynamic and LC change in the south of Nepal, using the transitions matrix method, trying to detect the effects of socioeconomic and demographic factors on land use and LC dynamics. Despite of the importance of these studies and its results, they were also conducted at big scales, so that their level of comparability with the results obtained here is limited.

The situation in tropical America is certainly not too different. Many of the available experiences are derived from studies at coarse scale level confined to the Amazonian region (e.g. Armenteras et al, 2006) (Mena, 2008). Etter et al (2006) modelled the native forest conversion in Colombia at regional and national levels, founding that in the Andean region the distance to towns, soil fertility and distance to roads were the most important explanatory variables driving the LULC changes in the region. They also identified the humid and sub humid high Andean forest vulnerable to clearing. Despite of the relevance of these results, they are difficult to compare with the results obtained here, due the differences in the scales and resolution.

Two important experiences highly similar to the study here conducted were developed in Mexico. Cayuela et al (2006) analyzed the clearance and fragmentation of Tropical Montane Forests in Chiapas, Mexico. The patterns and trends described by the authors in Chiapas are very similar to the results obtained in Boconó river basin, in terms of intensity of clearing, and fragmentation of the TMCF. Other similar experience but in methodological terms correspond to Pineda et al (2008), whose studied the LULC in the state of Mexico, using the systematic transitions method proposed by Pontius et al (2004). They pointed out that the systematic transitions demonstrated to be a very useful method for the understanding of the changes occurred in the forested LC in the study area. More recently, two relevant experiences were conducted in the Andean region from Chile. Schulz et al (2010) monitored the LC change of the dryland forest landscape of Central Chile using the same method as here. Although the study corresponds to a temperate region, the same trends respect to the trajectory of transition for the undisturbed Forest was founded. Also, the Shrubland showed the higher dynamism with a high level of swapping between the LC category and the other human-induced types of land cover. The same trend with respect the natural forest and its transitions was also observed by Echeverria et al (2012) in southern Chile.

This gentle comparison done here lead to the following statement: due the approach used in this case (a relatively new methodological approach); the results here obtained have a low level of comparability worldwide. However, the results showed similarities to those recently obtained in other mountainous regions in America Tropical and Sub Tropical.

4.6. - Implications for Land Planning and Watershed Management

The dynamic of the LULC in the Boconó River Basin for the considered period and through the approach used in this project, lead to establish key elements and a support basis to be considered in the planning processes at the watershed level or even at regional planning level also. Considering that the Boconó River Basin constitute a double "**Protected Area**", which has a paramount importance for the development of the water resources in the lowlands, the evaluation of LULC change under the ecosystem approach represent a innovative variation respect the traditional LULC evaluations, in which the LULC are usually considered categories in an abstract sense. In this case, the Land Cover categories are essentially valuable ecosystems which have an ecological richness as well as complementary environmental attributes, being very important to the conservation and sustainability of the three basic land resources: water, soils and biodiversity.

The systematic transitions show the directionality of the changes in a categorical sense, leading to identify not only the categories which are more dynamic in a spatial-temporal perspective, but also the possible biophysical and anthropogenic processes driving the transitions. When both interpretations are correctly established, they simply lead to define the key elements to be considered in the land planning processes:

a) the way how the land resources have been used in the river basin during the last twenty years

b) the form how the land cover categories as ecosystems have been affected

c) The trends existing for the different land cover/land uses categories, in a spatial/temporal perspective.

Particularly the spatial visualization (geographical visualization) results in a undoubtedly helpful tool for the planning process, allowing to perceive how these trends are spatially occurring, where are occurring specific processes accounted for problems to be solved, and where these problems are more diverse or intense (**hot spots**).

As an example, the Figure 4.5 show the geographic visualization of the transitions for the three main forested Land Cover Categories (LCC) (Tmc-F, Oc-F and Sm-F), for the period T0-T1. The transitions occurred during the Period T1-T2 are displayed on Figure 4.5. A simple observation of the maps, based on the systematic transitions above described, can lead to the following statements:

1. - The changes affecting the forested land covers, particularly the Tcm-F and the Sm-F tends to be produced in the boundary area between categories. The same trend was observed by Oñate & Bosque (2010) in Ecuador. This lead to define belts of clear cutting / logging, which are also called "**hot fronts**" of deforestation, being more evident for the categories: Tcm-F and Oc-F. In the Sub-montane Forest, the belts or "**hot fronts**" are not clearly defined, because this Land Cover is highly fragmented among the area. The "Río Negro" Sector located at the upper Boconó river (Figure 4.4) was severely affected by the changes on the three types of LC, indicating that the processes: clearcutting, logging, wood extraction and non wood & plant extractions were more intense in this sector, during the period. The sector could be defined as "**hot spot**" or "**red flag area**", considering that the deforestation and the LC change is occurring in the sector where the most important streams-sources of the river are located.

2.- Observing the two maps, is evident that in the first period, the Open-cleared Forest were systematically reduced among the river basin, meanwhile in the second period, the transition of the Tropical Montane Cloudy Forest was clearly spatially intensified. This lead to corroborate the fact that the dynamic of the TMCF is characterized by a systematic and progressive change, in which the category is migrating to an "intermediate" stage or LCC like Open-cleared Forest or Successional Shrubland, and in other successive stage it can to migrate to another LC or LU categories.

3.- Although the "Guaramacal National Park" was created on 1988, covering the flank south-east of the river Basin (Muñoz et al, 2006), a "**hot front**" of deforestation can be observed in the inferior border of this protected area (Figure 4.4), which clearly increased during the second period (Figure 4.6). This fact reveals that the creation of the Park has not been completely effective in the protection of the ecosystems included in the protected area.

4. - The transitions Sm-F – Fl-P; Cro-L – Fl-P and Ur-U – Fl-P suggests a relevant hydrological dynamic occurring during the period studied. The LC Flooding Plain changed actively on last 20 years, accounting for important events like peak flows or even flash-floodings, which expanded the limits of the category among the area, affecting other

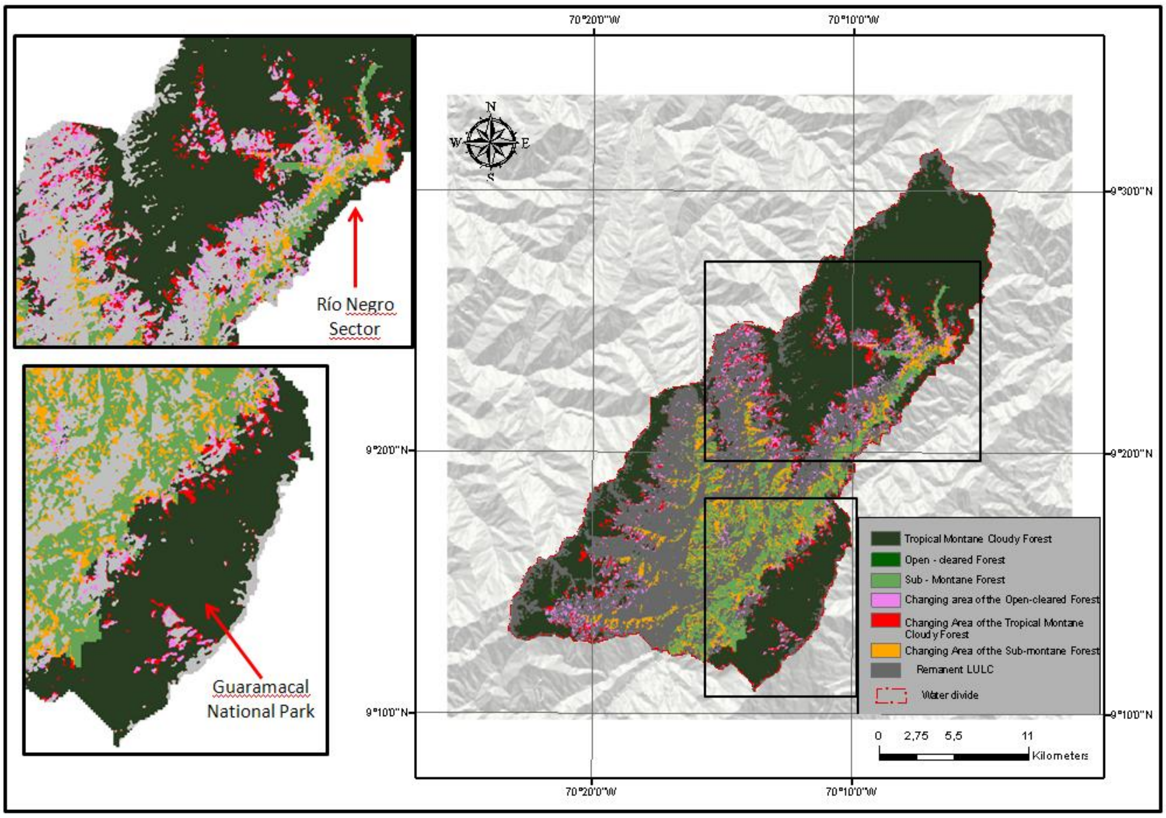


Figure 4.5.- Transition-area for the Forested Categories in the period T0-T1

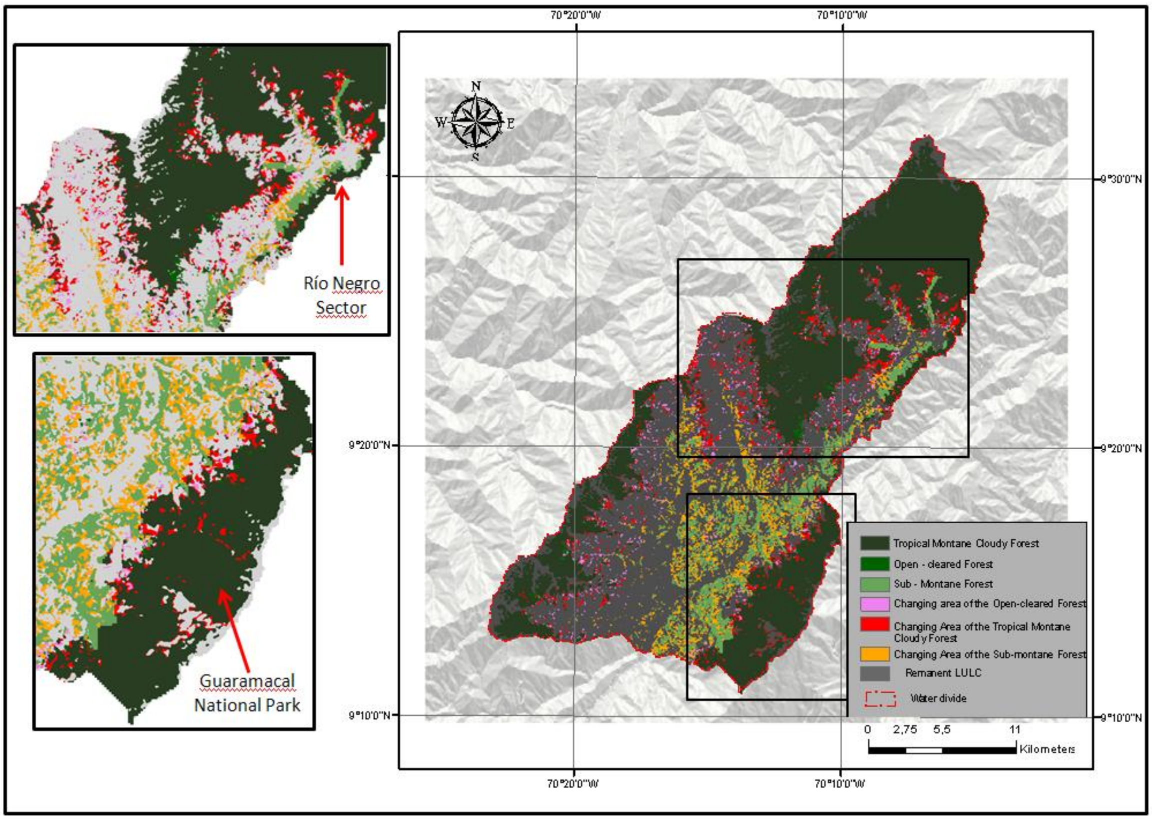


Figure 4.6.- Transition-area for the Forested Categories in the period T1-T2

categories like Sm-F, Cro-L and Ur-U. The dynamic accounted for the Forested LC and the increase of cultivated soils and grass could have been playing a role in the intensification of the hydrological events. The ecological conditions, and particularly the type and density of the land cover play a very important role in the hydrological behaviour and the hydrological response of the landscape. Many authors like: Naiman (1992), Chang (2003), Ward & Trimble (2004), Bonnel & Bruijnzeel (2004), Davie (2008), Dehnhardt & Petschow (2008) and Hölscher (2008) have been highlighting the importance of the forest ecosystems in the hydrological patterns. Particularly the TMCF is considered as “producer-water forest”, playing a paramount role in the rainfall dynamic, as well as the transpiration, interception, water budget and streamflows (Bonnel & Bruijnzeel, 2004) (Hölscher, 2008). Thus, the systematic reduction of this kind of forest may significantly reduce the rainfall interception, probably leading to an even higher streamflow.

5.- The transitions Sm-F – Ero-L; S-Shr – Ero-L; and Cro-L – Ero-L, indicate that the area is highly susceptible to soil degradation processes like laminar erosion, rill erosion, landslides and so on, processes which have been activating through the migration of Forested LCC to other categories like Cro-L. Only intense erosive processes like landslides were observed in the classification. However, Caraballo (2011) identified severe erosion processes, especially laminar erosion, in the San Miguel and San Rafael Watersheds (within the study area), which are spatially extended due the high accessibility (intricate road network), the fragile soils and the highly jointed bedrocks.

The Figures 4.7 and 4.8 show the transitions occurred in the Land Use Categories during the first and the second period, respectively. It can be clearly observed where the LUC grow up more intensively in the two periods. The superior window show the San Miguel – San Rafael Watersheds, the sectors where the croplands and the grass anthropogenic grow up more intensively for both periods. These are the sectors which have the most relevant problems related with land degradation in the area, as studied by Caraballo (2011). The inferior window show the expanding process that the Boconó city experienced during the two periods, showing how the city has been expanding among the flooding plain, in areas susceptible to be flooded. The transition Ur-U – Fl-P

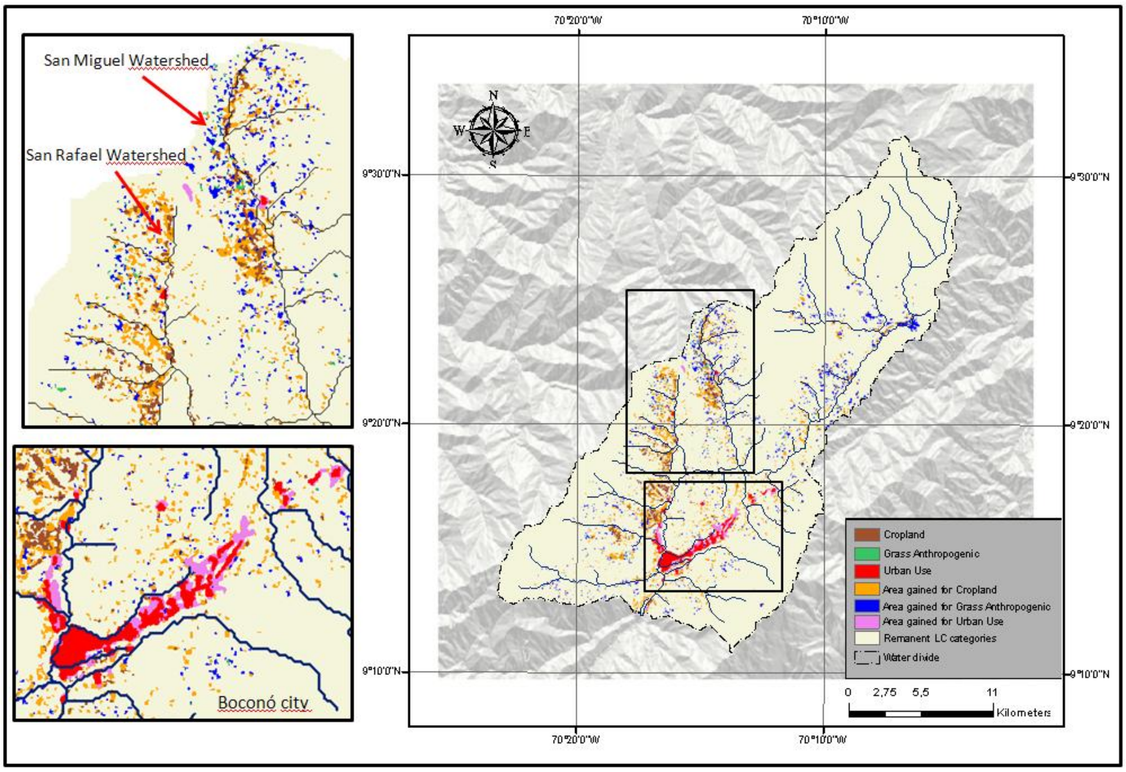


Figure 4.7.- Transition area for the Land Use categories in the period T0-T1

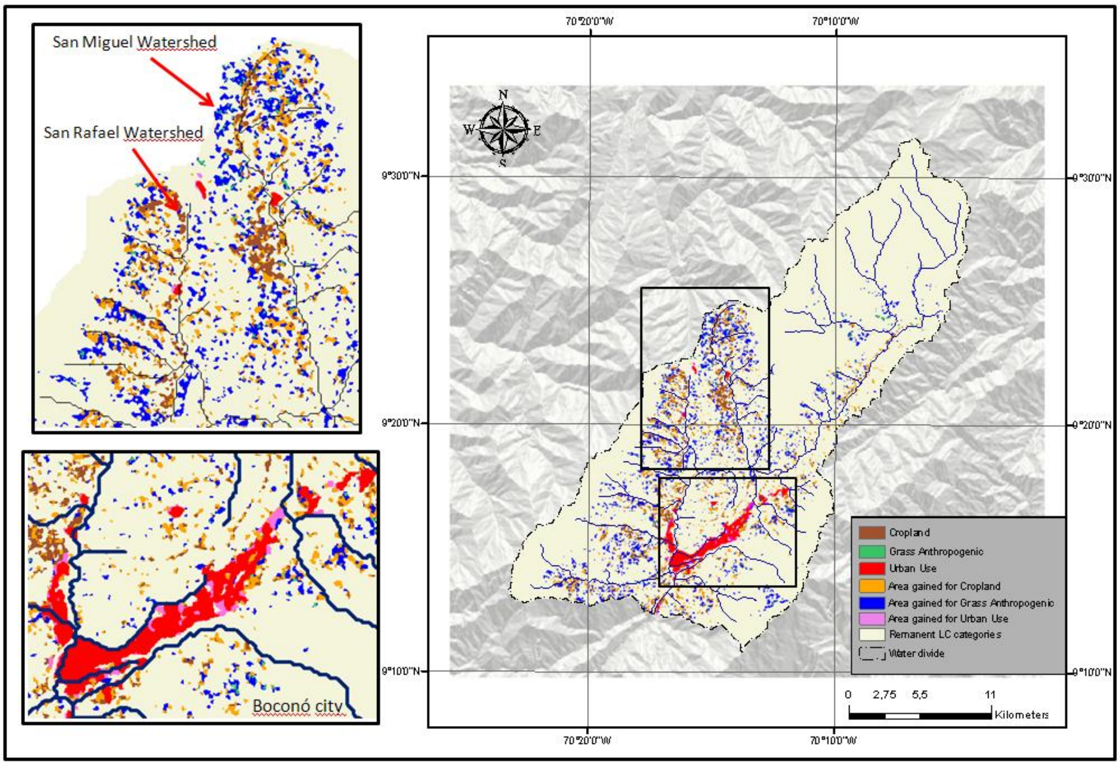


Figure 4.8.- Transition area for the Land Use categories in the period T1-T2

clearly indicates that some urban sectors have been damaged during the two periods analyzed.

All these interpretations constitutes important tools having practical importance for the institutions or stakeholders involved with the environmental and land planning at local/regional level, being a rational basis to design new plans, or even to improve those which already exists, in order to guaranty the optimization of the natural resource uses in the river basin. This is very important to encourage the effectiveness of the protective figures defined for the whole river basin, accounting for a more sustainable evolution of the LULC in this important "**water resource area**".

Chapter 5

Temporal & Spatial analysis of the Hydrological response for the Boconó River

5.1.- Introduction.

This Chapter aims to introduce the results derived from the development of the Third Methodological Approach, in order to analyze comprehensively the hydrological dynamic and response of the Boconó River Basin from a combined temporal-spatial perspective. At first, the relationship between rainfall and runoff in the area were gentle established, based on the scarce historical data available for the river Basin. After that, the hydrological landscape of the river Basin was described through the use of the HRU concept, being determined for three different time-points to be considered within the different scenarios which were simulated. The main results obtained during the simulation process using the model J2000g in three variations conceived for the river Basin are then presented and discussed, in terms of the ability to reproduce the hydrological dynamic, based on the efficiencies reached on each model after the calibration-validation period. Finally, the water balance components were spatially distributed in the catchment area through the modeling process, which is a very useful mechanism to have a concrete spatial visualization of the processes inherent to the water balance, and their spatial implications. The vision and the discussion offered in this Chapter is a basis to sustain the processes, results and discussion presented on Chapter 6.

5.2. - Temporal Relationship between Rainfall and Runoff in the Boconó River Basin

The Figure 5.1 shows the historical trend inherent to the annual precipitation and the average runoff, corresponding to the only ten years of data-records for runoff: 1968, 69, 70 71, 72, 73, 1988, 1989 and 1995 – 1996. The curve shows the evolution experienced for the average runoff during the same period. A very good fit between the two variables can be observed, being 1972 the most humid year in the area (Ostos, 1974), in which the recorded runoff was two times higher than the average runoff (15,55 m3/seg), meanwhile the driest recorded year was 1995, with a pp value of 734,2 mm and a average runoff of 14,148 m3/seg.

Only one divergence between the two variables can be observed on 1988, which can be explained through seasonal differences, which were particularly extreme during 1988, so that the flow values during the dry season for that year were quite lower as usual.

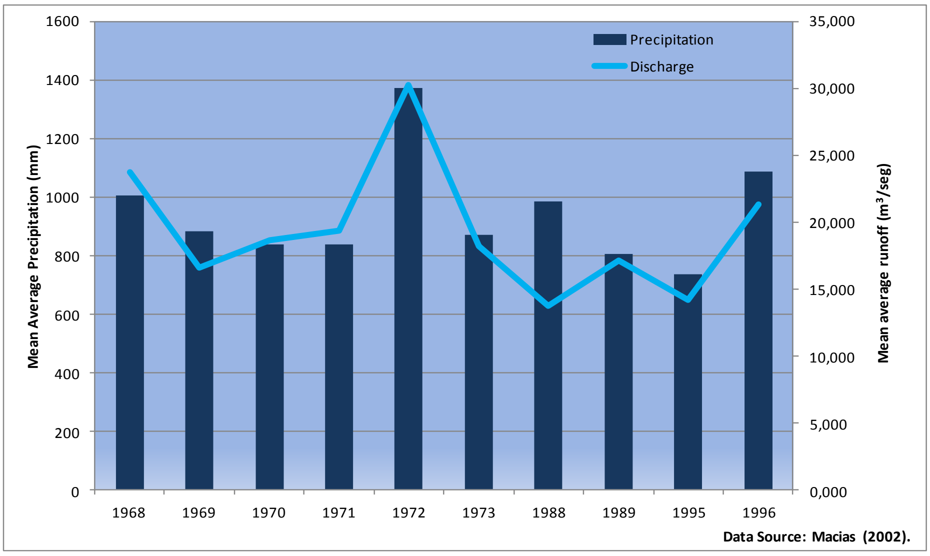


Figure 5.1. - Annual precipitation and annual average runoff for the available period of observed runoff data.

The seasonal variability for the two variables in the area during the same period recorded is displayed on Figure 5.2. As explained on Chapter 3, the dry season occur between November and March, and the rainy season range from April to August. Ostos (1975) defined September-November as a transitional period between the two main seasons above mentioned; however, other authors like Pulwarty et al., (1998) and Andressen et al., (2000) consider the rainy season to occur from April to October. The climate for this zone is defined by Andressen et al (2000) as perhumid mesotermic with a single maximum in rainfall occurring between May and July (unimodal regime). Such definition can be clearly observed in the Figure 5.2, so in this case the higher values for rainfall generally occur in June (143,49 mm) as usual in the region (Pulwarty et al, 1998), meanwhile the peaks flows occur one month later, in July, when the oversaturated soils facilitate the surface runoff, reaching the peak of 37,794 m^3/seg. On the other hand, the single minimum value for precipitation occur in January (18,87 mm), meanwhile the lowest value for the discharges (10,072 m^3/seg) is expected to occur two months later, on march, which suggest that the forested LCC in the area could play an important role in the persistence of the base flow during the dry season. The Figure 5.3 show the Boconó river at the outlet (La Cavita sector) flowing in the middle of the Dry Season (January).

According to Pulwarty et al (1998) the variability of the convection processes in the area is highly significant, and the whole region is directly influenced by both ENSO and A-ENSO anomalies (Aceituno (1987); Pulwarty et al (1998); Andressen et al (2000); Cárdenas et al

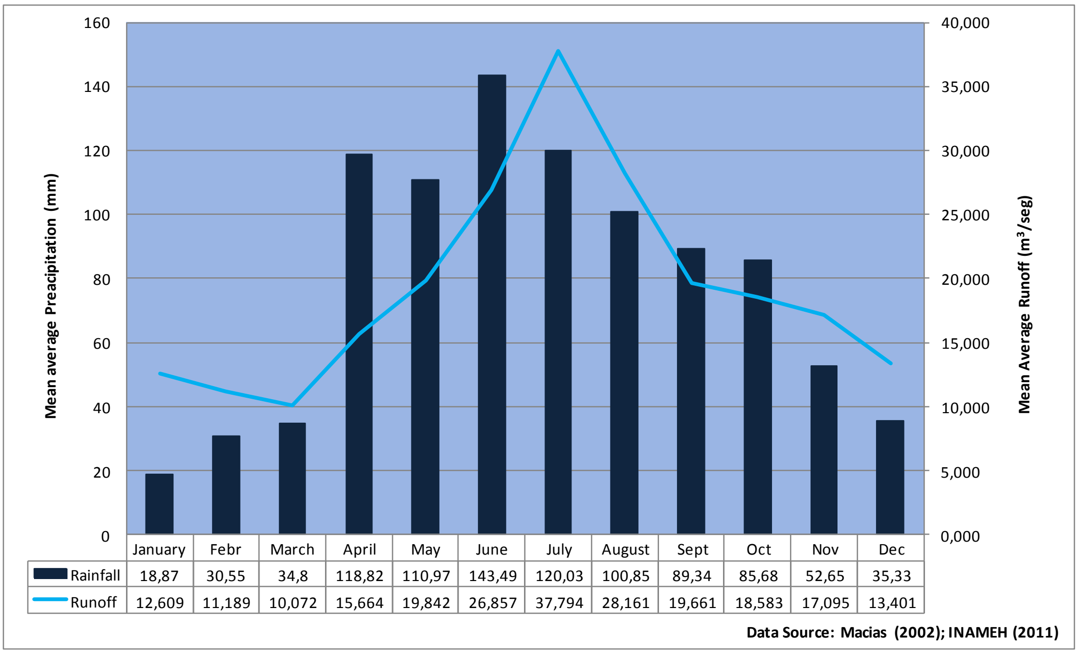


Figure 5.2.- Average monthly and average monthly runoff for the Boconó river Basin.

Figure 5.3. - The Boconó River at the outlet (La Cavita sector), during the low flow period, in January 2010.

(2002)). These considerations lead to define the relationship rainfall vs. runoff as highly dynamic in the river Basin. Macias (2002), affirms that the relation level-runoff in the Boconó river has been showing high instability on last years due to several factors like: alteration of the channel, heavy rainfall events, channeling works and others. This fact could be also derived from the multitemporal LULC analysis, due to the changes accounted by the Fluvial Plain (Fl-P) during the period, reflected in the various inter-category transitions to other LULC that such category experienced on last 20 years.

5.3. - Functional Hydrological Landscape system in the Boconó River Basin.

As mentioned on Chapter 2, the hydrological modeling requires a functional regionalization of the catchment area, using the distinctive variables controlling the hydrological processes once the water reach the biosphere to delineate landscape dependent process entities identified as hydrological response units (HRUs). Following the method explained on Chapter 2 and based in the research targets, three HRUs maps were delineated for the research, in which the hydrological response units based on the LULC for the 1988, 2008 and 2028 were identified. The Figure 5.4 contain, as example, the HRUs map derived using the LULC map of 1988. The corresponding HRUs maps for 2008 and 2028 are displayed on Appendix D. The basic information concerning the HRUs maps are gentle resumed on Table 5.1.

As seen on Figure 5.4, the method used lead to reach an adequate level of aggregation in the delineation of the HRUs in the area, improving the excessive tessellation produced by the intersection method commonly used. But the idea was not only to reduce the tessellation, but to incorporate the topographic and the geomorphological dimensions as well as observed

Table 5.1. - General information about the HRUs maps generated for the modeling process.

HRUS MAP	Total of HRUs classes	Total of polygons	Min area (ha)	Max area (ha)	Ave area (ha)	ρ HRU (N° HRUs/Km2)
1988	121	13801	0,18	400,901	3,90	25,69
2008	121	13979	0,27	380,371	3,84	26,02
2028	122	14107	0,18	283,399	3,808	26,26

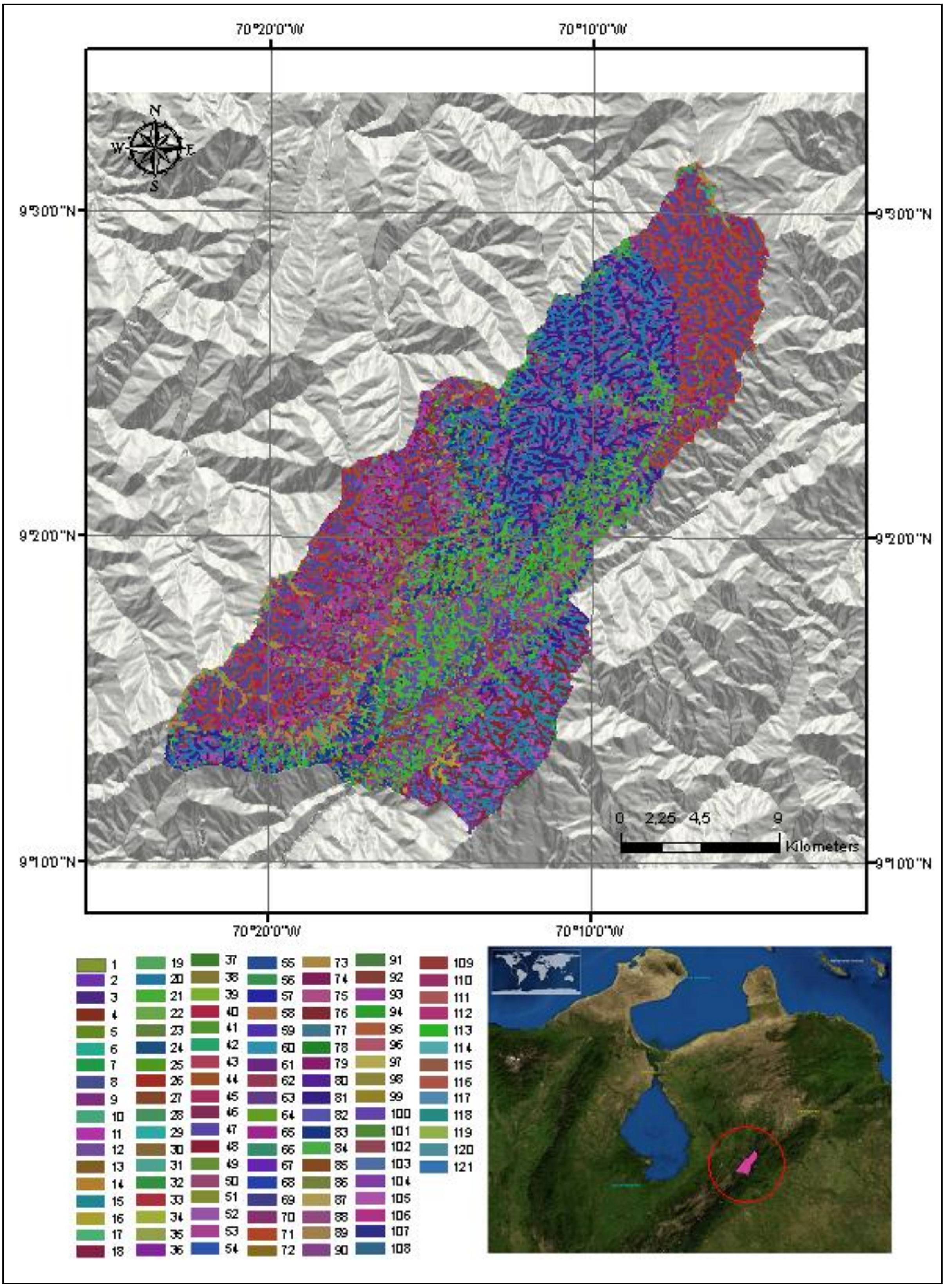


Figure 5.4. - Hydrological Response Units (HRUs) delineated for the year 1988.

patterns, like the land forms system, using it as a target variable. The use of observed patterns in this case can improve the spatial estimates of the hydrologic quantities within catchments (Grayson et al, 2002). In addition, the incorporation of the landforms as a target variable makes easier the identification of the connectivity across the landscape system, facilitating the conduction of the flows within the simulation process (Khan et al, 2009).

The aggregation was quite higher across the forested concave and convex breaks, and lower in the middle sector of the river Basin, were the LULC categories are highly fragmented, as discussed on Chapter 4. A total of 121 classes were finally identified in the maps for 1988 and 2008, and 122 classes were delineated on the map for 2028 (Table 5.1). The number of polygons tended to increase from 1988 to 2028, although the average surface area for the polygons as well as the density of polygons tended to remain stable, ranking from 25, 69 to 26,26 polygons / Km^2.

5.4. - Modeling the Hydrological Response through the Model J2000g

In this section the results obtained from the simulation process using the J2000g model are presented. The runoff-precipitation simulation of the Boconó River has been carried out, as explained on Chapter 2, for the time frame between 1988 -1990 and 1995 - 1996, corresponding to the period with available discharge observed data. Following the "**split sample validation**" method, the first period (1988-1990) was used for the calibration, meanwhile the second one was used to validate the model.

At first, the model was built considering the scarce real data for evaporation in order to derive the potential and actual evapotranspiration. Only the Boconó-Aeropuerto station accounted for data inherent to parameters like: temperature, evaporation, humidity and wind speed in the river Basin. For that reason, a virtual station with evaporation data was needed to be created in order to distribute the variable spatially among the catchment. A visualization of the main output of the so-called Model B-1 from J2000g showing the observed runoff vs. simulated runoff and the precipitation for the calibration period (88-90) is displayed on Figure 5.5.

The simulated discharge (red line) is shown being compared with the observed runoff data (blue line); the gray columns in the upper part of the Figure display the daily precipitation occurred across the catchment area. Despite of the limitations founded in the basis data (observed runoff, soil information), it can be seen that the J2000g model is able to predict the

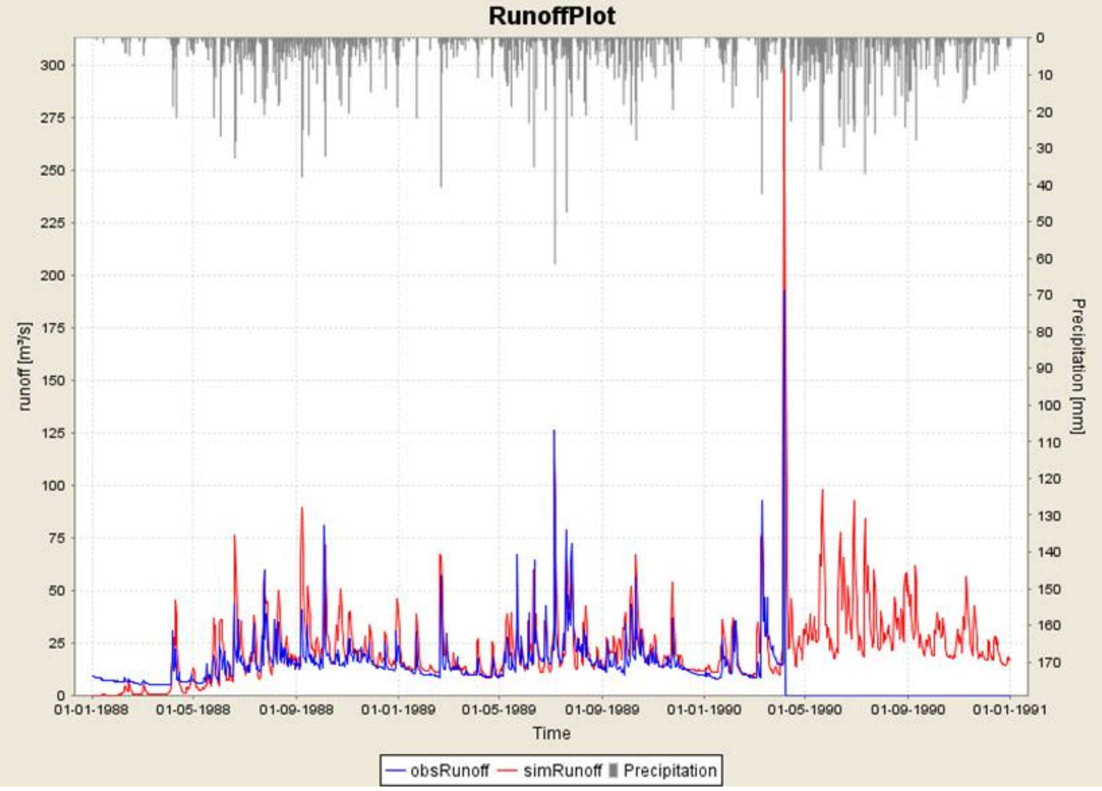


Figure 5.5. - Main output of the modeling process in J-2000g for the Model B-1. (RunoffPlot), showing the Observed runoff (obsRunoff), the simulated runoff (simRunoff) and the precipitation.

runoff dynamics of the Boconó River with an adequate level of accuracy. Some indicators for the efficiency of the Model B-1 are resumed on Table 5.2.

As seen on the Figure 5.5 and in the Table 5.2, the model is able to reproduce the hydrological response and the dynamic of the runoff quite good, despite of the limitations for data basis already mentioned. However, the model B-1 was not really able to reproduce and to reflect the dynamic due to LULC changes in the posterior phase, accounting for no changes in the different simulated scenarios. The careless of station with evaporation data did not possible to reach an adequate and realistic spatial distribution of the parameter, so the potential and the actual evapotranspiration could be not well reproduced by the model. For that reason, a second model was created, in which the evapotranspiration was planned to be calculated through the Hargreaves-Samani method. This method is very easy to apply because of the low requirement for data (Garcia et al , 2011), been also proved to produce

Table 5.2. - Basic Efficiency Criteria obtained for the Model B-1 in J2000g.

Phase	Time-period	NSC (E2)	Log E2	r2	PBIAS (%)
Initialization	01/1988 – 12/1990	-0,36736	-1,31391	0,68568	28,33566
Calibration	01/1988 – 12/1990	0,34456	0,25820	0,72578	20,54168
Validation	04/1995 – 12/1996	0,35695	0,29396	0,45282	26,34049

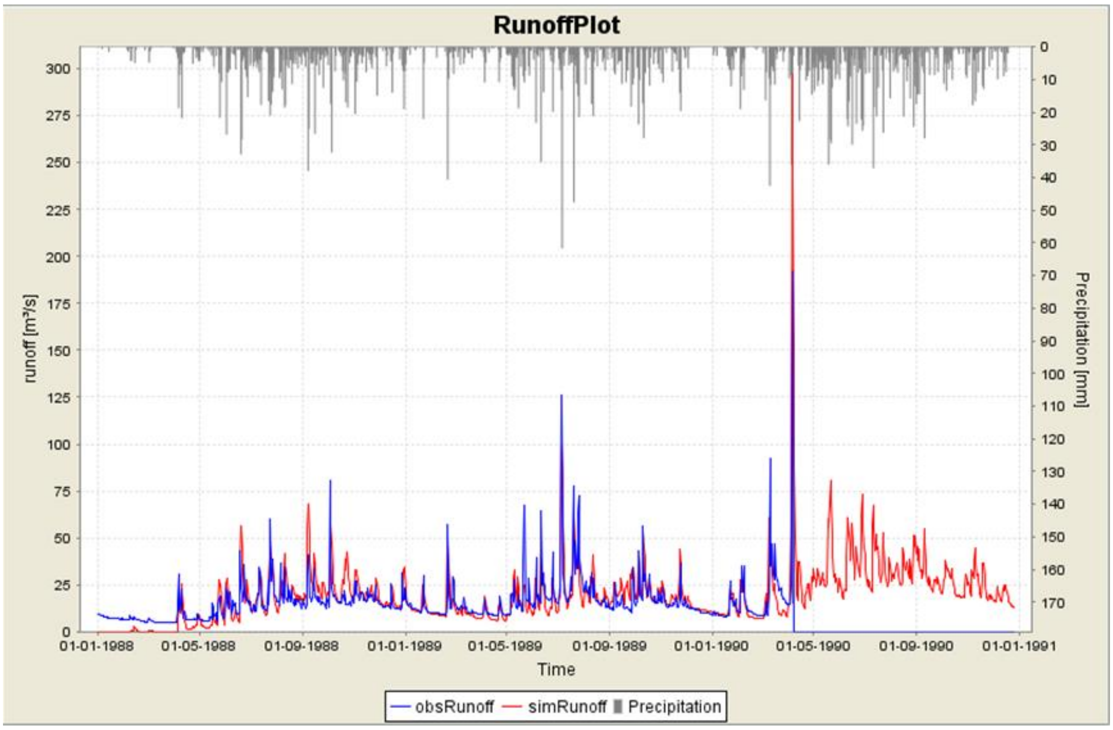
good results despite its simplicity (Gonzalez et al., 2009). The Model B-2 could be then able to reproduce the hydrological response for the period 2007-2009, for which no observed data for evaporation exist, and theoretically could to simulate the future scenarios with a better performance as those obtained by the model B-1. However, not considering the vegetation parameters into the ET calculation, the Hargreaves – Samani method couldn't represent well the role of the vegetation in the soil-water storage, so even when the performance obtained for the scenarios was better than those obtained for the M-1, it was not considered successfully in modeling the influences of the vegetation classes in the hydrological regime, and consequently the impact of the LULC changes couldn't be adequately determined.

A third model – the B-3 model was built, in which the evapotranspiration could be calculated according to the Penman-Monteith method. The Penman-Monteith method takes into account some parameters derived from vegetation, so they are combined with a land cover parameterization of the complex soil-water storage, so that the method can reflect the influences of different types of vegetation in the hydrological cycle (Krause, 2002). LULC classes or even vegetation types are specified within the model using values for LAI, vegetation height and albedo, as well as constant values for canopy resistance, stomatal resistance and the relative fraction of roots in each of the three soil layers (Mao & Cherkauer, 2009). It has been shown to be the most accurate method and can be calculated even with missing data with reasonable accuracy (Gonzalez et al, 2009). Due to the low availability of measured data for humidity and wind speed, the B-3 model only could simulate the hydrological response for the years 1988 and 1989.

The Figure 5.6 display the main outputs (Hydrographs) obtained for the models B-2 and B-3, respectively. As the model B-1, both models could also reproduce well the flow regimes in the catchment.

A comparison between the observed values and estimated runoff values can be observed in Figure 5.7. The quality of the models is practically the same, expressed in the similar values

(A)



(B)

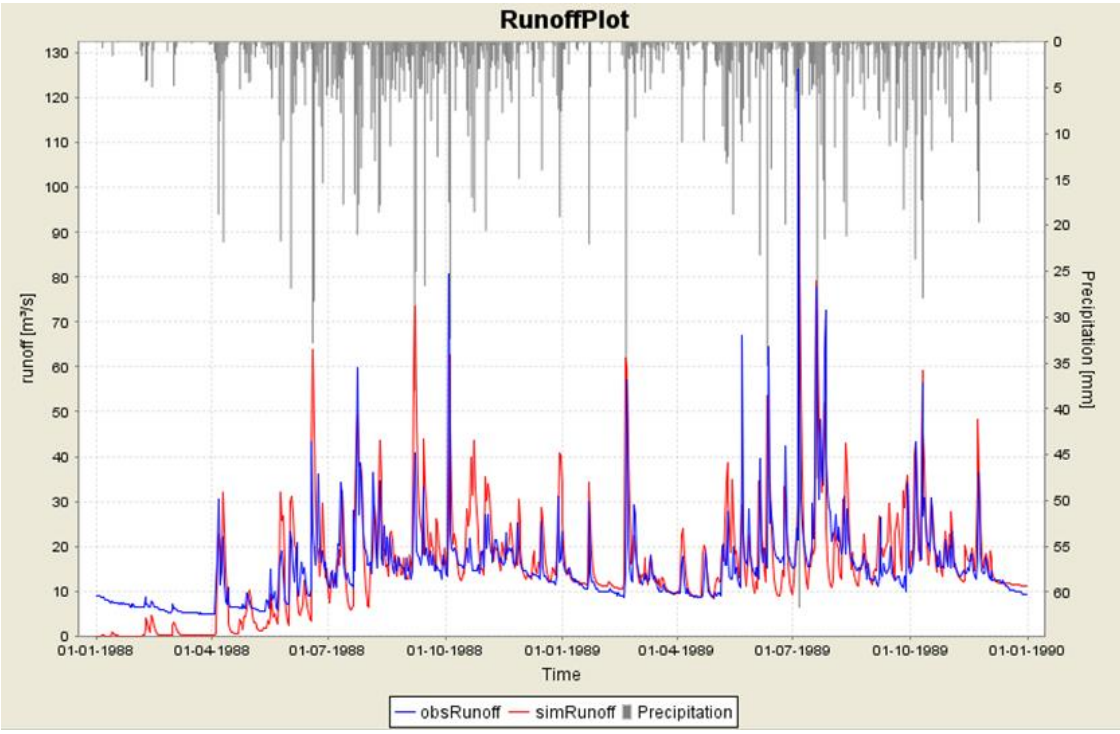
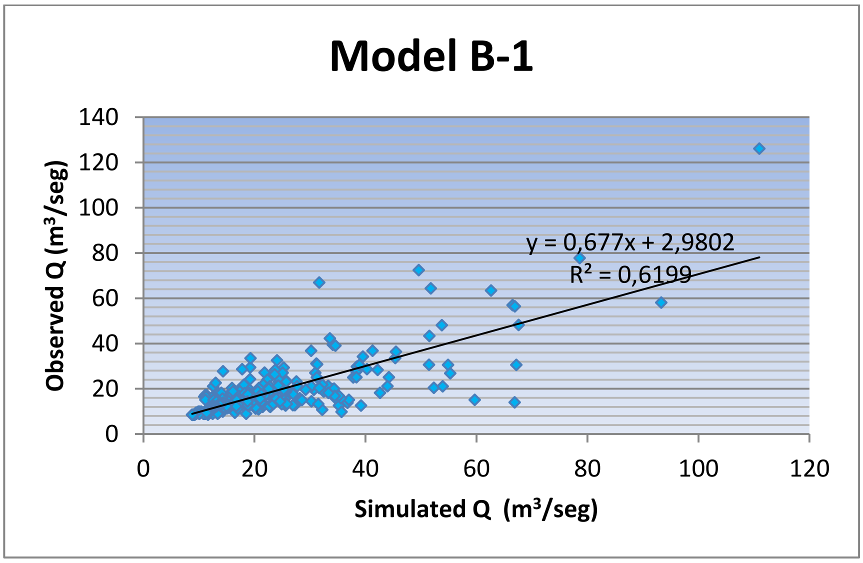
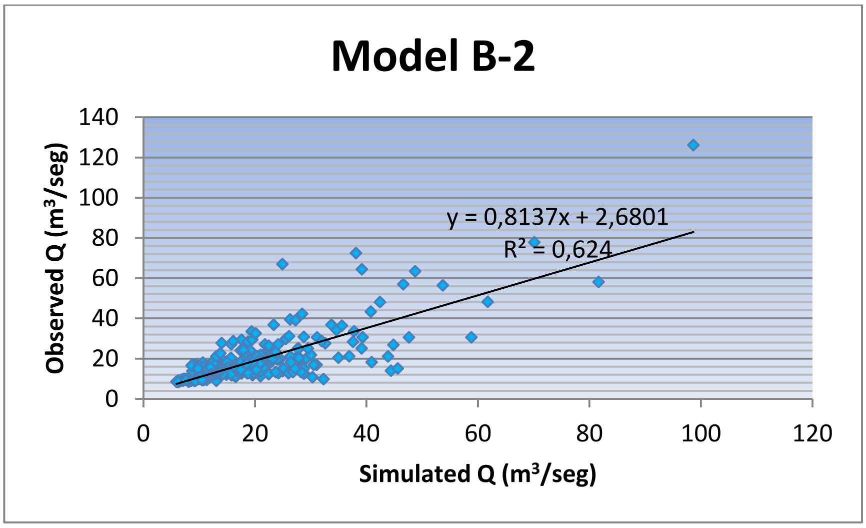


Figure 5.6.- Main output of the modeling process in J-2000g for the Models B-2 (A) and B-3 (B).





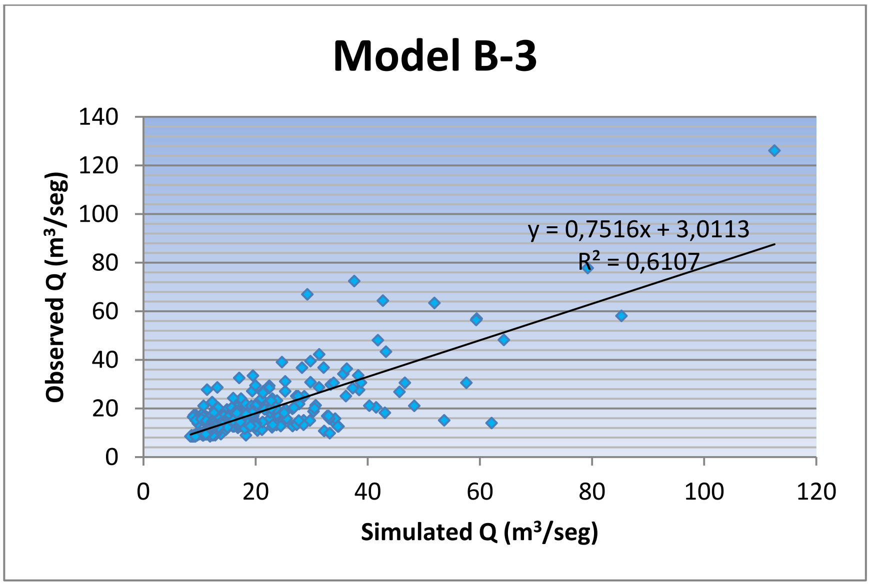


Figure 5.7. - Comparison between observed and simulated values produced by the models B-1, B-2 and B-3.

for r². It can be observed that in the three models, the dispersion tends to be lower for low flow values, whereas for peak flows a higher dispersion is quite evident. This fact suggests that the models designed can to predict the low flows more accurately than peaks flows.

The Figure 5.8 shows a gentle comparison between the water balance components estimated by the three models. A minimal difference is observed between the models for the components basQ (base flow) and gwrecharge (groundwater recharge); for the components dirQ (direct flow) ant totalQ (total runoff) there is a moderate difference, so in these cases the model B-1 produced quite higher values as the other two. The lower values for dirQ and totalQ were estimated by the M-2.

Obviously, much higher differences were observed by the actEt. The values obtained in model B-1 are higher than the values calculated by the models B-2 and B-3, and the lower values being observed in B-3.

The efficiencies obtained for models B-2 and B-3 are resumed in Tables 5.3 and 5.4 respectively. The model B-2 show the better condition respect the efficiencies, whereas in the model B-3 the shorter simulation period probably reduced the potential to get a better efficiency in the results.

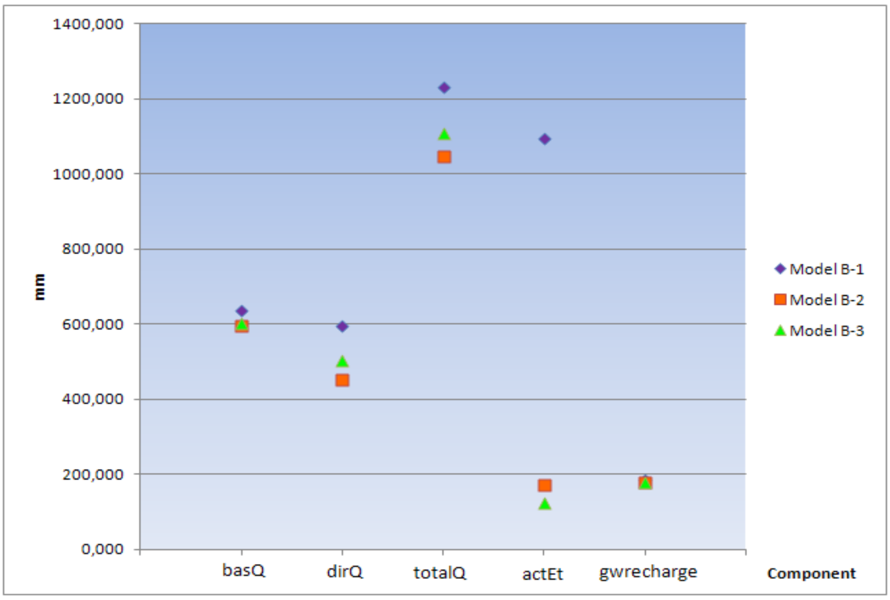


Figure 5.8. - Comparison between the water balance components estimated by the Models B-1, B-2 y B-3.

Table 5.3. - Basic Efficiency Criteria obtained for the Model B-2 in J2000g.

Phase	Time-period	NSC (E2)	Log E2	r2	PBIAS (%)
Initialization	01/1988 – 12/1990	0.10820	-6.34880	0.68995	-63.19494
Calibration	01/1988 – 12/1990	0.56639	0.46049	0.74409	2.00074
Validation	04/1995 – 12/1996	0.47421	0.51676	0.47846	6.69547

Table 5.4. - Basic Efficiency Criteria obtained for the Model B-3 in J2000g.

Phase	Time-period	NSC (E2)	Log E2	r2	PBIAS (%)
Initialization	01/1988 – 12/1989	0.36055	0.38962	0.58722	10.16264
Calibration	01/1988 – 12/1989	0.299,1	-0.57260	0.63644	-8.62256
Validation	04/1995 – 10/1996	0.50743	0.41883	0.51056	5.76682

As seen on Tables 5.2, 5.3 and 5.4, the calibration process lead to improve the efficiencies of the model, even when a high level of uncertainties derived from the scarcity and quality of the data sources persist. Despite of the good fit reached in some indicators like the r^2, some problems still remains in the simulation which can directly affect the efficiency criteria of the models in this case. The main problems observed in the simulation output are related with:

a) Overestimation of some peaks flows in single events

This problem can be observed in some events like that occurred on 06/09/1988, and the most evident occurred on 05/04/1990.

b) Underestimation of some peak flows in single events. This situation is particularly evident during the rainy season of 1989.

c) Inconsistencies in the observed runoff data. Some inconsistencies between the simulated rainfall and the observed runoff data were detected in the period used for the validation, as some important precipitations events are not reflected in the runoff curve, even when they were apparently intense in the occurrence. Is important to quote here that a short data serie of observed runoff had to be discarded to be used in the simulation process, as the values were much higher as the values of the series used into the model.

Checking the scarce Literature about the River Basin, another inconsistence about the observed data was found, which could be seriously affecting the level of the certainty in the modeling process. Quevedo (1997) studied the relationship precipitation-runoff in the river Basin, through the analysis of 5 peaks flows occurred on: 03.10.88, 05.07.89, 28.06.91 and 23.06.1995. The two first events are into the simulated period used during the calibration. The last one is into the period considered for the validation. In all the cases the observed values reported by Quevedo (1997) for the respective events are much higher that the observed runoff data available for the same datum were those events occurred. On the other hand, Cornieles (1997) also analyzed a discharge event occurred on 10.07.1995 for the Boconó river, and the peak runoff reported is quite higher as those of the observed data.

This situation is illustrated on Figure 5.9, through the comparison between the simulated values, the observed values and the values reported by the authors above mentioned. It can be clearly observed that the peak flows analyzed are severely underestimated in the observed data source, so in some cases the difference is almost the double as the observed value. For example, the peak discharge for the event occurred on 10.07.95 was 37,85 m^3/seg according to the observed data, meanwhile Cornieles (1997) reported for the same event a highest peak of 230 m^3/seg, a difference of 608 %.

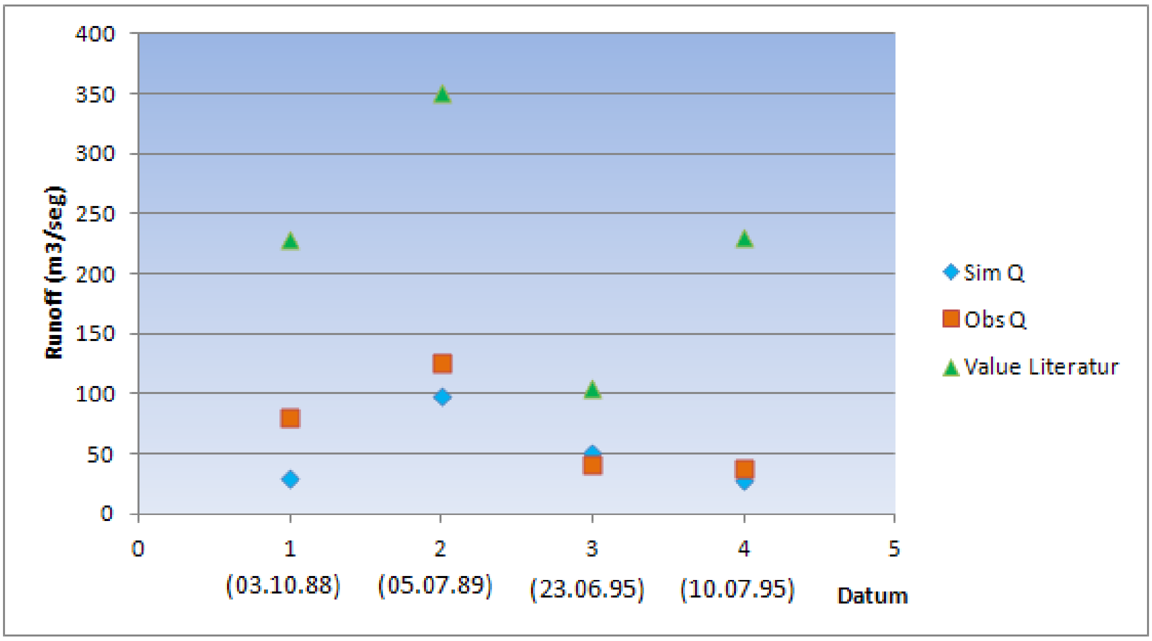


Figure 5.9.- Comparison between simulated runoff, the observed data and the values founded in the Literature for 4 discharge events occurred in the Boconó river.

Three of the fourth cases illustrated are showing underestimation of the peaks flows, except in the case of the event of 23.03.95, in which the simulated value is slightly higher than the observed one.

This comparison reveals an important fact: the observed runoff data for Boconó River, particularly those referred to the peaks flows is not reliable, which could indicate that some peak discharges of the river could be underestimated. Obviously, this fact had a direct influence in the calibration process, and could be an important limiting factor in the simulations for future scenarios.

Unfortunately, the scarcity of historical runoff data in the whole catchment represent a serious limitation for a comprehensive analysis of the dynamic of the flows, in order to find a possible reason for the over and underestimation in this case. An analysis of the precipitation data reveal that the events really occurred. However, the spatial distribution of the stations makes it not possible to represent adequately the local variability of the precipitation, due to the high variability of the convection in the area. Another possible cause of the over/underestimation could be the scarce soil information for the entire catchment. The model lies on very coarse soil information, and some important parameters like soil density and air capacity were simply not available for the soils in the area.

Krause (2002) detected underestimation of high flow peaks modeling a river basin in Germany, using the J2000 model (a more sophisticated version of the 2000g). Problems related with over/underestimation of high peak flows using the J2000 Model was reported by Scheffler (2008) in the simulation of the Great Letaba River in South Africa. Problems related with underestimation of seasonal flows using the J2000g model were reported by Donmez et al (2009), and by Behrawn (2010). Underestimation has also being reported as an important problem in other simulation models, like the HBW model (Wilk et al, 2001); the SWAT model (Wang et al, 2008); (Kim et al ,2009); and the PRMS model (Qi et al, 2009); (Legesse et al, 2010).

The over/underestimation in this case is surely affecting the efficiency of the model; particularly the NSC coefficient (e^2) is especially sensitive for runoff peaks and fast runoff components (Wolf et al, 2009). The coarse level of information about soils and geological framework could be affecting the value of log-e^2, which is an indicator for the simulation of the groundwater drainage. However, the R^2 value obtained in the calibration indicates the rendering of the temporal dynamic for the simulated runoff in the Boconó River.

Respect to the third problem, the inconsistencies in the runoff data are affecting the lower efficiencies values obtained for the validation period, particularly the value for NSC. The degree of certainty for the validation exercise was lower as those obtained during the calibration process. The same problem about the lower performance during the validation was also reported by Qi et al (2009) and Legesse et al (2010). He & Hogue (2011) also reported a reduction in the efficiencies criteria during the validation period, when using the HSPF model in a monthly and daily scale. Wang & Kalim (2011) obtained lower efficiencies-values during validation when used the SWAT Model at daily scale, in contrast with higher efficiencies reached during the simulations at monthly scale. It suggests that the daily simulations of total stream flows are not as good as monthly simulations. Some authors like: Legesse et al (2003), Wang et al (2008), Qi et al(2009), and Legesse et al (2010), have highlighted the better performance obtained by monthly simulations in comparison with daily ones.

The Table 5.5 display the variability of the values concerning to the parameters used into the model, during the calibration process. The parameters maxPercAd, BFk and FCA experienced the biggest changes during the calibration process. Particularly the parameter BFk was highly sensitive to improve the model efficiencies.

Due to the lack of observed measures for runoff and discharges within the river Basin, the quality of the model couldn´t be tested inside the catchment, so that the model was validated only at the basin´s outlet using the observed data from La Cavita Station, as quoted on Chapter 2. The Figure 5.10 shows the simulation of the validation period (1995-1996) using the model B-3. The efficiencies resulted quite lower in comparison to those obtained during the calibration period (Table 5.4). The inconsistencies mentioned on point “c” were detected in this period, so they could be influencing the results obtained during the validation.

Table 5.5. - Changes in the parameter values during the calibration process.

Identity Name	Range Value	Initial Value	Final Value	Dif
FCA	0 – 20	5	0.2	4.8 (-)
LatVertDist	0 – 100	4	1.2	2.8 (-)
linETRed	0 – 1	0.8	0.9	0.1 (+)
petMult	0 – 10	1.2	0.2	1 (-)
maxPercAd	0 – 100	0.3	36	35.7 (+)
DFk	1 – 1000	3.1	1.71	1.39 (-)
BFk	1 – 1000	30	45	15 (+)

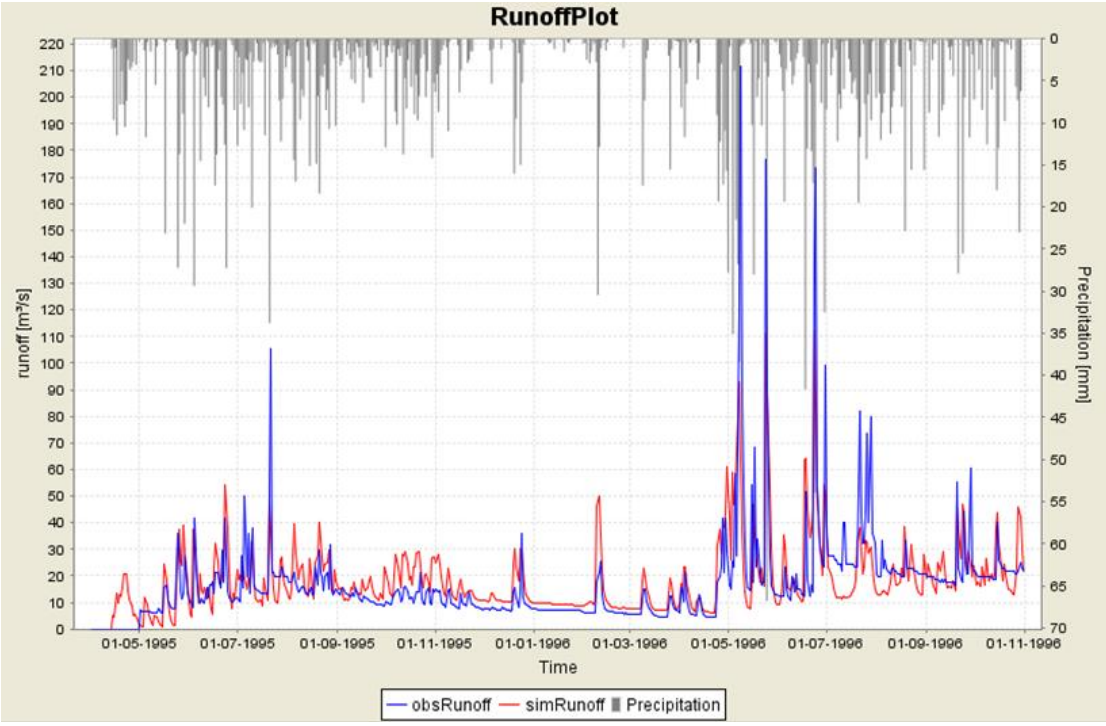


Figure 5.10. - Hydrograph resulted from the Validation process, using the model B-3.

5.4.1. - Verification of the Modeling results

In order to verify the model results, the water balance components for the three years simulated were determined. They are showed on Table 5.6.

The PET values calculated into the model are concurrent with the values reported by Bone et al (1985) in the Mosquey Station (out of service since 1983). The abundant precipitation in the area takes account for a positive water balance from April to middle November, when the dry season comes out until March. The dry season is relatively short but intense, so that a hydrological deficit occur during this time; however, the 97 % of the PotET can effectively be evapotranspirated during the year. The actET represent only the 14% of the total incoming precipitation, meanwhile the 84% of the incoming precipitation can be apparently converted into runoff, enforcing the role of the Boconó river Basin as a water producer zone, as illustrated on Chapter 3.

Table 5.6. - Water Balance components derived from the simulation for the period 1988 – 1990.

Year	Precip (mm)	Pot ET (mm)	Act ET (mm)	Δ Storage (mm)	Q sim (mm)	Q Obs (mm)	Annual WBE (%)
1988	1209,636	246,509	234,482	0,591	917,566	810,3041	5
1989	1164,293	171,847	168,787	-8,996	1008,187	1009,151	0,32
1990	1846,892	176,054	173,172	4,947	1665,021	306,556*	0,20
Mean	1406,940	198,137	192,147	-1,153	1196,925	909,746	1,84
Std Dev	381,683	41,944	36,729	7,133	407,908	140,580	2,737
C.V %	27,129	21,169	19,115	-618,841	34,080	15,453	148.75

* The total value of Q obs for 1990 only considers the available data from January to March.

Unfortunately, the J2000g model does not includes the simulation of the interception, a very important process to consider in the case of Boconó river Basin due the presence of the Tropical Montane Cloudy Forest in the 44 % of its surface area. The existence of this ecosystem in the area sensibly affects the hydrological dynamic, especially the interception, transpiration and a strong regulation of the surface runoff. According to Hölscher (2008), the TMCF can to intercept about the 40% of the total rainfall; Ataroff (2002) measured 45% of interception in a TMCF in Mérida – Venezuela. (Bruijnzel & Hamilton (2000), said that under certain conditions the interception can be 50-60% of the total precipitation, which could be traduced in about 700-1000 mm/year); an important portion remains in the dense foliar system or is re-evaporated, and other portion is reconduced through the foliar mass to the soil. The ET is usually lower in the TMCF due to the excessive humidity, and the quasi permanent presence of clouds; the horizontal precipitation typically occurring in this ecosystem may compensate the losses due to the evapotranspiration (Bonell & Bruijnzel, 2004). The cloud water deposition rates from 1-2 mm/day, with a range from 0,2 to 4,0 mm/day (Bruijnzeel (2000). Unfortunately, these facts cannot be analyzed in this case, due the limited information of climatic parameters, and the absence of climatic measures in the upland parts of the river where the TMCF is located.

The values for Water Balance Error (WBE) shows that the model reached a high level of values prediction, despite of the limitations inherent to the data basis already mentioned. The WBE was slightly higher (5%) in 1988, probably lying in the lower performance that the model shows in the first two months of the simulation period.

5.5. - Spatial relationship of the water balance components in the Boconó river basin.

Now is important to take into account the geo-spatial considerations in the modelled runoff generation. The spatial configuration of the river Basin, conveniently discussed on Chapter 3, play a paramount role in the hydrological response, and the dynamics of the flows. The relief structure and configuration and the altitude define the spatial expression of the climatic variables, and the vegetation systems, defining the behaviour and distribution of the temperatures, precipitation regimes as well as the evapotranspiration patterns. All these conditions converge to govern the variation of the water balance components.

The Figure 5.11 displays the spatial distribution of the precipitation in the river Basin. As seen on the map, the precipitation shows a spatial trend which is governed by both the orographical configuration and the elevation. The precipitation progressively increases from south west to north east, which is the direction followed by the air masses coming from the lowlands of the west high plains (Altos Llanos Occidentales). They penetrate the catchment in a double form: the first one, following the corridor sculpted by the Boconó River through the Guaramacal Branch (El Rosario Branch). In the second one, the air masses penetrates the north west border of the catchment area, ascending through the Guanare River Basin, so that they originate the highest levels of rainfall discharge in the area of Rio Negro sub-basin, and also in the Mosquey sector (middle east sector). The orographic obstacles in this sector are less important and the air masses can to penetrate, originating abundant and heavy orographic precipitation discharges in this area.

The Guaramacal Branch also receives important pp discharges due to the orographic convection; however, the spatial distribution of the rain gauges cannot reflect adequately the spatial variability in the area, fact which had been already pointed out by Ostos (1975). The south-west side of the catchment represent the area receiving less than 1000 mm/year of rainfall, being the sector with a less abundant regime of rainfall. The watersheds of San Miguel, San Rafael, La Encomienda, La Milla and Las Guayabitas are located in this sector, less influenced by the air mass flowing in direction SW-NE, so that the convective systems loss intensity there. The upper sector of the San Miguel Watershed is strongly influenced by the dry air masses coming up across the Burbusay watershed, so the dry conditions are relatively stronger in this area (Cornieles, 1997).

The spatiality of the rainfall regime naturally defines the runoff patterns in the whole catchment area. The Figure 5.12 shows the spatial distribution of the average mean annual runoff in mm/year. As in the case of the precipitation patterns, the runoff production

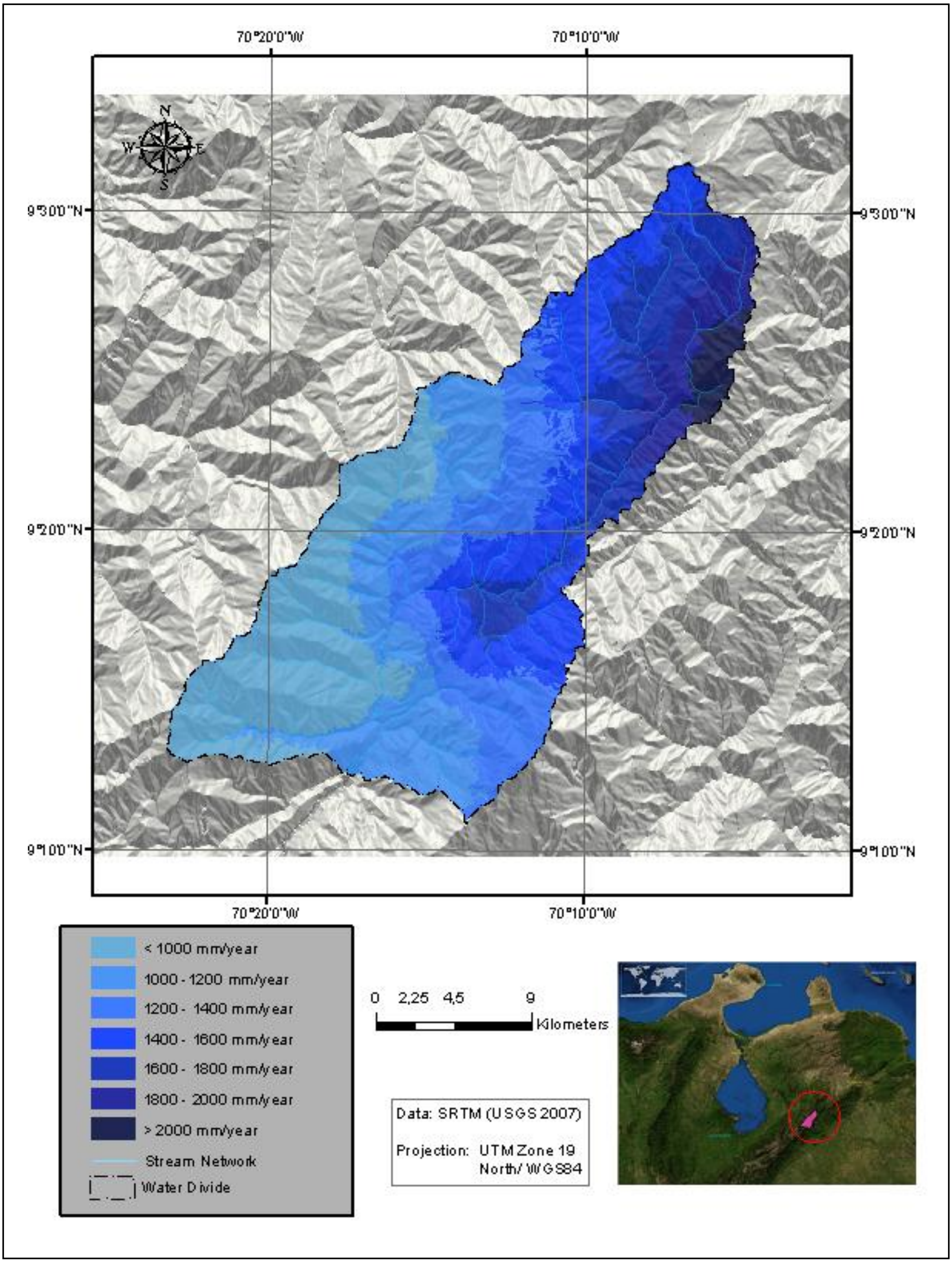


Figure 5.11. - Mean average precipitation in mm/year, for the Boconó river Basin.

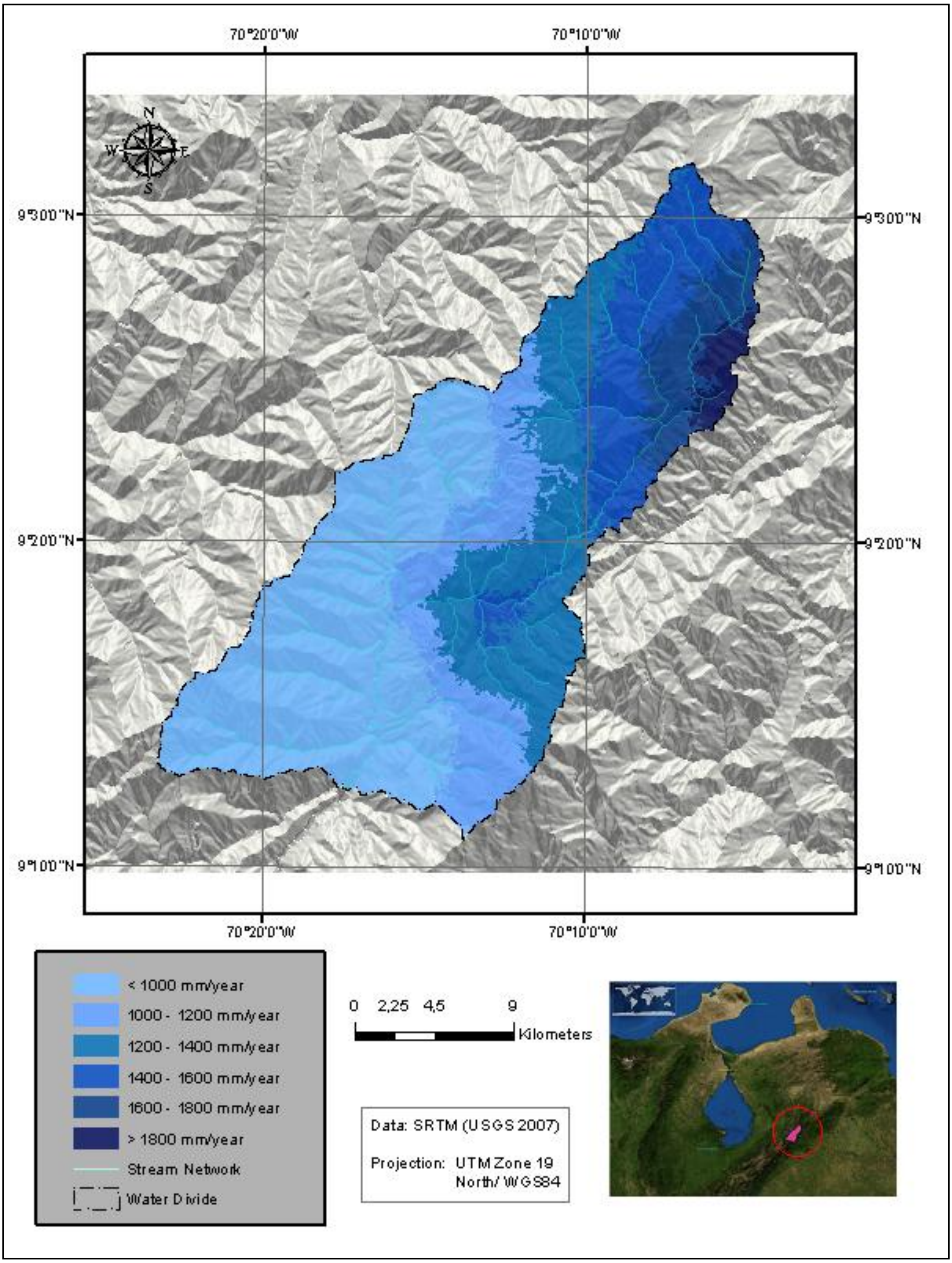


Figure 5.12. - Mean average runoff in mm/year for the Boconó river Basin.

increases from SW to NE, being the Rio Negro sub-basin the most important sector for the water production in the catchment area, where the water production rank between 1200 and 2000 mm/year (Figure 5.12). The dense TMCF widely distributed in the sector, plays an important role in the control and regulation of the runoff in the area, which is particularly relevant during the dry season, when the base flow depend on the runoff coming from the forested area located on the upland sectors, mainly in the Rio Negro sub-basin. The dissected sloping areas lying under the laminated silty slates and phyllites from Mucuchachí Formation (Table 3.1), makes it easier to produce abundant drainage, particularly overland flows, in contrast with the middle lower sector where the slopes are less pronounced. The SW part of the catchment produces less overland flows, in comparison with the opposite part. Particularly the watersheds: San Miguel, San Rafael, La Encomienda, La Milla and Las Guayabitas accounts for the lower mean average runoff values, being under 1000 mm/year. The runoff in these watersheds is more vulnerable to the seasonal periods, so during the dry season the base flows in this sector are quite more diminished.

The dynamic of the actual Evapotranspiration displayed on Figure 5.13 helps to complement the spatial visualization of the hydrological response in the catchment area. The actET is basically governed by the altitude and the vegetation type and structure. The upper sectors usually reveal lower intensity for the actET, mostly due to the lower temperatures. The forested sloping areas, particularly those having the TMCF also shows lower values for actET, because of the higher moisture and the semi permanent cloudy conditions, as already mentioned. In these types of forests, the transpiration is controlled by some characteristics like: stem density, size distribution and sapwood area, depending strongly on solar radiation and atmospheric demand for moisture (Höscher, 2008). The cloudiness reduces the solar radiation in those kinds of forests; however this parameter remains as one of the most uncertain parameters simulated by global and mesoscale circulation models (Bendix, 2006). Certainly, the occurrence of clouds and fog in the forests and its role in the hydrology of the forested ecosystems is difficult to measure and to estimate (Ataroff, 2001).

The corresponding values of actET for the TMCF area in this case are quite lower as those estimated by Ataroff and Rada (2000) for La Mucuy – Mérida State (Venezuela). However, Bonnell & Bruijnzel (2004) reveals contradictions between the current available measures for the ET in the TMCF worldwide.

The middle lower sector of the catchment under LULC like pasture, cropland and shrubland shows values for actET ranging from 150 to 250 mm/year. The highest values were located

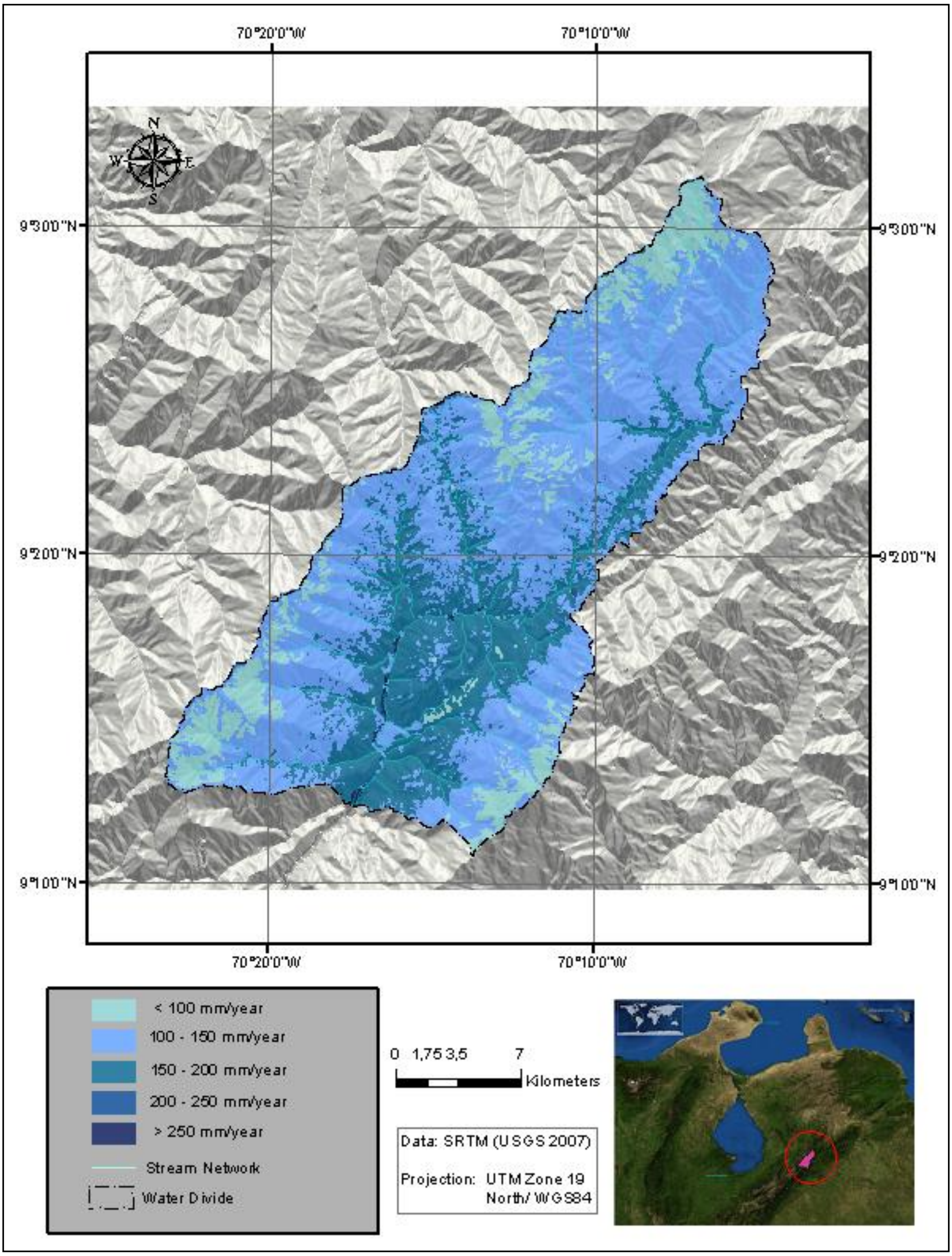


Figure 5.13. - Mean annual actual Evapotranspiration (actET) in mm/year, for the Boconó River Basin.

in the fluvial plain, where the moisture conditions of the humid plain and the higher temperature values can to encourage the evapotranspiration.

The Figure 5.14 displays the spatial distribution of the direct flow in the catchment. The direct component of the flow has a very important contribution during the year, supporting the 45,5 % of the total annual runoff, so only for few days during the dry season the contribution is disrupted and the base flow account for the total runoff. As seen on the map, the direct flow dominates in the convex / convexes dissected areas, where the overland flow can easily be produced. The flat areas like broad ridges as well as the bottom valleys and fluvial plains with coarse soil textures and sandy soils tend to produce less direct runoff.

The contribution derived from the groundwater recharge can be seen on Figure 5.15. In this case this contribution dominates on such flat areas having gentle slopes, where the infiltration is easy to occur. The areas showing the most important contribution are located in the NE sector (Rio Negro sub-basin), as well as in the middle east sector (Mosquey), where the precipitation is heavily abundant, and the TMCF is widely distributed across the landscape. This recharge accounts for the contribution of the base flows, which represent the 54% of the total annual runoff, being particularly relevant during the dry season, when the direct flow becomes very weak or simply disappear.

On the contrary, the areas with less contribution to the groundwater recharge are located in the south-west part of the river basin, where the strongly dissected slopes joined to drier environmental conditions can seriously affect the percolation process; thus the contribution to the groundwater is evidently poorer in this sector of the river basin.

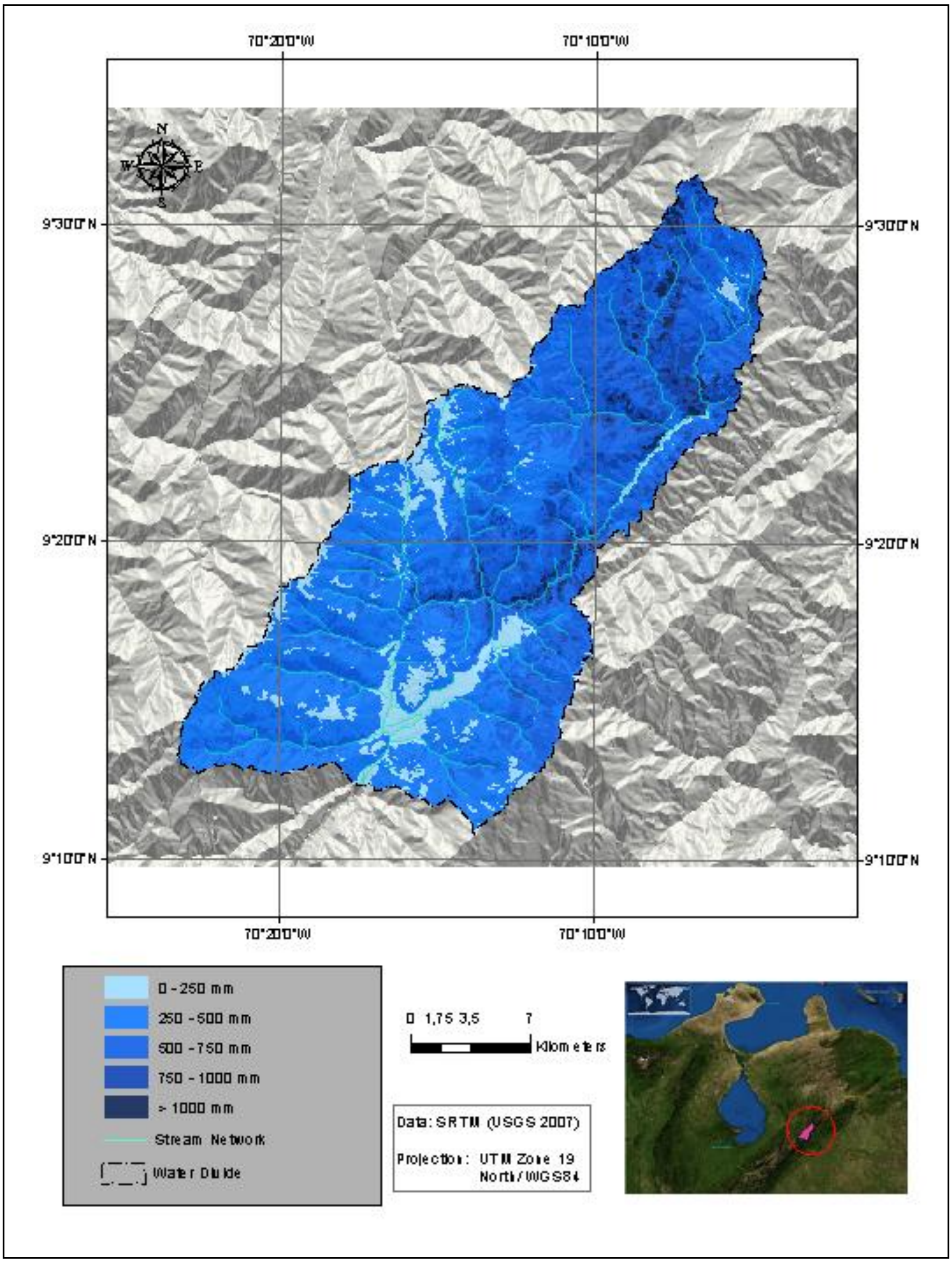


Figure 5.14.- Mean average Direct Flow in mm/year, for the Boconó River Basin.

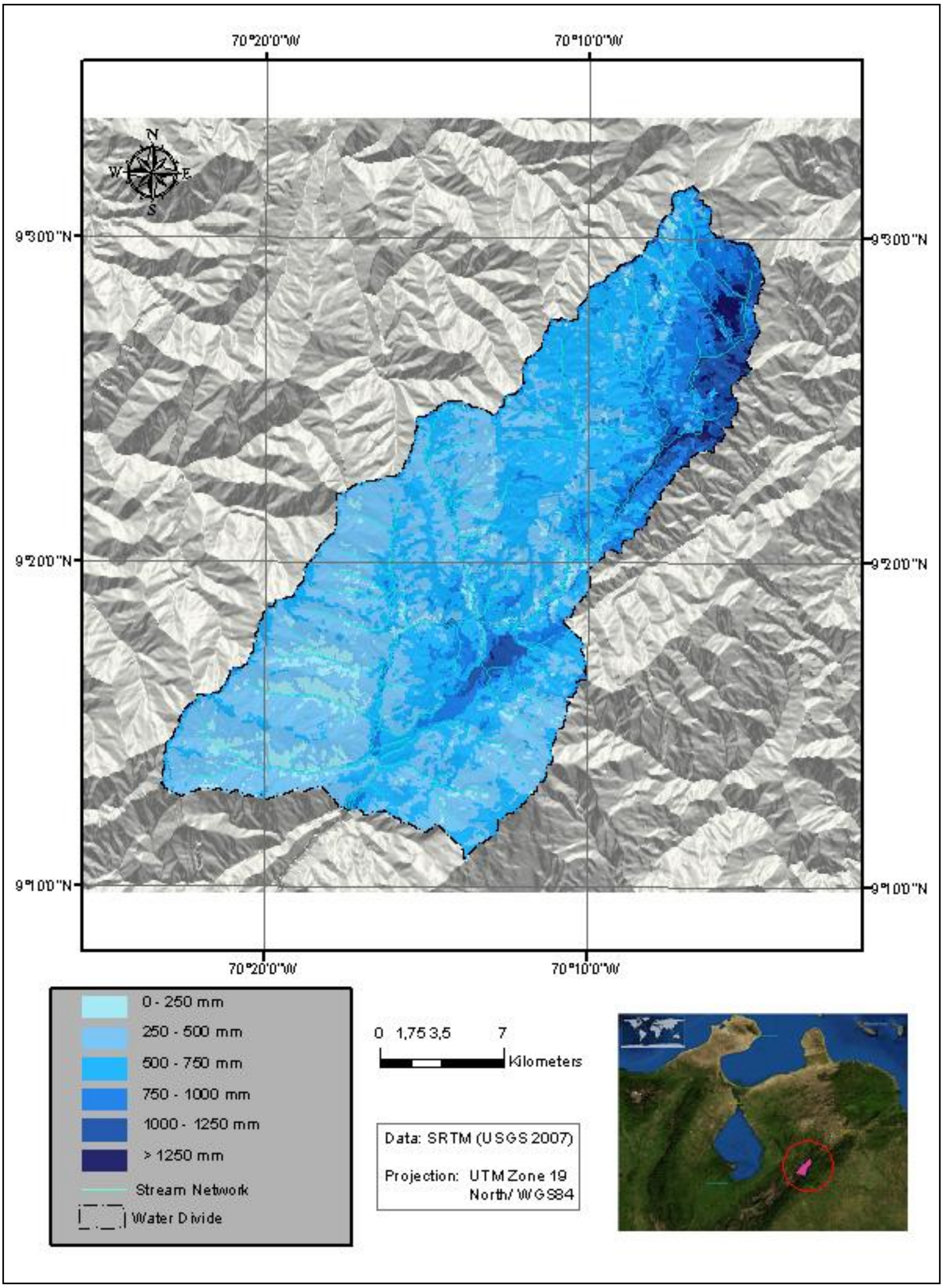


Figure 5.15. - Mean average groundwater recharge in mm/year, for the Boconó River Basin.

Chapter 6

Spatial Changes vs Hydrological Response through specific Scenarios in the Boconó River Basin

6.1. - Introduction.

The central focus of this study was to evaluate the incidence of the spatial changes, basically considering those occurring in the LULC system, as well as the possible changes induced by the global climate change, in the hydrological response of the Boconó River Basin. This Chapter present the results of such evaluation through the modelling process in J2000g for the different scenarios which were defined according to the research targets. At first, a visualization of the LULC dynamic projected to 2028 is presented. This projection was conducted following the main inter-categorical transitions identified on Chapter 4. After that, the results obtained for the nine scenarios are presented and discussed. The scenarios were compared through the use of some basic indicators, in order to get a better understanding of the changes and a better illustration of the differences among them. The statistical significance of the results will be tested with the use of the Signal to Noise Ratio (SNR) method. The overall results were finally discussed considering the more relevant aspects involved in such complex dynamic, taking into account similar experiences produced worldwide.

6.2.- LULC projection for 2028. A Basic map for the future Scenarios simulated in J2000g.

In the point 2.3.6 (Chapter 2) was explained the process followed to derive the projection for the LULC dynamic in the future through the Land Change Modeler (LCM). As explained there, the most relevant systematic transitions were selected, and individually modeled in order to estimate the probability of change to another category. As example of the modeling in LCM, the Figure 6.1 display the partial results obtained after one run for one specific transition. The window on the left show the basic information concerning to the modeling process, like: training parameters, stopping criteria with the iterations used into the simulation, a graphic showing the training and the testing RMS, and the running statistics. The window on the right side displays the map with the resulting potential transition (% of probabilities) after the simulation.

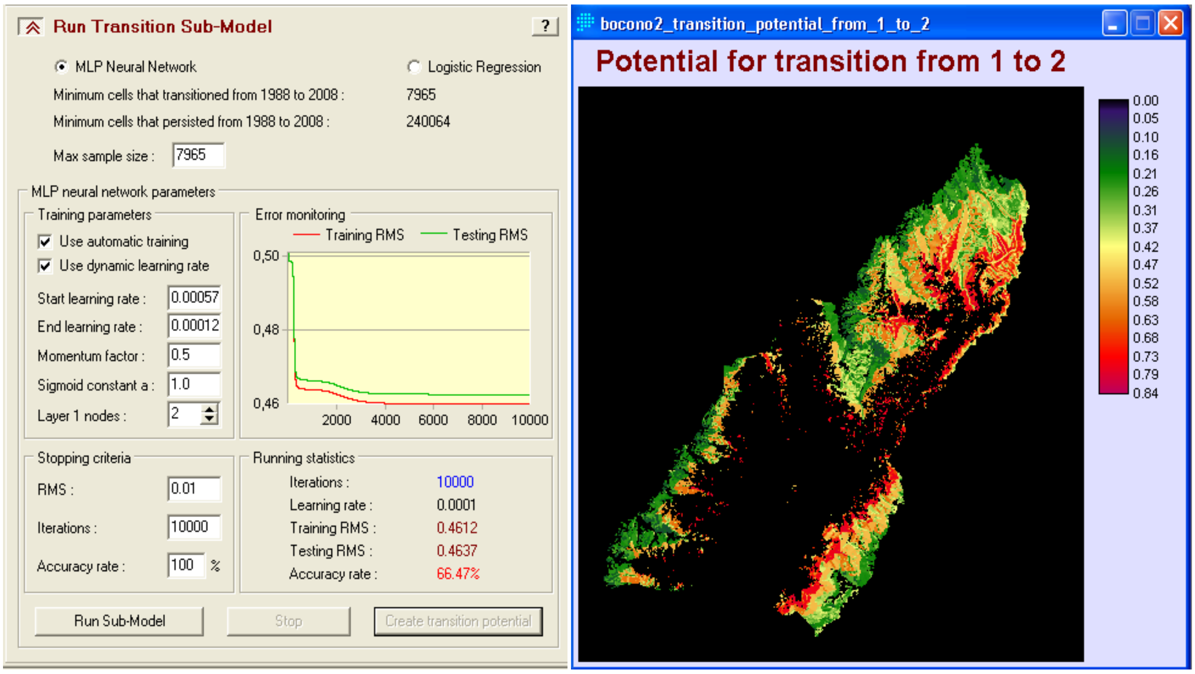


Figure 6.1. - Main output of the LCM after the simulation of a specific LULC transition.

The Table 6.1 resumes the running statistics for the 14 systematic transitions simulated. The highest accuracy rate (100%) was obtained for the transition Fluvial plain to Cropland. High accuracy rates were also obtained for the transitions migrating to urban use: Grass Anthropogenic to urban use (89,52 %); Shrubland to Urban use (88,84 %); Grassland to Urban Use (88,05%); and Cropland to Urban Use (85,33%). Lower accuracy rates were obtained for the LULC migrating to Cropland (50,43% for Sub-montante Forest to Cropland; 50,97% for Eroded Soil to Cropland; and 56,14% for Grass-Anthropogenic to Cropland). This is logical because Cropland was the category showing lowest predictive power during the validation process in LULC classification. That is coincident with other study cases like this from Oñate & Bosque (2010), for which Agriculture was also the most difficult LU to predict. The results are finally summarized in the LULC Map for 2028, displayed in Figure 6.2.

In order to make a comparison with the other two LULC maps used to delineate the HRUs for the years to be considered in the scenarios, the Figure 6.3 show the LULC maps used in the hydrological modeling process, to delineate the HRUs. Attached to the Figure, the corresponding surface values in Ha and % are also shown. The absolute values are also displayed in the Figure 6.4. The modeled transitions to 2028 indicate that the TMCF could be reduced 13,3% respect the surface occupied by this LC in 1988, basically migrating to

Table 6.1. - Running Statistics from the Transition Sub-Models simulated in LCM.

Transition	Iterations	Learning Rate	Training RMS	Testing RMS	Accuracy Rate %
TMCF to open-cleared forest	10000	0,0001	0,4612	0,4637	66,47
Sub-montane forest to urban use	10000	0,0010	0,3497	0,3423	85,44
Grassland to urban use	10000	0,0010	0,3231	0,3176	88,08
Grass-Anthro to urban use	10000	0,0010	0,1790	0,2734	89,52
Cropland to urban use	10000	0,0010	0,3218	0,3436	85,33
Fluvial plain to urban use	10000	0,0005	0,4190	0,4573	66,91
Shrubland to urban use	10000	0,0005	0,2545	0,2877	88,84
Open-cleared forest to cropland	10000	0,0010	0,4877	0,4861	60,25
Sub-montane forest to cropland	10000	0,0010	0,4931	0,4926	50,43
Grassland to cropland	10000	0,0001	0,4653	0,4651	67,62
Grass anthro to cropland	10000	0,0003	0,4954	0,4920	56,14
Fluvial plain to cropland	890	0,0010	0,5000	0,4997	100
Eroded soil to cropland	10000	0,0001	0,4998	0,4999	50,97
Shrubland to cropland	10000	0,0001	0,4721	0,4714	63,04

categories like Shrubland or Grassland. The Sub-montane Forest could to experience low level of changes in the near future, considering that an important portion of the LC is in the form of Agroforestry (coffee plantations under shadow). The surface area for Cropland could reach the double as in 1988, meanwhile the Urban Use could have a huge increase of 543% in surface area respect to 1988. Nevertheless, this change probably will not have a significant impact in the hydrological regimes, as the category is still proportionally small respect the rest in the river Basin. The values shown in the Figures 6.3 and 6.4 are going to be very important to take into account in the evaluation of the future scenarios.

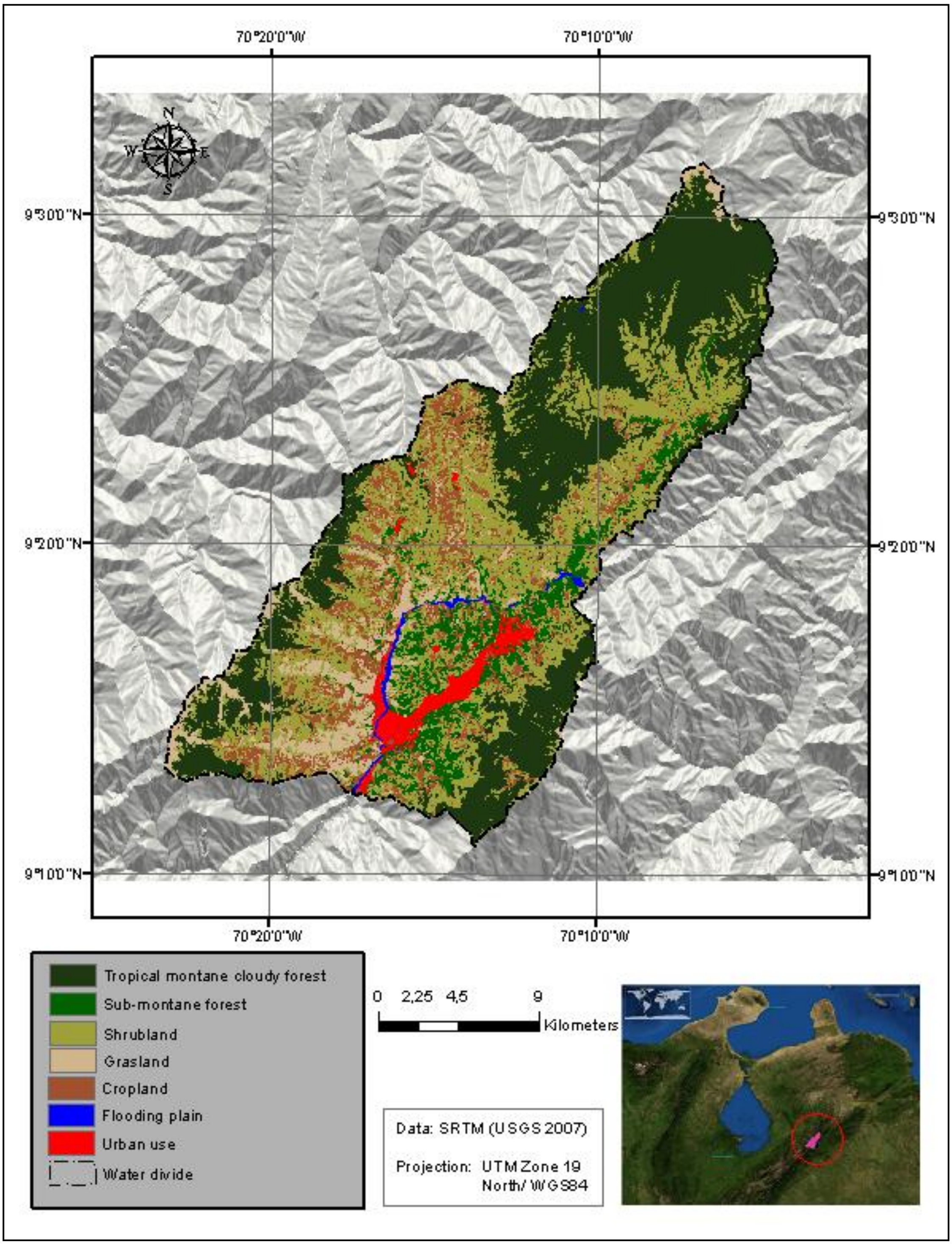
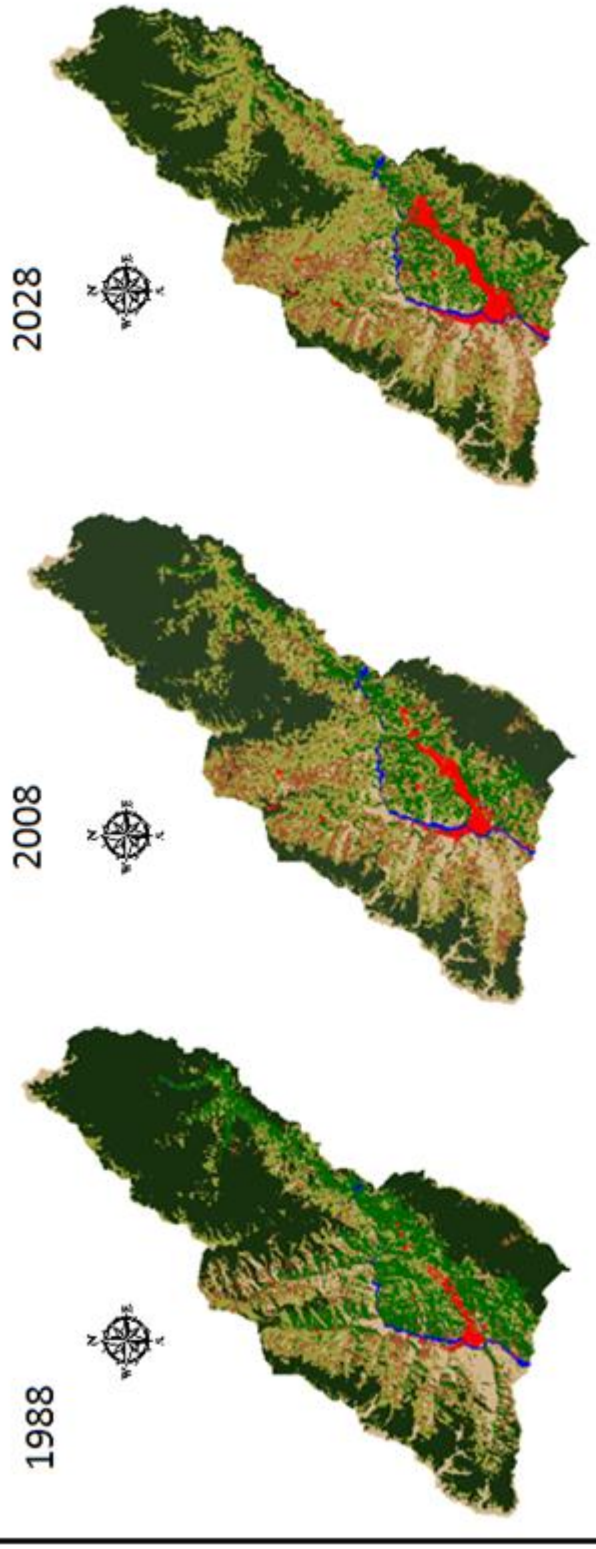


Figure 6.2. - LULC Map for 2028 derived from the Land Change Modeler – LCCM.



	LULCC	1988	% Area	2008	% Area	2028	% Area
	TMCF	27029,52	50,30	24053,85	44,77	19883,07	37,00
	Sub-montane forest	8012,7	14,91	4271,67	7,95	4153,23	7,73
	Shrubland	4751,82	8,84	4435,11	8,25	10390,07	19,34
	Grasland	9754,29	18,15	14221,62	26,47	11028,4	20,52
	Cropland	3487,86	6,49	5534,37	10,30	6531,84	12,16
	Flooding plain	435,33	0,81	880,02	1,64	323,82	0,60
	Urban use	261,81	0,49	336,69	0,63	1422,9	2,65
	Total	53733,33	100	53733,33	100	53733,33	100,00

Figure 6.3.- Comparative distribution of the LULC for the three maps used to delineate the HRUs.

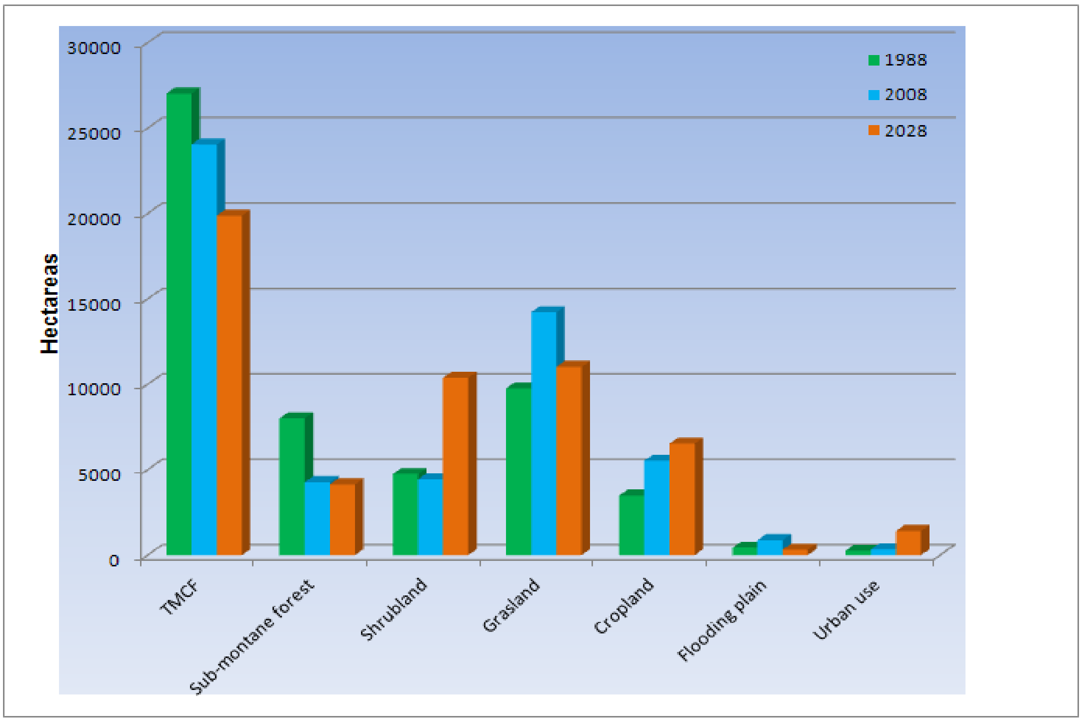


Figure 6.4. - Areal distribution of the LULC for 1988, 2008 and 2028 in the Boconó River Basin.

6.3. - The Scenarios for the simulation process.

Normally, the nature of the evaluation like this conduced here have to rest in the definition of specific scenarios based on assumptions in which the variables considered relevant for the hydrological response shows a specified trend, behaviour or evolution. In this particular case and based on the research goals expressed on Chapter 1, two kinds of spatial changes were considered as baseline to define the different scenarios to be simulated:

6.3.1. - Changes occurring in the LULC system at the river Basin level.

The different LULC categories have been experiencing specific trends and spatial patterns expressed in categorical or inter-categorical transitions on the last 20 years, period considered and analyzed on Chapter 4.

The LULC play a paramount role in the hydrological cycle in all scales ranging from local to global (Lorup et al. (1998); Brown & Dee (2000); Steuer & Hunt (2001); Krause (2002); Legesse et al. (2003); Bäse et al. (2006); Pizarro et al. (2006); Siriwardena et al. (2006);

Marshall & Randhir (2008); Bruns & Fetcher (2008); Mialhe et al. (2008); Breuer (2009); Huisman et al. (2009); Schilling et al. (2010); Oñate & Bosque (2010); and Liu et al. (2012).
For the study area, a generalization process was convenient, in order to merge such categories with similar hydrological behaviour, so the maps containing the LULC initially delineated were subsequently reclassified, as mentioned on Chapter 2 (step 2.4.4). Thus, those categories with a more dynamic expression, or the most relevant for the hydrological dynamic (forested LCC) were considered necessary to be included into the simulation. Similarly, for the future projection of the LULC changes, only the changes or transitions referred to those relevant categories were considered in order to conceive the future land use map, following the methods and steps explained on Chapter 2 (Step 2.3.6).

6.3.2. - Changes occurring in the climatic system at the mesoscale level.

As already mentioned on this dissertation, the study area is directly influenced by climatic processes at global as well as regional scales (Cornieles, 1997; Pulwarty et al, 1998; Andressen et al, 2000), and the area is strongly affected by the anomalies: ENSO and A-ENSO (Pulwarty et al, 1998; Andressen at al, 2000; Cárdenas et al, 2002). For these reasons is very important to consider the possible changes to be occurred in the area, within the simulation of future scenarios, in order to make the exercise even more realistic.

Starting from the considerations above mentioned, the scenarios to be simulated aimed to reach some specific relevant tasks within the simulation. The Figure 6.5 illustrates the dynamic inherent to the scenarios to be simulated.

As seen there, the simulation exercises were temporally concentred on three important time-points: 1988, 2008 and 2028. The three HRUs maps used as platform for the simulation were delineated considering the LULC dynamic corresponding to these years, which are displayed on Figure 6.6. For each date there are specific functional simulation goals to be reached. The first time-point was basically defined as reference time-point for the simulation (also called “**Status Quo Scenario**”), because of the correspondence with the only observed runoff data available for the Boconó river in La Cavita Station. The functional goals for this date were to develop the reference simulation, as well as the calibration and validation of the model.

The simulation goals for the 2008 were to make a reconstruction of the yearly flows, because no more observed data exist, and also to evaluate the effect of the LULC changes occurred

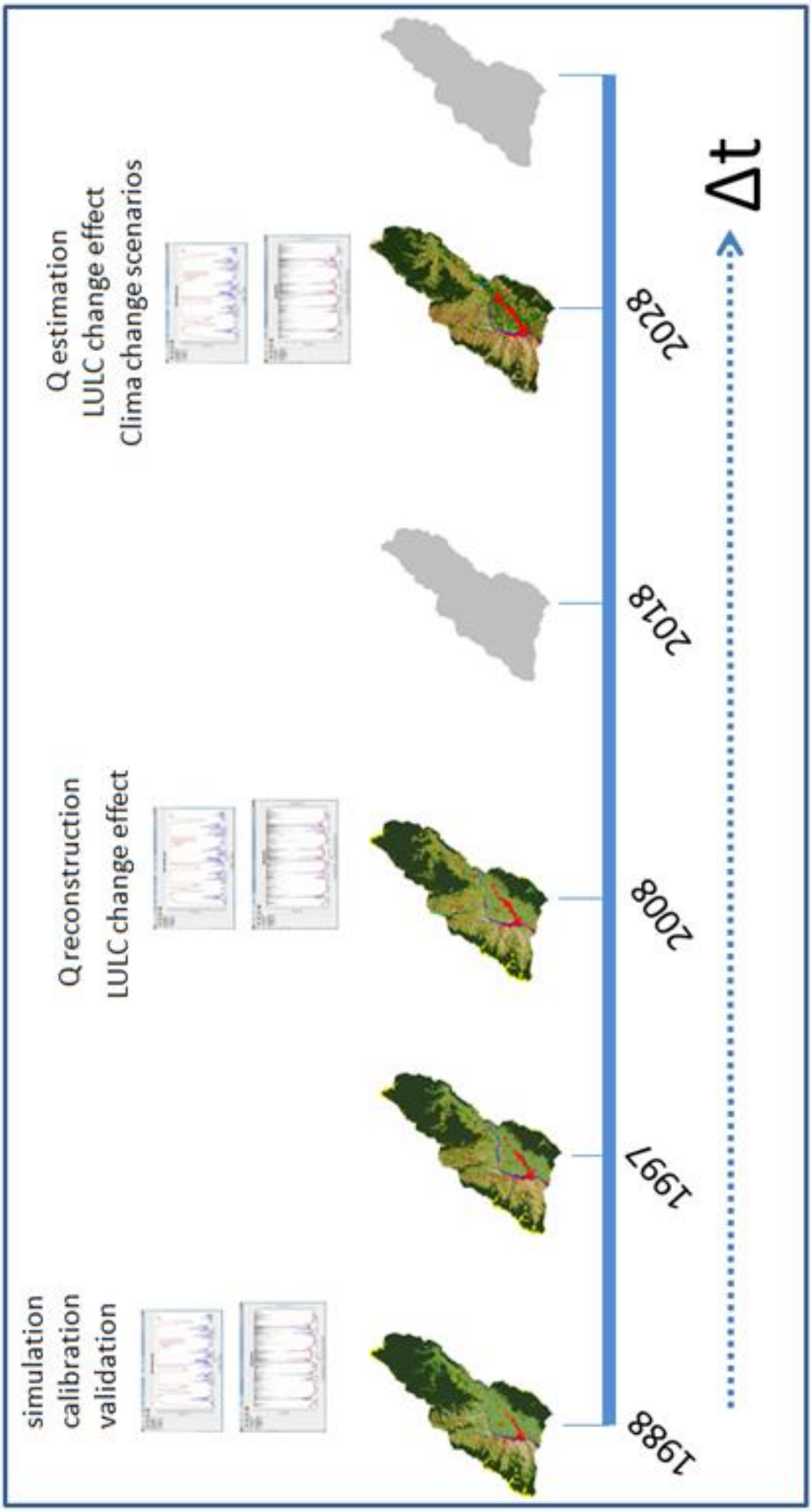


Figure 6.5.- Temporal distribution of the scenarios simulated and the main goals in each case.

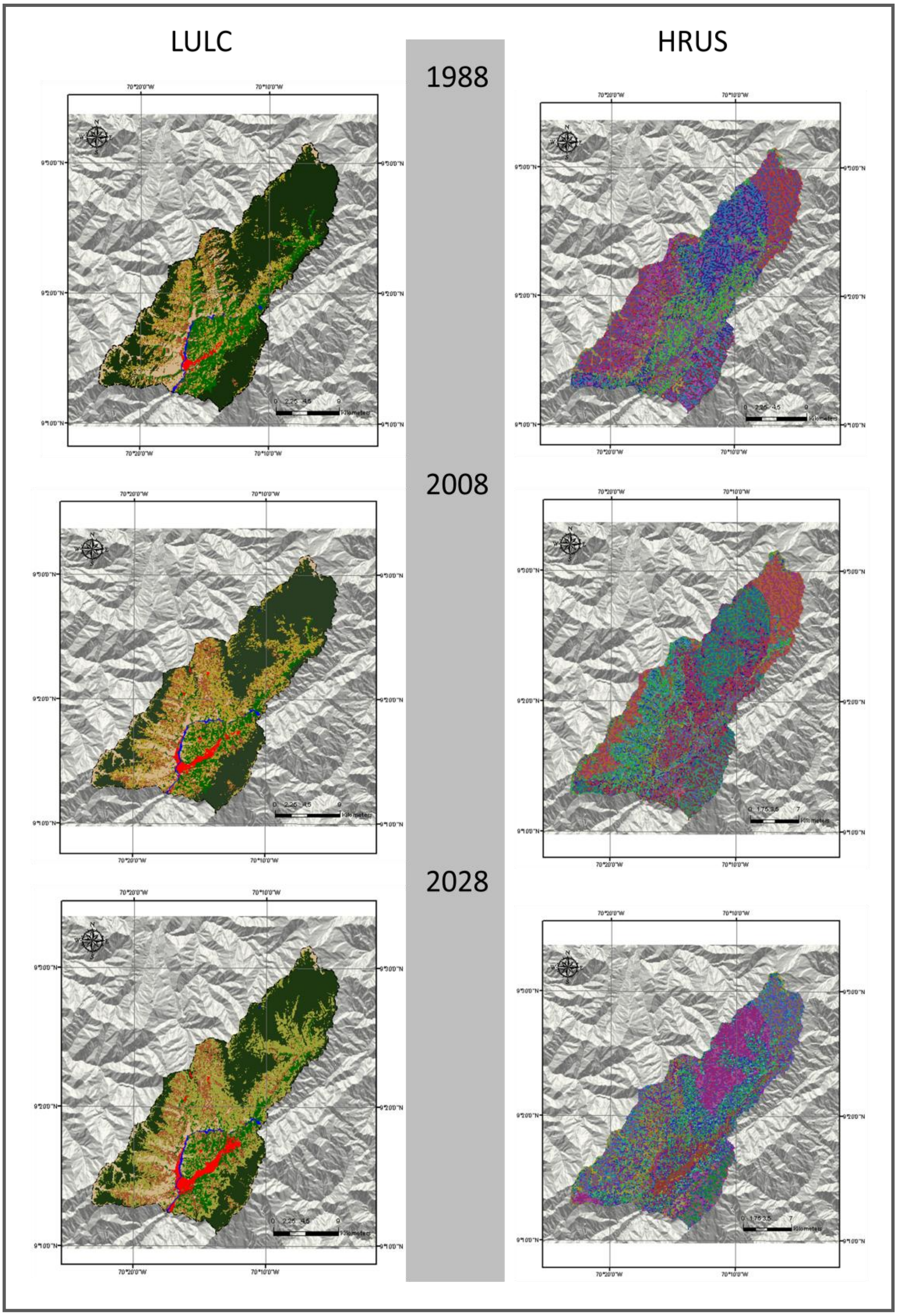


Figure 6.6. - LULC Maps and their corresponding HRUs maps delineated to simulate the different scenarios in J2000g Model.

20 years later in the area. More diverse goals were established for 2028, as reference future date. In this case, the simulations seeks to make Q estimations for different scenarios, the evaluation of the LULC changes effect, as well as to measure the effects of the climate change scenarios in the future and the level of incidence or impact that the climate variables can have on the hydrological response.

Considering the functional goals expressed on Figure 6.5, a total number of 9 scenarios were defined to simulate the hydrological response under different conditions. They are presented and gentle resumed on Table 6.2. The scenario 1 was simulated using the HRUs-map for 1988 (Figure 6.6), so it is considered the base or reference simulation, because of the observed data available for runoff. The period simulated correspond to 1988-1990, and the 1989 was selected as reference year to establish the comparisons between the scenarios. The scenarios 2 and 3 were developed using the HRUs map for 2008 (Figure 6.6). The scenario 2 aimed the reconstruction of the flows dynamics for the period 2008-2009, so that the climatic data for this period was used. In the scenario 3, the goal was to evaluate the impact of the LULC change, simulating the hydrological response in the same HRUs map, but using the climatic time data serie corresponding to the first scenario (1988-1990).

The scenarios 4 – 9 were developed using the same spatial platform (HRUs map) for 2028 (Figure 6.6). The scenario 4 considers the LULC changes occurred in the next years, projected to 2028. In this case, as in the scenario 3, the simulation was developed using the same climatic data corresponding to the scenario 1. This criteria was also assumed for the scenarios 5, 6 and 7. These three scenarios assumed a distinctive transformation across the landscape, where the forested LC systematically migrated to other LC categories, so they pretended to evaluate the impact of the reduction in the forested LCC in the hydrological response in the catchment. The scenario 5 takes the assumption that the whole Sub-montane Forest, that is, a total of 4153,23 ha of his LC in 2028, will disappear migrating to Grassland or to Shrubland. In the scenario 6, the whole TMCF (19883,07 ha in 2028) is completely cleared and transformed into a Shrubland; meanwhile in the scenario 7, the 44,73% (24036,3 ha) of the surface area under forested LC in 2008 (both, TMCF and Sub-montane Forest) is assumed to disappear, being converted into Grassland. These 3 scenarios can to illustrate the level of importance that the Forested LC could have on the hydrological behaviour.

The last two scenarios accounted by the impact of the climatic change in the area. They were defined under the scenarios proposed by IPCC (2007), to occur in terms of climatic

Table 6.2.- General description of the scenarios to be simulated in J2000g

Scenario	1	2	3	4	5	6	7	8	9
Main goal	Base or control simulation	Discharge reconstruction	LULC change effect	Future scenario A LULC change in 2028	Future scenario B LULC change in 2028	Future scenario C	Future Scenario D	Future scenario E Climate change for 2028	Future scenario F Climate change for 2028
HRUs map	1988	2008	2008	2028	2028	2028	2028	2028	2028
Climatic time-serie	1988-1990	2007-2009	1988-1990	1988-1990	1988-1990	1988-1990	1988 - 1990	1988-1990	1988-1990
Additional comments	"STATUS QUO" scenario	Reconstruction of the real discharge occurred at this time (no observed data exist)	Evaluate the effect of the LULC change occurred until 2008	The trends observed on last 20 years for LULC changes are assumed to continue on the next 20 years	The sub montane forest change to successive Shrubland	The TMCF disappear and migrate to successive Shrubland	All the forested LC disappear migrating to Grass	An increase of 10% in the rainfall is supposed to occur in this scenario, according to the IPCC projections	A decrease of 10% in the rainfall is supposed to occur in this scenario

change during the actual century. In this case the general assumptions included in the scenario **SRES A1B** (A standard scenario assuming a balance between fossil intensive use and non-fossil energy resources (IPCC, 2007)), accounts for a reduction of the precipitation regime in the Venezuelan Andean region in about 10%. In this sense, the scenarios 8 and 9 aimed to evaluate the possible effects produced by a variation of 10% in the precipitation regime for the catchment, in positive (increase of pp) and negative (decrease of pp) sense. Thus, in the scenario 8 it was assumed that the precipitation in the area will be a 10% higher than those registered on the base period 1988-1990). On the other hand, in the scenario 9 a reduction of the precipitation in 10% was assumed. In the construction of these scenarios the temporal distribution of the rainfall was not altered, so the values accounted by the period 1988-1990 were just proportionally changed. As the scenarios 8 and 9 were simulated using the HRUs produced for the year 2028, it can be said that these scenarios combine the effects produced by climatic changes together with the LULC changes that potentially could to occur in the catchment, according to the trends analyzed on Chapter 4.

6.4. - Hydrological response simulated under the specific scenarios

6.4.1. - Historical recent evolution of the seasonal flows (1989-2009)

The first part of the analysis intends to illustrate the hydrological dynamic for the last 20 years, comparing the results of the scenarios 1 and 2, which were simulated using the Model B-2. The Figure 6.7 shows the hydrographs resulted from the simulations of the scenarios 1 and 2 (M2). In both cases the “control” years used to the comparison (1989 in the scenario 1, and 2009 in the scenario 2) were extracted from the hydrographs and showed in a “close up” window. It can be clearly observed a differential pattern in the seasonal flows between the two scenarios. The Hydrograph of 1989 shows a “normal” pattern, which is similar to the average pattern observed in the Boconó River displayed on Figure 5.2. The Hydrograph for 2009 shows a more heterogeneous behaviour in the seasonal flows, quite different from the normal trend of the Figure 5.2. The precipitation shows also different trends between the scenarios, where the scenario 2 accounts for a more abundant precipitation, having also a higher variability in the temporal distribution of the rainfall events than in the scenario 1.

The overlap of the two runoff curves in the Figure 6.8, helps to visualize more detailed the differences in the seasonal flows patterns between the two scenarios. The seasonal peaks

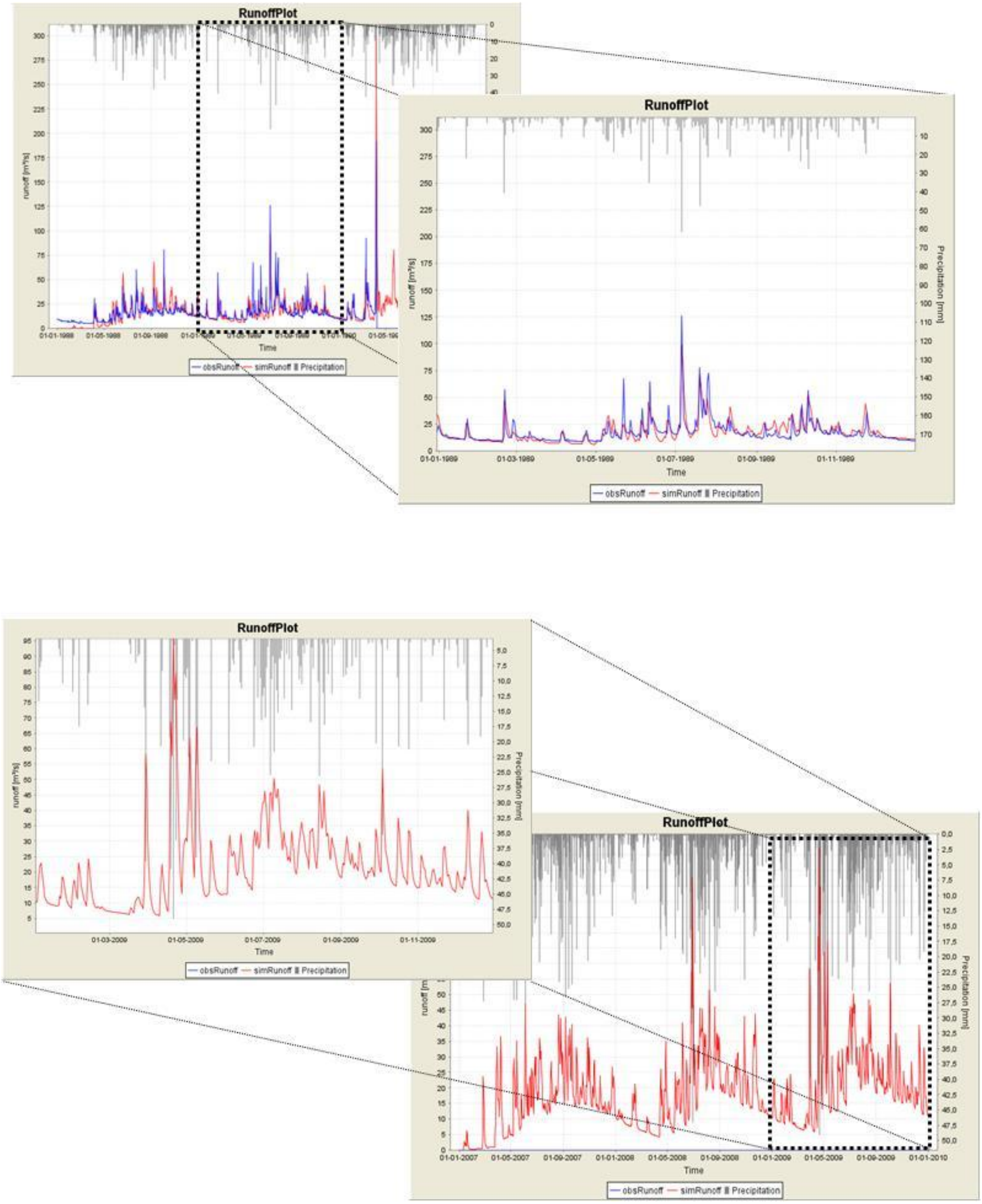


Figure 6.7. - Hydrographs corresponding to the “control” years to be used in the comparison of scenarios 1 and 2.

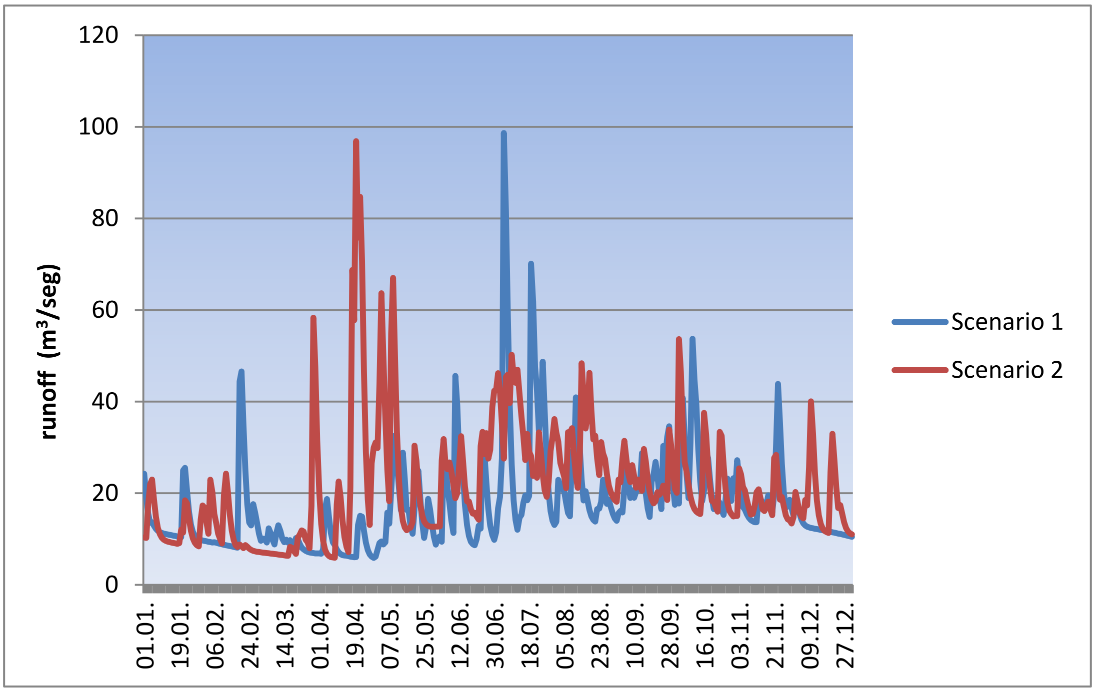


Figure 6.8. - Total daily runoff simulated for the scenarios 1 and 2.

flows occurred earlier as usual in 2009, so the highest peak flow was recorded on 20/04/09 (three months before than usual), produced by a heavy precipitation event. The curve for 2009 shows a very intense dynamic, with important discharge episodes occurring during the whole year, inclusive during the dry season. The precipitation was particularly intense and the frequencies were higher in the scenario 2 during the whole simulated period, as seen on Figure 6.7, with important events occurring across the whole year. The temporal distribution of the precipitation occurred in 2009 is displayed on Figure 6.9. The Figure 6.10 show how different were the simulated values for runoff in 2009, with respect of the observed runoff data. A higher dispersion is clearly observed in the peak flows, indicating a high deviation of the peak flow values in 2009 with respect to the observed runoff data for 1989.

As already mentioned on Chapter 5, the convection processes are highly variable in the Andean region (Pulwarty et al, 1998), so that the occurrence of rainfall events in the area is considered essentially aleatory and erratic. Moreover, the area is strongly influenced by the ENSO / A-ENSO (El Niño – La Niña) anomalies, and during those events the regime and occurrence of the precipitation follows an even more erratic pattern (Cárdenas et al., 2002). The occurrence of El Niño (ENSO event), generates negative rainfall anomalies in the area, with an intensification of the dry season. On the opposite side, the occurrence of La Niña, generate positive rainfall anomalies in the whole country (Caviedes & Waylen, 1998).

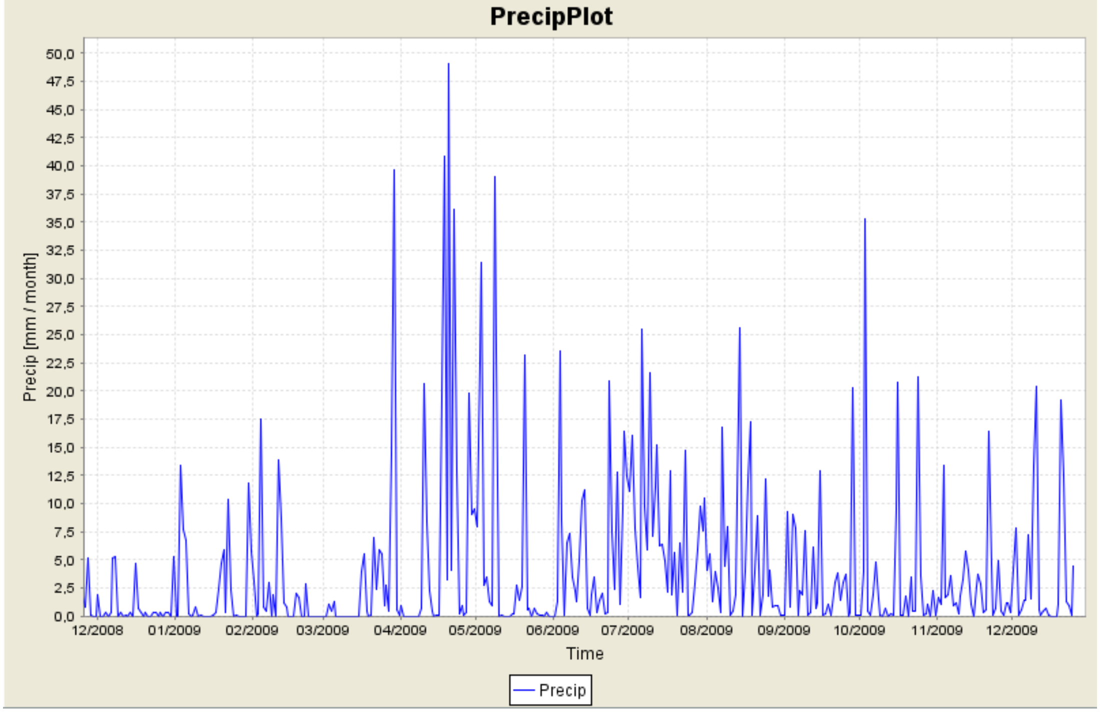


Figure 6.9. - Average daily precipitation simulated on J2000g for the scenario 2 (year 2009).

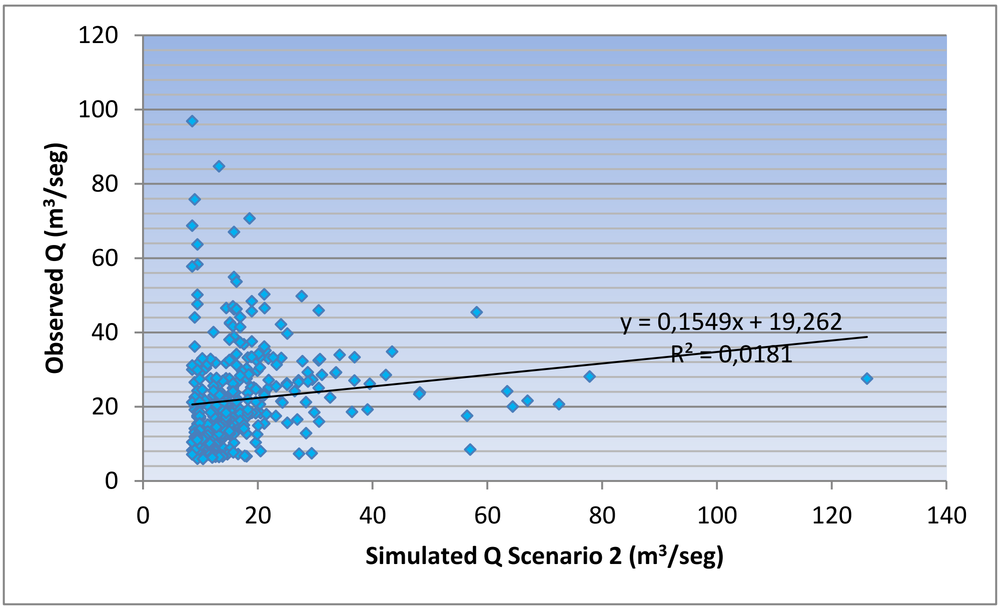


Figure 6.10.- Comparison between the simulated runoff for scenario 2 and the observed data for 1989.

Guevara (2006) states that the occurrence of rainfall excesses due A-ENSO events are more frequent than rainfall deficits due to ENSO events. This is clearly evident in the Andean region of Venezuela, where the positive anomalies from A-ENSO are quite higher than the negatives ones from ENSO, as seen on Table 6. 3.

Three important successive A-ENSO events occurred between 2007 – 2009, followed by a stronger ENSO event that occurred between August 2009 and April 2010 (NOAA, 2010).

They can be observed on Figure 6.11, where the values for the Oceanic Niño Index Values from 2000 to 2010 are displayed. Taking into account the A-ENSO events occurred on 2008 and 2009, they could be correlated with the higher rainfall values observed in the study area during the same period, so the higher precipitation values resulted from the simulation of the scenario 2 can be explained by the occurrence of these successive A-ENSO events. Although the ENSO event for 2009-2010 was stronger than usual, it appears to have had a little impact in the rainfall regime in the catchment area, from July to December.

The Figure 6.12 compares the total values for the basic components of the hydrological balance between the two scenarios. The total values with the correspondent RMSD and r^2 values are also displayed on Table 6.4.

Table 6.3. - Percentage of monthly rainfall anomalies for all events associated with ENSO and A-ENSO events in the Andean Region – Venezuela. (S= strong; M= moderate).

Intensity	ENSO Events			A-ENSO Events		
	F	M	All events	F	M	All Events
Guayana	-16,03	-14,36	-13,15	20,43	18,53	18,75
Delta Plains	-21,60	-18,19	-16,91	28,41	22,88	20,23
Los Llanos	-11,94	-12,88	-10,44	19,70	20,48	18,05
Los Andes Mountains	**-25,48**	**-24,12**	**-20,22**	**45,89**	**36,20**	**29,26**
Coro Mountains	-19,40	-20,20	-15,02	39,10	33,70	31,00
Maracaibo Lake depression	-15,06	-14,55	-9,03	31,08	21,64	14,73
Coast Mountains and Islands	-15,59	-16,09	-8,64	15,58	21,19	14,04

Source: Guevara (2006)

As seen on Figure 6.12, the precipitation in 2009 was **36,5 %** higher as the total measured on 1989. This percentage value is absolutely concordant with the average value observed for positive anomalies in the Andean region during moderate A-ENSO events (Table 6.3). The total runoff was 23 % higher in 2009 respect to 1989, difference that can be explained by the occurrence of more peak flows events, which are reflected on the direct flow value, being 29 % higher in 2009. In the case of the base flows, the difference was slightly lower (17%), indicating that during the dry season the incidence of the positive anomaly was lower than in the rainy season. The seasonal flows of the rivers in the whole region are strongly influenced by both ENSO and A-ENSO events; the lowest flows occur during the ENSO years, meanwhile the highest discharges are observed during the A-ENSO years or also during "normal" years (Caviedes, 1998).

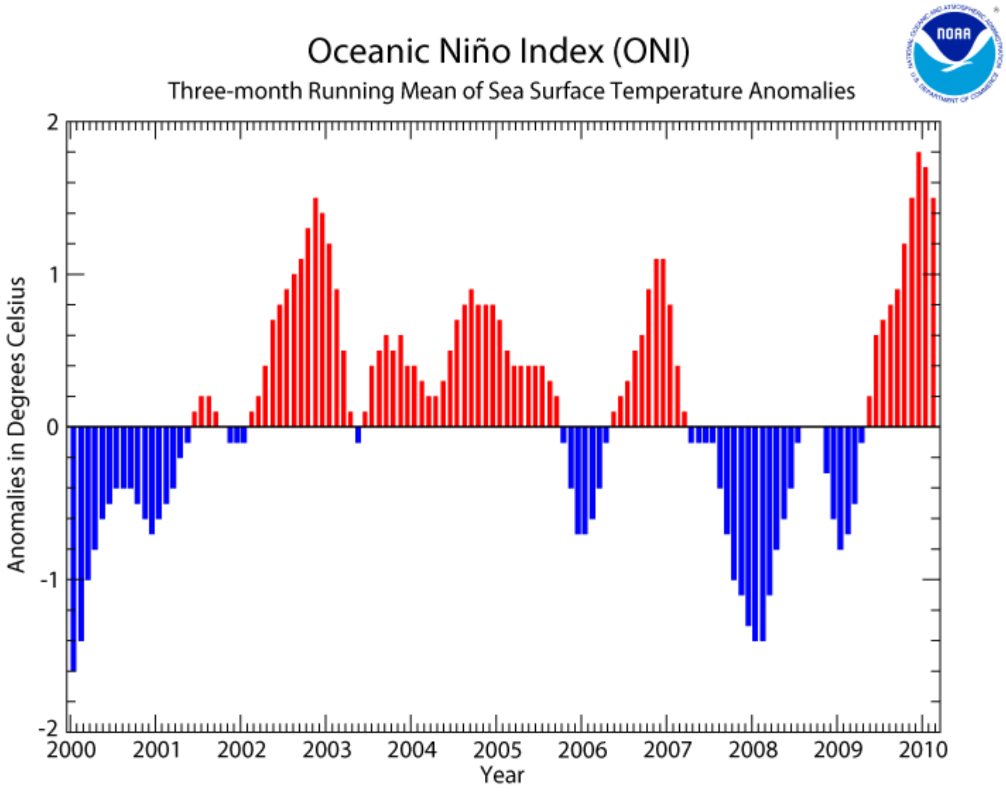


Figure 6.11. - Oceanic Niño Index from 2000 to 2010 (Source: NOAA, 2010)

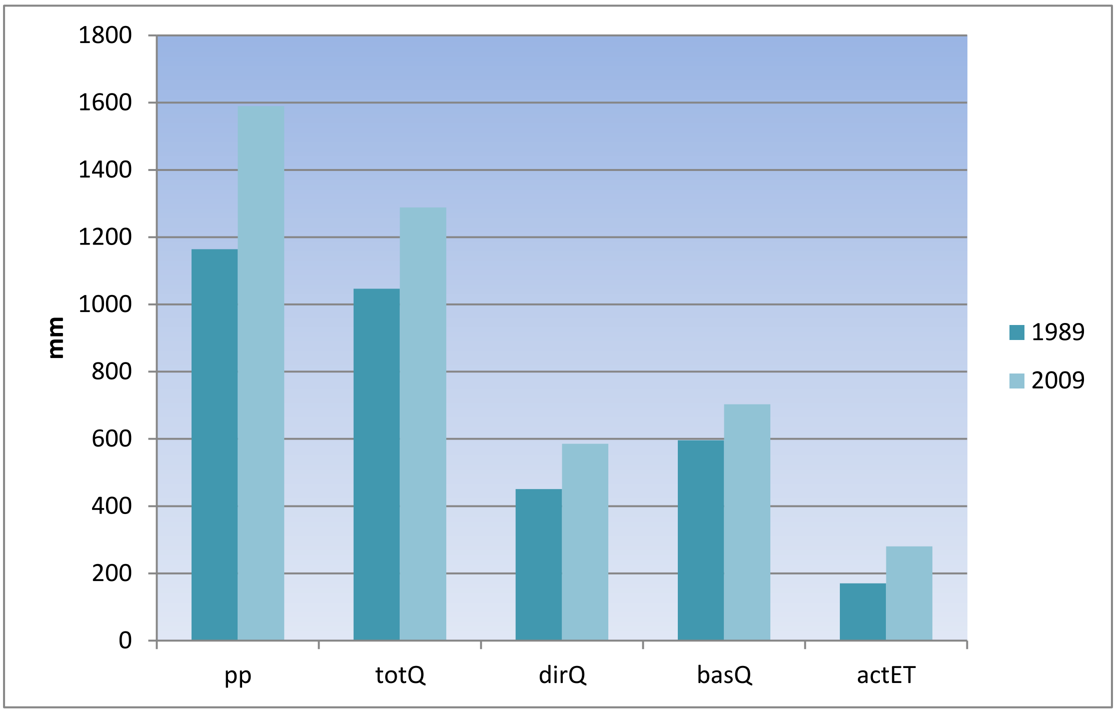


Figure 6.12. - Comparison of total values of hydrological variables for the scenarios 1 and 2.

Table 6.4. - Basic components of the hydrological balance for the scenarios 1 and 2.

	Pp (mm)	totQ (mm)	dirQ (mm)	basQ (mm)	actET (mm)
1989	1164,294	1046,642	450,546	596,094	170,592
2009	1589,595	1288,468	585,344	703,124	280,513
RMSD	9,991	16,166	15,874	3,241	0,332
r^2	0,00014	0,0311	0,0106	0,5113	0,0017

The increase of pp can lead to a consequent increase of the Evapotranspiration (Qi et al, 2009), although it is dependent also in the variability of the temperature. In this case, the actual evapotranspiration also showed an important difference, being 64% higher in 2009 respect to the scenario 1. The ENSO and A-ENSO events also affects the temperature, and the anomalies are almost positive, with mean values bigger than 0,5 °C for all months of the year (Guevara, 2006). However, Lozada et al (2003) consider that in the A-ENSO years a diminishing temperature values can also be expected to occur. Obviously, it can to affect sensibly the evaporation and transpiration processes. A comparison between the temperatures simulated on both scenarios is done in the Figure 6.13. The difference

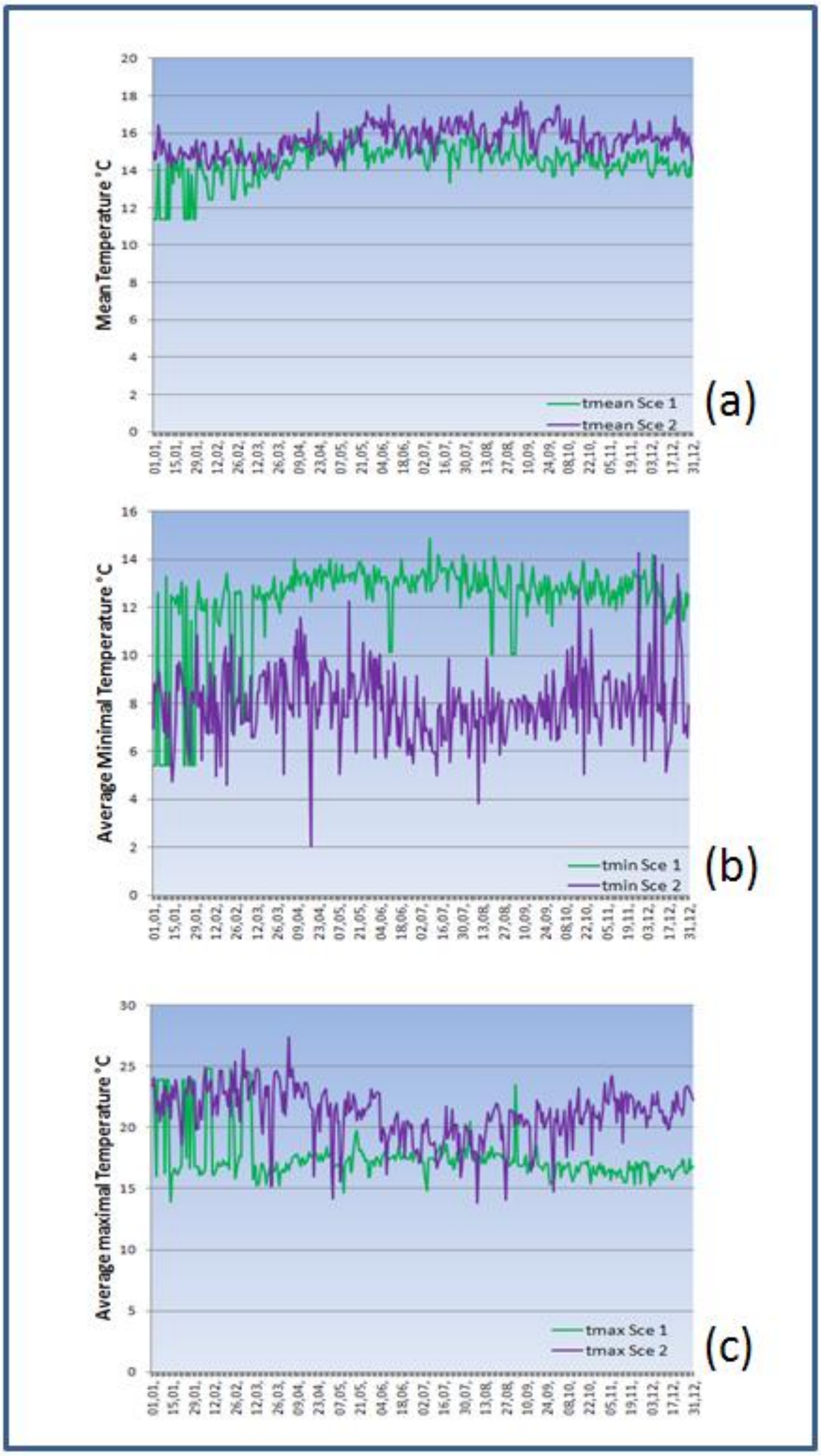


Figure 6.13. - Comparison between the average (a), minimal (b) and maximal (c) temperatures measured for the scenarios 1 and 2.

accounted by the temperature in the scenarios is clearly evident, where the average temperatures were 1,15 °C higher in 2009 with respect to 1989. However, different trends in the extreme values can be also observed in this case.

As seen on the Figure 6.13 (a), the average mean daily temperatures were higher in the scenario 2 during the year, except for the more wet months (April, May and July), where the differences were minimal and the values tended to be similar to those measured in 1989. This can be explained by the effect produced by cloudiness during the unstable rainy season, which simply limit the radiation income, reducing the temperatures, being even more evident in the minimum values measured. In effect, in Figure 6.13 (b) can be observed the trends for tmin (average minimal temperatures), having a quite different trend as those observed in (a). The minimal temperatures were evidently lower in the scenario 2, which suggest that the more frequent precipitation events occurred in 2009 were accompanied by an important occurrence of clouds in the catchment area which reduced the radiation and the income of solar energy. The maximal average temperatures displayed on Figure 6.13 (c), show the opposite pattern observed on (b), so the maximal average temperatures were higher in the scenario 2, with a more amplitude in the difference occurring during the dry season. The lowest values for the scenario 2 are coincident with the days where important precipitation events occurred.

Changes in the temperature are accompanied by several other factors and feedback mechanisms, such as changes in solar radiation, changes in humidity and also change sin rainfall regimes (Legesse et al., 2003). All these feedbacks obviously will have a direct impact in the ET patterns. In consequence, the increment observed in the ET for the scenario 2 can be explained by both the increased precipitation and the higher values for temperature observed during 2009.

The RMSD values indicates that the variability within the values was more evident in the total annual runoff (16,166) as well as in the direct flow values (15,87), meanwhile the base flow values showed a lower variability among the scenarios (3,241). This suggest that the variability occurred in the direct flows among the scenarios, mostly contribute to explain the difference in total runoff. The values for actET showed the lower RMSD (0,332), indicating that the variable showed a similar temporal pattern.

Due to the strong influence of the climatic factors in the hydrological dynamic, is considered extreme difficult to intend to explain the differences between the two scenarios through the changes occurred in the LULC system. For this reason it was considered necessary to define the scenario 3, in which the hydrological response was simulated for 2008, using the climatic data correspondent to the scenario 1. So, the possible influence of the LULC changes on the dynamic reflected on the scenario 2 is going to be evaluated in the following section.

6.4.2.- Hydrological response of the Boconó River Basin under different scenarios accounting for spatial changes in the catchment area.

For this second stage in the simulation process, the model built to calculate the ETP through Penman – Monteith method (Model B-3) was used to simulate the scenarios 1, 3, 4,5,6,7,8 and 9, so that a better approximation of the water balance steps could be reached. As above mentioned on this Chapter, the 1989 was used as “**control year**” or “**status Quo**” scenario, in order to compare the results and to detect how each scenario can deviate or differ from the “**satus quo**” scenario.

The first results of the simulations, that is, the total annual runoff values simulated for each scenario are displayed in Figure 6.14. Two patterns can be clearly distinguished between the scenarios. The scenarios 3,4,5,6 and 7 show a very similar trend, with a pattern tending to be homogeneous. In effect, there are a decreasingly trend in the average runoff among the scenarios, but with a very low intensity. As already mentioned before, only the LULC changes were considered to be evaluated in this group of scenarios. The combined scenarios 8 and 9 show a more dissimilar pattern as the other group, which clearly suggest a more variability in the hydrological response due to the conditions under which the simulations were developed. The values displayed in the Figure 6.14 are showed in Table 6.5, together with the respective RMSD and r^2 values showing the magnitude of the difference between the scenarios respect the “**status quo**” scenario. The RMSD values were plotted in the Figure 6.15, expressing how the values for the scenarios 8 and 9 are significantly different respect the “**status quo**”.

This simple comparison intended in Figure 6.14 is quite limited, as it cannot reflect the internal variability that the flows experienced through the year, so it cannot reflect adequately the differences between the diverse scenarios simulated and the “**status quo**” scenario. In this sense, a group of indicators corresponding to the different elements of the streamflow

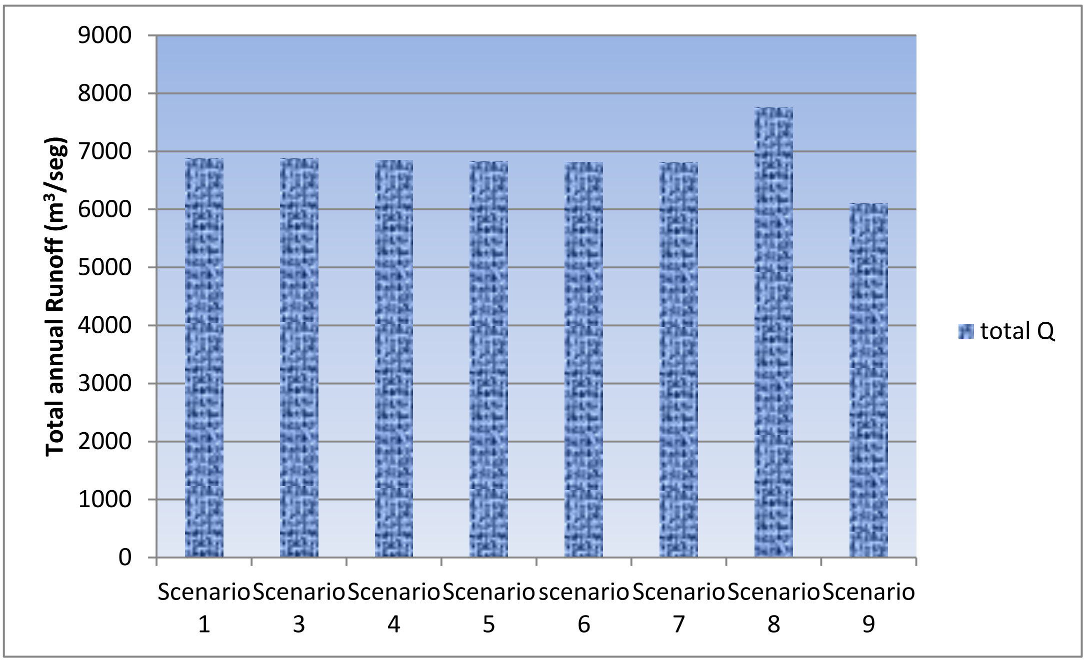


Figure 6.14. - Total annual runoff in m³/seg simulated for the scenarios, using the Model B-3.

Table 6.5. - Total annual Runoff in m³/seg obtained for the different scenarios.

	Sce 3	Sce 4	Sce 5	Sce 6	Sce 7	Sce 8	Sce 9
Total Q	6877,331	6844,702	6855,088	6812,761	6804,017	7753,198	6095,97
RMSD	0,0118	0,0921	0,0674	0,1836	0,2109	2,9303	2,2536
R2	0,9999996	0,9999942	0,9999966	0,9999705	0,9999553	0,9814933	0,9977951

dynamic was selected, in order to express quantitatively and more clearly the differences between the scenarios. These indicators reflect specific conditions which are important to characterize the hydrological dynamic inherent to the seasonal flows. The Total Annual Runoff (TAR), already above considered, is obviously an important indicative of the total amount of water produced in each simulated scenario; but, it needs to be considered together with other important values that reflect the seasonal behaviour and take into account the extreme conditions that eventually can be expected to occur. Together with TAR, the Average Base Flow (ABF), as well as the Average Peaks Flows (APF) were also introduced as indicators.

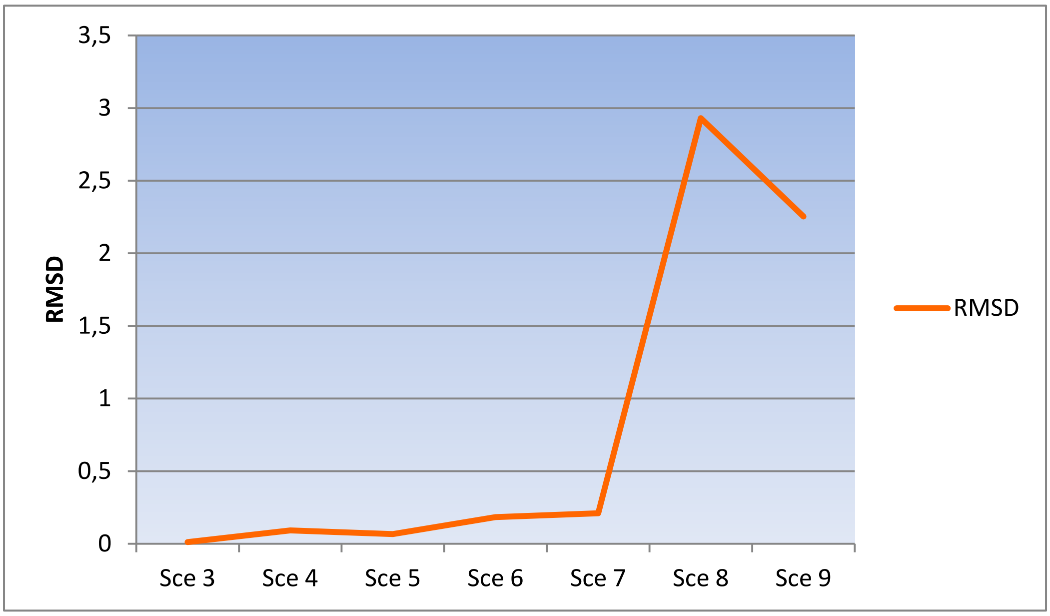


Figure 6.15. - Trend followed by the RMSD across the different scenarios.

In the first case (ABF), it was determined considering the runoff values from November to March, which define the dry season in the area. In this period very low precipitation values occur, and the base flow represent during some weeks the entire runoff value in the catchment. In the case of the Average Peak Flows (APF), the flows over 24 m^3/seg were considered for the calculation, according to the criteria adopted by Garcia et al (2011) for a catchment with similar dimensions in Argentina.

Two additional indicators which could reflect the extreme hydrological conditions were added. The Dry Out Day (DOD) is here defined as the day when the lowest possible runoff value was measured at the output gauge. This value is expected to occur in the area during the late dry season (February-March). The opposite indicator to DOD correspond to the Highest Peak Discharge (HPD), which is simply the extreme peak flow value measured at the output gauge, usually expected to occur in the middle of the rainy season (July). The last indicator to consider in the evaluation is the Actual Evapotranspiration (actET), as one very important indicative about the exchange of water between the biosphere and the atmosphere, being thus particularly sensitive to climatic targets (pp and temp), as well as to the form and conditions in which the surface is covered by a specific Land Use or land Cover.

The values corresponding to the selected indicators are resumed in Table 6.6. They were conveniently plotted in Figure 6.16, in order to get a better idea of the trends between the scenarios. In this Figure, the values for each indicator are compared with the "**status quo**" value, in order to visualize the way in which each scenario is deviating from the scenario 1.

The two specific trends mentioned for the Figure 6.14 prevail here, but with interesting variations accounted for some indicators that are going to be highlighted here. The values for TAR show a decreasing trend from scenario 4 to scenario 7, being the scenarios where only the LULC changes have been considered. The scenario 3 show the lower positive deviation value, accounted by 2,087 m³/seg respect the "**satus quo**". For the scenario 4, which consider the potential transitions observed in the recent past and projected until 2028, the TAR value slightly decrease in 30,542 m³/seg respect to the status quo. This suggest that the potential LULC transitions that are waiting to occur in the main LULC appears not to explain the changes that could be occur in the hydrological response and the water yield in the river basin. For the Scenario 5 the TAR show a decreasing value of 6855,088 m³/seg with a difference of -20,156 m³/seg respect the "**satus quo**". This difference is theoretically explained by the suppression of the sub-montane forest in the middle –lower sector of the catchment, being substituted by Shrubland. The difference of TAR value accounted by the scenario 6 (62,483 m³/seg less than the status quo) is theoretically explained by de depletion of the TMCF, which in the scenario had a systematic transition to the category Shrubland.

Table 6.6. - Indicators for the evaluation of the simulated scenarios

Scenario	TAR	APF	ABF	DOD	HPD	actET
1	6875,244	37,998	11,157	8,382	112,536	123,611
3	6877,331	38,016	11,072	8,388	112,587	123,376
4	6844,702	37,965	11,09	8,307	112,673	128,399
5	6855,088	38,003	11,034	8,325	112,709	126,624
6	6812,761	37,862	11,026	8,262	112,574	133,739
7	6804,017	37,831	12,494	8,251	112,539	135,642
8	7753,198	36,635	9,891	10	116,454	129,158
9	6095,97	37,204	11,072	7,311	109,194	127,796

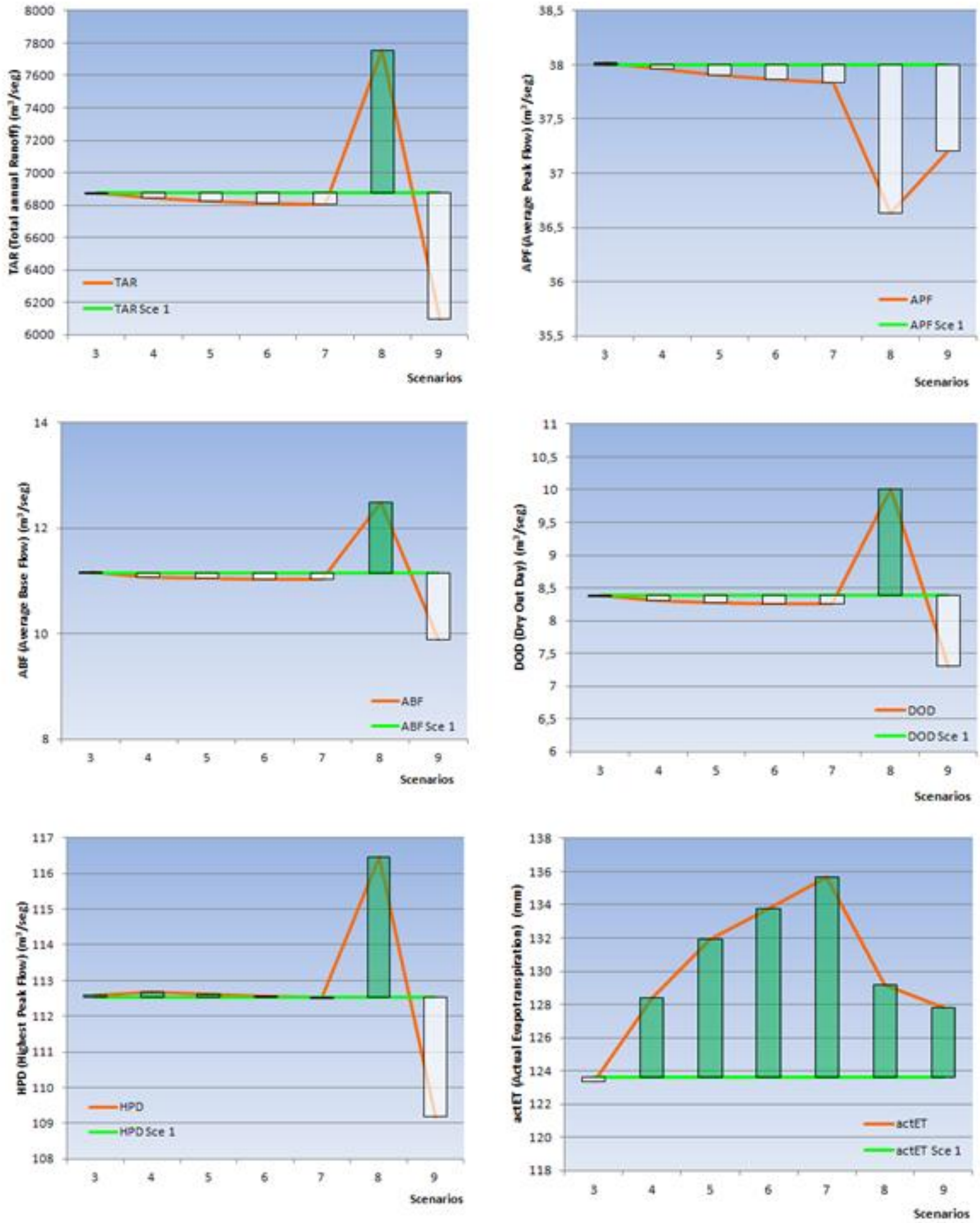


Figure 6.16. - Deviation of the Indicators from the "status quo" scenario (1).

In the scenario 7, the total suppression of the forested land covers, migrating to grassland accounted by a depletion in the TAR value of only -71,227 m³/seg. In appearance, the suppression of the forested LC in the area doesn't have a significant impact in the TAR value, but this fact will be later discussed in this chapter. The last two scenarios show a dissimilar trend respect to the group already mentioned, with a very contrasting pattern between them. In the scenario 8, an increase in the total value of TAR is evident, reaching 7753,198 m³/seg, which represent 877,954 m³/seg more than the status quo scenario. In contrast, the scenario 9 denotes an important decrease in water yield, reporting 779,274 m³/seg less than the scenario 1.

The APF values show a quite different trend compared to the TAR values. In this case, all the scenarios, except the scenario 3, show a decreasing pattern for the average peak flows in the catchment. The increase accounted for the scenario 3 is very poor, as the average peaks flows only increased in 0,018 m³/seg. For the scenario 7, the decrease reaches the 37,831 m³/seg, meanwhile for the scenarios 8 and 9 the lowest values are reported by the simulation. In the scenario 8 the APF descended in 1,363 m³/seg respect the status quo, which is the lowest decrease reported by the scenarios; and for the scenario 9, the reduction of the pp in 10% could ocassionate a negative difference of about 0,794 m³/seg in the APF. Thus, the scenarios 8 and 9 continue to show a more significance explaining the hydrological response and the water yield in the catchment.

For the ABF and the DOD indicators, the dynamic is quite similar as this observed for the TAR. In both cases the scenario 3 had a very low impact in terms of change, increasing the respective values in only 0,006 m³/seg for ABF, and also 0,006 m³/seg for DOD. The scenarios 4, 5, 6 and 7 show the same increasingly trend as observed in TAR values, where the values for the two scenarios increase progressively from scenario 4 to scenario 7. Meanwhile, the scenarios 8 and 9 were the most dynamic, showing the particular opposite ambivalent trend, suggesting that the area is more sensitive to the combined scenarios, in which the climate change and LULC change are considered together.

For the HPD the situation is a little bit different in comparison to the last two indicators. The indicators 3 to 8 showed increasingly values of highest peak flows, with a decreasing trend from scenario 4 to scenario 7, meanwhile the scenario 8 continue to show the highest difference respect to the status quo, in terms of the highest peak flow occurred. In this case the value for HPD in the scenario 8 was 3,918 m³/seg more than the scenario 1. Only the scenario 9 showed negative trend with a difference of 3,342 m^3/seg less than the **status quo** scenario.

The trend or pattern observed for the last indicator totally differs from the others above presented. Except for the scenario 3, the Evapotranspiration values experienced an increase in the scenarios 3 to 9, with an inverse trend as those already observed for the rest of indicators. Here the evapontraspiration progressively increased from scenario 4 to scenario 7, which has the highest difference respect the status quo (12,031 mm higher than the status quo). In contrast with the rest of indicators, the actET decreased in the scenarios 8 and 9, accounting for a difference in ET of 5,547 and 4,185 mm respectively. This particular trend reveal two important facts: at first, the observed values suggest that the ET tends to be more sensible to the LULC dynamics, as showed in the simulated scenarios 4 to 7, where the LULC changes were the target for the evaluation. Second, the combined scenarios revealed a less contribution in the explanation of the changes occurred in the evapotranspiration. Both scenarios were simulated using the HRUS map for 2028, so that the changes in the ET values showed by the two scenarios is coincident with the increment showed in the scenario 4. So it suggests that the climatic variability could have a secondary role in the explanation of the variability showed by actET, at least in this case.

As already mentioned, the simulation of this group of scenarios was conduced using the Penman-Montheih method for the calculation of the Potential and actual evapotranspiration. The Penman-Montheih method is well known as a more comprehensive method due to the diversity of variables and processes considered to make the estimations. Important information about the vegetation like leaf area Index (LAI), stomatal resistance, as well as albedo is included in the formula. So, the inclusion of the method into the simulation structure implies that the calculation of the hydrological processes like interception and evapotranspiration can be better taken into account for the simulation of the hydrological cycle at the catchment level.

Now its time to take a view into the differences among the scenarios from another perspective. The deviations that the different indicators experienced respect to the status quo into the hydrological simulation process were calculated. They are displayed on Table 6. 7. Values which were not highlighted indicate a positive deviation from the status quo scenario, meanwhile the highlighted values indicate negative deviation. They were finally plotted in the Figure 6.17 for a better comparative visualization.

Table 6.7. - Percentage of deviation of the scenarios from the status quo scenario.

Indicator	Sce 3	Sce 4	Sce 5	Sce 6	Sce 7	Sce 8	Sce 9
TAR	0,03	-0,444	-0,293	-0,909	-1,036	12,77	-11,334
APF	0,047	-0,087	0,013	-0,358	-0,439	-3,587	-2,09
ABF	0,054	-0,762	-0,601	-1,102	-1,174	11,984	-11,347
DOD	0,072	-0,895	-0,68	-1,432	-1,563	19,303	-12,777
HPD	0,045	0,122	0,154	0,034	0,003	3,482	-2,97
actET	-0,19	3,873	2,437	8,193	9,733	4,487	3,386

As seen on Figure 6.17, the impact derived from the spatial changes, concretely LULC change and combined LULC-Climate change could have a distinctive form in occurrence and intensity in the catchment. The LULC change could have a slightly effect in the hydrological response and water yield, with the exception of the indicator actET, which apparently could experienced more variability in response to the LULC dynamic. The scenario 3 (Figure 6.17, window) reveal the smaller deviation from the **status quo**, indicating that only a minuscule portion of the changes in hydrological response that the river basin experienced during the last 20 years could be finally explained by the changes occurred in LULC system.

These changes apparently contributed to a very slightly increase of the indicators TAR, APF, ABF, DOD and HPF. On the contrary, the actET experienced a slight decrease in this scenario. However, comparing the results from this calculation with those obtained by the scenario 2 (explained on point 6.4.1) it can be easy to conclude that the climate variability had a higher contribution in the explanation of the hydrological pattern that the Boconó river experienced on last 20 years, as the changes accounted by the LULC system.

In the scenario 4, it could be expected that the changes induced by the inter-categorical transitions among the LULC system, could generate a possible situation in which the TAR, APF, ABF and DOD would have a negative impact, meanwhile the HPF and the actEt could increase, although the % of change accounted for the HPF is very poor.
The scenario 5 show the same trend patterns observed in scenario 4, but with a lower intensity in the variation of the indicators. The actEt differ from the status quo only in 2,437 %.

The scenarios 6 and 7 follow the same trends in hydrological response; just the deviation of the indicators from the status quo is more intense in the scenario 7, in which the Forested LC systematically changed to grassland in the whole catchment area.

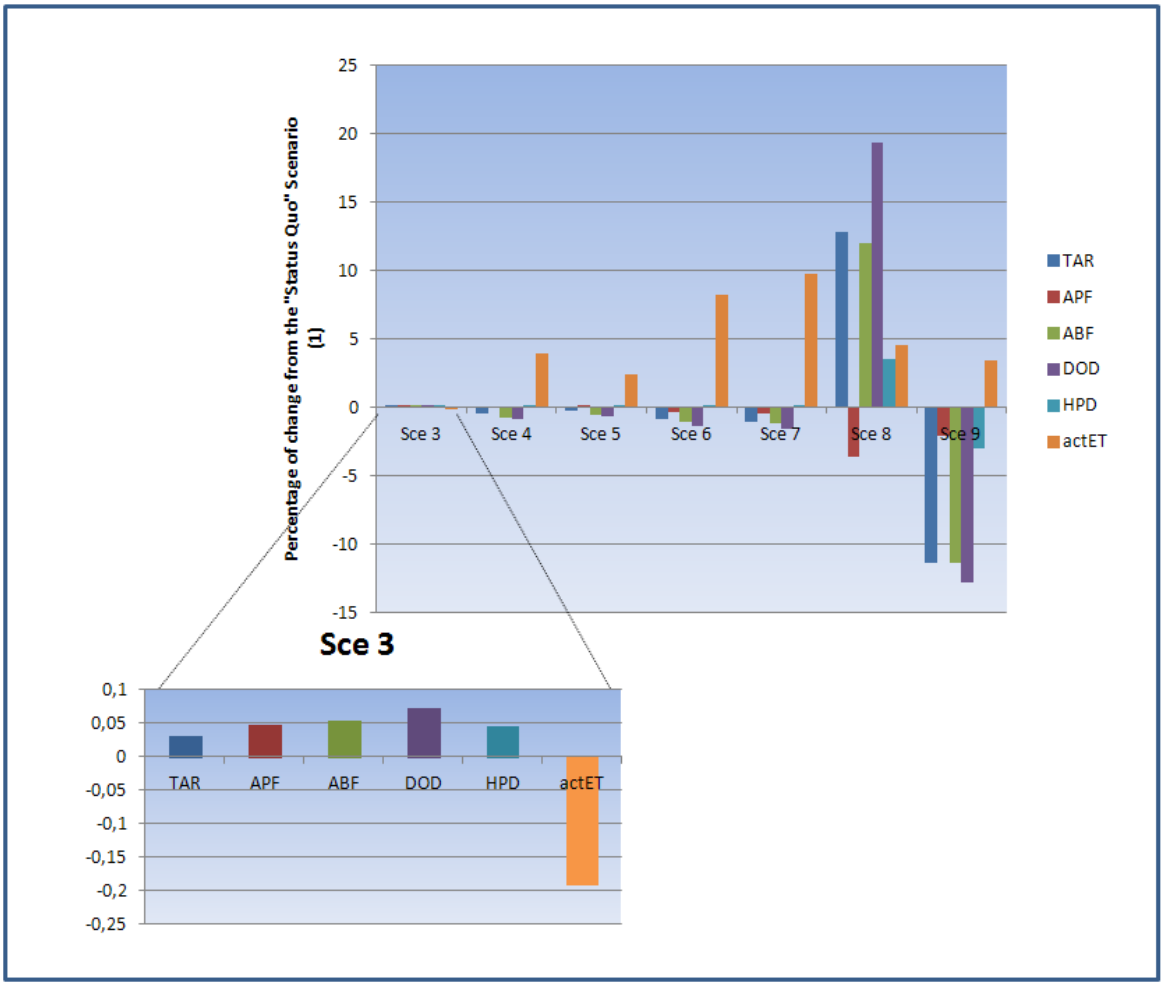


Figure 6.17. - Percentage of change of the indicators with respect to the “status quo”.

The scenarios 8 and 9 show again the most relevant changes, expressed in the deviation from the **status quo** scenario. These changes appear to be more intense during the scenario 8, in which the indicators, with the exception of the APF experienced a positive anomaly after the simulation. Particularly the changes observed in TAR, ABF and DOD are important in this case, indicating that under these conditions the total runoff and the base flows could increase in 12,77 and 11,984 % respectively, respect to the status quo scenario. The DOD shows the most extreme trend, indicating that the lowest flow could increase in 19,303 %. The rest of indicators show patterns with less intensity in their occurrence under the scenario.

In the scenario 9, inverse trends as in scenario 8 could be expected, in which all the indicators with the exception of actET have a negative deviation respect the **status quo**. The total runoff, as well as the base flows and the lowest flow could decrease more than 10 %

respect the scenario 1. The actET on the contrary, show a positive deviation (3,386 %) explained by the changes in LULC that could be expected to occur during the next 20 years.

Nejadhashemi et al (2011) introduced a criterion to differentiate the impact derived from environmental conditions in the hydrological response in a qualitative form. Thus, the changes in a river basin can be grouped in three main classes:

Class 1: Positive high changes, if the % of the observed changes is equal or more than 10% of the original value.

Class 2: Modest changes: if the % of changes is between 10 and -10% of the original values.

Class 3: Negative high changes, if the percentage of changes is equal or less than -10% of the original value.

According to these criteria, the following asseverations could be done:

- Apparently, the LULC changes that occurred or that could occur in the Boconó river basin originate only **Modest changes** in the hydrological response and water yield, being the changes in actET the most evident in this case.
- Under the combined scenario 8, **Positive high changes** in the hydrological regimes could be expected to occur, accounting for the higher intensity in this case. Particularly the indicators TAR, ABF and DOD could reflect this type and intensity of changes.
- Under the combined scenario 9, **Negative high changes** could be expected to occur, particularly in the same indicators above highlighted: TAR, ABF and DOD. The rest of the indicators are expected to experienced **Modest changes**.
- The dynamic displayed on Figure 6.17 reveal that the catchment could be eventually more sensitive to the positive anomalies in precipitation as the negatives ones. Thus, the positive high changes could be expected to occasionate a bigger impact in the hydrological regime, as the negative high changes.

6.4.3. - Level of uncertainty & Significance of the Changes.

Normally, the application of hydrological models is subject to a numerous factors limiting the performance as well as the precision in the results obtained. Such factors are responsible for the uncertainties accompanying the simulation process from the preliminary phase to the hydrograph resulting from the simulation exercises. In order to assess the suitability of any hydrological model in a complementary way as the conventional standard quality measures like the Nash and Suttcliffe coefficient or even the r² coefficient, both already used in this project, Bormann (2005) introduces an objective index in order to directly compare the uncertainty of a model caused by the data availability and quality and/or the model parameters to the calculated effect of the scenarios. The **Signal to Noise Ratio (SNR)**, formally defined by Bormann (2005), can help to assess the significance of the changes simulated in a specific scenario, analyzing the relation of model sensitivity of such scenario compared to the model uncertainty (Elfert & Bormann, 2010), through the following equation (6-1):

$$SNR = \frac{|scenario - status\ quo|}{|water\ balance\ error|} - 1 \qquad \text{(Equation 6-1)}$$

Where:
SNR = signal to Noise Ratio
Scenario = annual water balance of the land use scenario
Status quo = annual water balance of the reference period
Water balance error = absolute water balance error

The positive SNR values indicate that the difference between scenario and status quo is at least as big as the water balance error. Values larger than one are a signal of significance, because the effect is at least double than the WBE (Elfert & Bormann, 2010).

For this case, the significance of the changes evaluated through the simulated scenarios was determined comparing the components from the water balance, with the absolute water balance error using the expression explained above. The results of such operation are displayed in Table 6.8, so they were also plotted on Figure 6.18.

As seen on Table 6,8 and also on Figure 6.18, the scenarios evaluating only the LULC changes in the catchment area are not significant, or, in other words, the changes in the hydrological response accounting from these scenarios are not significant. Only the changes induced in actET in the scenarios 5, 6 and 7 resulted significant, which means that in those cases, the value obtained for actET is bigger as the WBE calculated for the Model results. Respect to the Total runoff (TotQ), only the scenarios 6 and 7 also showed positive values for SNR, accounting for significant changes. This poor performance showed by this group of scenarios can be explained by two possible reasons:

Table 6.8. - Signal to Noise Ratio values obtained for the water balance components of the different scenarios (Model B-3).

Scenarios	DirQ	BasQ	TotQ	actET	Gwrecharge
3	-0,993	-0,973	-0,966	-0,976	-0,997
4	-0,997	-0,497	-0,500	-0,513	-0,840
5	-0,811	-0,337	-0,148	0,030	-0,778
6	-0,743	-0,234	0,023	0,030	-0,749
7	-0,660	-0,173	0,166	0,223	-0,723
8	5,675	6,702	13,377	-0,436	1,279
9	4,523	6,237	11,761	-0,574	1,157

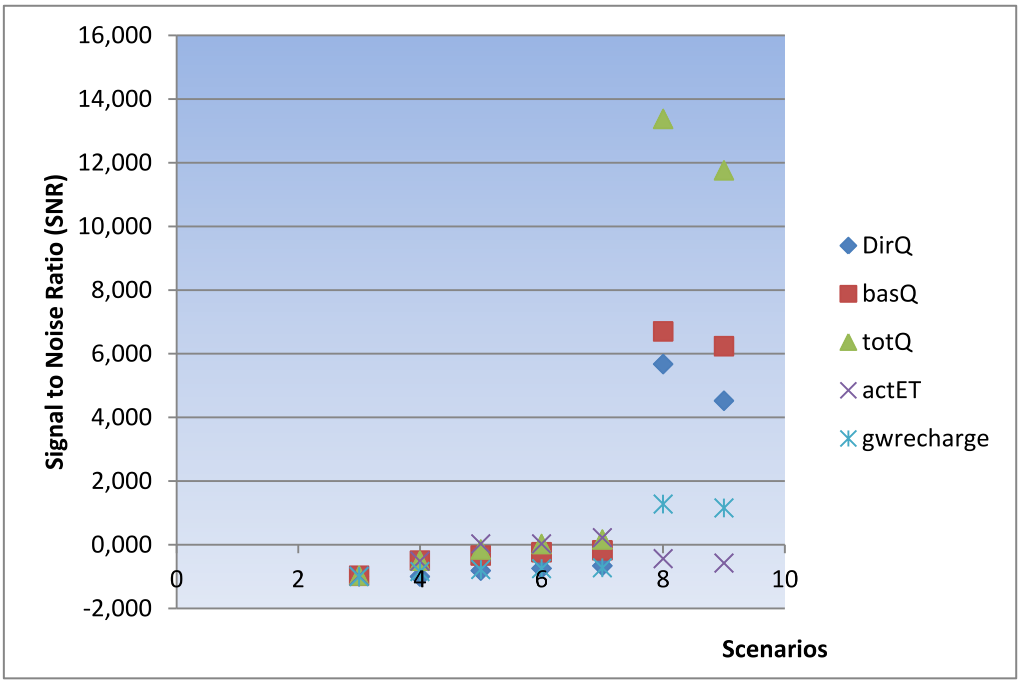


Figure 6.18. - Values of SNR for the Water Balance components.

A- The model cannot explain the changes in the hydrological response due to the LULC dynamic. This statement can be possible, considering the level of uncertainty that the simulations contain, due to different reasons (scarce data basis, gaps of information in the data series, doubtful quality of the reference data, etc).

B. - The changes or even the variability of the hydrological regime simulated cannot be explained by the LULC changes, or the level of influence of the LULC changes in the hydrological response is very limited or simply not relevant. This asseveration could be sustained by the results obtained in the last two scenarios. This will be more detailed discussed below in this chapter.

The results of the Table 6.8 reveal that the values obtained for the two combined scenarios (8 and 9) are significant for the components here evaluated, except for the actET. Thus, the hydrological response of the catchment can be influenced by the climatic changes combined with LULC changes in a significant way.

The results here obtained are concordant with the classes above defined using the criteria from Nejadhashemi et al (2011). The Figure 6.19 shows the Hydrograph with the total annual runoff for the most contrasting scenarios for 2028 (Scenarios 4, 8 and 9). They display the three possible variations that the hydrological regime for Boconó River could reflect due to the combined effect between LULC evolution and the climatic variability.

6.4.4. - The role of the spatial changes (LULC changes and climatic changes) in the Hydrological response of the river Basin. Discussion of the results.

The Boconó River Basin has been experiencing important changes in the past recent, as a consequence of the combined effect of the LULC changes and the influence of the climatic factors at regional or meso-scale level. The magnitude and intensity of the LULC changes, and particularly the inter-category transitions showing the changing trends have been conveniently evaluated in this study. The effects or the impact that such changes could have in the hydrological response and the water yield as evaluated here lead to establish the following statements:

Despite of the limitations in observed data as well as relevant detailed information about the environmental conditions, the models designed under the scheme J2000g could to reproduce adequately the hydrological dynamic and the water yield in the catchment. Moreover, despite of the relatively easy structure where the hydrological processes are quite simplified, the model could reproduce the hydrological response under the different conditions required by the scenarios.

According to the results obtained for the different scenarios, the following considerations must be taken into account:

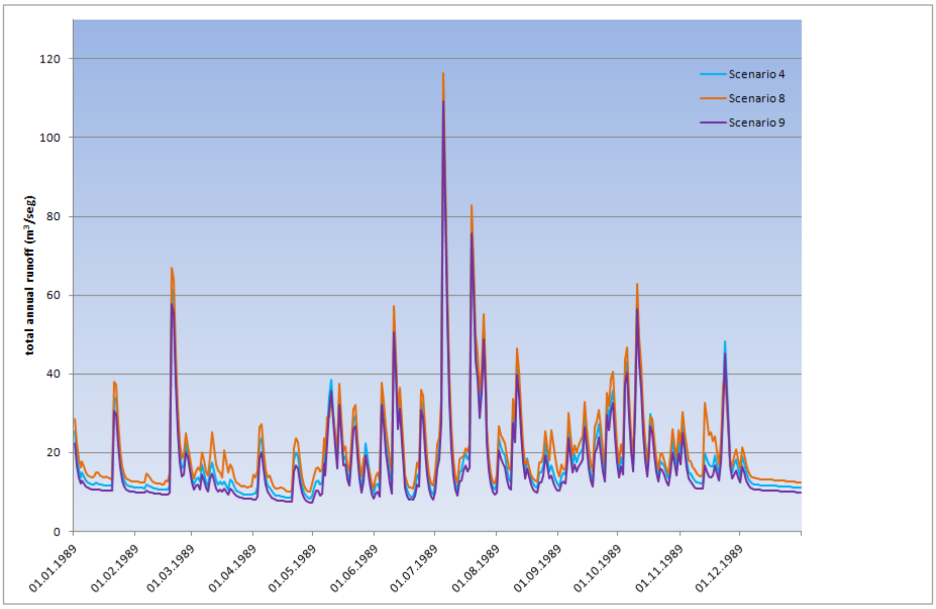


Figure 6.19. - Simulated Hydrographs corresponding to the scenarios 4, 8 and 9.

At first, the results obtained by the simulation of the different scenarios reveal that the LULC dynamic, as those occurring in the catchment area, could have an impact in the hydrological response, particularly in the seasonal flows, but this impact seems to be slight or simply less important as thought. In appearance, the changes occurring in the forested LC in the area have a direct impact in the dynamic accounted by the actual evapotranspiration (actET). As seen on the simulation results, the progressive reduction of the forested LC in the area, have a direct impact in the ET values, so it seems to be even more intense when the TMCF is altered or deforested.

As seen on the map displayed in Figure 5.12, the ET in the catchment tends to be higher in the middle-lower sectors, where the temperatures are slightly higher and the LC (Grass, shrubland and cropland) lead the radiation to reach the soil more easily. The Forested LC and especially the TMCF produce less Evapotranspiration, due the excess of moisture, lower temperatures and the cloudiness effect. The richness and the diversity of the forest is reflected in the values accounted by LAI and the stomatal resistance, carefully established for the simulations in this case, as mentioned on Chapter 2 (**2.4.5.2.3**).

Ataroff & Rada (2000) studied the possible impact produced by deforestation in the TMCF located in the Sector La Mucuy (Mérida – Venezuela). The Table 6.9 show a gentle resume of the water balance accounted for the TMCF in the area, compared with an adjacent pasture land. As seen on Table 6.9, the ET accounted for Grassland in the study area was about fourth times higher for Grassland than for the TMCF. The surface runoff and the soil storage were slightly increased in the Grassland area and decreased in the TMCF.

The results obtained by Ataroff & Rada (2000) can to support the modelling results for the future scenarios here obtained for the potential and actual evapotranspiration. Considering the extreme complexity otorgued to this ecosystem, particularly that referred to the hydrological processes like interception, water retention, sapping flows ant others, which are still not well documented and studied for this types of forests, its logical to think that the decreasing values for actET here obtained (particularly in the scenarios 6 and 7, in which the TMCF is eliminated) could be severely underestimated.

As already known, the ET is a very sensitive parameter to changes in precipitation and temperature. This fact have already corroborated in various studies worldwide like: Mimikou et al (1999); Still et al., (1999); Li et al (2009); Qi et al (2009); Kigobe & Griensven (2010); Mango et al (2011); Nejadhashemi et al (2011); Liu et al (2012); Combalicer & In (2012). However, climatic variability is not included into the scenarios 3 – 7, so they were simulated under the same conditions for pp and air temperature. Thus, the change in actET reflected in those simulations can be only explained by the LULC change in the area. Li et al (2009) also obtained an increase in ET values for about 8% due to LULC changes in the Loess Plateau – China, which caused a decrease in the runoff values. Liu et al (2012) stated that the ET cloud explain more than 80% of the runoff changes in two regions of China in simulated future scenarios.

Table 6.9. - Simplified water balance of the TMCF in comparison with Grassland in La Mucuy Sector, Mérida – Venezuela.

System	units	Inputs		Outputs					
		pp	cw	tr	fi	li	r	ev.s	s+D
TMCF	%	91	9	16	51	6	1	0	26
	mm	3124	-309	-558	1751	-214	48	-	-
Grassland	%	100	0	-66	-7	0	2	-	25
	mm	3124	-	2067	-625	-	63	-	-

(pp)= rainfall; (cw) = cloud-water interception; (tr) = transpiration; (fi) = foliage interception; (li) = litter interception; (s) = surface runoff; (ev.s) = soil evaporation; (s) = soil storage; (D) = throughflow.
(Source: Ataroff & Rada, 2000)

The ET has a direct impact in the water availability in soils, affecting also the rates of infiltration, reducing the groundwater recharge, so it can be reflected in a decreasing base flows, particularly during the dry season. It can to explain the decreasing trends observed in the scenarios 4, 5, 6 and 7 respects to the indicators TAR, ABF, and particularly, DOD, which seemed to be the most sensitive indicators due to the changes accounted by LULC changes. The decreasing values for low flows during the dry season have been widely reported in other similar researches, like: Pikounis et al (2003); Bewket & Sterk (2005); Mishra (2008); Odira et al (2010); Mango et al (2011) and Nejadhashemi et al (2011). Thus, the trends showed by the low flows (ABF) (DOD) are totally concordant with those observed in the cases above mentioned.

Adequate base flow during the dry season is often of great concern in the tropics (Wilk et al, 2001). In some areas where croplands under irrigation exist, the decrease of the base flows could be certainly a critical issue; that is the case of San Miguel watershed, where drier conditions justify the irrigation as a common practice to sustain the crops production, especially during the dry season. So, an eventually decrease of the base flows could be critical in some sectors of the catchment, leading to increase the water demand for irrigation during the dry season, which implies a more intensive water extraction from the first order streams in the area.

The indicators related to the peaks flows (APF and HPD) showed low variability among the simulations of the scenarios 3 to 7. That could be explained by the low performance of the models respect to the peaks flows (underestimation). The uncertainty derived from the observed runoff data exposed in 5.4 (Chapter 5), could make the underestimation even worst in this case.

Apart from the changes in evapotranspiration, the LULC changes could be impact in other processes like erosion and sediment transport. Is already well known that the changes in vegetation cover affect the surface as well underground fluxes, process that determine the risk of erosion, particularly in steep slopes. However, the research about this dynamic in mountain areas is very scarce, so the relationship cannot be precisely established. Rincon (2001) modeled the hydrological sensitivity to LULC change in a TMCF area in Colombia, detecting a strong level of influence in the risk of erosion derived from the deforestation of the TMCF in steep lands. The areas with steep slopes located at the highest altitudes, as well as those sectors close to the river channel with steep slopes, were founded by the author to be the most sensitive to the occurrence of erosion, where the erosion could to remove 23 mm/m²/year of soil.

Slope is a determinant factor for the overland flow, affecting directly the occurrence of erosion processes in both form and magnitude. The altitude is also an important factor affecting the rainfall occurrence in mountainous areas, so in the case of the Tambito watershed in Colombia, the maximum values for erosion sensitivity were founded in deforested areas located between 2000 and 2400 m.a.s.l (Rincon (2001). In our case, both elements have to be critically considered, as the "**hot fronts**" of deforestation for the TMCF are currently occurring within this altitudinal range. Obviously, it could be directly affecting the charge of sediments transported by the river. In fact, some authors like: Cornieles (1997); Macias (2002) and Gásperi (2006) have highlighted the increasingly trend in the sediments transported by the Boconó river.

The Figure 6.20 shows the sediments emission corresponding to the three last years measured in La Cavita Station. However, the biophysical conditions within the river basin as well as the complex dynamic of the LULC make it very difficult to define precisely the origin of the sediments. Caraballo (2011) studied the sheet and rill erosion processes in the San Rafael – San Miguel watersheds, both located into the study area, identifying severe occurrence of such processes, which were closely related to the high and intricate roads network, the fragility of the soils and the jointed bedrocks. However, the deforestation is currently occurring with more intensity in others sectors in the river basin, as shown in Chapter 4 (Figures 4.4 and 4.5), so the real effect of the deforestation in the sediments emission cannot be determined in this case. This concern should be then considered to be studied at smaller scale (watershed level).

In general, the changes in the hydrological response for the scenarios considering only the LULC changes were not significant, according to the SNR values. Effectively, they appear to be careless of important, considering the huge changes assumed in some scenarios like 6 and 7. However, similar findings were also reported in other similar cases where the relationship between the LULC changes and hydrological response was studied. For example, Mishra (2008) observed an increase of only 4,53% in the annual streamflow in 30 years due to land use changes in Mahadani River Basin, India. Wang et al (2008) founded an increase of 3,4% in the mean annual streamflow produced by a reduction of 33,9% of the forest cover in Zamu river Basin, Northwest China. Low incidence of the LULC changes in streamflow amounts were also reported by: Wilk et al (2001); Lahmer et al

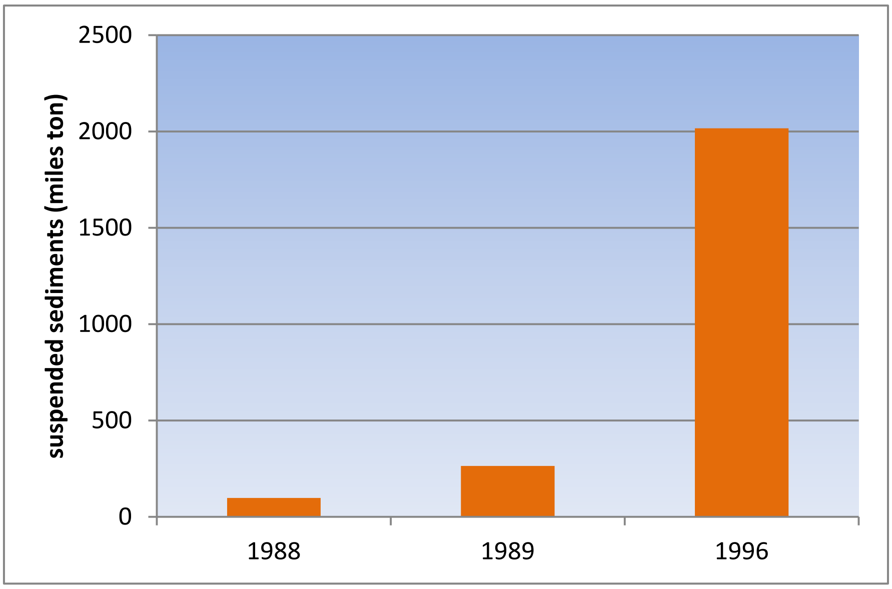


Figure 6.20. - Suspended sediments of the Boconó River measured in La Cavita Station (Source: Macias, 2002).

(2001); Pikounis et al (2003); Thanapakparwin et al (2006); Guo et al (2008); Qi et al (2009); Elfert & Bormann (2010), and Wang & Kalin (2011).

The fact that a large reduction in forested LC (like the TMCF in this case) could not be shown to have significantly altered the water balance and the river discharge is obviously contrary to small-scale studies where forest removal with replacement by agricultural crops has been shown to increase the streamflow. Wilk et al (2001) states that the criteria for land classification between forest and no forest currently used could be incorrect. They say: “the areas with swidden agriculture contain high amounts of shade trees and any abandoned areas will quickly be replaced secondary forest. The presence of these trees outside the strict “forest classification” clouds the interpretation of these land uses on hydrological processes”. The statement is greatly coincident with the conditions founded in the catchment area, and the LULC classification was developed taking into account the considerations from Wilk et al (2001).

Moreover, the role of the LULC in the streamflows dynamic and the possible impact in the water yield is also dependent on the scale. Nejadhashemi et al (2011) studied the impact of LULC in the Great Lakes region (USA), considering the impacts at local (watershed) and regional (Sub-basin, river basin) level. They detected differences in the intensity of changes among the scales used. At the watershed level the changes were more intense, meanwhile at the river basin the changes in streamflows were considered "**modest**". Under all the considerations above mentioned, it can be concluded that the results obtained in the scenarios considering only the LULC are concordant and supported by similar cases worldwide already mentioned.

Respect to the last two scenarios, the results obtained here are an undoubtedly signal about the importance of the climatic variability in the streamflow response and the water yield in the Boconó River Basin. As already mentioned before, the river Basin is strongly governed by the meso climatic system of the Llanos Region, and also strongly influenced by the anomalies ENSO and A-ENSO. Both conditions converge in a very complex situation conditioning the climatic system in the area, influencing the precipitation patterns as well as the temperatures. Obviously, the climate change, in this case translated into a probably intensification and more frequently anomalies ENSO / A-ENSO, is going to affect deeply the hydrological response of the river Basin.

Similar finding and conclusions about the role of the climate variables in the hydrological response were also established by: Niehoff et al (2002); Bronstert et al, (2002); Legesse etl al (2003); Pizarro et al (2006); Bäse et al (2006); Guo et al (2008); Wang et al (2008); Hejazi & Moglen (2008); Qi et al (2009); Li et al (2009); Adnan (2010); Legesse et al (2010); Mango et al (2011); Liu et al (2012).

The results suggest that the river Basin seems to be more sensitive to an increase of the precipitation than in the opposite condition. Even a small positive change in the amount of rainfall could cause stronger changes in the runoff. Similar trends were also observed by Bronster et al (2002) analyzing two catchments in Germany, and also by Legesse et al (2010) in the Meki river Basin – Ethiopia. In the case of Boconó river basin, this fact take more relevance because of the major impact showed by the A-ENSO in the whole region, so the area is more vulnerable to the positive anomalies of precipitation, than to those negatives anomalies.

Based on the last assumptions, it's very important to consider the LULC together with the climate changes, as the **TWO BASIC DRIVERS** influencing the hydrological response at the river Basin level or regional scale. The combined effect of Land Use and climate change may notably influence on hydrological cycle (Homdee et al (2011). This asseveration can be validated by the findings of this research, so the combined scenarios seems to be more useful in obtaining results which could be more realistic, considering the big influence of the meso scale climatic system and the anomalies ENSO/A-ENSO. The importance to adopt this "**combined approach**" in the evaluation of the hydrological dynamic have been highlighted by some authors like: Legesse et al (2003); Wang et al (2008); Hejazi & Moglen (2008); Adnan (2010); Delgado et al (2010); and Homdee et al (2011).

Finally, is important to quote here that the model simulation results obtained here are subject to various sources of uncertainty. Some uncertainties are present in the input data (scarce information, gaps, inconsistent information); others are in the model structure and some are due to possible errors in the calibration input data and parameter estimates. According to Legesse et al (2010), most physically based models cannot fully account for the complexity and heterogeneity of processes occurring in a catchment.

Land Use and hydrological models are usually accompanied by a high degree of uncertainty, due to insufficient data availability or quality and related space-time heterogeneity (this case is not an exception of that). Another important limitation rest on the insufficient knowledge on the physics and the stochastic features of the processes involved, as well as other simplifications inherent in the model structure (Niehoff et al, 2002).

In this case, the short length of the hydrological data represents an important constraint that limited the length of the simulated period. The scarce data about important climatic parameters like evaporation, humidity and wind speed in the area made that limitation in the length of simulated period even worst. Moreover, the constraint related with overestimation/underestimation could have sensitively affected the results for the scenarios simulated.

These as well as other constrains inherent to the uncertainties in the simulation process have also pointed out by some authors like: Lahmer et al (2001); Wilk et al (2001); Niehoff et al (2002); DeFries & Eshelman (2004); Brath et al (2006); Kim et al (2009); Legesse et al (2010); Elfert & Bormann (2010) and Homdee et al (2011).

Chapter 7

Summary, Conclusions & Future Research

Summary, Conclusions & Further Research

7.1. – Summary

The main goal of the present research study was to analyze the effect of the spatial changes, particularly inherent to the LULC changes in a tropical River Basin, and its possible impact in the water resources - response. The Boconó River Basin, located in the North Venezuelan Andean Region was selected as study area, being a very representative Andean Basin in which the biophysical and the socio-cultural systems are strongly interacting to generate a quite complex dynamic reflected in the form and intensity of the natural resources use. In order to achieve such transcendental goal, fourth main research targets were established as follows: (1) To analyze the spatial dynamic of the Boconó River Basin during the Period 1988 – 2008, in terms of changes occurring in Land use/ Land cover (LULC); (2) To analyze the dynamic of water resources into the River Basin, through the study of annual flows and seasonal flows; (3) To analyze the potential impact that such changes in LULC, in combination with climatic variability, could have in the future hydrological response; and (4) To discuss the possible relationships and its geographical implications between the spatial changes and the dynamic of water flows within the Boconó River Basin. The study was based in the combination of three theoretical approaches: the "**Ecosystem-Oriented**" approach, used as a basis in the LULC process; the "**Hydrological landscapes**" approach, used as a basis to delineate the Hydrological Response Units for the modelling process, and the "**geographic visualization**" providing the principles and techniques to analyze and to represent adequately the spatial processes; all of them combined into a regional perspective (meso-scale analysis).

The realization of such research targets rested in a conceived relevant methodological approach containing 3 main grouping and interacting Methods: Geoinformatic & GIS, Remote Sensing and Hydrological Modelling, which were continuously acting in an integrated form, so that the exchange of data, parametric and non-parametric information as well as maps between them were always needed.

The group Geoinformatic & GIS aported the approaches, software and techniques for the construction of the DEM of 90 m resolution, which were the spatial support for all the processes involved in the whole research, as well as other important processes and tasks involved with the geographical visualization of the results (spatial analysis, overlays, spatial statistics calculation, Land Use Change modelling and map composition). The analysis of the LULC dynamic in the recent past was driven through Remote Sensing procedures, using LANDSAT TM images for three selected time-points (1988-1997-2008). The classification process was developed through a semi – supervised method, following a multi – level clustering for a multi – class segmentation of the scenes. In the first level the “hyperclustering approach” was applied to delineate the “pure classes” with a highly defined spectral signal. Classes having a mixed spectral signal as well as clouds and fog were prone to a second and third level of classification, where masking process combined with pixel-oriented classification was then applied. In the third level the LU classes were ecologically differentiated through a simple modelling process using the DEM to make an altitudinal differentiation according to ecological criteria.

During the post-classification, the maps with the merged LULC classes for 1988, 1997 and 2008 were processed in a spatial “matrix” analysis, in order to develop the multitemporal analysis, generating the cross-tabulation transition matrix for 1988-1997 and for 1997 -2008 respectively. The matrixes were processed following the criteria and methods proposed by Pontius et al (2004), which were very useful to identify the systematic “**inter-category**” transitions, process that account for the right trends being showed by the main LULC categories in the area, together with other indicators like: gain, losses, swapping and net change. The “**inter-category**” transitions were a basic input into the Land Change modeller for ecologically sustainability, in order to project the changes 20 years in the future, generating a potential LULC map for 2028, which was a very important input for the modelling process.

For the research targets 2 and 3, the third approach concerning to the development of a simulation process using the process-oriented model J2000g was driven. Such model required a pre-processing for the climatic data, as well as the compilation and processing of information concerning to the basic parameters required to model the hydrological cycle in J2000g.

For a process-oriented estimation of the meso-scale soil water distribution in the catchment the concept of HRUs was applied, being delineated from a perspective of the “**hydrological landscapes**” approach. Thus, the terrain landforms together with the geological framework and the LULC were the basic input for the delineation. Three HRUs maps were delineated for 1988, 2008 and 2028. Due to the limitations derived from the hydro climatic input data, three models were designed, with different methods to estimate the evapotranspiration. The models were calibrated and validated using the “**split-sample**” method, and the basic indicators for efficiencies were evaluated.

Finally, nine scenarios were considered in order to simulate and to evaluate the hydrological response in both, the recent past, and the possible impact of the LULC changes and the climatic variability projected in the future.

The methodological approach gentle summarized above, lead to obtain some important outputs which represent valuable products and advances that could be made throughout this thesis, these they are:

- A Digital Elevation Model (DEM) for the Boconó River Basin, with the corresponding annexe information about some important parameters for topography, hydrology and geomorphometry.
- The LULC Maps of the Boconó River Basin, for the years: 1988, 1997 and 2008, rigorously processed and produced with a high degree of accuracy.
- Cross-tabulation transition matrixes for the Period 1988 – 1997 and 1997 – 2008, with the subsequent analysis of the systematic “**inter-category**” transitions.
- The identification of the real trends and “**inter-category**” transitions that have been occurring in the LULC for the Boconó River Basin during the last 20 years.
- The identification of the most sensitive areas in which the LULC changes have been occurring with more intensity, for example: the “**Hot Fronts**” of deforestation.
- The development of a Land Change Model in which the main systematic “**inter-category**” transitions could be projected in the future, in order to obtain a LULC Map for the year 2028.
- Three maps displaying the Hydrological Response Units (HRUs) corresponding to the years 1988, 2008 and 2028 for the River Basin, following an alternative process, complementary to the traditional one.
- The development of three hydrological distributed Models (B-1, B-2 and B-3) for the Boconó River Basin, through the use of the J2000g Model Platform.
- An adequate characterization of the hydrological dynamic and the description of the seasonal flows and the water balance for the Boconó River Basin.

- Maps of the water balance components showing the spatial distribution of the water production in the catchment area.

- The analysis of the hydrological response and water yield occurred in the river Basin in the last 20 years, through the reconstruction of the streamflow for the Boconó River for the year 2009.

- The combination of diverse scenarios for LULC change and also climatic change into the distributed models to assess the potential impact of those changes in the hydrological response.

- The strong influence of the River Basin to the climatic variability governed by the meso climatic system, and especially by the Anomalies ENSO and A-ENSO.

- The high sensitivity of the Boconó River to the positive anomalies or positive changes in the precipitation regimes.

- The role of the TMCF in the control of the hydrological cycle, particularly the evapotranspiration.

All these products together and the subsequent analysis driven in the Chapters 4, 5 and 6 were the target keys for the conclusions that are going to be presented below.

7.2. - Conclusions

7.2.1. - Conclusions oriented to the Target Questions formulated on Chapter 1.

Now it´s important to go back to the Chapter 1, in order to review the target question in which the research targets for the thesis were based. Thus, the conclusions were arranged according to the sequence of the target question formulated at the beginning of the project, as follows:

A. - What kind of changes in land use/land cover (LULC) have been occurring in the Boconó river basin, during the last 20 years?

The results of the multitemporal evaluation show that the persistence dominates widely the landscape system of the river basin, which is considered normal. However, a very important dynamic was observed in the area, in which the categories: Successional Srhubland (S-Shr), Sub-montane Forest (Sm-F), Open-cleared Forest (Oc-F) and Cropland (Cro-L) were the most dynamic among the two considered periods, accounting for the highest total change value, as well as gains, losses, swapping and net change.

The systematic transitions that have been occurring in the LULC categories reveal that the Land Uses Cropland (Cro-L) and Grass Anthropogenic (Gr-An) have been growing, gaining surface basically from Sucessional Shrubland (S-Shr), Sub-montane Forest (Sm-F), and Grassland (Gr-L).This justify the higher values for swapping-change observed in these categories. On the other hand, the urban areas (Ur-U) have been growing basically at the expense of Cro-L, Gr-L and Fl-P.

B. - How intense have been the changes experimented by the forest cover, and particularly the Tropical Montane Cloudy Forest in the area during the last 20 years?

The results derived from the cross-tabulation matrix, revealed that the TMCF experimented a reduction of 12,8% (3530,43 ha) in the last 20 years. This is a considerable reduction taking into account the important role of the ecosystem in hydrological, ecological and biological terms.

The study also demonstrated that the changes and the reduction showed by the Tropical Montane Cloudy Forest in the area, cannot be directly associated to the expansion of Land Use categories like Cropland or Grass Anthropogenic. At least on the last 20 years, the TMCF have been systematically changing to an intermediate condition for LC, basically to Open-cleared Forest (Oc-F) and Sucessional Srhubland (S-Shr). Even when the TMCF is under anthropogenic pressure, it can be only associated with logging, wood and timber extraction, as well as the extraction of non wood products and plants.

The dynamic accounted for the LULC also revealed that the anthropogenic pressure over the TMCF unfortunately continue, as evidenced by the “**Hot fronts**” of deforestation observed in important sectors where the ecosystem exist. The Rio Negro sector, as well as the TMCF located into the Guaramacal National Park seems to be actually prone to the clearing and deforestation processed. This fact was discussed in Chapter 4.

C. - How was the dynamic of streamflows, particularly seasonal flows and peak flows in the river basin during the same time- period?

According to the historical data and also to the hydrographs simulated in the model J2000g, the Boconó River Basin show a hydrological dynamic typically observed in the tropical mountainous rivers. This pattern is characterized by a well defined seasonality of the streamflows, and a rapid response to the convective and heavy precipitation events, which are very typical in the region. The highly variability of the convection processes reported in the literature and the influence of the anomalies ENSO and A-ENSO suggest that the seasonal flows patterns can be highly variables among the years.

The systematic transitions Sm-F – Fl-P; Cro-L – Fl-P and Ur-U – Fl-P, as well as the variation of the category Fl-P during the period considered for the multitemporal evaluation of LULC, suggest an intense dynamic of the streamflows in the area, and the occurrence of high peak flows and important flooding events during the period, which have been affecting the urban expanding area, as well as croplands. Such dynamic have been also reported by some authors like, Cornieles (1997), Quevedo (1997) (Macias, 2002). This fact demonstrated the usefulness of the systematic transitions of LULC as here analyzed.

The spatial distribution of the water balance components across the catchment area, helped to reach an adequate geographical visualization of the water yield. It can be clearly observed that the Rio-Negro Sector, located at the North-east, constitutes the water producer sector in the catchment. The sector also reported the highest values for precipitation, and also shows the highest values for the groundwater recharge. It can be also clearly observed, that the spatial distribution of the precipitation has a paramount importance in the water yield.

The spatial distribution of the actual Evapotranspiration also demonstrated the very important role of the LC, particularly the type of the vegetation, in the spatial dynamic observed for the ET.

The comparison between the scenarios 1 (**status quo** scenario) and scenario 2 revealed a high variability in the streamflows occurred in the last 20 years, derived from the variability of the meso-scale climatic processes, and the alternate sequence of ENSO and A-ENSO events. The evident difference between the scenario 2 in comparison with the **status quo** scenario, reveal that the Boconó River is very sensitive to the variability imposed by the climatic processes.

D. - Is there a kind of correlation between the dynamic of seasonal flows, and the spatial changes that the river Basin experimented during this time-period?

The comparison between the scenarios 2 and 3 revealed that the changes occurred in the LULC in the river Basin during the last 20 years were not significant in terms of their impact in the seasonal flow patterns. Possibly, the extents of the LULC changes during the last 20 years were still relatively small compared to the entire area. Apparently, the variability in the seasonal flows, the recurrence of peak flows and the severity of the low flows in some years is more explained by the climatic variability strongly influenced by the anomalies ENSO/ A-ENSO.

E. - Does the future LULC changes -according to the trends observed in the area- could have an impact in the streamflows patterns or in the water yield in the area?

Responding to this question, the results of the simulation and its comparison revealed that the future variability for the streamflows and the water yield in the area is mostly explained by the climatic conditions and patterns, as by the LULC alone. Thus, the possible intensification and more frequently recurrence of the anomalies ENSO and A-ENSO could be responsible for the intensification and seasonal variability of the streamflows.

The results for the scenarios 8 and 9 broadly suggest that **<u>the Boconó River is highly sensitive to the positive changes in the climatic variables precipitation and temperature</u>**. Thus, a relatively small positive change in the precipitation patterns could generate an important change in the hydrological response, as seen on the simulation for these scenarios. A comparison between the two scenarios (8 and 9) demonstrated that the river tended to be more sensitive to the positive anomalies and variations in the rainfall, with respect to the negative ones.

The results obtained for the scenarios 3 to 7 denotes clearly the low impact of the LULC changes in the hydrological regimes. Those changes only could impact the water balance through the variation in the evapotranspiration rates. However, the actET seemed to be quite underestimated by the model B-3, and when considering the ET values for the TMCF reported by Ataroff & Rada (2000), both facts could suggest that the role of the forested LC in the water balance, and particularly the role of the TMCF could be greatly underestimated in the future scenarios simulated here.

Nevertheless, the results accounted by the SNR contribute to reaffirm the conclusions related to this relevant question. So, they revealed the low impact of the LULC in the hydrological response and water yield, except for the case of the actET, were the impact could be significant. According to the SNR values, the scenarios combining LULC with climate variability (8 and 9) show a high contribution in the explanation of the hydrological response and the water yield in the Boconó River.

7.2.2. - Conclusions oriented to the Methods & Models used in the thesis.

The overall results obtained in this thesis revealed that the comprehensive methodological approach developed, with the combination of Geoinformatic-GIS, Remote Sensing and distributed Hydrological modeling was effective and useful to get an integrated geographical visualization of the hydrological dynamic and the water yield in a tropical river Basin at a meso-scale level.

The methodological approach combining the multitemporal LULC evaluation, together with the ecosystem approach and the **inter-category** transitional method, represented a very useful tool to define, to describe an to analyze the LULC system in the Boconó River Basin and the changes occurred in the last 20 years. The method adopted here to analyze the LULC changes lead to an adequate segregation of the changes according to its different components, so that the systematic inter-category transitions, as well as the swapping between categories can to show a better orientation into the processes driving the change, linking patterns to process.

The modeling of the systematic inter-category transitions through the use of the MLP (Multi layer Perceptron) Neural Network method into the Land Change Model provided a very useful way to predict the future LULC changes based on the real trends observed in the recent past. Thus, an adequate logic prediction for the LULC in 2028 was finally obtained, being a basic target variable to delineate the HRUs map for the future sceneries evaluated into the simulation model.

The method assumed here to delineate the Hydrological Response Units – HRUs provided a reasonable alternative to differentiate the landscape taking into account the basic land forms –the physiographic expression of the hydrological landscapes- together with the comprehensive LULC map and the geological framework for the catchment. Thus, the physio-geographical variability of the catchment was clearly represented in the HRUs map, avoiding the excessive tessellation and disaggregation of the landscape obtained through the conventional overlay procedure.

The results provided by the simulation process have shown that the J2000g model could to reproduce the hydrological response, reflected in the streamflow, the seasonal flows dynamic and the water yield with a reasonable level of precision, accounted by the values for efficiencies obtained for the three models designed to be used here. A relatively good fit was reached between observed and simulated runoff values, and through the concept of HRUs, the model could to reflect well the spatial variability of the water balance components.

Despite of the undoubtedly relevance of the results obtained from the modeling process, they should be carefully considered, because the Land Use and hydrological models are always accompanied by a high degree of uncertainty, due to the limitations in the data availability, quality and acquisition, as well as the related space-time heterogeneity. Particularly in this case the input uncertainty governed by the limitations in the data already mentioned as well as other factors like the spatial distribution of the rain gauges, and the careless of measures for evaporation, humidity and wind speed for other stations, surely influenced the efficiencies of the results here obtained.

7.3. - Further Research

The results of the investigation process as well as its analysis reflect facts and concerns which are prone to be needs for future research in the topics studied here. These needs are going to be mentioned below:

7.3.1. - In terms of LULC Change.

The dynamic accounted by the LULC have been studied here without take into account socioeconomic, demographic and sociocultural variables, which have also a decisive influence and thus power explanatory in the form, patterns and intensity of the LULC changes, especially at local and regional levels in the developing countries and those located in tropical regions. Having the study area a paramount importance for the Water yield in the region, the dynamic of LULC must be continued under analysis, from a more comprehensive approach, in which the variables above mentioned can be reasonable included.

Similarly, those socioeconomic, demographic variables should be also considered in the Land Change modelling, as basic drivers or explicative variables together with those biophysical ones. Thus, a more realistic prediction of the systematic transitions for future scenarios could be possibly obtained.

7.3.2. - In terms of hydrological modelling.

Hydrological modelling is always prone to further research. Further studies must be focused in trying to improve as possible, the performance of the models like these here developed. That would be possible improving the parameterization process, enriching it with more reliable information about some parameters like soil depth, porosity, bulk density, etc, in order to improve some basic process like soil moisture, permeability, infiltration and groundwater recharge into the model. Of course, that requires further oriented studies that can to generate such information for the catchment. The SRTM images constitute a very useful tool from which spatial information about some important geomorphic parameters could be derived. However, such information must be supported with rigorous field validation process, which are usually expensive and time consuming.

The careless and low availability climatic data could be in part solved with some data from Satellite systems, so that the spatial distribution of the climatic parameters could be more realistic.

Further research is also needed respect the role of the TMCF in the hydrological cycle in mountainous areas. Such a complex ecosystem is still not well studied worldwide, and due this fact its effect in the hydrological regime in upland areas could be severely underestimated. More knowledge is still required in the real role that the cloudiness plays in the moisture and in the water addition into the forest. More knowledge is required about the dynamic of the evapotranspiration and the interception in the TMCF. Both are two relevant processes in the hydrological cycle, and the structure and richness of the TMCF make these processes to be more complex.

Finally, DeFries & Eshelman (2004) proposes that "**interactions between land-use change and hydrologic processes will be a major issue in the decades ahead**". I totally agree with the affirmation, so further research about the combined effect of the LULC and climate change in hydrology is needed. Particularly the anomalies ENSO / A-ENSO has to be subject to a more comprehensive analysis, in order to get more knowledge about the impact of these anomalies in climate variability at regional and local levels. Obviously the potential to experiment with future scenarios is vast, and will depend on the geographical region where they will be evaluated, the LULC conditions and the process of the climate that at meso-scale or even regional scale, could affect the hydrological cycle, and thus the simulation process.

References

ACEITUNO, P. (1987): **On the Functioning of the Southern Oscillation in the South American Sector. Part I: Surface Climate**. Monthly Weather Review, 116: 505 – 524.

ADNAN, N. (2010): **Quantifying the Impacts of Climate and Land Use Changes on the Hydrological Response of a Monsoonal Catchment**. University of Southampton, Faculty of Social and Human Sciences, School of Geography. PhD Thesis.

ALBRECHT, J. (2007): **Key Concepts & Techniques in GIS**. London. SAGE Publications.

ARVIDSON, T., GASCH, J., GOWARD, S. (2001): **LANDSAT 7´s long-term acquisition plan – an innovative approach to building a global imagery archive**. Remote Sensing of Environment, 78: 13 – 26.

AKPABIO, E; WATSON, N; ITE, U; UKPONG, I. (2007): **Integrated Water Resources Management in the Cross River Basin, Nigeria**. Water Resources Development, 23(4): 691-708.

ANDERSEN, J., REFSGAARD, J., JENSEN, K. (2001): **Distributed hydrological modelling oft he Senegal River Basin – Model construction and validation**. Journal of Hydrology, 247: 200 – 214.

ANDRESSEN, R., DIAZ, A., LAZO, J. (2000): **Influencia de la altitud y distancia al Lago de Maracaibo en la caracterización pluviométrica del estado Trujillo, Venezuela**. Revista de la Facultad de Agronomía de la UCV, 26: 107 – 124.

ARMENTERAS, D., RUDAS, G., RODRIGUEZ, N., SUA, S., ROMERO, M. (2006): **Patterns and causes of deforestation in the Colombian Amazon**. Ecological Indicators, 6: 353-368.

ATAROFF, M., RADA, F. (2000): **Deforestation Impact on Water Dynamics in a Venezuelan Andean Cloud Forest**. AMBIO, 29 (7): 440 – 444.

ATAROFF, M. (2001): **Venezuela**. In: KAPPELLE, M., BROWN, A. (Edit): **Bosques Nublados del Neotrópico**. Costa Rica. Editorial IMBIO.

ATAROFF, M. (2002): **Precipitación e Intercepción en ecosistemas boscosos de los Andes venezolanos**. ECOTROPICOS, 15: 195 – 202.

AUDEMARD, F; AUDEMARD, F. (2002): **Structure of the Mérida Andes, Venezuela: relation with the South America – Caribbean geodynamic interaction**. Tectonophysics. 345 (1-4): 299 – 327.

BALDYGA, T., MILLER, S., DRIESE, K., GICHABA, Ch. (2007) **Assessing land cover change in Kenya´s Mau Forest region using remotely sensed data**. African Journal of Ecology, 46: 46 – 54.

BANCO INTERAMERICANO DE DESARROLLO (BID). (2005): **Buenas prácticas para la creación, mejoramiento y operación sostenible de organismos y organizaciones de Cuencas**. Caracas.

BARRIOS, A. (1994): **Diagnosis del enfoque de manejo de cuencas y el continuo deterioro de los recursos naturales en las cuencas altas de Venezuela.** Memorias del 11 Congreso Latinoamericano de Manejo de Cuencas. Mérida - Venezuela.

BÄSE, F. (2005): **Beurteilung der Parametersensitivität und der Vorhersagesicherheit am Beispiel des hydrologischen Modells J2000**. Jena. Friedrich-Schiller Universität. Geographisches Institut. Fachbereich Geoinformatik, Geohydrologie und Modellierung. Diplomarbeit.

BÄSE, F., HELMSCHROT, J., MÜLLER, H., FLÜGEL, W. (2006): **The impact of land use change on the hydrological dynamic of the semi arid Tsitsa catchment in South Africa**. Göttingen. Procedure 2nd Göttingen GIS and Remote Sensing Days.

BATTAGLIN, W., KUHN, G., PARKER, R. (1996): **Using GIS to Link Digital Spatial Data and the Precipitation Runoff Modelling System: Gunnison River Basin, Colorado**. In: GOODCHILD, M., STEYAERT, L., PARKS, B., JOHNSTON, K., MAIDMENT, D., CRANE, M., GLENDINNING, S. (Ed) (1996): GIS and Environmental Modeling: Progress and Research Issues. Fort Collins, GIS WORLD Books, Inc.

BECKER, R. (2012): **Wasserbilanzmodellierung zur Ermittlung räumlich differenzierter Wasserdefizite. Auswirkungen von Landnutzungsveränderungen auf hydrologische Prozesse im semi-ariden Rautén-Einzugsgebiet in Zentralchile**. Tübingen. Eberhard-Karls Universität. Mathematisch-Naturwissenschaftliche Fakultät. Fachbereich Geowissenschaften. Diplomarbeit.

BEHRAWAN, H. (2010): **Hydrological Snowmelt Modelling in Snow Covered River Basins by means of Geographic Information System and Remote Sensing. Case Study: Latyan Catchment in Iran**. Jena. Friedrich Schiller Universität. Chemisch – Geowissenschaftlichen Fakultät. PhD Thesis.

BENDIX, J. (2006): **Climate dynamics in tropical mountains of south Ecuador: past and present characteristics and variability**. In: Biodiversity and Sustainable

Management of a Mega diverse Mountain Ecosystem in South Ecuador. New Proposal 2007 – 2010.

BEWKET, W., STERK, G. (2005): **Dynamics in land cover and its effect on stream flow in the Chemoga watershed, Blue Nile basin, Ethiopia**. Hydrological Processes, 19: 445 – 458.

BHATTARAI, K., CONWAY, D. (2008): **Evaluating Land Use Dynamics and Forest Cover Change in Nepal´s Bara District (1973 – 2003)**. Human Ecology, 36: 81 – 95.

BIZZARRO, C. (1985): **Determinación de los Factores “C” de Cobertura Vegetal y “P” de Prácticas Conservacionistas en la Cuenca Alta del Río Boconó, Estado Trujillo**. Mérida. Universidad de Los Andes. Facultad de Ciencas Forestales y Ambientales. Escuela de Ingeniería Forestal. Trabajo de Grado.

BOISSONNADE, A., HEITKEMPER, L., WHITEHEAD, D. **Weather Data: Cleaning and Enhancement**. In: DISCHEL, R. (Edit) (2002): Climate Risk and the Weather Market. Financial Risk Management with Weather Hedges. London. Risk Waters Group Ltd.

BOLCH, T. (2006): **GIS– und fernerkundungsgestützte Analyse und Visualisierung von Klima- und Gletscheränderungen im nördlichen Tien Shan (Kasachstan / Kyrgyzstan) mit einem Vergleich zur Bernina-Gruppe / Alpen**. Den Naturwissenschaftlichen Fakultäten der Friedrich-Alexander-Universität Erlangen-Nürnberg zur Erlangung des Doktorgrades. Dissertation.

BONE, J; HIDALGO, P; VELASQUEZ, F. (1985): **Diagnóstico de la Cuenca del Río Boconó. Informe de avance del Plan de Desarrollo.** Boconó, Centro de Ecología.

BONELL, M. BRUIJNZEEL, L. (Edit.). (2004): **Forest, water and people in the humid Tropics. Past, present and future hydrological research for integrated land and water management**. Cambridge. Cambridge University Press. and UNESCO.

BORMANN, H. (2005): **Evaluation of hydrological models for scenario analyses: signal-to-noise-ratio between scenario effects and model uncertainty**. Advances in Geosciences, 5: 43 – 48.

BORMANN, H., BREUER, L., GRÄFF, T., HUISMAN, J., CROKE, B. (2009): **Assessing the impact of land use change on hydrology by ensemble modelling: IV. Model sensitivity to data aggregation and spatial (re-)distribution**. Advances in Water Resources, 32: 171 – 192.

BRAIMOH, A., VLEK, P. (2005): **Land-Cover Change Trajectories in Northern**

Ghana. Environmental Management, 36 (3): 356 – 373.

BRATH, A., MONTANARI, A., MORETTI, G. (2006): **Assessing the effect on flood frequency of land use change via hydrological simulation (with uncertainty)**. Journal of Hydrology, 324: 141 – 153.

BREUER, L. (2009): **Assessing the impact of land use change on hydrology by ensemble modelling (LUCHEM)**. Editorial. Advances in Water Resources.32: 127-128.

BREUER, L., HUISMAN, J., WILLEMS, P., BORMANN, H., BRONSTERT, A., CROKE, B., FREDE, H., GRÄFF, T., HUBRECHTS, L., JAKEMAN, A., KITE, G., LANINI, J., LEAVESLEY, G., LETTENMAIER, D., LINDSTRÖM, G., SEIBERT, J., SIVAPALAN, M., VINEY, N. (2009): **Assessing the impact of land use change on Hydrology by ensemble modelling (LUCHEM). I: Model intercomparison with current land use**. Advances in Water Resources, 32: 129 – 146.

BRIGGS, D., SMITHSON, P. (1993): **Fundamentals of Physical Geography**. London. Routledge.

BRONSTERT, A., NIEHOFF, D., BÜRGER, G. (2002): **Effects of climate and land-use change on storm runoff generation: present knowledge and modelling capabilities**. Hydrological Processes, 16: 509 – 529. DOI: 10.1002/hyp.326.

BROOKS, K., & ECKMAN, K. (2000): **Global Perspective of Watershed Management**. USDA Forest Service Proceedings RMRS - P - 13: 11 - 20.

BROWN, S., DEE, D. (2000): **Using a GIS-Based solution for watershed analysis and automation: a case study**. Conference on water resource Engineering and water resources planning and management. Minneapolis.

BRUIJNZEEL, S. (2000**): Hydrology of tropical montane cloud forests: a re-evaluation**. In: Gladwell J.S. (ed). Proceedings of the Second International Colloquium on Hydrology of the Humid Tropics. CATHALAC. Panama City, Panama.

BRUIJNZEEL, S., HAMILTON, L. (2000): **Decision Time for Cloud Forests**. IHP Humid Tropics Programme Series N° 13. Paris: IHP – UNESCO, Amsterdam: IUCN-NL and Gland, Switzerland: WWF International.

BRUNS, D., FETCHER, N. (2008): **CITY green Watershed Analysis of Toby Creek: An American Heritage River Tributary**. Journal of Contemporary Water Research & Education, 139: 29 – 37.

BRUZZONE, L., COSSU, R., VERNAZZA, G. (2004): **Detection of Land Cover Transitions by combining multidate classifiers**. Pattern Recognition Letters, 25 (13): 1491 – 1500.

BUGAN, R., JOVANOVIC, N., DE CLERCQ., HELMSCHROT, J., FLÜGEL, W., LEAVESLEY, G. (2009): **A comparative analysis of the PRMS and J2000 hydrological models applied to the Sandspruit Catchment (Western Cape, South Africa)**. Management of Natural Resources, Sustainable Development and Ecological Hazards, II: 391 – 402.

BURGA, C., KLÖTZLI, F., GRABHERR, G. (2004): **Gebirge der Erde. Landschaft, Klima Pflanzenwelt**. Stuttgart. Wissenschaftliche Buchgesellchaft.

BURROUGH, P., Mc. DONNELL, R. (2006): **Principles of Geographical Information System. Spatial Information Systems and Geostatistics**. Oxford. Oxford University Press.

BYRNE, G., CRAPPER, P., MAYO, K. (1980): **Monitoring Land-Cover Change by Principal Component Analysis of Multitemporal LANDSAT Data.** Remote Sensing of Environment, 10: 175 – 184.

CAMARA, G., DRUCK, S., MONTEIRO, A., CAVALHO, M. (Ed.). (2004): **Análise Espacial de Dados Geográficos**. Brasilia. EMBRAPA.

CARABALLO, N. (2011): **Aproximación al estudio de procesos de erosión en cuencas altas tropicales. Caso: Subcuencas de San Miguel y San Rafael, Municipio Boconó**. Escuela de Geografía, Facultad de Ciencias Forestales y Ambientales. Universidad de Los Andes, Mérida – Venezuela. Tesis de Grado.

CARDENAS, A. (1964): **Geografía Física de Venezuela**. Mérida. Talleres Gráficos Universitarios de la Universidad de Los Andes.

CÁRDENAS, P., GARCIA, L., GIL, A. (2002): **Impacto de los Eventos El Nino – Oscilación del Sur en Venezuela**. Caracas. Corporación Andina de Fomento – CAF.

CARRAO, H., GONCALVES, P., CAETANO, M. (2008): **Contribution of multispectral and multitemporal information from MODIS images to land cover classification**. Remote Sensing of Environment, 112: 986 – 997.

CAVIEDES, C. (1998): **Influencia de ENOS sobre las variaciones interanuales de ciertos Ríos en América del Sur**. Bulletin Inst. Fr. Ètudes Andines, 27 (3): 627 – 641.

CAVIEDES, C., WAYLEN, P. (1998): **Respuestas del Clima de América del Sur a las fases de ENSO**. Bulletin Inst Fr. Études Andines, 27 (3): 613 – 626.

CAYUELA, L., BENAYAS, J., ECHEVERRIA, C. (2006): **Clearance and fragmentation of tropical montane forests in the Highlands of Chiapas, Mexico (1975-2000)**. Forest Ecology and Management, 226: 208 – 218.

CHANG, M. (2003): **Forest Hydrology. An Introduction to Water and Forest.** Florida – USA. CRC PRESS. 373 pp.

CHAPAGAIN , A., HOESKSTRA, A. (2008): **The global component of freshwater demand and supply: assessment of virtual water flows between nations as a result of trade in agricultural and industrial products**. Water International, 33 (1): 19 – 32.

CHENOWETH, J. (2008): **A re-assessment of indicators of national water scarcity**. Water International, 33 (1): 5 – 18.

CIHLAR, J. (2000): **Land cover mapping of large areas from satellites: status and research priorities**. International Journal of Remote Sensing, 21 (6&7): 1093 – 1114.

CIMMERY, V. (2007): **User Guide for SAGA (Version 2.0). 366 pp.**

CLARKS LAB (2009): **IDRISI Focus Paper. The Land Change Modeller for Ecological Sustainability**. Worcester, MA. Clark University. [http://www.clarklabs.org/applications/upload/land-change-modeler-idrisi-focus-paper.pdf] [consulted: 20/08/2012].

COMBALICER, E., IM, S. (2012): **Change Anomalies of Hydrologic Responses to Climate Variability and Land-Use Changes in the Mt. Makiling Forest Reserve**. Journal of Environmental Science and Management (Special Issue 1 – 2012): 1 – 13.

CONESE, C., MASSELLI, F. (1991): **Use of Multitemporal Information to improve classification performance of TM scenes in complex terrain.** ISPRS Journal of Photogrammetry and Remote Sensing, 46: 187 – 197.

CORNIELES, M. (1997): **Estudio y Modelización del transporte de agua, de elementos disueltos y de particulas en una Cuenca torrencial. Caso del Río Boconó en los Andes venezolanos**. Resumen de Tesis presentada ante la Universidad de Avinon y de los Países de Vaucluse para obtener el Título de Doctor en Hidrogeología. Caracas. Ministerio del Ambiente y de los Recursos Naturales Renovables. Servicio Autónomo de Geografía y Cartografía Nacional.

CUESTA, J. (1984): **Estimación den Indice de Erosividad de la lluvia (Factor R), en la Cuenca Alta del Río Boconó**. Universidad de Los Andes. Facultad de Ciencias Forestales y Ambientales. Escuela de Ingeniería Forestal. Trabajo Especial d

Grado.

CURRAN, P. (1985): **Principles of Remote Sensing**. New York. Longman Group Limited.

DAVIE, T. (2008): **Fundamentals of Hydrology**. Second Edition. London. Routledge Taylor and Francis Group.

DAWEI, H; JINGSHENG, CH. (2001): **Issues, perspectives and needs for integrated watershed management in China**. Environmental Conservation 28 (4): 368 - 377.

DEFRIES, R., ESHELMAN, K. (2004): **Land-use change and hydrologic processes: a major focus for the future**. Hydrological Processes, 18: 2183 – 2186. DOI: 10.1002/hyp.5584

DE GAETANO, A., EGGLESTON, K., KNAPP, W. (1995): **A Method to Estimate Missing Daily Maximum and Minimun Temperature Observations**. Journal of Applied Meteorology, 34: 371 – 380.

DEHNHARDT, A; PETSCHOW, U (Ed). (2008): **Sustainability in River Basins. A question of Governance**. Münich, OEKOM Verlag.

DELGADO, J., LLORENS, P., NORD, G., CALDER, I., GALLART, F. (2010): **Modelling the hydrological response of a Mediterranean medium-sized headwater basin subject to land cover change: the Cardener River Basin (NE Spain)**. Journal of Hydrology, 383: 125 – 134.

DENG, H., CHEN, G., WANG, Q. (2000): **Watershed Ecology and studies on forested watershed in Changbai Mountain**. Beijing. Ecosystem Service and Sustainable Watershed Management in North China International Conference. (August 23 – 25).

DIOUF, J. (2002): **Majestuosas pero frágiles**. Nuestro Planeta, 13(1): 6-7

DODGE, M., McDERBY, M., TURNER, M. (Edit.)(2008): **Geographic Visualization. Concepts, Tools and Applications**. Chichester, John Wiley & Sons Ltd.

DONMEZ, C., KRAUSE, P., BERBEROGLU, S., HELMSCHROT, J., THOMAS, E. (2009): **Modelling Hydrological Dynamics in Eastern Turkey using J2000g Model**. ESA-ESRIN Earth Observation and Water Cycle Science Symposium. Frascati, Italy. November 18 – 20, 2009.

DOUROJEANNI, A; JOURALEV, A. (1999): **Gestión de Cuencas y Ríos vinculados con Centros Urbanos**. Santiago de Chile. Comisión Económica Para América Latina - CEPAL.

ECHEVERRIA, C, NEWTON, A., NAHUELHUAL, L., COOMES, D., REY-BENAYAS, J.

(2012): **How landscapes change: Integration of spatial patterns and human processes in temperate landscapes of southern Chile**. Applied Geography, 32: 822 – 831.

EISCHEID J., BAKER, C., KARL, Th., DIAZ, H. (1995): **The Quality Control of Long – Term Climatological Data Using Objective Data Analysis**. Journal of Applied Meteorology, 34: 2787 – 2795.

ELFERT, S., BORMAN, H. (2010): **Simulated impact of past and possible future land use changes on the hydrological response of the Northern German lowland "Hunte" catchment**. Journal of Hydrology, 383: 245 – 255.

ERDAS. (2008): **Change Detection**. White Paper. Online Material, available: http://www.erdas.com/Libraries/White_Papers/Change_Detection.sflb.ashx [Accessed 13/09/2011]

ETTER, A., Mc ALPINE, C., WILSON, K., PHINN, S., POSSINGHAM, H. (2006): **Regional patterns of agricultural land use and deforestation in Colombia**. Agriculture, Ecosystems and Environment, 114: 369 – 386.

FARR, T.G., ROSEN, P., CARO, E., CRIPPEN, R., DUREN, R., HENSLEY, S., KOBRICK, M., PALLER, M., RODRIGUEZ, E., ROTH, L., SEAL, D., SHAFFER, S., SHIMADA, J., UMLAND, J., WERNER, M., OSKIN, M., BURBANK, D., ALSDORF, D. (2007): **The Shuttle Radar Topographic Mission**. Rev. Geophys. 45, RGD2004, doi:10. 1029/2005RG000183.

FAUSTINO, J. (1995): **Curso Regional: Gestión integrada de Cuencas hidrográficas para lograr el desarrollo sostenible**. Piura – Perú. (s/e).

FINK, M., KRAUSE, P., KRALISCH, S., BENDE-MICHEL, U., FLÜGEL, W. (2007): **Development and application of the modelling system J2000-S for the EU-Water Framework Directive**. Advances in Geosciences, 11: 123 – 230.

FISCHER, C., KRALISCH,S., KRAUSE,P., FINK, M., FLÜGEL,W. (2009): **Calibration of hydrological model parameters with the JAMS framework**. 18th World IMACS / MODSIM Congress, Cairns, Australia. 13 – 17 July 2009.

FLÜGEL, W. (1995): **Delineating Hydrological Response Units by Geographical Information System Analyses for Regional Hydrological Modelling using PRMS/MMS in the Drainage Basin of the River Broel, Germany**. Hydrological Processes, 9 (3-4): 423 – 436.

FLÜGEL, W. (1996): **Hydrological Response Units (HRUs) as modelling entities for hydrological river basin simulation and their methodological potential for**

modelling complex environmental process systems, results from the Sieg catchment. Die Erde, 127: 42 – 62.

FLÜGEL, W. (1997): **Combining GIS with regional hydrological modelling using hydrological response units (HRUs): An application from Germany**. Mathematics and Computers in Simulation, 43: 297 – 304.

FOTHERINGHAM, St., ROGERSON, P. (2002): **Spatial Analysis and GIS**. London. Taylor & Francis Ltd.

GALATI, S. (2006): **Geographic Information System Demystified**. Boston. ARTECH HOUSE INC.

GARCIA, C., KRAUSE, P., GARCIA, C., RAVELO, A., FLÜGEL, W. (2011): **Water availability for a growing population in the face of climate and land use change**. XIV IWRA World Water Congress. Recife, Brazil.

GÁSPERI, T. (2006): **Condición de sedimentación del Embalse Boconó. Propuesta para su estimación futura.** Mérida. Centro Interamericano de Investigación Ambiental y Territorial (CIDIAT). Tesis MSc.

GAUTAM, A., WEBB, E., SHIVAKOTI, G., ZOEBISCH, M. (2003): **Land Use dynamics and landscape change pattern in a mountain watershed in Nepal**. Agriculture, Ecosystem and Environment, 99: 83 – 96.

GIL, J. (2000): **Estudio Geográfico del Municipio Boconó**. Boconó. Fundación La Salle de Ciencias Naturales.

GONZALEZ, A. (2000): **Informe Nacional sobre la Gestión del Agua en Venezuela**. Caracas. (http://www.cepis.org.pe/bvsarg/e/fulltext/infven)

GONZALEZ, A., VILLAZÓN, M., WILLEMS, P. (2009): **Reference evapotranspiration with limited climatic data in the Bolivian Amazon**. 1st International Congress of Hydroclimatology. Cochabamba – Bolivia, August 2009.

GORDON, G. (1994): **Introduction to watershed analysis: a retrospective**. (http://www.watershed.org/news/fall_94/retro.html).

GOUDIE, A. (1985): **The Nature of the Environment**. Oxford. Basil Blackwell Ltd.

GOWARD, S., MASEK, J., WILLIAMS, D., IRONS, J., THOMPSON, R. (2001): **The LANDSAT 7 Mission. Terrestrial research and applications for the 21st century**. Remote Sensing of the Environment, 78: 3 – 12.

GRAYSON, R., BLÖSCHL, G., WESTERN, A., McMAHON, Th. (2002): **Advances in the use of observed spatial patterns of catchment hydrological response**. Advances in Water Resources, 25: 1313 – 1334.

GREGORY, K., WALLING, D. (1973): **Drainage Basin Form and Process. A**

geomorphological approach. London. Edward Arnold Ltd.

GUERRERO, J. (1984): **Estimación del Indice de Erosividad de la Lluvia (Factor R), en la Cuenca Alta del Río Boconó**. Mérida. Universidad de Los Andes. Escuela de Ingeniería Forestal. Trabajo de Grado.

GUEVARA, E. (2006): **The Influence of El Nino Phenomenon on the Climate of Venezuela**. Hydrology Days.

GUO, H., HU, Q., JIANG, T. (2008): **Annual and seasonal streamflow responses to climate and land-cover changes in the Poyang Lake Basin, China**. Journal of Hydrology, 355: 106 – 122.

GUPTA, H., SOOROSHIAN, S., YAPO, P. (1998): **Toward improved calibration of hydrologic models: Multiple and nonconmensurable measures of information**. Water Resources Research, 34 (4): 751-763.

HADGU, K. (2008): **Temporal and spatial changes in land use patterns and biodiversity in relation to farm productivity at multiple scales in Tigray, Ethiopia**. Wagenigen- The Netherlands. Wagenigen University. PhD Thesis.

HARRIS, R. (1987): **Satellite Remote Sensing: An Introduction**. London. Routledge & Kegem Paul.

HAUCK, F. (1985): **Soil erosion and it's control in developing countries**. In El - Swaify et al., (ed). Soil Erosion and Conservation. Soil Conservation Society of America. Ankeny, Iowa. USA.

HE, M., HOGUE, T. (2011): **Integrating hydrologic modelling and land use projections for evaluation of hydrologic response and regional water supply impacts in semi-arid environments**. Environmental Earth Sciences. DOI 10.1007/s12665-011-1144-3.

HEJAZI, M., MOGLEN, G. (2008): **The effect of climate and land use change on flow duration in the Maryland Piedmont region**. Hydrological Processes, 22: 4710 – 4722. DOI: 10.1002/hyp.7080

HERNANDEZ, E. (1987): **Manejo de Cuencas. Fundamentos**. Universidad de Los Andes. Facultad de Ciencias Forestales y Ambientales. Escuela de Ingeniería Forestal. Mérida.

HIDALGO, J. (2007): **Análisis Geográfico para una propuesta de Area Protegida en el Páramo La Cristalina, Estado Trujillo**. Universidad de Los Andes. Facultad de Ciencias Forestales y Ambientales. Escuela de Geografía. Tesis de Grado.

HOCHSCHILD, V. (2001): **Retrieval of hydrological parameters from remote**

sensing data. In: LEIBUNDGUT, Ch., UHLENBROOK, S., Mc DONNELL, J. (Eds). (2001): Runoff Generation and Implications for River Basin Modelling. Institute für Hydrologie der Universität Freiburg.

HÖLSCHER, D. (2008): **Hydrology of natural and anthropogenically altered tropical montane rainforests with special reference to rainfall interception**. Biodiversity and Ecology Series, 2: 129 – 136.

HOMDEE, T., PONGPUT, K., KANAE, S. (2011): **Impacts of land cover changes on hydrologic responses: a case study of Chi river Basin, Thailand**. Annual Journal of Hydraulic Engineering, JSCE, 155: 31 – 36.

HUISMAN, J., BREUER, L., BORMANN, H., BRONSTERT, A., CROKE, B., FREDE, H., GRÄFF, T., HUBRECHTS, L., JAKEMAN, A., KITE, G., LANINI, J., LEAVESLEY, G., LETTENMAIER, D., LINDSTRÖM, G., SEIBERT, J., SIVAPALAN, M., VINEY, N., WILLEMS, P. (2009): **Assessing the impact of land use change on hydrology by ensemble modelling (LUCHEM). III: Scenario analysis**. Advances in Water Resources, 32: 159 – 170.

HUTJES, R., KABAT, P., RUNNING, S., SHUTTLEWORTH, W., FIELD, C., BASS, B., DA SILVA, M., AVISSAR, R., BECKER, A., CLAUSSEN, M., DOLMAN, A., FEDDES, R., FOSBERG, M., FUKUSHIMA, Y., GASH, J., GUENNI, L., HOFF, H., JARVIS, P., KAYANE, I., KRENKE, A., LIU, CH., MEYBECK,M., NOBRE, C., OYEBANDE,L., PITMAN, A., PIELKE, R., RAUPACH,M., SAUGIER, B., SCHULZE, E., SELLERS, P., TENHUNEN, J., VALENTINI, R., VICTORIA, R., VÖRÖSMARTY, C. (1998): **Biospheric Aspects of the Hydrological Cycle**. Journal of Hydrology (212 – 213): 1 – 21.

IPCC (2007): **Climate Change 2007: Synthesis Report**. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on climate Change. [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

JAMSWIKI (2011): **Hydrological Model J2000g**. Online Material available: http://www.geogr.unijena.de/jamswiki/index.php/Hydrological_Model_J2000g [accessed 23/09/11].

KAHN, U., SHARMA, A., TUTEJA, N. (2009): **A new approach for delineation of hydrologic response units in large catchments**. 18th World IMACS / MODSIM Congress. Cairns, Australia. 13 – 17 July 2009.

KEMP, W., BURNELL, D., EVERSON, D., THOMPSON, A. (1983): **Estimating Missing Daily Maximum and Minimum Temperatures**. Journal of Climate and Applied Meteorology, 22: 1587 – 1593.

KIAGE, L., LIU, K., WALKER, N., LAM, N., HUH, O. (2009): **Recent land-cover/use change associated with land degradation in the Lake Baringo catchment, Kenya, East Africa: evidence from Landsat TM and ETM+**. International Journal of Remote Sensing, 28 (19): 4285 – 4309.

KIGOBE, M., GRIENSVEN, A. (2010): **Assessing hydrological response to change in climate: Statistical downscaling and hydrological modelling within the upper Nile**. International Congress on Environmental Modelling and Software. Modelling for Environment´s Sake, Fifth Biennial Meeting, Ottawa, Canada.

KIM, H., CROKE, B., JAKEMAN, A., CHIEV, F. (2009): **Towards model adequacy for identifying the impacts of climate and land use on catchment hydrology**. 18th World IMACS / MODSIM Congress. Cairns, Australia, 13 – 17 July 2009.

KIM, J., PACHEPSKY, Y. (2010): **Reconstructing missing daily precipitation data using regression trees and artificial neural networks for SWAT streamflow simulation**. Journal of Hydrology, 394: 305 – 314.

KRALISCH, S., KRAUSE, P. (2006): **JAMS – A Framework for Natural Resource Model Development and Application**. Proceedings of the International Environmental Software Society (IEMSS). Vermont, USA. (Reviewed paper).

KRAUSE, P. (2001): **Das hydrologische Modellsystem J2000 – Beschreibung und Anwendung in großen Flussgebieten**. Reihe Umwelt / Environment, Vol 29. Schriften des Forschungszentrums Jülich.

KRAUSE, P. (2002): **Quantifying the impact of land use changes on the water balance of large catchments using the J-2000 model**. Physics and Chemistry of the Earth, 27: 663 – 673.

KRAUSE, P., BOYLE, D., BÄSE, F. (2005): **Comparison of different efficiency criteria for hydrological model assessment**. Advances in Geosciences, 5: 89 – 97.

KRAUSE, P., BÄSE, F., BENDE-MICHL, U., FINK, W., FLÜGEL, W., PFENNING, B. (2006): **Multiscale investigations in a mesoscale catchment – hydrological modelling in the Gera catchment**. Advances in Geosciences, 9: 53 – 61.

KRAUSE, P., HANISCH, S. (2009): **Simulation and analysis of the impact of projected climate change on the spatially distributed waterbalance in Thuringia, Germany**. Advances in Geosciences, 21: 33 – 48.

KRAUSE, P. (2010): **Uncertainty analysis of the hydrological model J2000g**. (In review).

KRISHNA, V., BADARINTH, K. (2004): **Land use changes and trends in Human Appropriation of Above Ground Net Primary Production (HANPP) in India (1961-98)**. The Geographical Journal, 170 (1): 51 – 63.

LAHMER, W., PFÜTZNER, B., BECKER, A. (2001): **Assessment of land use and climate change impacts on the mesoscale**. Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere, 26 (7-8): 565 – 575.

LAKHTAKIA, M., MILLER, D., WHITE, R., SMITH, Ch. (1996): **GIS as an Integrative Tool in Climate and Hydrology Modelling**. In: GOODCHILD, M., STEYAERT, L., PARKS, B., JOHNSTON, C., MAIDMENT, D., CRANE, M., GLENDINNING, S. (Ed). (1996): GIS and Environmental Modelling. Progress and Research Issues. Fort Collins – USA. GIS World Books.

LAMBIN, E., STRAHLER, A. (1994): **Change – Vector Analysis in Multitemporal Space: A Tool to Detect and Categorize Land – Cover Change Processes using High Temporal – Resolution Satellite Data**. Remote Sensing of the Environment, 48: 231 – 244.

LANG, S., BLASCHKE, Th. (2007): **Landschaftanalyse mit GIS**. Stuttgart. Verlag Eugen Ulmer Stuttgart.

LEAVESLEY, G., LICHTY, R., TROUTMAN, B., SAINDON, L. (1983): **Precipitation – Runoff Modelling System: User´s Manual**. Denver – Colorado. Water – Resources Investigations Report 83-4238.

LEAVESLEY, G., MARKSTROM, S., RESTREPO, P., VIGER, R. (2002): **A modular approach to addressing model design, scale, and parameter estimation issues in distributed hydrological modelling**. Hydrological Processes. 16: 173 – 187.

LE COZ, M., DELCLAUX, F., GENTHON, P., FAVREAU, G. (2009): **Assessment of Digital Elevation Model (DEM) aggregation methods for hydrological modelling: lake Chad Basin, Africa**. Computer & Geosciences, 35 (8): 1661 – 1670.

LEGESSE, D., VALLET-COULOMB, Ch., GASSE, F. (2003): **Hydrological response of a catchment to climate and land use changes in tropical Africa: case study South Central Ethiopia**. Journal of Hydrology, 275: 67 – 85.

LEGESSE, D., ABIYE, T., VALLET-COULOMB, C. (2010): **Modelling impacts of climate and land use changes on catchment hydrology: Meki River, Ethiopia**.

Hydrology and Earth System Sciences Discussions, 7: 4535 – 4565. DOI: 10.5194/hessd-7-4535-2010.

LEICA GEOSYSTEMS. (2007): **ERDAS Field Guide**. Volume Two. Norcross – USA.

LI, Z., LIU, W., ZHANG, X., ZHENG, F. (2009): **Impacts of land use change and climate variability on hydrology in an agricultural catchment on the Loess Plateau of China.** Journal of Hydrology, 377: 35 – 42.

LILLESAND, TH & KIEFER, R. (1994): **Remote Sensing and Image Interpretation.** New York . John Wiley & Sons, Inc. 750 pp.

LINTZ, J., SIMONETT, D. (Eds) (1976): **Remote Sensing of Environment**. Reading – Massachusetts, Addison – Wesley Publishing Company.

LIU, Y. (2002): **An automation system: generation of digital map from pictorial map resources**. Pattern Recognition, 32 (9): 1973 – 1987.

LIU, Z., YAO, Z., HUANG, H., WU, S., LIU, G. (2012): **Land use and climate changes and their impacts on runoff in the Yarlung Zangbo river basin, China**. Land Degradation & Development. DOI: 10.1002/ldr.1159.

LONGLEY, P., BATTY, M. (2003): **Advanced Spatial Analysis. The CASA book of GIS**. Redlands – California. ESRI.

LO PRESTI, R., BARCA, E., PASSARELLA, G. (2010): **A methodology for treating Messing data applied to daily rainfall data in the Candelaro River Basin (Italy)**. Environmental Monitoring Assessment, 160: 1 – 22.

LORUP, J., REFSGAAR, J., MAZVIMAV, D. (1998): **Assessing the effect of land use change on catchment runoff by combined use of statistical tests and hydrological modelling: Case studies from Zimbabwe**. Journal of Hydrology, 205: 147 – 163.

LOVELAND, Th., COCHRANE, M., HENEBRY, G. (2008): **LANDSAT still contributing to environmental research**. Trends in Ecology & Evolution, 23 (4): 182 – 183.

LOZADA, B., PRELA, A., SENTEHLAS, P. (2004): **Influencia del Fenómeno ENOS (El Nino y La Nina) en la disponibilidad de Grados-día**. Agronomia Tropical, 54 (3): 309 – 320.

LUDWIG, R., SCHNEIDER, Ph. (2006): **Validation of digital elevation models from SRTM X-SAR for applications in hydrological modelling**. Journal of Photogrametry and Remote Sensing, 60 (5): 339 – 358. LUDWIG, R., SCHNEIDER, Ph. (2006): **Validation of digital elevation models from SRTM X-SAR for applications in hydrological modelling**. Journal of Photogrametry and Remote Sensing, 60 (5): 339 – 358.

MACIAS, M. (2002): **Estimación de la producción de sedimentos en la Cuenca alta del Río Boconó, usando regresiones y curvas de duración de caudal. Municipio Boconó, Estado Trujillo**. Trujillo. Universidad de Los Andes - Núcleo Universitario Rafael Rangel. Departamento de Ingenieria. Tesis.

MANGO, L., MELESSE, A., McCLAIN, M., GANN, D., SETEGN, S. (2011): **Land use and climate change impacts on the hydrology of the upper Mara River Basin, Kenya: results of a modelling study to support better resource management**. Hydrology and Earth System Sciences, 15: 2245 – 2258. DOI: 10.5194/hess-15-2245-2011

MANNION, A. (2002): **Dynamic World. Land Cover and Land-Use Change.** London. Hodder Headline Group. 230 pp.

MAO, D., CHERKAUER, K. (2009): **Impacts of land use change on hydrologic responses in the Great Lakes region**. Journal of Hydrology, 374: 71 – 82.

MARSHALL, E., RANDHIR, T. (2008): **Spatial modelling of land cover change and watershed response using Markovian cellular automata and simulation**. Water Resources Research, 44: W04423.

MASEK, J., HONZAK, M., GOWARD, S., LIU, P., PAK, E. (2001): **LANDSAT – 7 ETM+ as an observatory for land cover Initial radiometric and geometric comparisons with LANDSAT 5 Thematic Mapper**. Remote Sensing of Environment, 78: 118 – 130.

MATTHEß, G., UBELL, K. (1983): **Allgemeine Hydrogeologie Grundwasserhaushalt**. Berlin. Gebrüder Bornträger.

MEDINA, R. (1990): **Conservación de suelos y aguas en el manejo integral de cuencas: un enfoque metodológico**. USA. General Technical Report US Department of Agriculture - Forest Service: 148 - 150.

MEJIA, J. (2000): **Un modelo suelo-paisaje para la evaluación automatizada de tierras con fines conservacionistas en cuencas altas. Caso: microcuenca del río Zarzales, Edo. Mérida**. Centro de Estudios Forestales y Ambientales de Postgrado. Facultad de Ciencias Forestales y Ambientales. Universidad de Los Andes. Mérida. Tesis MSc.

MENA, C. (2008): **Trajectories of Land-use and Land-cover in the Northern Ecuadorian Amazon: Temporal Composition, Spatial Configuration, and Probability of Change**. Photogrametric Engineering & Remote Sensing, 74 (6): 737 – 751.

MENDEZ, G., RIVERO, J., DIAZ, M. (2004): **Actualización del Plan de Ordenamiento**

y Reglamento de Uso de la Zona Protectora de las Cuencas hidrográficas de los Ríos: Guanare, Boconó, Tucupido, La Yuca y Masparro. Barinas, Edo. Barinas. IV Congreso Forestal Venezolano.

MENDOZA, M., LOPEZ, E., GENELETTI, D., PEREZ, D., SALINAS, V. (2011): **Analysing land cover and land use change processes at watershed level: A multitemporal study in the lake Cuitzeo Watershed, Mexico (1975 – 2003)**. Applied Geography, 31 (1): 237 – 250.

MIALHE, F. GUNNELL, Y. and MERING, C. (2008): **Synoptic assessment of water resource variability in reservoirs by remote sensing: General approach and application to the runoff harvesting systems of south India**. Water Resources Research 44: W05411.

MIMIKOU, M., KANELLOPOULOU, S., BALTAS, E. (1999): **Human implication of changes in the hydrological regime due to climate change in Northern Greece**. Global Environmental Change, 9: 139 – 156.

MINISTERIO DE MINAS E HIDROCARBUROS. (1969): **Léxico Estratigráfico de Venezuela**. Segunda Edición. Caracas. Editorial Sucre.

MISHRA, N. (2008): **Macroscale hydrological Modelling and Impact of landcover change on streamflows of the Mahadani River Basin**. Andhra University. MSc Thesis.

MOREIRA, E., AGUIAR, A., COSTA, S., CAMARA, G. (2008): **Spatial relations across scales in land change models**. Rio de Janeiro. X Brazilian Symposium on Geoinformatics, GEOINFO – 2008.

MORRIL, R. (1970): **The Spatial Organization of the society**. Belmont – California. Wadsworth.

MOTZER, Th., MUNZ, N., KÜPPERS, M., SCHMITT, D., ANHUF, D. (2005): **Stomatal conductance, transpiration and sap flow of tropical montane rain forest trees in the southern Ecuadorian Andes**. Tree Physiology, 25: 1283 – 1293.

MUÑOZ, D., CASTILLO, R., SALAS, V. (2006): **Estado de Conservación del Parque Nacional Guaramacal**. Caracas. BIOPARQUES.

MÜSCHEN, B., FLÜGEL, W., HOCHSCHILD, V., STEINNOCHER, K., QUIEL, F., and XIE, X. (2000): **Derivation of Hydrological and Solute Transport Model Parameters by Remote Sensing Methods in the ARSGISIP Project**. Photogrammetrie Fernerkundung Geoinformation, 5: 319 – 329.

MZIRAI, O., TUMBO, S., BWANA, T., HATIBU, N., RWEHUMBIZA, F., GOWING, J. (2005): **Evaluation of Simulators of Synthetic Missing Climate Data Required**

for Agro-hydrological Modelling and Water Management Planning: The case of the PARCHED – THIRST and Marksim Models. East Africa Integrated River Basin Conference, ICE-SUA Morogoro 7 – 9th March 2005, SWMRG.

NAIMAN, R. (Edit). (1992): **Watershed Management. Balancing Sustainability and Environmental Change**. New York. Springer Verlag Inc.

NASA (2012): **Earth Observatory – Glossary**. Available online [http://earthobservatory.nasa.gov/Glossary/index.php?mode=alpha&seg=b&segend=d] [accessed: 01/09/2012].

National Oceanic and Atmospheric Administration (NOAA) (2010): **2009/2010 Cold Season**. PDF Document, available on: http://www.ncdc.noaa.gov/special-reports/2009-2010-cold-season.html#elnino [accessed on: 08.08.2012]

NEJADHASHEMI, A., WARDYNSKI, B., MUNOZ, J. (2011): **Evaluating the impacts of land use changes on hydrologic responses in the agricultural regions of Michigan and Wisconsin**. Hydrology and Earth System Sciences Discussions, 8: 3421 – 3468. DOI: 10.5194/hessd-8-3421-2011.

NIEHOFF, D., FRITSCH, U., BRONSTERT A. (2002): **Land-use impacts on storm-runoff generation: scenarios of land-use change and simulation of hydrological response in a meso –scale catchment in SW-Germany**. Journal of Hydrology, 267: 80 – 93.

NIKOLAKOPOULOS, K., KAMARATAKIS, E., CHRYSOULAKIS, N. (2006): **SRTM vs ASTER elevation Products. Comparison for two regions in Crete, Greece**. International Journal of Remote Sensing, 27 (21): 4819 – 4838.

NSIDC (2012): **Artic Climatology and Meteorology – Glossary**. Available Online. http://nsidc.org/arcticmet/glossary/climate_change.html [accessed: 01/09/2012]

NUÑEZ, Y. (1984): **Estimación del Factor K de Erodabilidad del Suelo en la Cuenca Alta del Río Boconó**. Mérida. Universidad de los Andes. Facultad de Ciencias Forestales y Ambientales. Escuela de Ingeniería Forestal. Tesis de grado.

OCHOA-GAONA, S. (2001): **Traditional land-use systems and patterns of forest fragmentation in the Highlands of Chiapas, Mexico**. Environmental Management, 27 (4): 571-586.

ODIRA, P., NYADAWA, M., OKELLOH, B., JUMA, K., OBIERO, J. (2010): **Impact of Land Use /Cover dynamics on Streamflow: A case of Nzoia River Catchment, Kenia**. Nile Basin Water Science & Engineering Journal, 3 (2): 64 – 78.

OLAYA, V. (2004): **A Gentle Introduction to SAGA GIS. 194 pp.**

OñATE, F., BOSQUE, J. (2010): **Application of GIS and remote sensing techniques**

in generation of land use scenarios for hydrological modeling. Journal of Hydrology, 395: 256 – 263.

OSTOS, O. (1975): **Estudio integral de la Cuenca alta del Río Boconó (Estados Trujillo, Portuguesa y Barinas Venezuela). Estudio preliminar del uso actual de la tierra en el área San Miguel – Boconó – Páramo de Guaramacal**. Guanare. División de Edafología del Ministerio de Obras Públicas.

O`SULLIVAN, D., UNWIN, D. (2003): **Geographic Information Analysis**. New Jersey. John Wiley & Sons, Inc.

PARK, S; VAN DE GIESEN, N. (2004): **Soil-landscape delineation to define spatial sampling domains for hillslope hydrology**. Journal of Hydrology. 295 (1-4): 28 – 46.

PETIT, C., SCUDDER, T., LAMBIN, E. (2001): **Quantifying processes of land-cover change by remote sensing: resettlement and rapid land-cover changes in south-eastern Zambia**. International Journal of Remote Sensing, 22 (17): 3435 – 3456.

PEUQUET, D. (1994): **It´s about Time: A Conceptual Framework for the Representation of Temporal Dynamics in Geographic Information Systems**. Annals of the Association of American Geographers, 84 (3): 441 – 461.

PFANNSCHMIDT, K. (2008): **Optimierungsmethoden zur HRU-basierten N/A – Modellierung für eine operationelle Hochwasservorhersage auf Basis prognostischer Klimadaten des Deutschen Wetterdienstes. Untersuchungen in einem mesoskaligen Einzugsgebiet im Thüringer Wald**. Dissertation. Chemisch-Geowissenschaftlichen Fakultät der Friedrich-Schiller-Universität Jena.

PIKOUNIS,M., VARANOU, E., BALTAS, E., DASSAKLIS, A., MIMIKOU, M. (2003): **Application of the SWAT Model in the Pinios river Basin under different Land-use scenarios**. GLOBAL NEST: The International Journal, 5(2): 71 – 79.

PINEDA, N., BOSQUE, J., GÓMEZ, M., PLATA, W. (2009): **Análisis de cambio del uso del suelo en el Estado de México mediante sistemas de información geográfica y técnicas de regresión multivariantes. Una aproximación a los procesos de deforestación**. Investigaciones Geográficas, Boletín del Instituto de Geografía, UNAM (69): 33 – 52.

PIZARRO, R., ARAYA, S., JORDÁN, C., FARÍAS, C., FLORES, J y BRO, P. (2006): **The effects of changes in vegetative cover on river flows in the Purapel river basin of central Chile**. Journal of Hydrology, 327: 249 – 257.

PLAPADA – **Plant Parameter Database** (http://www.uni-giessen.de/~gh1461/plapada/plapada.html) [Accessed 05/11/2011].

PLATA, R. (2007): **Descripción del crecimiento urbano en la comunidad de Madrid en el período 1987 – 2000 y una aproximación al análisis de factores explicativos**. Tutelado del Doctorado en Cartografía, SIG y Teledetección, Universidad de Alcalá.

PONTIUS, R., SHUSAS, E., McEARCHEN, M. (2004): **Detecting important categorical land changes while accounting for persistence**. Agriculture, Ecosystem and Environment (101): 251 – 268.

POUDEL, K. (2003): **Watershed Management in the Himalayas. A Resource analysis approach**. Delhi. ADROIT Publishers. 361 pp.

PULWARTY, R., BARRY, R., HURST, C., SELLINGER, K., MOGOLLON, L. (1998): **Precipitation in the Venezuelan Andes in the Context of Regional Climate**. Meteorology and Atmospheric Physics. 67: 217 – 237.

QI, S., SUN, G., WANG, Y., McNULTY, S., MYERS, J. (2009): **Streamflow response to climate and landuse changes in a coastal watershed in North Carolina**. Transactions of the ASABE, 52 (3): 739 – 749.

QUEVEDO, M. (1997): **Análisis de la relación Precipitación – Escorrentía en la Cuenca alta del Río Boconó, Estado Trujillo**. Universidad de Los Andes. Núcleo Universitario Rafael Rangel. Departamento de Ingeniería. Trabajo Especial de Grado.

RABUS, B., EINEDER, M., ROTH, A., BAMLER, R. (2003): **The Shuttle radar topographic mission – a new class of digital elevation models acquired by spaceborne radar**. Journal of Photogrametry and Remote Sensing, 57 (4): 241 – 262.

RAMOELO, A. (2007): **An innovative method to map land cover changes at a country level utilising hyper-temporal satellite images. A case of study of Portugal**. International Institute for Geo-information Science and Earth Observation – ITC. Enschede, The Netherlands. Thesis for the degree of Master of Science in Geo-information Science and Earth Observation for Environmental Modelling and Management.

RAO, K., PANT, R. (2001): **Land use dynamics and landscape change pattern in a typical micro watershed in the mid elevation zone of central Himalaya, India**. Agriculture, Ecosystems and Environment, 86: 113 – 123.

RAPER, F., CHEYLAN, J. (Eds) (2001): **Life and Motion of Socio-Economic Units**. London, Taylor & Francis, GISDATA Series 8.

REFSGAARD, J., STORM, B. (1996): **Construction, Calibration and Validation of Hydrological Models**. In: M. B. ABBOTT & J.C. REFSGAARD (Eds): Distributed Hydrological Models. Dordrecht. Kluwer Academic Publishers.

REFSGAARD, J. (1997): **Parameterisation, calibration and validation of distributed hydrological models**. Journal of Hydrology, 198: 69 – 97.

REID, R., KRUSKA, R., MUTHUI, N., TAYE, A., WOTTON, S., WILSON, C., MULATU, W. (2000): **Land-use and land-cover dynamics in response to changes in climatic, biological and socio-political forces: the case of southwestern Ethiopia**. Landscape Ecology, 15: 339 – 355.

REYES, J. (1990): **Marco conceptual y legal del Manejo Integrado de Cuencas Hidrográficas**. USA. General Technical Report – US Department of Agriculture – Forest Service: 148 – 150.

RICHARDS, J., JIA, X. (1999): **Remote Sensing Digital Image Analysis. An Introduction**. Heidelberg, Springer Verlag.

RICHTER, D; SAPLACO, S; NOWAK, P. (1985): **Problemas de gestión de las cuencas en las tierras altas tropicales húmedas.** La Naturaleza y sus Recursos, 21(4): 10-21.

RICHTER, R., KELLENBERGER, T., KAUFMANN, H. (2009): **Comparison of Topographic Correction Methods**. Remote Sensing, 1: 184 – 196.

RINCON, M. (2001): **Modelling the Hydrological Sensitivity to Land Use Change in a Tropical Mountainous Environment**. Department of Geography, King´s College – London. PhD Thesis.

RODRIGUEZ, E., MORRIS, C., BELZ, J., CHAPIN, E., MARTIN, J., DAFFER, W., HENSLEY, S. (2005): **An assessment of the SRTM topographic products**. Technical Report JPL D-31639, Jet Propulsion Laboratory, Pasadena – California. 143 pp.

SABINS, F. (2000): **Remote Sensing. Principles and Interpretation.** New York. W.H. Freeman & Company. 494 pp.

SANDERS, B. (2007): **Evaluation of on-line DEMs for flood inundation modelling**. Advances in Water Resources, 30 (8): 1831 – 1843.

SARMIENTO, L., ATAROFF, M. 2004. **Las Unidades Ecológicas de los Andes de Venezuela**. In: LA MARCA, E., Soriano P. (Ed) (2004): Reptiles de los Andes de Venezuela. BIOGEOS.

SAXTON, K., RAWLS, W. (2006): **Soil Water Characteristics by texture and Organic Matter for Hydrologic Solutions**. Soil Science Society American Journal, 70: 1569 – 1578.

SCHEFFLER, C. (2008): **Development of a Downscaling Scheme for a Coarse Scale Soil Water Estimation Method. Case Study: Great Letaba River in South Africa**. Chemisch – Geowissenschaftlichen Fakultät der Friedrich-Schiller-Universität Jena. Doktorarbeit.

SHILLING, K., CHAN, K., LIU, H., ZHANG, Y. (2010) **Quantifying the effect of land use land cover change on increasing discharge in the Upper Mississipi River**. Journal of Hydrology, 387: 343 – 345.

SCHLEGEL, G. (2008): **Entwicklung eines objektbasierten Ansatzes zur Ableitung von Hydrological Response Units (HRU) und seine vergleichende Bewertung zum pixelbasierten Ableitungskonzept im GIS. Institut für Geographie**. Chemisch – Geowissenschaftlichen Fakultät der Universität Jena. Diplomarbeit.

SCHMULLIUS, CH., FLÜGEL, W., FROTSCHER, K., HOCHSCHILD, V., MÜSCHEN B. (2000): **The Shuttle Radar Topographic Mission (SRTM) and Applications in Europe, Africa and Siberia**. Photogrametrie, Fernerkundung, Geoinformation (5): 361 – 366.

SCHNEIDER, T. (2001): **Analysis of Incomplete Climate Data: Estimation of Mean Values and Covariance Matrices and Imputation of Missing Values**. Journal of Climate, 14: 853 – 871.

SCHUMANN, G., MATGEN, P., CUTLER, M., BLACK, A., HOFFMANN, L., PFISTER, L. (2008): **Comparison of remotely sensed water stages from LIDAR, topographic contours and SRTM**. Journal of Photogrametry and Remote Sensing, 63 (3): 283 – 296.

SHIKLOMANOV, I., RODDA, J. (Edit.) 2003**. World Water Resources at the Beginning of the Twenty-First Century.** Cambridge. Cambridge University Press & UNESCO.

SCHULZ, J., CAYUELA, L., ECHEVERRIA, C, SALAS, J., REY-BENAYAS, J, (2010): **Monitoring land cover change of the dryland forest landscape of Central Chile (1975-2008)**. Applied Geography, 30: 436 – 447.

SCHWARZKOPF, T., RIHA, S., FAHEY, T., DEGLORIA, S. (2011): **Are cloud forest tree structure and environment related in the Venezuelan Andes?**. Austral Ecology. A Journal of ecology in the Southern Hemisphere, 36: 280 – 289.

SIRIWARDENA, L. FINLAYSON, B. and MCMAHON, T. (2006): **The impact of land**

use change on catchment hydrology in large catchments: The Comet River, Central Queensland, Australia. Journal of Hydrology, 326: 199 – 214.

SOAKODAN, M (2007): **Multitemporal Remote Sensing for Mapping and Monitoring Floods. An Approach towards validation of the KAFRIBA Model, Kafue Flats, Zambia**. International Institute of Geo-information Science and Earth Observation. Enschede – The Netherlands. MSc. Thesis.

SPITZ, K., MORENO, J. (1996): **A practical guide to groundwater and solute Transport Modeling**. New York. John Wiley & SONS, INC.

STAUDENRAUSCH, H., HOCHSCHILD, V., HELMSCHROT, J., MÜLLER, A., GERLACH, R., REINEKE, A., and FLÜGEL, W. (2000): **Application of Remote Sensing and GIS for integrated Water Resources Management in Southern Africa**. Photogrammetrie, Fernerkundung und Geoinformation, 5: 331 – 342.

STEUER, J., HUNT, R. (2001): **Use of a Watershed – Modeling Approach to Assess Hydrologic Effects of Urbanization, North Fork Pheasant Branch Basin near Middelton, Wisconsin**. Water-Resources Investigations Report 01-4113. Middleton. U.S. Geological Survey, in cooperation with the City of Middleton and the Wisconsin Department of Natural Resources.

STILL, Ch., FOSTER, P., SCHNEIDER, S. (1999): **Simulating the effects of climate change on tropical montane cloud forests**. NATURE, 398: 608 – 610.

STRAGER, M., FLETCHER, J., STRAGER, J., YUILL, Ch., ELI, R., PETTY, J., LAMONT, S. (2010): **Watershed analysis with GIS: The watershed characterization and modelling system software application**. Computers & Geosciences.(In Press).

STRAHLER, A. (1969): **Physical Geography**. New York. John Wiley & Sons. Inc.

SUI, D., MAGGIO, R. (1999): **Integrating GIS with hydrological modelling: practices, problems, and prospects**. Computers, Environment and Urban Systems, 23 (1): 33 – 51.

TEKLE, K., HEDLUND, L., (2000): **Land Cover Changes between 1958 and 1986 in Kalu District, Southern Wello, Ethiopia**. Mountain Research and Development, 20 (1): 42 – 51.

THANAPAKPAWIN, P., RICHEY, J., THOMAS, D., RODDA, S., CAMPBELL, B., LOGSDON, M. (2006): **Effects of landuse change on the hydrologic regime of the Mae Chaen river basin, NW Thailand**. Journal of Hydrology, 334: 215 – 230.

THAPA, G. (2001): **Changing approaches to mountain watersheds management in mainland south and Southeast Asia**. Environmental Management, 27(5):

667 - 679.

UNITED NATIONS (1992): **United Nations Framework Convention on Climate Change**. Available online: http://unfccc.int/resource/docs/convkp/conveng.pdf [accessed: 01/09/2012]

USGS – NASA. (2010): **LANDSAT: A Global Land – Imaging Project**. Online Material, available: http://pubs.usgs.gov/fs/2010/3026/pdf/FS2010-3026.pdf. [accessed 26/08/2011].

VALERIANO, M., KUPLICH, T., STORINO, M., AMARAL, B., MENDES, J., LIMA, D. (2006): **Modeling small watersheds in Brazilian Amazonia with shuttle radar topographic mission – 90m data**. Computers & Geosciences, 32 (8): 1169 – 1181.

VAN DAM, J. (Edit). (1999): **Impacts of Climate Change and Climate Variability on Hydrological Regimes.** Cambridge. Cambridge University Press / UNESCO. 140 pp.

VAN ZYL, J. (2001): **The Shuttle Radar Topographic Mission (SRTM): A breakthrough in remote sensing of topography**. Acta Astronautica, 48 (5 – 12): 559 – 565.

VELÁZQUEZ, A., MAS, J., DÍAZ, G., MAYORGA, S., ALCÁNTARA, C., CASTRO, R., FERNÁNDEZ, T., BOCCO, G., EZCURRA, E., PALACIO, J. (2002): **Patrones y tasas de cambio de uso del suelo en México**. Gaceta Ecológica (62): 21 – 37.

VERBURG, P., DE KONING, G., KOK, K., VELDKAMP, A., BOUMA, J. (1999): **A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use**. Ecological Modelling, 116: 45 – 61.

VERBURG, P., OVERMARS, K., WITTE, N. (2004): **Accessibility and land-use patterns at the forest fringe in the northeastern part of the Philippines**. The Geographical Journal, 170 (3): 238 – 255.

VINEY, N., BORMANN, H., BREUER, L., BRONSTERT, A., CROKE, B., FREDE, H., GRÄFF, T., HUBRECHTS, L., HUISMAN, J., JAKEMAN, A., KITE, G., LANINI, J., LEAVESLEY, G., LETTENMAIER, D., LINDSTRÖM, G., SEIBERT, J., SIVAPALAN, M., WILLEMS, P. (2009): **Assessing the impact of land use change on hydrology by ensemble modelling (LUCHEM) II: Ensemble combinations and predictions**. Advances in Water Resources, 32: 147 – 158.

VIVAS, L. (1992): **Los Andes Venezolanos**. Caracas. Academia Nacional de la Historia.

WAGNER, W; GAWEL, J; FURUMAI, H; PEREIRA, M; TEIXEIRA, D; RIOS, L;

OHGAKI, SH; ZEHNDER,A; HEMOND, H. (2002): **Sustainable Watershed Management: An international Multi-watershed case study.** AMBIO, 31(1): 2 -12.

WALSH, S., CRAWFORD, T., WELSH, W., CREWS-MEYER, K. (2001): **A multiscale analysis of LULC and NDVI variation in Nang Rong district, northeast Thailand**. Agriculture, Ecosystems and Environment, 85: 47 – 64.

WANG, S., KANG, Sh., ZHANG, L., LI, F. (2008): **Modelling hydrological response to different land-use and climate change scenarios in the Zamu River Basin of Northwest China**. Hydrological Processes, 22: 2502 – 2510. DOI: 10.1002/hyp.6846.

WANG, R., KALIN, L. (2011): **Modelling effects of land use/cover changes under limited data**. ECOHYDROLOGY, 4: 265 – 276. DOI: 10.1002/eco.174

WARD, A & TRIMBLE, St. (2004): **Environmental Hydrology. II Edition.** Boca Ratón – USA. LEWIS PUBLISHERS. 475 pp.

WASKE, B., BRAUN, M. (2009): **Classifier ensembles for land cover mapping using Multitemporal SAR Imagery**. ISPRS Journal of Photogrammetry and Remote Sensing, 64 (5): 450 – 457.

WATSON, N., WALKER, G., MEDD, W. (2007): **Critical perspectives on integrated water management. Editorial.** The Geographical Journal, 173 (4): 297-299.

WERNINGHAUS, R. (2001): **The SRTM Project and beyond: The German Radar Programme**. Shuttle Radar Lab Mission Science Workshop. Florence, Italy, 17 – 19 September 2001.

WESCOAT, J; WHITE, G. (2003): **Water for Life. Water Management and Environmental Policy**. Cambridge. The Cambridge University Press.

WIESLAW, M. (1993): **GIS in land use change analysis: integration of remotely sensed data into GIS**. Applied Geography, 13: 28 – 44.

WILK, J., ANDERSON, L., PLERMKAMON, V. (2001): **Hydrological impacts of forest conversion to agriculture in a large river basin in northeast Thailand**. Hydrological Processes, 15: 2729 – 2748. DOI: 10.1002/hyp.229.

WINTER, T. (2000): **The vulnerability of wetlands to climate change: a hydrological landscape perspective**. Journal of the American Water Resources Association. 36 (2): 305 - 311.

WINTER, T. (2001): **The Concept of Hydrological Landscapes**. Journal of American Water Resources Association. 37 (2): 335 – 349.

WOLF, M., PFENNING, B., KRAUSE, P., FLÜGEL, W. (2009a): **Delineation of topographic process entities using SRTM for hydrological modelling**. 18th World IMACS / MODSIM Congress, Cairns, Aurtralia. 13 – 17 July 2009.

WOLF,M., PFENNING,B., KRAUSE,P., FLÜGEL,W. (2009b): **Landscape dependent derivation of J2000 model parameters for hydrological modelling in ungauged basins**.18th World IMACS / MODSIM Congress, Cairns, Australia. 13 – 17 July 2009.

WULDER, M., FRANKLIN, S., WHITE, J. (2004): **Sensitivity of hyperclustering and labelling land cover classes to Landsat image acquisition date.** International Journal of Remote Sensing, 25 (23): 5337 – 5344.

WULDER, M., WHITE, J., GOWARD, S., MASEK, J., IRONS, J., HEROLD, M., COHEN, W., LOVELAND, Th., WOODCOK, C. (2008): **LANDSAT continuity: Issues and opportunities for land cover monitoring**. Remote Sensing of Environment, 112: 955 – 969.

XIA, Y., FABIAN, P., STOHL, A., WINTERHALTER, M. (1999): **Forest climatology: estimation of missing values for Bavaria, Germany**. Agricultural and Forest Meteorology, 96: 131 – 144.

XIAN, G., HOMER, C., FRY, J. (2009): **Updating the 2001 National Land Cover Database land cover classification to 2006 by using Landsat imagery change detection methods.** Remote Sensing of Environment, 113 (6): 1133 – 1147.

ZEVENBERGER, L., THORNE, C. (1987): **Terrain analysis for quantitative description of zero-order basins**. Erosion and Sedimentation in the Pacific Rim (Proceedings of the Corvallis Symposium. August. 1987. IAHS Publ N° 165.

Appendix

Appendix A

Set of Pictures showing the different LULC Categories identified in the area

(a)

(b)

(c)

(d)

(e)

(f)

(a) Tmc-F (Tropical Montane Cloudy Forest - Guaramacal National Park)

(b) Oc-F (Open-cleared Forest in Río Negro Sector)

(c) Sm-F (Sub-montane Forest in San Rafael Watershed)

(d) Schr (Schrub in Las Lajas – La Cristalina Sector)

(e) Gr-L (Grassland in Vega Arriba Sector)

(f) Sa-P (Sub-Andean Páramo – Páramo Cendé)

(g)

(h)

(i)

(j)

(k)

(l)

(g) S-Shr (Successional Shrubland in San Miguel Watershed)

(h) Gr-An (Grass Anthropogenic in Río Negro Sector)

(i) Cro-L (Cropland in San Miguel Watershed)

(j) Ero-L (Eroded Land in Las Palmitas Sector – Mosquey)

(k) Fl-P (Fluvial Plain in Vega Arriba Sector)

(l) Ur-U (Urban Use – Boconó city)

Appendix B

Results obtained in the Accuracy Assessment of the LULC Classifications for T0, T1 and T2

B-1.- Accuracy Assessment for T0 (1988)

LULC Category	Ur-U	Tmc-F	Oc-F	Sm-F	Schr	Gr-L	Cro-L	Sa-P	Gr-An	S-Shr	Fl-P	Ero-L	Row Total
Ur-U	1	0	0	0	0	0	0	0	0	0	0	0	1
Tmc-F	0	98	6	0	0	0	1	0	1	5	0	0	111
Oc-F	0	0	8	0	0	0	1	0	0	1	0	0	10
Sm-F	0	0	0	25	0	1	0	0	0	0	0	0	26
Schr	0	1	0	0	4	0	0	0	0	0	0	0	5
Gr-L	0	0	0	0	0	15	3	0	0	2	0	0	20
Cro-L	0	0	0	0	0	1	12	0	0	1	0	0	14
Sa-P	0	0	0	0	0	0	0	8	0	0	0	0	8
Gr-An	0	0	0	0	0	0	0	0	11	0	0	0	11
S-Shr	0	3	2	0	0	0	1	0	1	36	0	0	43
Fl-P	0	0	0	0	0	0	1	0	0	0	3	0	4
Ero-L	0	0	0	0	0	0	0	0	0	0	0	0	0
Column Total	1	102	16	25	4	17	19	8	13	45	3	0	253

LULC Category	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	Users Accuracy	Kappa
Ur-U	1	1	1	100.00%	100.00%	1.000
Tmc-F	102	111	98	96.08%	88.29%	0.8053
Oc-F	16	10	8	50.00%	80.00%	0.7867
Sm-F	25	26	25	100.00%	96.15%	0.6690
Schr	4	5	4	100.00%	80.00%	0.7968
Gr-L	17	20	15	88.24%	75.00%	0.7322
Cro-L	19	14	12	63.16%	85.71%	0.6940
Sa-P	8	8	8	100.00%	100.00%	1.000
Gr-An	13	11	11	84.62%	100.00%	1.000
S-Shr	45	43	36	80.00%	83.72%	0.8025
Fl-P	3	4	3	100.00%	75.00%	0.7470
Ero-L	0	0	0	---	---	0.0000
Totals	253	253	221	87.35 %		0.7883

B-2.- Accuracy Assessment for T1 (1997)

LULC Category	Tmc-F	Oc-F	Sm-F	Schr	Gr-L	Sa-P	Gr-An	Cro-L	Ero-L	Ur-U	Fl-P	S-Shr	Row Total
Tmc-F	82	1	0	0	0	0	1	0	0	0	0	6	90
Oc-F	0	8	0	0	0	0	1	1	0	0	0	5	15
Sm-F	0	0	25	0	1	0	0	0	0	0	0	5	31
Schr	0	0	0	14	0	0	0	0	0	0	0	0	14
Gr-L	0	0	0	0	17	0	1	1	0	0	0	2	21
Sa-P	0	0	0	0	0	14	0	0	0	0	0	0	14
Gr-An	0	0	0	0	0	0	8	1	0	0	0	5	14
Cro-L	0	1	0	0	1	0	0	12	0	0	0	4	18
Ero-L	0	0	0	0	0	0	0	0	3	0	0	0	3
Ur-U	0	0	0	0	0	0	0	0	0	12	0	0	12
Fl-P	0	0	0	0	0	0	0	1	0	0	10	0	11
S-Shr	2	2	0	0	1	0	5	3	0	0	0	37	50
Column Total	84	12	25	14	20	14	16	19	3	12	10	64	293

LULC Category	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	Users Accuracy	Kappa
Tmc-F	84	90	82	97.62%	91.11%	0.8754
Oc-F	12	15	8	66.67%	53.33%	0.5134
Sm-F	25	31	25	100.00%	80.65%	0.7884
Schr	14	14	14	100.00%	100.00%	10.000
Gr-L	20	21	17	85.00%	80.95%	0.7956
Sa-P	14	14	14	100.00%	100.00%	10.000
Gr-An	16	14	8	50.00%	57.14%	0.5467
Cro-L	19	18	12	63.16%	66.67%	0.6436
Ero-L	3	3	3	100.00%	100.00%	10.000
Ur-U	12	12	12	100.00%	100.00%	10.000
Fl-P	10	11	10	100.00%	90.91%	0.9059
S-Shr	64	50	37	57.81%	74.00%	0.6673
Totals	293	293	242	82.59%		0.7939

B-3.- Accuracy Assessment for T2 (2008)

LULC Category	Tmc-F	Oc-F	Sm-F	Schr	Gr-L	Sa-P	Gr-An	Cro-L	Ero-L	Ur-U	Fl-P	S-Shr	Row Total
Tmc-F	29	1	0	0	0	0	0	0	0	0	0	0	30
Oc-F	2	28	0	0	0	0	0	0	0	0	0	0	30
Sm-F	0	0	28	0	1	0	1	0	0	0	0	0	30
Schr	1	0	0	9	0	0	0	0	0	0	0	0	10
Gr-L	0	0	0	0	24	0	0	5	0	0	0	1	30
Sa-P	0	0	0	0	0	10	0	0	0	0	0	0	10
Gr-An	0	0	0	0	0	0	24	4	0	0	0	2	30
Cro-L	0	0	1	0	0	0	2	26	0	0	1	0	30
Ero-L	0	0	0	0	0	0	0	0	5	0	0	0	5
Ur-U	0	0	0	0	0	0	0	0	0	10	0	0	10
Fl-P	0	0	0	0	0	0	0	0	0	0	5	0	5
S-Shr	0	0	1	0	0	0	4	1	0	0	0	24	30
Column Total	32	29	30	9	25	10	31	36	5	10	6	27	250

LULC Category	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	Users Accuracy	Kappa
Tmc-F	32	30	29	90.63%	96.67%	0.9618
Oc-F	29	30	28	96.55%	93.33%	0.9246
Sm-F	30	30	28	93.33%	93.33%	0.9242
Schr	9	10	9	100.00%	90.00%	0.8963
Gr-L	25	30	24	96.00%	80.00%	0.7778
Sa-P	10	10	10	100.00%	100.00%	10.000
Gr-An	31	30	24	77.42%	80.00%	0.7717
Cro-L	36	30	26	72.22%	86.67%	0.8442
Ero-L	5	5	5	100.00%	100.00%	10.000
Ur-U	10	10	10	100.00%	100.00%	10.000
Fl-P	6	5	5	83.33%	100.00%	10.000
S-Shr	27	30	24	88.89%	80.00%	0.7758
Totals	**250**	**250**	**222**	**88.80%**		**0.8747**

Appendix C

Cross-Tabulated Matrixes for Losses and Gains for the two Cross-periods

C-1.- Resume Cross-tabulated Matrix for losses (T0-T1)

	cat 1	cat 2	cat 3	cat 4	cat 5	cat 6	cat 7	cat 8	cat 9	cat 10	cat 11	cat 12	Total	Loss
cat 1	22883,67	441,27	0,99	58,32	17,37	6,93	49,59	73,35	0	1,17	0	1041,12	24573,78	1690,11
Tmc-f	22883,67	92,6229	349,6464	67,40439	182,6117	62,78841	66,35278	130,9158	1,531918	40,96237	22,01816	673,2552		
Ov - Ev	0	348,6471	-348,656	-9,08439	-165,242	-55,8584	-16,7628	-57,5658	-1,53192	-39,7924	-22,0182	367,8648		
Ov–Ev / Ev	0	3,764157	-0,99717	-0,13477	-0,90488	-0,88963	-0,25263	-0,43972	-1	-0,97144	-1	0,546397		
cat 2	30,51	450,45	130,32	0,09	149,31	0,18	168,93	176,76	0,09	3,06	0,36	1863,45	2973,51	2523,06
Oc-f	1146,276	450,45	301,3404	58,09203	157,3827	54,11378	57,18571	112,8289	1,320273	35,30315	18,97621	580,2406		
Ov - Ev	-1115,77	0	-171,02	-58,002	-8,0727	-53,9338	111,7443	63,93109	-1,23027	-32,2432	-18,6162	1283,209		
Ov–Ev / Ev	-0,97338	0	-0,56753	-0,99845	-0,05129	-0,99667	1,95406	0,56662	-0,93183	-0,91332	-0,98103	2,211513		
cat 3	0,09	124,29	4630,86	0,36	132,03	0	124,65	339,48	12,33	61,92	83,7	2013,39	7523,1	2892,24
Sm-f	1440,469	100,314	4630,86	73,00141	197,7751	68,00214	71,86247	141,7866	1,659123	44,36374	23,84647	729,1599		
Ov - Ev	-1440,38	23,97603	0	-72,6414	-65,7451	-68,0021	52,78753	197,6934	10,67088	17,55626	59,85353	1284,23		
Ov–Ev / Ev	-0,99994	0,23901	0	-0,99507	-0,33242	-1	0,734563	1,394303	6,431637	0,395734	2,509954	1,761246		
cat 4	0	0	0	1141,02	0	0	0	0	0	0	0	1,35	1142,37	1,35
Sch	0,608093	0,042348	0,15986	1141,02	0,083491	0,028707	0,030337	0,059855	0,0007	0,018728	0,010067	0,307815		
Ov - Ev	-0,60809	-0,04235	-0,15986	0	-0,08349	-0,02871	-0,03034	-0,05986	-0,0007	-0,01873	-0,01007	1,042185		
Ov–Ev / Ev	-1	-1	-1	0	-1	-1	-1	-1	-1	-1	-1	3,385757		
cat 5	28,89	34,29	136,08	0	1685,61	0	174,33	316,53	0	31,32	31,32	1224,45	3662,82	1977,21
Grs	926,7738	64,54033	243,6362	46,96789	1685,61	43,75144	46,23512	91,22311	1,067452	28,54289	15,34242	469,1293		
Ov - Ev	-897,884	-30,2503	-107,556	-46,9679	0	-43,7514	128,0949	225,3069	-1,06745	2,777108	15,97758	755,3207		
Ov–Ev / Ev	-0,96883	-0,4687	-0,44146	-1	0	-1	2,770511	2,469844	-1	0,097296	1,041399	1,610048		
cat6	0	0	0	0	0	1110,42	0	0	0	0	0	3,78	1114,2	3,78
Sa-p	1,700004	0,118388	0,446908	0,086154	0,233409	1110,42	0,08481	0,167333	0,001958	0,052357	0,028143	0,860536		
Ov - Ev	-1,7	-0,11839	-0,44691	-0,08615	-0,23341	0	-0,08481	-0,16733	-0,00196	-0,05236	-0,02814	2,919464		
Ov–Ev / Ev	-1	-1	-1	-1	-1	0	-1	-1	-1	-1	-1	3,392614		
cat 7	28,44	51,39	54,36	0	230,4	0	95,67	100,89	0	9,72	2,79	706,68	1280,34	1184,67
Gr-an	533,4323	37,14811	140,2321	27,03377	73,23978	25,18245	95,67	52,50618	0,614404	16,42871	8,830788	270,0214		
Ov - Ev	-504,992	14,24189	-85,8721	-27,0338	157,1602	-25,1824	0	48,38382	-0,6144	-6,70871	-6,04079	436,6586		
Ov–Ev / Ev	-0,94668	0,383381	-0,61236	-1	2,145831	-1	0	0,921488	-1	-0,40835	-0,68406	1,617126		
cat 8	58,77	33,75	283,32	0	221,85	0	70,11	541,26	0	98,1	49,05	846,63	2202,84	1661,58
Cr-a	764,8938	53,26705	201,0802	38,76399	105,0192	36,10936	38,15921	541,26	0,881	23,55729	12,66255	387,1863		
Ov - Ev	-706,124	-19,517	82,23981	-38,764	116,8308	-36,1094	31,95079	0	-0,881	74,54271	36,38745	459,4437		
Ov–Ev / Ev	-0,92317	-0,3664	0,40899	-1	1,11247	-1	0,837302	0	-1	3,164316	2,873626	1,186622		
cat 9	7,74	0,36	0,99	0	0	0	0,09	1,35	13,68	0	1,35	3,06	28,62	14,94
E-so	6,582714	0,458419	1,730506	0,333605	0,903801	0,310759	0,3284	0,647942	13,68	0,202735	0,108975	3,332144		
Ov - Ev	1,157286	-0,09842	-0,74051	-0,3336	-0,9038	-0,31076	-0,2384	0,702058	0	-0,20274	1,241025	-0,27214		
Ov–Ev / Ev	0,175807	-0,21469	-0,42791	-1	-1	-1	-0,72594	1,08352	0	-1	11,38821	-0,08167		
cat 10	0	0	0	0	0	0	0	0	0	433,26	0,72	0	433,98	0,72
Ur-u	0,321438	0,022385	0,084502	0,01629	0,044133	0,015175	0,016036	0,031639	0,00037	433,26	0,005321	0,162711		
Ov - Ev	-0,32144	-0,02238	-0,0845	-0,01629	-0,04413	-0,01517	-0,01604	-0,03164	-0,00037	0	0,714679	-0,16271		
Ov–Ev / Ev	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	134,3054	-1		
cat 11	0	0	2,52	0	2,7	0	0,45	14,31	0	6,57	196,92	11,43	234,9	37,98
Fp	16,84872	1,173341	4,429298	0,853875	2,313314	0,7954	0,840553	1,658433	0,019406	0,518909	196,92	8,528755		
Ov - Ev	-16,8487	-1,17334	-1,9093	-0,85387	0,386686	-0,7954	-0,39055	12,65157	-0,01941	6,051091	0	2,901245		
Ov–Ev / Ev	-1	-1	-0,43106	-1	0,167157	-1	-0,46464	7,628627	-1	11,66118	0	0,340172		
cat 12	638,01	513	984,69	0,09	811,44	0,18	497,34	766,53	1,17	84,06	25,74	4269,42	8591,67	4322,25
S-sh	2449,511	170,5834	643,943	124,1385	336,3156	115,6373	122,2018	241,1073	2,82133	75,44032	40,5508	4269,42		
Ov - Ev	-1811,5	342,4166	340,747	-124,049	475,1244	-115,457	375,1382	525,4227	-1,65133	8,619678	-14,8108	0		
Ov–Ev / Ev	-0,73954	2,007327	0,529157	-0,99928	1,412734	-0,99844	3,069826	2,179206	-0,5853	0,114258	-0,36524	0		
Total	23676,12	1648,8	6224,13	1199,88	3250,71	1117,71	1181,16	2330,46	27,27	729,18	391,95	11984,76	53762,13	
Gains	792,45	1198,35	1593,27	58,86	1565,1	7,29	1085,49	1789,2	13,59	295,92	195,03	7715,34		

C-2.- Resume Cross-tabulated Matrix for Gains (T0-T1)

	Tmc-f	Oc-f	Sm-f	Sch	Grs	Sa-p	Gr-an	Cr-a	E-so	Ur-u	Fp	S-sh	1997	
1988	cat 1	cat 2	cat 3	cat 4	cat 5	cat 6	cat 7	cat 8	cat 9	cat 10	cat 11	cat 12	Total	Loss
cat 1	22883,67	441,27	0,99	58,32	17,37	6,93	49,59	73,35	0	1,17	0	1041,12	24573,78	1690,11
Tmc-f	22883,67	579,8147	846,745	27,48801	767,6837	3,402657	508,2638	852,7543	6,215073	136,3609	89,53619	4197,324		
Ov - Ev	0	-138,545	-845,755	30,83199	-750,314	3,527343	-458,674	-779,404	-6,21507	-135,191	-89,5362	-3156,2		
Ov–Ev / Ev	0	-0,23895	-0,99883	1,121652	-0,97737	1,036644	-0,90243	-0,91398	-1	-0,99142	-1	-0,75196		
cat 2	30,51	450,45	130,32	0,09	149,31	0,18	168,93	176,76	0,09	3,06	0,36	1863,45	2973,51	2523,06
Oc-f	80,7294	450,45	102,459	3,326142	92,89231	0,411733	61,50163	103,1861	0,752045	16,50012	10,83418	507,8903		
Ov - Ev	-50,2194	0	27,86101	-3,23614	56,41769	-0,23173	107,4284	73,57386	-0,66204	-13,4401	-10,4742	1355,56		
Ov–Ev / Ev	-0,62207	0	0,271924	-0,97294	0,607345	-0,56282	1,746757	0,713021	-0,88033	-0,81455	-0,96677	2,669001		
cat 3	0,09	124,29	4630,86	0,36	132,03	0	124,65	339,48	12,33	61,92	83,7	2013,39	7523,1	2892,24
Sm-f	204,2486	177,5064	4630,86	8,415273	235,0213	1,041701	155,6016	261,0651	1,902703	41,74598	27,41091	1284,983		
Ov - Ev	-204,159	-53,2164	0	-8,05527	-102,991	-1,0417	-30,9516	78,41491	10,4273	20,17402	56,28909	728,407		
Ov–Ev / Ev	-0,99956	-0,2998	0	-0,95722	-0,43822	-1	-0,19892	0,300365	5,480254	0,483257	2,053528	0,566861		
cat 4	0	0	0	1141,02	0	0	0	0	0	0	0	1,35	1142,37	1,35
Sch	31,01481	26,95405	39,36293	1141,02	35,68758	0,158181	23,62784	39,64229	0,288922	6,339056	4,162301	195,1225		
Ov - Ev	-31,0148	-26,9541	-39,3629	0	-35,6876	-0,15818	-23,6278	-39,6423	-0,28892	-6,33906	-4,1623	-193,772		
Ov–Ev / Ev	-1	-1	-1	0	-1	-1	-1	-1	-1	-1	-1	-0,99308		
cat 5	28,89	34,29	136,08	0	1685,61	0	174,33	316,53	0	31,32	31,32	1224,45	3662,82	1977,21
Grs	99,44384	86,4237	126,2107	4,097198	1685,61	0,50718	75,75874	127,1064	0,926381	20,32513	13,34573	625,6279		
Ov - Ev	-70,5538	-52,1337	9,869281	-4,0972	0	-0,50718	98,57126	189,4236	-0,92638	10,99487	17,97427	598,8221		
Ov–Ev / Ev	-0,70948	-0,60323	0,078197	-1	0	-1	1,301121	1,490275	-1	0,540949	1,346819	0,957154		
cat6	0	0	0	0	0	1110,42	0	0	0	0	0	3,78	1114,2	3,78
Sa-p	30,25001	26,28938	38,39227	1,246334	34,80755	1110,42	23,04519	38,66474	0,281798	6,18274	4,059661	190,3109		
Ov - Ev	-30,25	-26,2894	-38,3923	-1,24633	-34,8076	0	-23,0452	-38,6647	-0,2818	-6,18274	-4,05966	-186,531		
Ov–Ev / Ev	-1	-1	-1	-1	-1	0	-1	-1	-1	-1	-1	-0,98014		
cat 7	28,44	51,39	54,36	0	230,4	0	95,67	100,89	0	9,72	2,79	706,68	1280,34	1184,67
Gr-an	34,76063	30,20943	44,117	1,432177	39,99776	0,177285	95,67	44,4301	0,323817	7,104657	4,665003	218,6885		
Ov - Ev	-6,32063	21,18057	10,243	-1,43218	190,4022	-0,17728	0	56,4599	-0,32382	2,615343	-1,875	487,9915		
Ov–Ev / Ev	-0,18183	0,701124	0,232178	-1	4,760323	-1	0	1,270758	-1	0,368117	-0,40193	2,231446		
cat 8	58,77	33,75	283,32	0	221,85	0	70,11	541,26	0	98,1	49,05	846,63	2202,84	1661,58
Cr-a	59,80607	51,97568	75,90382	2,464077	68,81661	0,305021	45,56172	541,26	0,557131	12,22365	8,026193	376,2561		
Ov - Ev	-1,03607	-18,2257	207,4162	-2,46408	153,0334	-0,30502	24,54828	0	-0,55713	85,87635	41,02381	470,3739		
Ov–Ev / Ev	-0,01732	-0,35066	2,732619	-1	2,223785	-1	0,538792	0	-1	7,025429	5,111241	1,250143		
cat 9	7,74	0,36	0,99	0	0	0	0,09	1,35	13,68	0	1,35	3,06	28,62	14,94
E-so	0,77702	0,675285	0,986167	0,032014	0,894087	0,003963	0,591952	0,993165	13,68	0,158814	0,104279	4,888439		
Ov - Ev	6,96298	-0,31528	0,003833	-0,03201	-0,89409	-0,00396	-0,50195	0,356835	0	-0,15881	1,245721	-1,82844		
Ov–Ev / Ev	8,961139	-0,46689	0,003887	-1	-1	-1	-0,84796	0,35929	0	-1	11,94606	-0,37403		
cat 10	0	0	0	0	0	0	0	0	0	433,26	0,72	0	433,98	0,72
Ur-u	11,78235	10,23969	14,95376	0,485446	13,55751	0,060092	8,976084	15,05989	0,10976	433,26	1,581235	74,12595		
Ov - Ev	-11,7824	-10,2397	-14,9538	-0,48545	-13,5575	-0,06009	-8,97608	-15,0599	-0,10976	0	-0,86123	-74,1259		
Ov–Ev / Ev	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	-0,54466	-1		
cat 11	0	0	2,52	0	2,7	0	0,45	14,31	0	6,57	196,92	11,43	234,9	37,98
Fp	6,377425	5,542431	8,094009	0,262757	7,338265	0,032526	4,858478	8,151452	0,05941	1,303469	196,92	40,12209		
Ov - Ev	-6,37742	-5,54243	-5,57401	-0,26276	-4,63826	-0,03253	-4,40848	6,158548	-0,05941	5,266531	0	-28,6921		
Ov–Ev / Ev	-1	-1	-0,68866	-1	-0,63207	-1	-0,90738	0,755515	-1	4,040395	0	-0,71512		
cat 12	638,01	513	984,69	0,09	811,44	0,18	497,34	766,53	1,17	84,06	25,74	4269,42	8591,67	4322,25
S-sh	233,2598	202,7192	296,0454	9,610566	268,4034	1,189663	177,703	298,1464	2,172961	47,67551	31,30432	4269,42		
Ov - Ev	404,7502	310,2808	688,6446	-9,52057	543,0366	-1,00966	319,637	468,3836	-1,00296	36,38449	-5,56432	0		
Ov–Ev / Ev	1,73519	1,530594	2,326146	-0,99064	2,023211	-0,8487	1,798715	1,570985	-0,46156	0,763169	-0,17775	0		
Total	23676,12	1648,8	6224,13	1199,88	3250,71	1117,71	1181,16	2330,46	27,27	729,18	391,95	11984,76	53762,13	
Gains	792,45	1198,35	1593,27	58,86	1565,1	7,29	1085,49	1789,2	13,59	295,92	195,03	7715,34		

C-3.- Resume Cross-tabulated Matrix for losses (T1-T2)

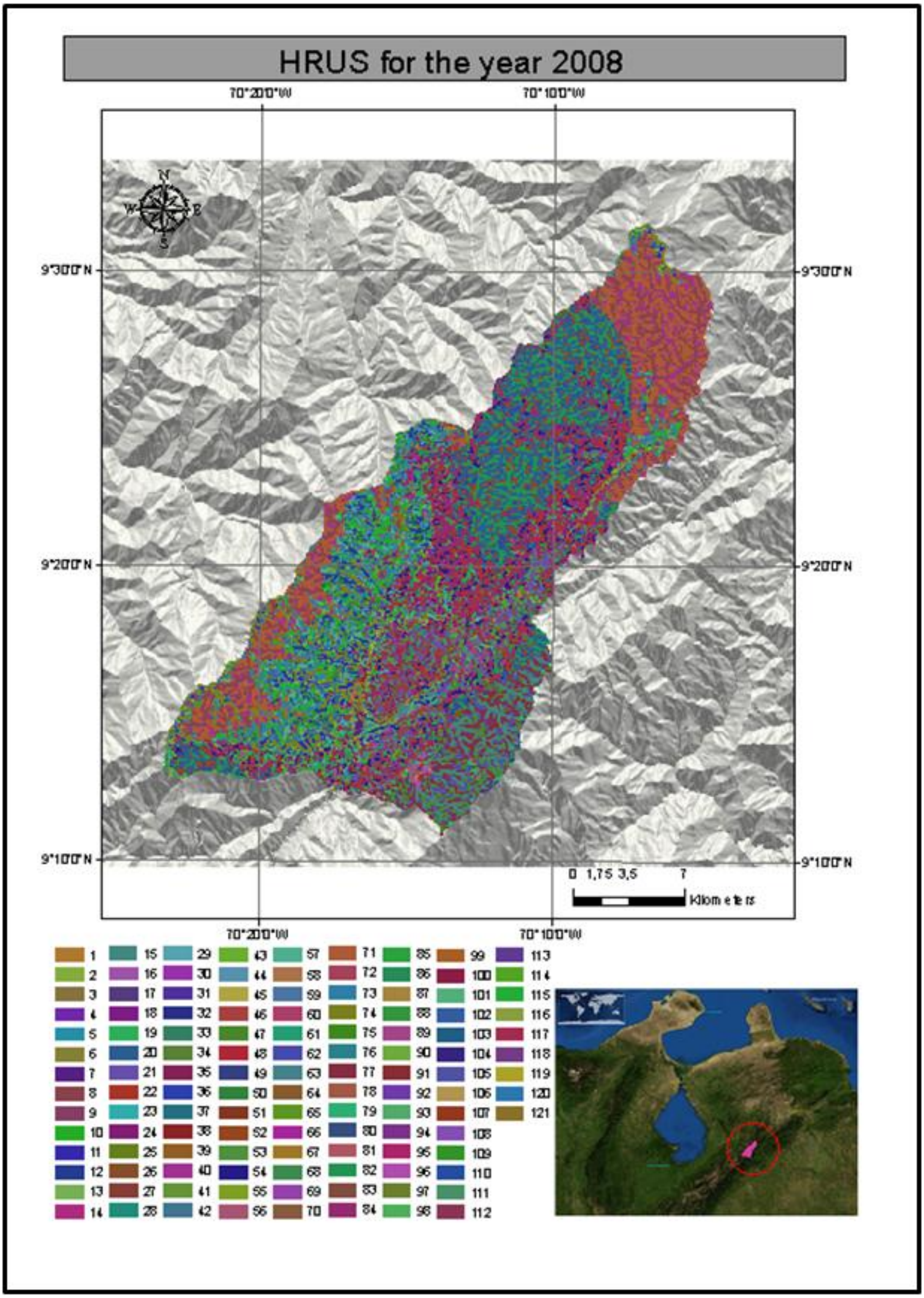
	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Cat 6	Cat 7	Cat 8	Cat 9	Cat 10	Cat 11	Cat 12	Total	Loss
Cat 1	21652,38	470,07	0	14,67	35,73	3,33	101,25	54,72	5,31	3,51	0	1335,15	23676,12	2023,74
	21652,38	98,89369	277,2791	79,55583	216,1455	72,84356	183,5056	185,7974	2,583436	56,06581	19,03462	832,0355		
Ov - Ev	0	371,1763	-277,279	-64,8858	-180,416	-69,5136	-82,2556	-131,077	2,726564	-52,5558	-19,0346	503,1145		
Ov–Ev / Ev	0	3,753286	-1	-0,8156	-0,83469	-0,95429	-0,44825	-0,70549	1,055402	-0,93739	-1	0,604679		
Cat 2	31,41	535,59	6,39	0	31,5	0	77,13	66,78	0	0	0	900	1648,8	1113,21
	480,1388	535,59	91,19553	26,16547	71,08905	23,95784	60,35396	61,10774	0,849678	18,43973	6,260379	273,6518		
Ov - Ev	-448,729	0	-84,8055	-26,1655	-39,5891	-23,9578	16,77604	5,672261	-0,84968	-18,4397	-6,26038	626,3482		
Ov–Ev / Ev	-0,93458	0	-0,92993	-1	-0,55689	-1	0,277961	0,092824	-1	-1	-1	2,288851		
Cat 3	0	80,82	3432,24	0	149,31	0	117,09	269,37	3,15	43,38	6,39	2122,38	6224,13	2791,89
	1271,165	86,11133	3432,24	69,27295	188,2079	63,42827	159,7868	161,7825	2,249518	48,8191	16,57432	724,4919		
Ov - Ev	-1271,17	-5,29133	0	-69,273	-38,8979	-63,4283	-42,6968	107,5875	0,900482	-5,4391	-10,1843	1397,888		
Ov–Ev / Ev	-1	-0,06145	0	-1	-0,20668	-1	-0,26721	0,665014	0,4003	-0,11141	-0,61446	1,929474		
Cat 4	0	0	0	1198,53	0	0	0,18	0	0,72	0	0	0,45	1199,88	1,35
	0,578961	0,03922	0,109965	1198,53	0,085721	0,028889	0,072776	0,073685	0,001025	0,022235	0,007549	0,329975		
Ov - Ev	-0,57896	-0,03922	-0,10997	0	-0,08572	-0,02889	0,107224	-0,07368	0,718975	-0,02223	-0,00755	0,120025		
Ov–Ev / Ev	-1	-1	-1	0	-1	-1	1,473342	-1	701,7419	-1	-1	0,36374		
Cat 5	22,05	8,37	48,87	0	1603,98	0	502,83	361,17	0	3,69	3,6	696,15	3250,71	1646,73
	735,7386	49,84044	139,7431	40,09454	1603,98	36,71169	92,48313	93,63818	1,302	28,25604	9,593064	419,3292		
Ov - Ev	-713,689	-41,4704	-90,8731	-40,0945	0	-36,7117	410,3469	267,5318	-1,302	-24,566	-5,99306	276,8208		
Ov–Ev / Ev	-0,97003	-0,83206	-0,65029	-1	0	-1	4,436991	2,85708	-1	-0,86941	-0,62473	0,660152		
Cat 6	0	0	0	0,36	0	1117,08	0,18	0	0	0	0	0,09	1117,71	0,63
	0,26965	0,018267	0,051216	0,014695	0,039924	1117,08	0,033895	0,034319	0,000477	0,010356	0,003516	0,153685		
Ov - Ev	-0,26965	-0,01827	-0,05122	0,345305	-0,03992	0	0,146105	-0,03432	-0,00048	-0,01036	-0,00352	-0,06369		
Ov–Ev / Ev	-1	-1	-1	23,49854	-1	0	4,31047	-1	-1	-1	-1	-0,41439		
Cat 7	40,5	14,76	23,85	0,27	124,29	0	243,18	172,44	0,09	3,78	0,81	557,19	1181,16	937,98
	414,933	28,1084	78,81061	22,61203	61,43471	20,70421	243,18	52,80893	0,734286	15,9355	5,41018	236,4882		
Ov - Ev	-374,433	-13,3484	-54,9606	-22,342	62,85529	-20,7042	0	119,6311	-0,64429	-12,1555	-4,60018	320,7018		
Ov–Ev / Ev	-0,90239	-0,47489	-0,69738	-0,98806	1,023123	-1	0	2,265357	-0,87743	-0,76279	-0,85028	1,356101		
Cat 8	78,03	28,62	161,73	0,36	266,58	0	213,39	867,15	1,89	46,08	10,08	656,55	2330,46	1463,31
	647,7723	43,88142	123,0351	35,30076	95,90877	32,32237	81,42568	867,15	1,14633	24,8777	8,446099	369,1934		
Ov - Ev	-569,742	-15,2614	38,69486	-34,9408	170,6712	-32,3224	131,9643	0	0,74367	21,2023	1,633901	287,3566		
Ov–Ev / Ev	-0,87954	-0,34779	0,314503	-0,9898	1,779516	-1	1,620672	0	0,648739	0,852262	0,19345	0,778336		
Cat 9	0,09	0	1,89	0	0	0	0	0,9	22,41	0	0,45	1,53	27,27	4,86
	2,038172	0,13807	0,387122	0,111071	0,301771	0,1017	0,2562	0,2594	22,41	0,078276	0,026575	1,161642		
Ov - Ev	-1,94817	-0,13807	1,502878	-0,11107	-0,30177	-0,1017	-0,2562	0,6406	0	-0,07828	0,423425	0,368358		
Ov–Ev / Ev	-0,95584	-1	3,882184	-1	-1	-1	-1	2,469543	0	-1	15,93315	0,317101		
Cat 10	0	0	0	0	0	0	0	0	0	727,02	2,16	0	729,18	2,16
	0,919989	0,062322	0,174739	0,050135	0,136213	0,045905	0,115644	0,117088	0,001628	727,02	0,011995	0,524341		
Ov - Ev	-0,91999	-0,06232	-0,17474	-0,05014	-0,13621	-0,04591	-0,11564	-0,11709	-0,00163	0	2,148005	-0,52434		
Ov–Ev / Ev	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	179,0683	-1		
Cat 11	0	0	41,31	0	11,16	0	5,4	36,9	0,18	5,85	257,22	33,93	391,95	134,73
	56,77096	3,845781	10,78284	3,093769	8,405473	2,832742	7,13617	7,225296	0,100465	2,180289	257,22	32,35622		
Ov - Ev	-56,771	-3,84578	30,52716	-3,09377	2,754527	-2,83274	-1,73617	29,6747	0,079535	3,669711	0	1,573782		
Ov–Ev / Ev	-1	-1	2,831089	-1	0,327706	-1	-0,24329	4,107057	0,791674	1,683131	0	0,048639		
Cat 12	705,42	387,99	562,95	13,59	1113,21	3,78	1571,4	1037,97	6,12	31,95	13,05	6537,33	11984,76	5447,43
	2999,164	203,1695	569,6486	163,4414	444,0544	149,6515	376,9982	381,7066	5,307471	115,1829	39,10516	6537,33		
Ov - Ev	-2293,74	184,8205	-6,69858	-149,851	669,1556	-145,872	1194,402	656,2634	0,812529	-83,2329	-26,0552	0		
Ov–Ev / Ev	-0,76479	0,909686	-0,01176	-0,91685	1,506923	-0,97474	3,16819	1,719288	0,153092	-0,72262	-0,66628	0		
Total	22529,88	1526,22	4279,23	1227,78	3335,76	1124,19	2832,03	2867,4	39,87	865,26	293,76	12840,75	53762,13	
Gain	877,5	990,63	846,99	29,25	1731,78	7,11	2588,85	2000,25	17,46	138,24	36,54	6303,42	15568,02	

C-4.- Resume Cross-tabulated Matrix for Gains (T1-T2)

	Cat 1	Cat 2	Cat 3	Cat 4	Cat 5	Cat 6	Cat 7	Cat 8	Cat 9	Cat 10	Cat 11	Cat 12	Total	Loss
Cat 1	21652,38	470,07	0	14,67	35,73	3,33	101,25	54,72	5,31	3,51	0	1335,15	23676,12	2023,74
	21652,38	450,0629	421,8401	13,17536	811,7339	3,197627	1165,705	920,7976	7,693052	61,7161	16,2099	3572,282		
Ov - Ev	0	20,00713	-421,84	1,494641	-776,004	0,132373	-1064,46	-866,078	-2,38305	-58,2061	-16,2099	-2237,13		
Ov–Ev / Ev	0	0,044454	-1	0,113442	-0,95598	0,041397	-0,91314	-0,94057	-0,30977	-0,94313	-1	-0,62625		
Cat 2	31,41	535,59	6,39	0	31,5	0	77,13	66,78	0	0	0	900	1648,8	1113,21
	48,08953	535,59	29,37686	0,917529	56,52898	0,222682	81,17948	64,12415	0,535742	4,297896	1,128854	248,7729		
Ov - Ev	-16,6795	0	-22,9869	-0,91753	-25,029	-0,22268	-4,04948	2,655848	-0,53574	-4,2979	-1,12885	651,2271		
Ov–Ev / Ev	-0,34684	0	-0,78248	-1	-0,44276	-1	-0,04988	0,041417	-1	-1	-1	2,617757		
Cat 3	0	80,82	3432,24	0	149,31	0	117,09	269,37	3,15	43,38	6,39	2122,38	6224,13	2791,89
Sm-f	181,5353	118,3154	3432,24	3,463623	213,3938	0,840613	306,4481	242,0652	2,022399	16,22432	4,261363	939,1042		
Ov - Ev	-181,535	-37,4954	0	-3,46362	-64,0838	-0,84061	-189,358	27,30483	1,127601	27,15568	2,128637	1183,276		
Ov–Ev / Ev	-1	-0,31691	0	-1	-0,30031	-1	-0,61791	0,112799	0,557556	1,673763	0,49952	1,260005		
Cat 4	0	0	0	1198,53	0	0	0,18	0	0,72	0	0	0,45	1199,88	1,35
	34,99616	22,8087	21,3784	1198,53	41,13779	0,162052	59,07668	46,66502	0,389875	3,127705	0,8215	181,0393		
Ov - Ev	-34,9962	-22,8087	-21,3784	0	-41,1378	-0,16205	-58,8967	-46,665	0,330125	-3,1277	-0,8215	-180,589		
Ov–Ev / Ev	-1	-1	-1	0	-1	-1	-0,99695	-1	0,846743	-1	-1	-0,99751		
Cat 5	22,05	8,37	48,87	0	1603,98	0	502,83	361,17	0	3,69	3,6	696,15	3250,71	1646,73
	94,81144	61,79323	57,91827	1,808965	1603,98	0,439031	160,0503	126,4247	1,056249	8,473565	2,225605	490,471		
Ov - Ev	-72,7614	-53,4232	-9,04827	-1,80896	0	-0,43903	342,7797	234,7453	-1,05625	-4,78357	1,374395	205,679		
Ov–Ev / Ev	-0,76743	-0,86455	-0,15622	-1	0	-1	2,1417	1,8568	-1	-0,56453	0,617538	0,41935		
Cat 6	0	0	0	0,36	0	1117,08	0,18	0	0	0	0	0,09	1117,71	0,63
	32,59955	21,24671	19,91437	0,621987	38,3206	1117,08	55,031	43,46931	0,363176	2,913514	0,765242	168,6414		
Ov - Ev	-32,5996	-21,2467	-19,9144	-0,26199	-38,3206	0	-54,851	-43,4693	-0,36318	-2,91351	-0,76524	-168,551		
Ov–Ev / Ev	-1	-1	-1	-0,42121	-1	0	-0,99673	-1	-1	-1	-1	-0,99947		
Cat 7	40,5	14,76	23,85	0,27	124,29	0	243,18	172,44	0,09	3,78	0,81	557,19	1181,16	937,98
	34,45016	22,45285	21,04486	0,657295	40,49598	0,159524	243,18	45,93697	0,383793	3,078908	0,808684	178,2148		
Ov - Ev	6,049839	-7,69285	2,805137	-0,3873	83,79402	-0,15952	0	126,503	-0,29379	0,701092	0,001316	378,9752		
Ov–Ev / Ev	0,175611	-0,34262	0,133293	-0,58923	2,069194	-1	0	2,753839	-0,7655	0,227708	0,001628	2,126507		
Cat 8	78,03	28,62	161,73	0,36	266,58	0	213,39	867,15	1,89	46,08	10,08	656,55	2330,46	1463,31
	67,97108	44,30006	41,52207	1,296861	79,89963	0,314745	114,7413	867,15	0,757233	6,074767	1,595554	351,6226		
Ov - Ev	10,05892	-15,6801	120,2079	-0,93686	186,6804	-0,31475	98,64865	0	1,132767	40,00523	8,484446	304,9274		
Ov–Ev / Ev	0,147988	-0,35395	2,895037	-0,72241	2,336436	-1	0,859748	0	1,495928	6,585477	5,317555	0,867201		
Cat 9	0,09	0	1,89	0	0	0	0	0,9	22,41	0	0,45	1,53	27,27	4,86
	0,795367	0,518379	0,485873	0,015175	0,93495	0,003683	1,342652	1,060569	22,41	0,071084	0,01867	4,114531		
Ov - Ev	-0,70537	-0,51838	1,404127	-0,01518	-0,93495	-0,00368	-1,34265	-0,16057	0	-0,07108	0,43133	-2,58453		
Ov–Ev / Ev	-0,88684	-1	2,889908	-1	-1	-1	-1	-0,1514	0	-1	23,10225	-0,62815		
Cat 10	0	0	0	0	0	0	0	0	0	727,02	2,16	0	729,18	2,16
	21,26754	13,86109	12,99188	0,405776	24,99988	0,098481	35,90154	28,35884	0,236932	727,02	0,499235	110,0196		
Ov - Ev	-21,2675	-13,8611	-12,9919	-0,40578	-24,9999	-0,09848	-35,9015	-28,3588	-0,23693	0	1,660765	-110,02		
Ov–Ev / Ev	-1	-1	-1	-1	-1	-1	-1	-1	-1	0	3,326624	-1		
Cat 11	0	0	41,31	0	11,16	0	5,4	36,9	0,18	5,85	257,22	33,93	391,95	134,73
	11,43176	7,450636	6,983418	0,218114	13,43797	0,052936	19,29785	15,24349	0,127356	1,021689	257,22	59,13789		
Ov - Ev	-11,4318	-7,45064	34,32658	-0,21811	-2,27797	-0,05294	-13,8979	21,65651	0,052644	4,828311	0	-25,2079		
Ov–Ev / Ev	-1	-1	4,915441	-1	-0,16952	-1	-0,72018	1,420706	0,413363	4,725814	0	-0,42626		
Cat 12	705,42	387,99	562,95	13,59	1113,21	3,78	1571,4	1037,97	6,12	31,95	13,05	6537,33	11984,76	5447,43
	349,5521	227,8201	213,5338	6,669316	410,8965	1,618626	590,0756	466,1042	3,945734	31,24045	10,65868	6537,33		
Ov - Ev	355,8679	160,1699	349,4162	6,920684	702,3135	2,161374	981,3244	571,8658	2,174266	0,70955	2,391324	0		
Ov–Ev / Ev	1,018068	0,703054	1,63635	1,03769	1,709222	1,335314	1,663049	1,226906	0,551042	0,022713	0,224355	0		
Total	22529,88	1526,22	4279,23	1227,78	3335,76	1124,19	2832,03	2867,4	39,87	865,26	293,76	12840,75	53762,13	
Gain	877,5	990,63	846,99	29,25	1731,78	7,11	2588,85	2000,25	17,46	138,24	36,54	6303,42	15568,02	

Appendix D

HRUs Maps for 2008 and 2028


HRUS for the year 2008
70°20'0"W
70°10'0"W
9°30'0"N
9°20'0"N
9°10'0"N
N
S
W
E
0 1,75 3,5 7
Kilometers
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119 120 121

HRUS for the year 2028