Fachhochschule Köln
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Facultades De Ciencias Químicas, Ingeniería Y Medicina
Programas Multidisciplinarios De Posgrado En Ciencias Ambientales
And
Cologne University Of Applied Sciences
Institute for Technology and Resources Management in the Tropics and Subtropics

ANALYSIS OF A HYDROLOGICAL MODELLING TOOL FOR WATER RESOURCES MANAGEMENT IN THE VALLES RIVER BASIN, MEXICO

THESIS TO OBTAIN THE DEGREE OF
MAESTRÍA EN CIENCIAS AMBIENTALES
DEGREE AWARDED BY
UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ
AND
MASTER OF SCIENCE
“TECHNOLOGY AND RESOURCES MANAGEMENT IN THE TROPICS AND SUBTROPICS
FOCUS AREA “ENVIRONMENTAL AND RESOURCES MANAGEMENT”
DEGREE AWARDED BY COLOGNE UNIVERSITY OF APPLIED SCIENCES

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SAN LUIS POTOSÍ, MÉXICO SEPTEMBER 2011

PROYECTO FINANCIADO POR:
SISTEMA NACIONAL DE VIGILANCIA EPIDEMIOLÓGICA -SINAVEF

PROYECTO REALIZADO EN:

PMPCA - UASLP

AGENDA AMBIENTAL
UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ

INSTITUTE FOR TECHNOLOGY AND RESOURCES MANAGEMENT IN THE TROPICS AND SUBTROPICS
COLOGNE UNIVERSITY OF APPLIED SCIENCES

CON EL APOYO DE:
DEUTSCHER AKADEMISCHER AUSTAUSCH DIENST (DAAD)
CONSEJO NACIONAL DE CIENCIA Y TECNOLOGÍA (CONACYT)

LA MAESTRÍA EN CIENCIAS AMBIENTALES RECIBE APOYO A TRAVÉS DEL PROGRAMA NACIONAL DE POSGRADOS (PNPC - CONACYT)

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Acknowledgements

I dedicate the efforts made for this work to my family, my mother, father, sister and brother, who have always loved me and believed in me without asking anything in return. They have always been there for me to give all their support and wisdom, especially during hard times. For them, all of my love.

The experience of the master program and the elaboration of this thesis wouldn't have been possible without the financial support from the Consejo Nacional de Ciencia y Tecnología (CONACyT) in Mexico and the Deutscher Akademischer Austausch Dienst (DAAD) in Germany, whom I thank for allowing one of the best experiences of my life. I extend my gratitude also to the Universidad Autónoma de San Luis Potosí and the Fachhochshule Köln for giving me the opportunity to take this master program.

Among the staff of the two universities I would like to thank my tutor committee: to Dr. Maria Guadalupe Galindo for her demanding attitude, to Prof. Dr. Lars Ribbe for his guidance and, especially, to Dr. Maxime Souvignet for his enthusiasm and constant support for the modelling process. I give special thanks to some professors who supported me somehow: Dr. Carlos Contreras Servín, Dr. Javier Fortanelli Martínez, Dr. Juan Carlos García and Dr. Jackon Roehrig, mostly for their supportive and encouraging attitude. Sincere thanks to the coordination and administrative staff of both universities, especially to Dr. María Deogracias Ortiz for her hard work.

I'd also like to acknowledge the support I received from other people, like the SINAVEF staff from whom I got technical support and important information, to Noé Aguilar, also Mr. Melquiades de León in Ejido Laguna del Mante, Dr. Oscar Osmín Meraz from Fundación PRODUCE in Ciudad Valles and the people from El Estribo research centre in El Naranjo for their support during field visits and the information given.

I'm also very grateful with my master fellows, my roommates and all the people who made this stage of my life even more special. To the Mexican people, all my gratitude for your kindness.

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Abstract

Integrated Water Resources Management (IWRM) is a systematic process for the sustainable development, allocation and monitoring of water resources, which promotes more coordinated management of land and water, the river basin and upstream and downstream interests (UNW-DPC, 2010). As a way to approach the management of water resources in a given geographical context, it can take advantage of any available instrument or tool. Hydrological models are simplified representations of hydrological systems, and can be very useful tools for what is known as "water resources assessment", a process meant to gain an integral view of the water resources status, meaning a baseline for IWRM. Moreover, they can be used to study the possible impacts and trends resulting from different kinds of scenarios, such as land use changes, population growth and climate change. However, there are plenty of hydrological models, and not everyone is suitable for any purpose or for any geographical context.

Thus, with IWRM as the future application in mind, the general objective of this study was to analyze the suitability of the Soil and Water Assessment Tool (SWAT) for the specific purpose of modelling hydrological impacts of land use changes in the particular context of the Valles River Basin (VRB). This basin is located in the *Huasteca Potosina*, a humid/subhumid region in north-central Mexico. It constitutes the water source for the second most important city of the San Luis Potosí State and an important space for the sugarcane agribusiness. It is exposed to the impact of prolonged droughts, tropical cyclones, cold fronts and the El Niño Southern Oscillation (ENSO). The orographic barrier effect of the *Sierra Madre Oriental*, the shallow soils and the water extraction for irrigation and industrial purposes, among others, add to the climatic factors to make the VRB a very complex system. The frequent floodings and seasonal severe droughts are among the main issues that make it necessary to establish and consolidate a proper IWRM in this basin.

The SWAT model is considered as suitable for the established modelling purpose. It was specifically developed to assess the impacts of land management practices on hydrology and water quality on a river basin scale (Neitsch, et al., 2011). After recognizing this fact, the next step was to assess its suitability for the particular (complex) context of the VRB, and the best way to do that is to evaluate its performance when calibrating and validating it. Calibration of a model is the process of ensuring that it is reproducing the real world system, in this case through the use of stream flow records, while validation is performed to evaluate model's performance under conditions different from those used for calibration. Only when a model has been successfully calibrated and validated it is worth to be applied to simulate the desired scenarios.

The objective of calibrating the model to simulate land use/land cover change effects couldn't be accomplished, because some difficulties in collecting the required data, the impossibility of calibrating groundwater and surface runoff flow rates and an improper calibration of the biomass production submodel extended the project time. Finally the inability to overcome a bug in the software within the time prescribed for the project resulted in the necessity of reporting unsatisfactory results, which nevertheless are improvable with further work. Even though it was not possible to calibrate the model, it is not concluded that the model is not applicable to the VRB. Moreover, it is concluded that the SWAT hydrologic model is not the most suitable tool for modelling tasks at the daily scale under the current context of low information availability at the Valles River Basin.

Resumen

La Gestión Integrada de Recursos Hídricos (GIRH) es un proceso sistemático para la asignación, el monitoreo y el desarrollo sostenible de estos recursos, que promueve un manejo más coordinado de la cuenca, el suelo, el agua y los intereses de las partes altas y bajas en una cuenca hidrográfica (UNW-DPC, 2010). Como una forma de abordar la gestión del agua en determinado contexto, la GIRH puede hacer uso de cualquier instrumento o herramienta disponible. Los modelos hidrológicos son representaciones simplificadas de los sistemas hidrológicos, y pueden ser herramientas muy útiles para la "evaluación de recursos hídricos", un proceso dirigido a lograr una visión integral de la condición de estos y constituye por tanto una línea base para la GIRH. Más aún, pueden ser utilizados para estudiar los posibles impactos y tendencias resultantes de diferentes tipos de escenarios, tales como cambios de uso del suelo, crecimiento poblacional y cambio climático. Sin embargo, existen muchos modelos hidrológicos, y no todos son idóneos para cualquier propósito o para cualquier contexto geográfico.

De esta forma, con la GIRH como futura aplicación en mente, el objetivo general de este estudio fue analizar la idoneidad del modelo SWAT (Soil and Water Assessment Tool) para el propósito específico de modelar los impactos hidrológicos de los cambios de uso del suelo en el contexto particular de la Cuenca del Río Valles (CRV). Esta cuenca se localiza en la Huasteca Potosina, una región húmeda/subhúmeda en el norte-centro de México, y constituye la fuente de agua de la segunda ciudad más importante del Estado de San Luis Potosí y un importante espacio para la agroindustria de la caña de azúcar. Está expuesta al impacto de sequías prolongadas, ciclones tropicales, frentes fríos y al fenómeno del Niño (ENOS). El efecto de barrera orográfica de la Sierra Madre Oriental, los suelos superficiales y la extracción de agua para riego y usos industriales, entre otros, se suman a los factores climáticos para hacer de la CRV un sistema bastante complejo. Las frecuentes inundaciones y severas sequías estacionales están entre los principales problemas que hacen necesario establecer y consolidar una apropiada GIRH en esta cuenca.

El modelo SWAT es considerado como idóneo para el objetivo de modelación propuesto. Fue desarrollado específicamente para evaluar los impactos de las prácticas de manejo de la tierra en la hidrología y calidad del agua a nivel de cuenca (Neitsch, et al., 2011). Tras reconocer este hecho, el paso siguiente fue evaluar su idoneidad para el contexto particular (y complejo) de la CRV, y la mejor forma para lograr esto es evaluar su desempeño al calibrarlo y validarlo. La calibración de un modelo busca asegurar que este reproduzca el sistema real, en este caso usando registros de caudales medidos, mientras que la validación se lleva a cabo para evaluar su desempeño bajo condiciones diferentes a las utilizadas para la calibración. Sólo cuando el modelo ha sido calibrado y validado exitosamente vale la pena aplicarlo para simular los escenarios deseados.

El objetivo de calibrar y validar el modelo para la simulación de cambios de cobertura y uso del suelo no pudo ser alcanzado, debido a que dificultades en la obtención de los datos, la imposibilidad de calibrar los caudales base y la escorrentía superficial y una inadecuada calibración de la producción de biomasa extendieron la duración del proyecto. Finalmente, la incapacidad de superar un error de software dentro del tiempo establecido resultó en la necesidad de reportar resultados no satisfactorios, los cuales sin embargo se pueden mejorar con más trabajo. Aunque no fue posible calibrar el modelo no se concluye que el modelo no sea aplicable a la CRV. Más aún, se concluye que SWAT no es el modelo más idóneo para ejercicios de modelamiento a escala diaria bajo el contexto actual de baja disponibilidad de información en la Cuenca del Río Valles.

Zusammenfassung

Unter Integriertem Wasserressourcen-Management (IWRM) versteht sich ein systematischer Prozess zur Beobachtung und Steuerung dieser wichtigen Ressource, mit dem Ziel der nachhaltigen Nutzung, welcher eine koordinierte Analyse des Flussgebietes, Wassers und Bodenssowie der Interessen flussauf- und flussabwärts fördert (UNW-DPC, 2010). Für die Betrachtung einer Problemstellung macht das IWRM Gebrauch von jeglichenverfügbaren Mitteln und Werkzeugen.

Hydrologische Modelle sind Vereinfachungen hydrologischer Systeme die zur "Bewertung der Ressource Wasser" dienen und somit eine Basis des Prozesses der Einschätzung und Beschreibung des Zustandes der Ressource darstellen.Zudem findet sich ihr Nutzen in der Analyse möglicher Auswirkungen und resultierender Tendenzen verschiedener Szenarien wie veränderte Landnutzung, Bevölkerungswachstum und Klimawandel. Zur Verfügung stehen verschiedene hydrologische Modelle, die für unterschiedliche Zwecke und geografische Kontexte geeignet sind.

Mit dem Gedanken an das IWRM als Zukunftsanwendung ist das Ziel dieser Arbeit die Analyse der Tauglichkeit des Modells SWAT (Soil and Water Assessment Tool) für die Modellierung von hydrologischen Effekten durch wechselnde Landnutzungsformen des Flussgebietes Río Valles (FRV). Das Untersuchungsgebiet befindet sich in der HuastecaPotosinaim zentralen Norden Mexikos charakterisiert durch feuchtes/mittel-feuchtes Klima.Es stellt die Wasserversorgung der zweitgrößten Stadt in San Luis Potosí und eine wichtige Fläche für die industrielle Landwirtschaftdes Zuckerrohrs dar.Die Region ist langanhaltenden Dürren, Hurrikanen, Kaltfronten und dem Phänomen El Niño (ENSO) ausgesetzt. Die orografische Barriere der Sierra MadreOriental, die oberflächliche Bodenbildung und die Wasserförderung für Bewässerung und weitere Faktoren Industrie addieren sich und machen das FRV zu einem komplexen System.Regelmäßige Überschwemmungen und ernste jahreszeitlich bedingte Dürren zählen zu den Hauptproblemen, die das IWRM des Flussgebiets unabdingbar machen.

Das Modell SWAT wird als geeignet für die beschriebene Zielsetzung angesehen, da es speziell für die Bewertung der Einflüsse von Bodennutzungspraktiken auf die Hydrologie und Wasserqualität von Flüssen entwickelt wurde (Neitsch, et al., 2011). Die Absicht war es somit seine Eignung für den spezifischen (und komplexen) Untersuchungsfall des FRV anhand der Analyse seines Leistung während der Kalibrierung und Validierung zu bewerten. Die Kalibrierung eines Modells dient der Versicherung, dass dieses eine Reproduktion der Wirklichkeit darstellt, in diesem Fall wurden gemessene Abflusswerte dazu benutzt. Die Validierung hingegen wird genutzt um das Ergebnis unter zur Kalibration verschiedenern Bedingungen zu bewerten. Nur, wenn ein Modell erfolgreich kalibriert und validiert wurde, ist seine Anwendung in der Simulation der gewünschten Szenarien lohnenswert. Das Ziel der Kalibrierung und Validierung des Modells für die Simulation verschiedener Bodennutzungen konnte aufgrund von Schwierigkeiten bei der Datengewinnung, der Unmöglichkeit der Kalibrierung von Basisabflüssen und Oberflächenabfluss und der unzureichenden Kalibrierung der Biomassenproduktion, welche das Projekt in die Länge zogen, nicht erfüllt werden. Obwohl das Modell nicht kalibriert werden konnte, wird es als geeignet für die Modellierung des FRV angesehen, bedarf jedoch weiterführender Arbeiten.Es wird jedoch geschlussfolgert, dass das Modell SWAT nicht das Geeignetste für die Modellierung mit täglichen Zeitschritten, unter der aktuellen Bedingung fehlender Informationen des FRV ist.

1. INTRODUCTION

1.1. RESEARCH PROBLEM STATEMENT

1.1.1. INTEGRATED WATER RESOURCES MANAGEMENT AND HYDROLOGICAL MODELS

Water is essential to sustain life on earth, including human life. Concerns about its sustainability at an international scale emerged as part of the whole international environmentalist movement that began with the second half of the 20th century, especially during the 70's decade, slowly spreading from developed to developing countries. First concerns regarding water were related to its pollution (UNEP, 2002), but over the decades several other emerged, mainly related to the inadequate access to safe water in many regions of the world (WHO/UNICEF, 2008), due to scarcity, unequal distribution or poor quality status, but also related to sanitation, groundwater resources depletion, water borne diseases, impacts on wildlife and ecosystems and impacts of hydrometeorological phenomena.

The 'water crisis' (a term commonly used to embrace water-related issues) is mainly a crisis of governance than a crisis of physical scarcity, which aggravates and sometimes causes the aforementioned problems. Approaches implemented so far for water management and development have had a strong sectoral orientation, meaning that each sector has been managed separately, with limited coordination between them. The results have been to ignore the interactions between the different uses of water and the unintended social and environmental consequences of these sectoral water development projects. Moreover, governments have emphasized supply augmentation over demand management, ignoring the fact that water is a finite resource (GWP, 2000; World Bank Institute, 2006).

As a response to these sectoral approaches, the concept of Integrated Water Resources Management (IWRM) has emerged as a mean to tackle water issues at different spatial scales, looking for a sustainable use of water resources. Since IWRM is still an evolving concept, there are different conceptions about it, and an unambiguous definition does not currently exist. According to the Global Water Partnership (GWP, 2000), IWRM is a "process which promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems". UNW-DPC (2010) adds that IWRM is "a systematic process for the sustainable development, allocation and monitoring of water resources, which promotes more coordinated management of land and water, the river basin and upstream and downstream interests".

Watersheds or basins[1] are the more convenient spatial framework for water management. As they are the terrestrial forms that collect and concentrate water coming from precipitation, highly interdependent interrelations are created among uses and users of water within, which depend on an interconnected system formed by surface and ground water, aquifer recharge zones, extraction points, hydraulic works, wastewater discharge points and others. A special interrelation is among upstream and downstream uses and users, in which downstream users critically depend on quantity, quality and timing of the water remaining from the uses upstream. A tight interrelation

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[1] No distinction is made here between these two terms.

and interdependence exists also between water and the rest of natural resources such as soils, fauna and vegetation. Changes in use of natural resources have implications on water cycle downstream. Finally, watersheds also constitute a special framework for the interaction and interdependence among physical and biotic systems and the socioeconomic system formed by inhabitants and other natural resources users such as industries (Dourojeanni, et al., 2002).

In practice, IWRM can be considered as a set of decisions, policies, projects and actions headed to achieve sustainable development and management of water resources. IWRM can take advantage of any human, legal, financial, technical, technological and other types of resources. A way to organize the multiple instruments and tools available for IWRM is presented in the Global Water Partnership's IWRM Toolbox (GWP, 2008). This guide describes 54 tools usable for IWRM and classifies them into 3 hierarchical groups. The first one consists of policies, legislatives frameworks and financing structures, as the overall framework that enables IWRM to be implemented. The second group refers to the institutional organization and capacity development that has to take place in order to adequately implement IWRM. The third and largest category groups more technical and practical instruments and tools for planning, education, conflict resolution, and water use regulation, such as basin management plans, land-use plans, environmental assessments, water-use improvement programs, educational programs and economic instruments (water markets, subsidies, pollution taxes, hydrologic environmental services pricing, etc).

Included in the latter is the water resources assessment, which is meant to get a thorough and integral view of the status of water resources in the particular context (a country, state, region or basin), looking at quantity, quality and temporality of surface and groundwater, and also to their interaction with society. It identifies the major water resources issues and potential conflicts, their severity and social implications, as well as risks and hazards such as floods and droughts (GWP, 2008). Models are very useful tools for water resources assessment in the context of (I)WRM. They can be implemented as part of Decision Support Systems (DSS), which are means of collecting and generating data from many sources (experimental or survey data, output from models and expert or local knowledge) to provide useful and scientifically sound information to the actors involved in planning, management, policy- and decision-making processes, including public officials, planners and scientists, and the general public (GWP, 2008; Fedra, 1995).

At the river basin level, hydrological models allow policy makers and managers to study impacts and trends resulting from various development options (scenarios), on topics such as integrated water quantity, water quality and environmental regulation, the impacts of land use changes on flow regimes, climate change effects on flood and drought frequency / severity, inter-sectoral water allocation policies, effects of uncertainty and risks on water resources management and the impacts of economic incentives for pollution control, water conservation and more efficient irrigation (GWP, 2008). However, there are many different types of models (see chapter 2), and the most suitable one for a given modelling purpose and a specific basin has to be chosen.

1.1.2. MODELLING PURPOSE: IDENTIFICATION OF LAND COVER / LAND USE CHANGE HYDROLOGICAL EFFECTS IN THE VALLES RIVER BASIN

There are several problems related to water resources in the VRB. According to the analysis made by Santacruz de León (2007), these are basically related to water accessibility for agricultural and domestic use, which is diminished because of the temporality and the quality of the resource. The high frequency and severity of the meteorological drought, related in many cases to the effects of *El Niño* phenomenon, has caused important damages to the agriculture and the population in many cases. This problem is aggravated by the pollution of the water sources, especially the rivers, which is, perhaps, the most important environmental issue in the perception of the people. Floodings are other recurrent hydrometeorological phenomenon and affects especially Ciudad Valles but also some rural areas of the basin. In this sense, the degradation of the land covers in the mountainous areas, as part of the environmental degradation of the region documented by some specialists (Aguilar Rivera, et al., ND), is recognized as a factor enhancing the risk of floodings in Ciudad Valles (Agenda Ambiental, ND).

In the VRB Agricultural frontier has increased during recent decades. According to Santacruz de León (2007), between 1976 and 2000 544.26 km^2 of jungle and 10.84 km^2 of forest were lost, while the area of rainfed agriculture and settlements increased 404 km^2 and 216 km^2 respectively. Table 1.1 shows the coverage changes found by this author along this period in the Valles River basin. Despite its decrease, the deciduous forest and oak forest still occupy the largest areas. Among categories of human use rainfed agriculture dominates, although there was also an increase in irrigated agriculture.

Land Use	1976	2000	Change (km^2)	Change (%)
Irrigated agriculture	82.32	135.19	52.87	64.21
Rainfed agriculture	313.02	717.79	404.77	129.31
Pastures	372.2	481.86	109.66	29.46
Evergreen tropical forest	48.4	32.51	-15.89	-32.83
Deciduous tropical forest	1857.5	1329.11	-528.39	-28.44
Palm grove	88.54	41.23	-47.31	-53.43
Oak forest	399.94	410.78	10.84	2.71
Cloud forest	11.21	10.42	-0.79	-7.04
Xeric shrubs	7.74	1.45	-6.29	-81-13
Human settlements	9.27	29.32	20.05	216.28
Water bodies	8.16	9.23	1.07	13.11

Table 1.1. Land use changes in the Valles River Basin between 1976 and 2000 (Santacruz de León, 2007).

Much of this agricultural expansion is due to public policies implemented during the second half of the 20th century by the Mexican government to boost stagnant economic regions based on the development of regional projects for the mechanization of agriculture and intensification of cattle-raising systems (Reyes Hernández, et al., 2008). As part of these policies the government encouraged the cultivation of sugar cane. Several decrees were issued in relation to this regard, such as the Decree 36 of September 22/43, which stated that each sugar mill would have its own cane supply area fixed by the Agriculture Secretary. This forced every producer in the surrounding areas of a sugar mill to produce sugarcane for the mill, which was in turned obliged to buy the whole yield to the producers. Driving forces like these led to the establishment and consolidation in the basin of three of the four sugar mills in San Luis Potosi, in 1964, 1975 and 1984 (Santacruz de León, 2007). Another major land use change that has taken place is the increase of the urban zones. According to Agenda Ambiental (ND) the area of the city of *Ciudad Valles* increased in a 426%, going from 800 to 3000 ha between 1976 and 2000.

The status of land cover-soil system acts as a mitigating or aggravating factor of the drainage basin response to precipitation events, particularly to their intensity and duration. It affects the length of the streamflow low-level periods, the magnitude of the streams' level decrease during these periods, and the volumes of water flowing through channels and rivers during and after rainfall events. However, the variability of hydrological responses to land cover changes is high, in particular according to the climatic and soil conditions, and mainly in terms of peak flows and flooding, compared to those related to annual flows. Regarding the latter, it has been found that the removal of forests almost invariably results in increases of the total annual volumes of the streams. In general, the ways in which this increase can take place are two, according to whether this is expressed as surface flow or base flow, thus changing differently the distribution of flow throughout the year (Andréassian, 2004; Bruijnzeel, 2004; Bosch, et al., 1982).

Forest removal brings higher values of rain reaching the soil and an important reduction of evapotranspiration, due to the reduction of leave area and of the consumption of water from the soil. Nevertheless, the reduction in transpiration can be considerably compensated by the increase of the direct evaporation from the soil and of the evapotranspiration from herbaceous vegetation, due to the higher incident radiation. The removal of vegetation and litter causes less infiltration and hence the increase of surface flow, which is expressed as higher peak flows. This increase may also be due to compaction caused by some common practices such as overgrazing (Fu, et al., 2005; Andréassian, 2004; Bruijnzeel, 2004; Costa, et al., 2003; Putuhena, et al., 2000). Base flow is also usually increased with deforestation. According to Andréassian (2004) is almost a rule that deforestation of more than 25% of the biomass will lead to increased base flows due to reduced water consumption. When soil disturbance is minimal the effect is enhanced due to increased infiltration thanks to the conservation of the litter layer (Fu et al, 2005; Bruijnzeel, 2004; Costa et al, 2003).

Different positions regarding the effects of deforestation are summarized in two by Bruijnzeel (2004). The most traditional one is the basis of the concept of "water regulation". According to this, the soil-root-litter system in the forest acts like a sponge, absorbing water in winter and releasing it slowly during summer. As the disruption of this system is more intense the effect "a lot of water in winter and very little in summer" is increased, and thus floods and droughts can be eliminated by large-scale reforestation. A second, more modern, position argues that base flow is determined primarily by geological substrate, rather than by the vegetation. This approach emphasizes the existence of a threshold of intensity and duration of storms beyond which these exceed the capacity of soil water storage, which permits floods, as well as the increased water use by forests. Accordingly, deforestation causes increases in the annual volumes and peak and base flows, while reforestation brings reductions.

According to the existence knowledge in the field, it is expected that changes occurred in land use and land cover at the VRB have had effects on its hydrological behaviour. An increased water demand is expected, not only for cane processing at sugar refineries, but also for irrigation purposes at the sugar cane fields, which displaced some domestic crops with less water requirements. At the same time, the extension of the agricultural frontier is supposed to have effects on infiltration and surface runoff rates. However, these possible effects have to be verified through the analysis of the available data, and that constitutes the specific modelling purpose of the present study. In order to do so, the selected hydrological model has to demonstrate that it is capable of closely reproducing the hydrological behaviour of the real system, which is known in this case through the stream flow series measured at the outlet of the watershed.

1.1.3. RESEARCH QUESTION

While the SWAT model is recognized as suitable to model the hydrological impacts of land cover/land use scenarios (see chapter 2), it's necessary to assess its applicability or suitability to a particular context - climatic conditions, topography, soils, water use, land covers, etc. - in order to establish whether or not it may be employed for the management of water resources in that context. Thus, the present study seeks to answer the following research question:

¿Is the SWAT model a suitable tool for simulating the hydrological effects of land use/land cover scenarios in the Valles River Basin?

1.2. OBJECTIVES

1.2.1. GENERAL OBJECTIVE

To analyze the suitability of the Soil and Water Assessment Tool (SWAT) to model hydrological impacts of land use changes in the Valles River Basin.

1.2.2. SPECIFIC OBJECTIVES

a) To set up, calibrate and validate the SWAT hydrological model for the Valles River Basin.
b) To assess the suitability of the SWAT model for simulating the hydrological impacts of land use/land cover scenarios in the Valles River basin.
c) To identify the influence of land use/land cover changes on the base and peak flows of the Valles River.

1.3. JUSTIFICATION

The Valles River Basin (VRB) is an important watershed of the *Huasteca Potosina* region, in the state of San Luis Potosí, Mexico. This region has been considered as ecologically important for being the northern limit of the tropical Mexican forests and the dividing line between Arid-America and Mesoamerica (Aguilar Rivera, 2011; Algara Siller, 2009). Particularly, the VRB is important because it is the water source of the second largest city in the state, named *Ciudad Valles,* which is also the economical, social and political centre of the *Huasteca Potosina*. In total, the VRB directly supplies water to about 170,000 people living within its limits and in Ciudad Valles[2].

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[2] According to INEGI's 2010 National Census of Population and Housing (INEGI, 2010).

The VRB is also the space where the largest production of sugar from sugarcane in San Luis Potosí takes place. Sugarcane is the most important crop in Mexico (Aguilar Rivera, 2010) and San Luis Potosí is the third producer in terms of planted surface and production for industrial purposes[3] (SIAP, 2010). This entire surface is located in the *Huasteca* region, and about 40,000 hectares[4] are within the VRB. Moreover, three of the four sugar mills of the state are located in the basin (the fourth is located in the area but technically outside it). The area for sugarcane crops has considerably grown in the region during last decades, encouraged since the 1960s by governmental policies (Santacruz de León, 2007). Thus, it is important to stress that the most important activity in the area, the sugarcane agribusiness, is associated to the transformation of the landscape, which has impacts over the water cycle and the environment in general.

Despite the presence of an important urban area, the rural context is the predominant in the VRB. The predominance of the primary sector of the economy in two of the three most important municipalities, including the one which more population contributes to the watershed, is a reflection of the pressure exerted on the natural resources of the basin, especially by the sugarcane agribusiness. As the urban area of Ciudad Valles exerts also a demand of resources from the VRB, especially water, this basin constitutes an interesting case of a tight relationship between the environmental management of the rural areas and the benefits reported for the urban contexts. This is especially true in the case of the effects that watershed and water management (or they absence) in the upper basin have for the inhabitants of Ciudad Valles, which is located in the lower basin, in terms of quantity, quality and temporality of the water resources.

In this context, is necessary to consolidate Integrated Water Resources Management in order to achieve a sustainable use of the resource, reduce the possibility of conflicts and mitigate the impacts of the extreme hydrometeorological phenomena, which are characteristics of the climate of the region and whose effects are exacerbated by a mismanagement of the natural resources. It is necessary, for instance, to explore alternatives to mitigate the severe impacts of hydrometeorological phenomena in the basin. Some of these alternatives aim at population's vulnerability and some others directly approach the hazards or threats (floods, droughts). Land cover and land use are two factors that may have (or not) a significant influence on the magnitude and intensity of these threats, which are expected to intensify in Mexico and the *Huasteca Potosina* during this century, according to climate change projections (Jiménez Cisneros, 2009; Montero Martínez, et al., 2010; Prieto González, et al., 2010).

Hydrological models are tools that can be very useful for purposes like these. They can be implemented as part of Decision Support Systems (DSS) and thus provide information for management, policy- and decision-making processes. Besides land management, they may be used to study the impacts of several scenarios, such as climate change, water allocation and regulation policies, irrigation programs and more, on variables such as the general water balance, sediments transport and water quality parameters (GWP, 2008; Fedra, 1995). It is important to explore possible alternatives to implement such tools for IWRM, and even more in the particular context of the VRB. Therefore, this study undertook the analysis of the suitability for the specific

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[3] Surface planted with sugarcane for industrial purposes in 2010: Veracruz: 273006 ha, Jalisco: 69707 ha, San Luis Potosí: 68072 ha (SIAP, 2010).

[4] According to the identification of sugarcane areas for the *Huasteca Potosina* based on Landsat imagery from 2005, made by (Aguilar Rivera, 2011).

context of the VRB of a hydrological modelling tool that has gained international acceptance as a robust and effective watershed modelling tool, especially in the U.S. and Europe (Gassman, et al., 2007).

Besides its socioeconomical importance and the water issues present in it, the Valles River Basin was considered as a good study case for other reasons. The extreme hydrological behaviour, mainly determined by the very marked seasonal differences in rainfall and the occurrence of extreme hydrometeorological phenomena and influenced by the topography, the shallow nature of the soils and the human use of water, among others, makes it an interesting case from the hydrological modelling point of view. Additionally, the expansion of the sugarcane crop fields and the reduction of the areas covered by forests represent an opportunity to evaluate both the hydrological impacts of land use changes and the effects of past governmental policies.

1.4. ANTECEDENTS

1.4.1. WATER MANAGEMENT IN MEXICO

Mexico has passed through different approaches for the management of its water resources. During 19th and early 20th centuries, water management was project oriented, meaning that priority was given to isolated projects for water supply, irrigation, hydropower development, etc. With the creation in 1926 of the National Irrigation Commission, water management evolved to give priority to projects development within a subsectoral approach. It had a great influence from the North-American example given by the successful experience of the Tennessee Valley Authority (TVA) created in 1933. This evolution came along with a great technological and infrastructural development. Since 1947 and based on the TVA example, several "River Basin Commissions" were created for the rivers Papaloapan, Balsas, Lerma-Chapala-Santiago, Grijalva and others, with the purpose of planning and constructing infrastructure projects for the exploitation of water resources in a framework of regional economical development based on water as a territory integrating resource (Valencia Vargas, et al., 2004; Dourojeanni, et al., 2002).

These organisms reached their peaks during the 1950's and 1960's, due to their decentralized nature and large budgets, but disappeared in the 70's and 80´s when they became incompatible with the administrative functions of the states. Their functions were absorbed by Agriculture and Hydraulic Resources Secretary, created in 1977. In 1989 the National Water Commission (CNA) was created to be the superior federal body devoted to the administration, regulation, control and protection of national waters. With its birth, a sub-sector within the Environment sector for the water resources management was created, functioning with an emphasis on the construction of works for increasing water supply. In 1992, the National Waters Law (LAN) was published. Reformed in 2004, it establishes IWRM in a watershed framework as the basis of the National Water Policy, adopting the previously mentioned definition given by the Global Water Partnership. The LAN and the CNA are currently the two fundamental pillars for IWRM in Mexico. Following the publishing of the LAN, the CNA began to promote decentralization of functions and citizen participation (Valencia Vargas, et al., 2004; Dourojeanni, et al., 2002).

A major achievement within the process of hydrologic planning carried out by the CNA has been the division of the national territory, since 1997, into 13 hydrologic-administrative regions, constituted by groups of river basins, whose delimitation nevertheless respect political limits of municipalities. These hydrologic-administrative regions are managed through 13 River Basin Organisms, for which a particular hydraulic regional programme is elaborated once every some years, in congruence with the National Hydraulic Programme. Accordingly, the LAN provided for the creation of the River Basin Councils, which can be considered as the current primary tools for IWRM in the country. These councils, which are currently 26, are bodies for coordination and consensus–building between the CNA, the offices and units of federal, state or municipal agencies and representatives of the users of each particular river basin, in order to develop and carry out programs and initiatives for improved water administration, development of water control works and the respective services and the preservation of resources in the river basin. The process of establishing and developing River Basin Councils has been gradually consolidated over the last few years, and is now one of the most solid pillars of the structural changes underway in the water resources sector (Dourojeanni, et al., 2002; Dourojeanni, 2001).

Despite these advances on the establishment and consolidation of IWRM as the policy for water management in the country, there are still some conceptual misunderstandings that are reflected as obstacles for its implementation. A basic one, outlined by Landa, et al. (2008), is that the LAN refers to river basin organisms, councils, commissions and committees[5], as organic and participative structures for water management. The difference in relation to the watershed management approach is not clearly defined and thus gives rise to a confusion regarding the reaches and objectives of these management bodies. Since the objectives for water management and watershed management are different, there must be separate structures and mechanisms for each of them, although they must work in close interaction.

1.4.2. WATER MANAGEMENT AT THE VALLES RIVER BASIN

Santacruz de León (2007) carried out an analysis of the situation of water resources management at the VRB. This author analyzed the perception of the environmental problems at the watershed by local population and the possibilities to consolidate Integrated Water Resources Management. He found that drought impacts keep showing but there are others (as perceived by population) that are emerging and are related to deforestation, water access and discharge of wastewater into the rivers without previous treatment. According to his analysis, these problems are mostly consequences of activities such as intensive agriculture and associated agribusiness, insufficient public and sanitation services and absence of recollection and treatment systems of solid and liquid industrial residues. In the Integrated Watershed Management Plan of the VRB (Comité de Cuenca del Río Valles, 2008) some other problems are recognized, such as the impact of the reservoir *La Lajilla*, from which water flows out only when a volume has to be left available for flood control, and the impact of water diversion for hydropower generation on some stretches of the river El Naranjo.

The most important step towards a coordinated management of the water resources at the VRB has been the creation in December 2002 of the Valles River Basin Committee, as a resultant of the pressure exerted by the population, especially due to the perceived impacts of industrial waste water discharges at the Valles River by the sugar mills. The VRB Committee is an auxiliary body of

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[5] These are auxiliary bodies for River Basin Councils to attend more specific geographical zones. Commissions correspond to sub-basins and Committees correspond to micro-basins. There are also Technical Committees for ground waters and Beach Committees in coastal areas (CONAGUA, 2010).

the Pánuco River Basin Council, and constitutes a working group with the participation of the water users, the Federal, state and municipal governments and the civil society in general, with the objective of coordinating programs and actions to address the different issues regarding the conditions of the rivers and the management of natural resources in general (Comité de Cuenca del Río Valles, 2008). Currently the VRB Committee includes representatives of the Secretary of Ecology and Environmental Management (SEGAM), Secretary of Environment and Natural Resources (SEMARNAT), Secretary of Agriculture, rural development and fishery (SAGARPA), Secretary of Agricultural Development and Hydraulic Resources (SEDARH), Federal Attorney for Environmental Protection (PROFEPA), Secretary of Health, Secretary of Education, Secretary of Tourism, mayors, representatives of the private agricultural, public-urban and industrial sectors, and NGOs (Palafox Juárez, 2008).

Since the establishment of the VRB Committee several programs and actions have been implemented with relatively good results. Among these is the increase in hectares irrigated through pressurized irrigation systems for a more efficient agricultural use of water, the application of irrigation tandems to stabilize the level of the Valles River during the dry season and avoiding the critical scale, the increase of measuring systems for groundwater withdrawals by pumping, the increase of wastewater treatment coverage to 100% in the urban area of Ciudad Valles through the construction of the second treatment plant, large investments in wastewater treatment and reuse to reduce discharges to the river, and an environmental audit program sponsored by PROFEPA focused on the management of wastewater and solid residues (Comité de Cuenca del Río Valles, 2008; Palafox Juárez, 2008).

The creation of the Valles River Basin Committee was a big step towards the integrated management of its water resources. However, there are several issues to overcome for the Committee to consolidate. First of all, participatory management is still only in the paper. There is an important effort by the citizens to identify the problems, but there are not enough capabilities to enhance public participation. Thus, actions to be taken are conditioned by the perception of the CNA, which normally doesn't understand thoroughly the local water issues. Additionally, management and measures implemented so far have been focused on solving the problems present in the two most important sub-basins, especially in the principal urban centre within the watershed, which is *Ciudad Valles*, and tend to ignore those existing in small rural localities. Actions taken so far, mainly headed to solve the problems of pollution and availability of water for agriculture during dry season, have had mostly a corrective nature rather than a preventive one (Santacruz de León, 2007).

1.4.3. SWAT APPLICATIONS

The SWAT model has gained international acceptance as a robust watershed modelling tool as evidenced by international SWAT conferences, hundreds of SWAT-related papers presented and dozens of articles published in peer-reviewed journals (Gassman, et al., 2007). Gassman et al (2007) reported over 250 peer-reviewed published articles related to SWAT applications and reviews, concerning hydrologic analyses, climate change impacts on hydrology, pollutant load assessments, management scenarios, and sensitivity analyses and calibration techniques, among others. Simulation of the hydrologic balance is foundational for all SWAT watershed applications and is usually described in some form regardless of the focus of the analysis. The majority of SWAT applications also report some type of calibration validation results, usually for monthly flow volumes or monthly average flows (Gassman, et al., 2007; Borah, et al., 2003).

Many of these applications have been driven by the needs of various government agencies, particularly in the United States, which require direct assessments of anthropogenic, climate change, and other influences on water resources or exploratory assessments of model capabilities for potential future applications. One of the first major applications performed with SWAT was within the Hydrologic Unit Model of the U.S. (HUMUS) modelling system, which was implemented to support USDA analyses of the U.S. Resources Conservation Act Assessment of 1997. The model was used to simulate the hydrologic and/or pollutant loss impacts of agricultural and municipal water use, tillage and cropping system trends, and other scenarios within each of the U.S. Geological Survey Hydrologic Cataloguing Units. SWAT has also supported the USDA Conservation Effects Assessment Project, which is designed to quantify the environmental benefits of conservation practices at both the national and watershed scales.

Besides the U.S. SWAT has been successfully calibrated and validated in several countries around the globe besides the U.S., such as Finland, France, UK, Germany, Belgium, Greece, Italy, Ireland, Algeria, Tunisia, New Zealand, India, China, South Korea, Australia and Uruguay. To consider an application as successful the criteria was a Nash Sutcliff Efficiency (NSE; see chapter 4) over 0.5 for calibration and/or validation on a daily or monthly time scale. In Europe, SWAT was used along with other several models to quantify the impacts of climate change for five different watersheds in Europe within the Climate Hydrochemistry and Economics of Surface-water Systems (CHESS) project, sponsored by the European Commission (Gassman, et al., 2007). SWAT has also been applied in some parts of Mexico, as described in the following section.

1.4.4. HYDROLOGICAL MODELLING IN MEXICO

There are few hydrological modelling exercises or studies of the impacts of land cover changes on watershed hydrology carried out in Mexico and reported in the literature. One of them was carried out by Mendoza, et al. (2002), who analyzed the hydrological implications of vegetation cover and land use changes between 1975 and 2000 at the basin of the lake Cuitzeo in the State of Michoacán. The methodology was an integration of remote sensing tools and geographic information systems with a water balance model, and found an increase in runoff due to increased human settlement area. At the same area of study Ortiz Rivera (2010) applied the SWAT model to analyze the effect of land use and land cover changes between 1975 and 2008, on the basis of annual streamflow values and using 5 land use/land cover historical scenarios, which were changed while keeping same weather conditions. Results suggested that plant cover had improved its condition since the 1970's decade. No calibration was performed in this study.

Torres Benites, et al. (2005) applied SWAT to the Laja River watershed in the State of Guanajuato. The authors applied a sensibility analysis, a calibration for the period 1993 – 1997 and validation for the period 1998 – 2002, using regression analysis to assess the predictive capacity of the model and obtaining a determination coefficient (r^2) of 0.97 between simulated and measured yearly streamflow for calibration period, and 0.73 for validation period. Torres Benites, et al. (2004) in turn, calibrated SWAT for "El Tejocote" watershed, to assess its predictive capacity for simulating water yield, sediments, mean flows and corn production. Simulation outputs underestimated monthly water yield by 18%, and correlation coefficient for this variable was 0.94.

Finally, it is worth to note the development of the water-flow simulator (Simulador de Flujos de Agua de Cuencas Hidrográficas – SIATL) by the National Institute of Statistics and Geography (INEGI), which is a geospatial web-based open access system that allows users to search and identify hydrographical features and to carry out usual GIS navigation tasks on Mexico's 1:50000 hydrographical network. The modelling tools allow users to perform analysis in a simple and intuitive manner, for tasks such as identifying runoff coefficients, estimating stream flows (through the rational method), detecting rivers and streams from which water flow towards a point in the network, finding settlements lying in the path of a possible flooding, and more. The simulator is aimed mainly at decision-makers, as an aid in planning, resource management and disaster prevention and response but it is open to anyone with an Internet connection (Carrasco, et al., ND).

2. CONCEPTUAL FRAMEWORK

3.1. WATER CYCLE, HYDROLOGY AND WATERSHEDS

The water cycle is a global sun-driven process whereby water is transported from the oceans to the atmosphere, to the land and back to the sea, while it's being transformed between liquid, solid and gaseous phases. It is usually described in terms of five major components: precipitation (*P*), infiltration (*I*), evapotranspiration (*ET*), surface runoff *(R)* and groundwater flow (*G*). At the planet scale it can be considered as a closed system, because the total amount of water is fixed, even though it comprises many subcycles that are generally open (Viessman, et al., 2003).

When precipitation (e.g. rain, snow) reaches the land surface, it becomes of interest for hydrologists (Schuurmans, 2008). Hydrology is an earth science, which encompasses the occurrence, distribution, movement, quality and other properties of the waters of the earth, including the hydrologic cycle and the environmental watershed sustainability. Domains of hydrology include hydrometeorology, surface hydrology, hydrogeology, drainage basin management and water quality, where water plays the central role (Viessman, et al., 2003).

Some of the precipitated water is intercepted by the vegetation and other ground covers, from where it can evaporate back into the atmosphere. The other part reaches the soil and after that may form ponds on the surface, infiltrate or run over the ground. Ponds water can evaporate or infiltrate. Infiltrated water may too evaporate, percolate, be consumed by plants and then transpired or slowly move through the soil layers until reaching a stream (base flow). Finally stream water reaches lakes or oceans and evaporates back into the atmosphere (Viessman, et al., 2003; Ward, et al., 2000). Figure 2.1 shows a simple scheme of the water cycle.

The water cycle is a simple concept which represents and comprises a set of many complex processes. It is useful to illustrate the relation between precipitation and stream flow or discharge within a watershed, which is a topographically and geologically defined spatial unit, drained by a system of streams so that all outflow is discharged through the same point in space (Ward, et al., 2000). The behaviour of the drainage system and its streams constitutes the hydrologic response of the watershed to the precipitation. Such response is synthesized by constant measuring of the discharge (volume of water vs. time) at the outlet point, and is determined by the spatial and temporal variability of precipitation and the properties of the watershed, such as its physiographic characteristics (area, shape, slope, drainage density), its soils and ground cover, and the current hydrological state of the land surface (Schuurmans, 2008; Monsalve Sáenz, 1995).

Some concepts related to specific processes within a catchment level water cycle will be used along this document. Their definitions are presented in the following lines:

- → *Canopy storage:* Is the water intercepted by vegetative surface where it is held and made available for evaporation (Neitsch, et al., 2011).
- → *Infiltration:* Refers to the entry of water into a soil profile from the soil surface (Neitsch, et al., 2011).
- → *Percolation:* Is the downward movement of water trough the soil profile, even to the shallow and deep aquifers (Neitsch, et al., 2011).

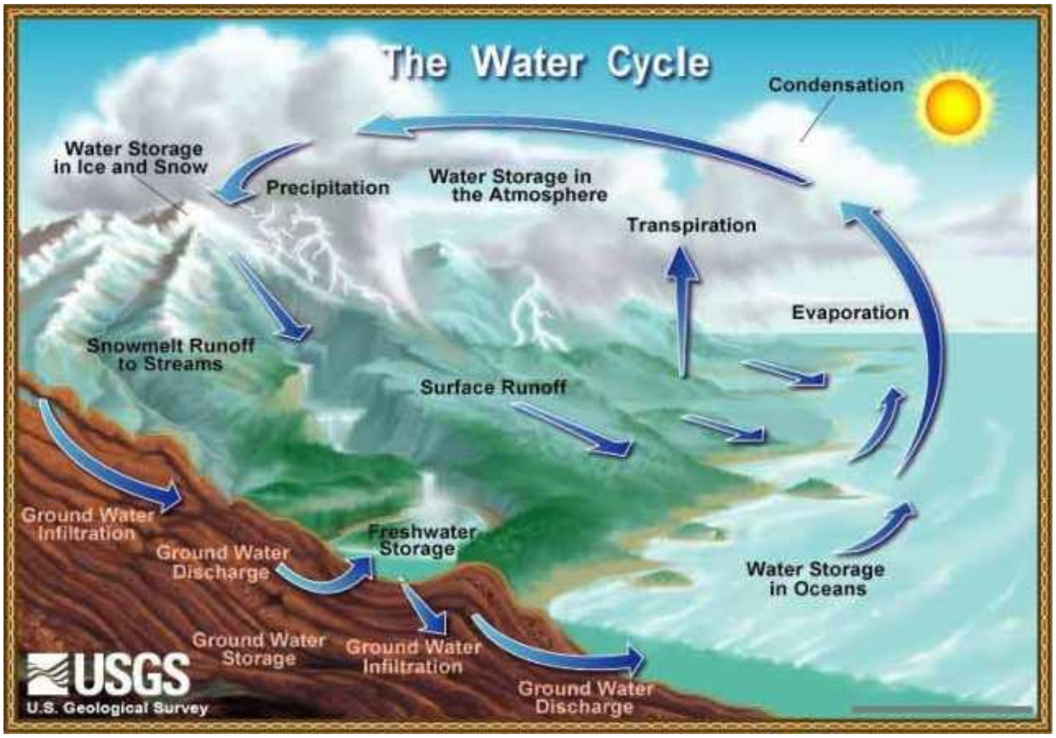

Figure 2.1. Water cycle scheme. Taken from USGS web page:
http://nd.water.usgs.gov/ukraine/english/pictures/watercycle.html

Evapotranspiration

→ *Evapotranspiration*: Collective term for all processes by which water in the liquid phase at or near the earth's surface becomes atmospheric water vapour (Neitsch, et al., 2011).

→ *Potential Evapotranspiration:* Is the rate at which evapotranspiration would occur from a large area completely and uniformly covered with growing vegetation which has access to an unlimited supply of water. It is usually defined as an atmospheric determined quantity (Xu, 2002).

→ *Actual Evapotranspiration:* Is the real rate of evapotranspiration from a certain surface determined by the actual conditions of land cover and water supply (Neitsch, et al., 2011).

Runoff sources and components

→ *Runoff, stream flow or discharge:* Is the rate of water flow through the outlet of the watershed. Constitutes the amount of water that is not extracted from the system, evapotranspired, or stored above or under the surface (water yield) (Xu, 2002).

→ *Overland flow:* Comprises the water which fails to infiltrate the soil surface and travels over the ground towards a stream channel either as quasi-laminar sheet flow or, more usually, as flow through small trickles and minor rivulets (Xu, 2002).

→ *Surface runoff:* Is that part of the total runoff which travels over the ground surface to reach a stream channel and thence through the channel to reach the drainage basin outlet (Xu, 2002).

→ *Interflow (lateral flow):* Is the lateral movement of infiltrated water through the upper soil horizons towards the stream channels, either as unsaturated flow or, more usually, as shallow perched saturated flow above the main groundwater level. There is rapid interflow and delayed interflow (Xu, 2002).

→ *Groundwater flow:* Is the volume of water contributed to the stream flow from the saturated zone or shallow aquifer. Since water can move only very slowly through the ground, the outflow of groundwater into the stream channels may lag behind the occurrence of precipitation by several days, weeks, or often years (Xu, 2002).

→ *Base flow, return flow or base runoff:* Is the sustained runoff and is constituted by the sum of groundwater flow and delayed interflow. It represents the main long-term component of total runoff and is particularly important during dry spells when surface runoff is absent (Xu, 2002). For practical purposes, sometimes this term is employed as synonym of groundwater flow.

→ *Subsurface runoff:* Is the sum of interflow and groundwater flow and is normally equal to the total flow of water arriving at the stream as saturated flow into the stream bed itself (Xu, 2002).

→ *Peak flow:* Is the maximum instantaneous discharge of a given hydrograph (UNESCO, 2011).

→ *Quick flow or direct runoff:* is the sum of channel precipitation, surface runoff and rapid interflow. Represents the major runoff contribution during storm periods and is also the major contributor to most floods (Xu, 2002).

→ *Transmission losses:* Are losses of surface flow via leaching through the streambed. They occur in ephemeral or intermittent streams where groundwater contribution occurs only at certain times of the year, or not at all (Neitsch, et al., 2011).

3.2. WATERSHED AND WATER RESOURCES MANAGEMENT

Water management and watershed management are two still evolving concepts that, although different, are closely related. They were synonyms originally, when, following the notion developed by forestry schools in the USA, "watershed management" was meant to manipulate the watershed in order to regulate water discharge, chiefly by modifying soil properties and thus enhancing or reducing infiltration, surface runoff and base flow, to finally improve possibilities for collecting and exploiting water. Since then the concept of watershed management evolved to include the protection of natural resources, mitigation of extreme events, soil conservation, erosion and pollution control, degraded zones reclamation, and finally forestry and agricultural production improvement. Recently, the inclusion of these aspects within the original concept, has extended it to the integrated natural resources management and ultimately to the integrated environmental management (Dourojeanni, et al., 2002)[6].

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[6] In this sense, Dourojeanni (2001) indicated that river basin management is one of the possible options for organizing the participation of users of natural resources within the process of environmental management. In relation to the latter, it is worth to say that there is not an unambiguous and unique definition about it. Rodríguez, et al. (2003) define it as a permanent process of successive approaches in which different private, public and civil stakeholders develop a set of efforts headed to preserve, restore, conserve and use the environment in a sustainable way. ECLAC/UNEP (1990), in turn, defined it as set of normative, administrative and operative actions taken by the State in order to achieve a development with environmental sustainability. In this study, environmental management is understood as a set of policies, strategies and actions taken by the government, the private sector and the civil society headed to consolidate the sustainable use of the environment by the human being.

Due to this evolution of the watershed management concept to include aspects not related to the water management, a distinction has to be made in relation to the latter. Still, water management is the basis of watershed management, since delimitation of watersheds is done based on hydrographical reasons (Dourojeanni, et al., 2002). Given the lack of clarity on the concepts related to water and watershed management, as well as consensus on definitions that spell out the objectives of that management, Dourojeanni, et al. (2002), classified approaches to watershed management according to the objectives and stage of the process (see table 2.1). Objectives are classified into three groups, according to the natural resources and elements that are considered in the process:

- First group: All the elements, resources and infrastructure for development of a river basin.
- Second group: All the natural elements and resources to be found in a river basin.
- Third group: Only water resources.

Likewise, these authors identified three stages within the management process. The preliminary stage consists of the elaboration of studies and the formulation of plans and projects. The second corresponds to the "development" stage, and comprises the investment for the use and management of its natural resources for economic and social development purposes. The third stage constitutes the permanent operation and maintenance of structures and management and conservation of natural resources and elements. This phase corresponds to the real notion of "management", understood as administration of the watershed.

Management stages	**Management objectives**			
	Integrated management	**Natural resources management**	**Water resources management**	
			Integrated	**Sectoral**
Preliminary	Studies, plans and projects			
Intermediate	River Basin development	Natural Resources development	Water resources development	
Permanent	Environmental management	Natural resources management	Water resources management	

Table 2.1. Different approaches to watershed management according to the objectives and the stage of the process. Taken from Dourojeanni, et al. (2002).

Integrated management is the most complete type of management. The adjective "integrated" has a lot of connotations. For watershed management, a first meaning is the necessary coordination of certain actions in order to provoke a joint effect, for flood control and water use, just to give some examples. To be integrated means also that actions have to be performed looking for benefits in both the socioeconomic and environmental senses. A third (not last) connotation is that the process has to allow participation from all the stakeholders and look for equity among the interests. The aforementioned traditional approach (aimed at regulating runoff) is part of the approach to natural resources management. The third level of management, dedicated exclusively to water resources, is headed towards coordination of investments in water resources development and subsequent management thereof (Dourojeanni, et al., 2002).

Thus, water resources management became just a part of what is considered a comprehensive watershed management. This concept has also had a parallel evolution, passing through different interpretations, where the United Nations and some other international organizations have played a significant role. According to the World Bank (1998, cited in Valencia Vargas, et al., 2004) there are four basic ways to undertake the management of water resources:

1. Project oriented management: Gives priority to isolated projects on water supply, irrigation, hydropower development, navigation, recreation, etc.
2. Sectoral development: There are several projects for similar uses conceived under a sectoral framework, identifying water sources for subsectors and maximizing benefits for the sector. Most of these cases are related to water supply, irrigation and sanitation programs.
3. Sectoral management: In this case, water issues are solved through institutional innovation or infrastructure projects.
4. Integrated Water Resources Management (IWRM): Is a process which considers all water uses, including the environment and conflicts among users are solved through the administration of supply and demand, but also through institutional innovation. A great deal of social participation exists for decision making processes.

The most important distinction, already made in table 2.1, is between sectoral and integrated management, although there is also a first level which doesn't even reach the sectoral level. Sectoral management was the only known level of river basin management in Latin-American countries until recent years, and it is at this level that most of the studies and investments in hydroelectricity, irrigation and drainage, drinking water supply and flood control have been conducted (Dourojeanni, et al., 2002). IWRM, on the other hand, has emerged during the last decades as a response to water scarcity and problems in water supply and water quality (UNW-DPC, 2010), among other issues related to the so-called "water crisis", such as floodings, droughts and conflicts at the local, national and international level related to the access to the resource (GWP, 2000).

IWRM is the only approach to water resources management that addresses the problem of water sustainability, looking for long-term solutions and a current water use which does not prevent future generations from obtaining the same quality of life from the same resource. The term "integrated" in IWRM refers to different levels of integration. According to Snellen, et al. (2004) the first notion of integration related to the concept was in reference to a broader development context, which referred to the need of complementing infrastructure development with the supporting of related services and implementing measures affecting other aspects of resource use. Afterwards, a new connotation was the necessity of coordination within water national sectors for the development and management of water resources. Sectoral integration was the next meaning embraced, after the recognition in the Agenda 21 of the great impediments that "fragmentation of responsibilities for water resources development among sectoral agencies" was representing for IWRM.

Dourojeanni, et al. (2002) recognize some other meanings for the integrated nature of water management, like the need of taking into account all the uses and users involved, the quantitative, qualitative and ecological aspects of the water cycle, and the whole system formed by surface water and groundwater. Moreover it can be related to the integration of the different uses and users with the purpose to reduce conflicts; integration of all aspects of water having an influence on use and users, such as quantity, quality, temporality and space of occurrence and the administration of both supply and demand; the integration of the different phases of the hydrologic cycle, such as surface water and groundwater; and the integration of water management into the management process of related natural resources (Dourojeanni, et al., 2002). Integrated management in a new sense refers to the fact that water resources should be managed as an integral part of a nation's social and economic development (Snellen, et al., 2004).

3.3. HYDROLOGICAL MODELLING

Watersheds, as most of the hydrologic systems, constitute complex systems which are not currently possible to understand in all their detail. Therefore, is necessary to make an abstraction of them: replacing the parts of the universe under consideration by a model of similar but simpler structure. A model is a simplified representation of a complex system, describing its basic and most important components. It involves similarity but not identity, and simulates some, but not all the characteristics of the prototype system (Xu, 2002).

Due to the complex nature of rainfall-runoff processes within a watershed, determined by a number of highly interconnected water, energy and vegetation processes, hydrologists rely on their own understanding of the system gained through interaction with it, observation and experiments. This process is known as perceptual modelling (Moradkhani, et al., 2009). Knowledge of the physical system helps in developing a good model and verifying its accuracy. Catchment or watershed modelling may have, broadly speaking, two purposes: 1) to gain a better understanding of the hydrologic phenomena and of how changes in the catchment may affect these phenomena, or 2) the generation of synthetic sequences of hydrologic data (Xu, 2002). According to this definition the present study correspond to the first purpose.

3.3.1. HISTORICAL OVERVIEW

The beginning of the development and application of models in hydrology can be traced back to the middle of the 19th century, when they arose in response to three types of engineering problems: urban sewer design, land reclamation drainage systems design, and reservoir spillway design. The concept of the rational method for determining flood peak discharge from measurements of rainfall depths owes its origins to Mulvaney (1850), an Irish engineer who was concerned with land drainage. This method may be seen as the first generation of hydrologic models. In it, the Peak Flow (*Qp*) was the output variable, the Intensity of Rainfall (i) in Time of Concentration (*Tc*) and the Area of the catchment were the inputs, and the Runoff Coefficient (*C*) was the model parameter (Xu, 2002).

During the decade of the 1920s many modifications were introduced into the rational method in order to cope with the non-uniform distribution, in space and time, of rainfall and catchment characteristics. The modified rational method was based on the concept of isochrones (lines of equal travel time), and can be seen as the first basic rainfall-runoff model based on a transfer function whose shape and parameter were derived by means of topographic maps and the use of Manning's formula to evaluate the different travel times. In 1932 Sherman, an American engineer, introduced the concept of the Unit Hydrograph, which made it possible to calculate not only the flood peak discharge but also the whole hydrograph, or the volume of surface runoff produced by the rainfall event. During the late 1930s and the 1940s the techniques of statistical analysis were introduced in order to improve the objectivity of the method and results (Xu, 2002).

In the 1950s hydrologists became aware of system engineering approaches used for the analysis of complex dynamic systems. They finally realised that the unit hydrograph was the solution of a linear time invariant system and that the use of mathematical techniques such as Laplace, Fourier and Z transforms could lead to the derivations of the response function from the analysis of input and output data. This was the period when conceptual models originated. Hydrologists found that shapes of the unit hydrograph could be provided on the basis of the solution of more or less simplified differential equations, such as those describing the time behaviour of the storage in a reservoir or in a cascade of reservoirs (Nash, 1958, 1960). The unit hydrograph could then be expressed in terms of few parameters to be estimated from catchment characteristics or by means of statistical procedures: moments, regression, maximum likelihood, etc. a bloom of these models gave rise to an unbelievable variety of solutions (Xu, 2002).

Many other approaches to rainfall-runoff modelling were developed during the 1960s. The search for a more physical interpretation of the process brought representations of the behaviour of single components of the hydrologic cycle, at the catchment scale, by using a number of interconnected conceptual elements, each of which represented the purpose of a particular subsystem. A large number of conceptual, lumped, rainfall-runoff models appeared thereafter. In the 1970s real-time forecasting models and other more complex models were developed, such as the TOPMODEL, the Autoregressive Moving Average (ARMA) model, and other forms of time series stochastic models (Xu, 2002).

Since their beginning hydrological catchment or runoff models have evolved to incorporate more complexity, looking for more accuracy in the representation of the real world systems. During last decades these efforts have been reflected in the development of mathematical distributed and semi-distributed physically-based models, which try to reflect more closely the physical laws governing the behaviour of water and related variables, while attempting to include the spatial heterogeneity of the hydrologic system's characteristics. These models were developed seeking to forecast, among others, the effects of land-use changes, the movements of pollutants and sediments, and the hydrological response of ungauged catchments. These models, like the *Systéme Hydrologique Européen* (*SHE*), have taken advantage of Digital Elevation Models (DEM) and various advances in Remote Sensing. During the late 1980s the evolution of continental-scale hydrology placed new demands on hydrologic modellers, and great focus was made on the development of macro-scale hydrological models. Due to all this development process, nowadays mathematical models have taken over the most important tasks in problem solving in hydrology (Xu, 2002).

3.3.2. HYDROLOGIC MODELS TYPES

There are several forms to classify existing hydrologic models. A first distinction can be made between material and symbolic models (see Figure 2.2), as did by Singh (1988, cited in Xu, 2002). Material models recreate the prototype system on a reduced scale, reproducing its main physical aspects, resembling the prototype (scale models) or relying on the correspondence between the symbolic models describing the prototype and the analogue system (analogue models). Symbolic models, on the other hand, are also called formal or abstract models, and are symbolic expressions in logical terms of an idealised, relatively simple situation sharing the structural properties of the original system (Xu, 2002).

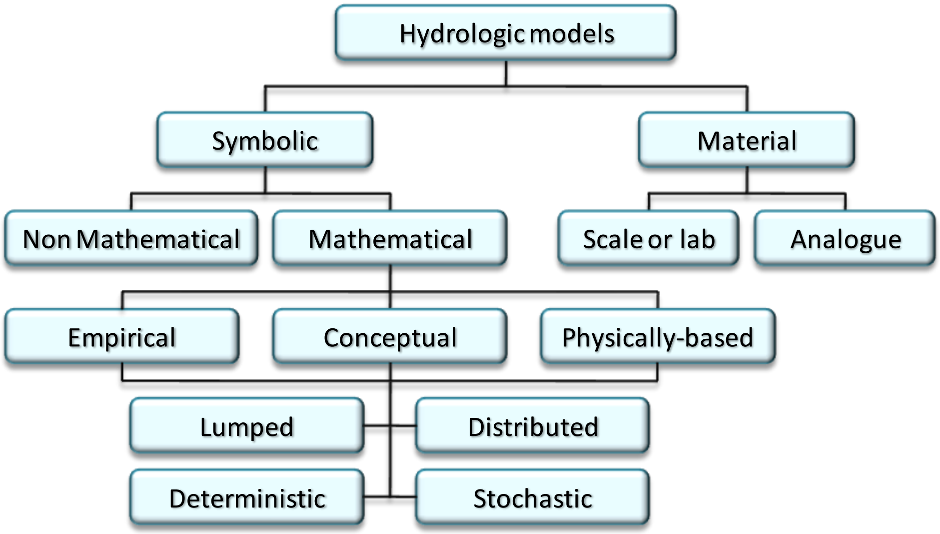

Figure 2.2: Classification of hydrologic models according to Singh (1988, cited in Xu, 2002).

Hydrologic systems are generally analyzed by using symbolic mathematical models (Viessman, et al., 2003). These models express the system behaviour by a set of equations and logical statements expressing relationships between variables and parameters. What all mathematical models have in common is that the observed output variable Y_t (often discharge from a basin) is finally derived from its fitted values by a residual amount. However, they differ on the assumptions made about the function relating inputs, parameters and outputs and about the residual amount (Xu, 2002).

Mathematical models are usually classified in terms of how processes are represented, the time and space scale that are used and what methods of solution to equations are used. The first feature defines if the model is based on a simple mathematical link between input and output variables or if it includes the description, even if in a simplified way, of the basic processes involved in the runoff formation and development. In the first case models are said to be empirical, parametric or black-box models. They vary from simple regression models to the more recent Artificial Neural Networks models, and contain parameters that may have little direct physical significance and can be estimated only by using concurrent measurements of input and output (Melone, et al., 2005; Xu, 2002).

In the second case models are called physically-based, theoretical or white-box models. They have a logical structure that tries to closely simulate the real-world system, based on the incorporation of the known physical laws governing the hydrologic phenomena. This type of models includes some such as watershed runoff models based on St. Venant equations and the *SHE* model. Finally, when the model structure considers only highly simplified physical laws, models are said to be conceptual, and they constitute an intermediate between physically-based and empirical models (Melone, et al., 2005; Xu, 2002).

Another important classification distinguishes between lumped, semi-distributed and distributed models. Models that ignore spatial variations in parameters within a system are lumped models. They treat the complete basin as a homogeneous whole, and impose many assumptions, especially in large watersheds, as variables and parameters are representative average values.

These models are generally designed to simulate the streamflow just at the watershed outlet. However, one may want to estimate the flow at some interior locations in a river basin for engineering design, for real time operational flood forecasting and also for studying the effects of land use or climate change. Distributed models, in turn, account for behaviour variations from point to point throughout the system. The basin is divided into elementary unit areas and flows are passed from one to another as water drains through the basin. Semi-distributed models attempt to calculate flow contributions from separate areas that are treated as homogeneous within themselves (Moradkhani, et al., 2009; Schuurmans, 2008; Melone, et al., 2005; Viessman, et al., 2003; Xu, 2002).

Hydrologic mathematical models can be classified in some more several forms. As an example, they can be stochastic or deterministic. If any of the input or output variables is regarded as random variable having distribution in probability, then the model is stochastic (or probabilistic). On the other hand, if all variables are regarded as free from random variation, so that none is thought of as having a distribution in probability, then the model is regarded as deterministic. Also, short-term models may be regarded as single-event or event-based models, as they describe the hydrologic response or a watershed to a single rainfall event, while long-term models may be called continuous models, simulating outflows for periods of years. However, the two most often classification criteria are the ones which distinguish between conceptual and physically based models, and between lumped and distributed models. Two typical model types are lumped conceptual and distributed physically based (Melone, et al., 2005; Viessman, et al., 2003; Xu, 2002).

A special denomination is that of the Rainfall-Runoff (R-R) models, which mathematically represent the interaction of surface and subsurface processes and the conversion of precipitation into runoff at the watershed level. This kind of model can be inserted in a mathematical framework irrespective of whether the model is physical, empirical and/or conceptual. R-R models may be denoted by a nonlinear function f (.) signifying the derivative of the state vector x with respect to time t. In addition, the system is characterized by k-member vector of parameters θ, and forcing field (input) variables u as follows:

$$\frac{\mathrm{d}x_t}{\mathrm{d}_t} = f\ (x_t\,, \theta, u_\mathrm{t}) +\ w_\mathrm{t} \tag{Eq. 2.1}$$

Where, x_t is an N_x-dimensional vector representing the system state (for example catchment soil moisture content) at time t. The function expresses the system transition over a time instant in response to the model input vector (forcing data, u, e.g., mean areal precipitation). Due to error associated with the observed input to the system, the uncertainty in parameter estimation and/or parameter identification and also model structural error for accurate representation of physical data generating process, the aggregate uncertainty may be defined through an additive error term w_t (Moradkhani, et al., 2009).

3.3.3. MODEL SELECTION

There are dozens of mathematical models of watershed hydrology available today. Their diversity is such that one can easily find more than one watershed model for addressing any practical problem (Singh, et al., 2006). With such a variety of models is necessary to make a conscious choice according to well established criteria. The most important set of criteria is the project-dependent. The choice should pursue the objectives or purposes for which it is to be used. Some elements to establish as selection criteria are (Haberlandt, 2010; Xu, 2002):

- Desired outputs: ¿Does the model predict the output variables required by the project?
- Desired processes: ¿is the model capable of simulating the hydrologic processes that are needed to be modelled?
- Temporal scale: ¿is it possible to perform simulations at the desired time-step?
- Spatial scale: ¿which are the basic modelling units of the model?
- Requirements: ¿what are the skills, computing and time resources required by the model?

The simplest model capable of achieving the objectives should be used. Besides, the nature of the physical processes involved, the complexity of the problem and the quality of the data available must be considered. Examining the nature of the physical processes involved concerns some aspects of them such as being deterministic or stochastic, dependent or independent, time-dependent or time-independent or influenced by man or not. Regarding the complexity of the problem, aspects like the number of variables and parameters involved and the nature of their interrelationships should be taken into account. Finally, considering the availability of data quality implies analyzing its availability, gaps, reliability and time intervals (Viessman, et al., 2003; Xu, 2002).

However, one may find several models that fulfil these requirements, and then other types of criteria, including personal preferences of the modeller (for instance for a Graphical User Interface or a computer operation system) may come into play. All these criteria are to be employed during a first phase of the model selection. However, after completing its calibration and validation, the outcomes of the model should confirm or reject the choice according to the previously established level of accuracy desired. Thus, the selection process ends when its performance in a given context is assessed (Haberlandt, 2010; Viessman, et al., 2003).

According to (Xu, 2002), model selection is part of the model evaluation process, along with calibration, validation and performance evaluation. Hence, as the established general objective was to analyze the applicability of the model to a specific watershed, this study can be regarded as part of a whole selection process of an appropriate hydrologic model for the Valles River Basin, a process which has to be concluded by testing other models. Although no exploration of other models was done, SWAT's properties were analyzed in relation to the specific objective of identifying land cover/land use change hydrological effects. It was considered as very convenient due to the following reasons:

- ✓ Its semi-distributed character allows to model spatial heterogeneity in land use and land covers (among other variables) without the huge data requirements of fully distributed models.
- ✓ It includes the possibility to model land management practices, such as tillage, fertilizing, irrigation and harvest.
- ✓ It allows to model streamflow at a daily scale, which was the time-step considered as necessary in this study.

- ✓ It can be operated under the ArcSWAT interface, which is an open source GIS Graphical User Interface that makes it easier to manipulate georreferenced inputs, processes, commands and outputs.
- ✓ ArcSWAT works under the ArcGIS software, and therefore constituted a personal preference of the modeller.
- ✓ SWAT has gained international acceptance as a robust watershed modelling tool as evidenced by international SWAT conferences, hundreds of SWAT-related papers presented and dozens of articles published in peer-reviewed journals (Gassman, et al., 2007).

Despite its convenient properties, every model has to be calibrated and simulated, and in this case a part of the applicability evaluation concerns some characteristics of the model, such as:

- Even though it is a semidistributed model, SWAT requires a lot of data, which may be very difficult to find in some countries or regions.
- It was developed in the United States, which implies two things:
  - The data availability which it was developed under is greater than that of Latin-American countries.
  - The databases included with the model, which contain required data about land covers, soils, tillage, fertilizers and others, were developed according to research carried out in different conditions from that of Latin-American countries.

3.3.4. THE SWAT MODEL

3.3.4.1. Generalities

The SWAT model was developed at the U.S. Department of Agriculture (USDA) – Agricultural Research Service (ARS) Grassland, Soil and Water Research Laboratory in Temple, Texas (Borah, et al., 2003). It is a basin-scale, continuous-time, physically-based and deterministic model that operates on a daily time step and is designed to assess the impacts of land management practices on a watershed or river basin scale (Neitsch, et al., 2005). It is a physically based model, meaning that it directly models the movement of water by solving a set of equations that simulate the physical process within the watershed, rather than incorporating regression equations to describe the relationship between inputs and output variables. It is capable of modelling basically all hydrologic processes in a watershed, all driven by the water balance. Major model components include weather, hydrology, soil temperature and properties, plant growth, nutrients, pesticides, bacteria and pathogens, and land management (Neitsch, et al., 2005). This section briefly describes the relevant components for this study's objectives.

Hydrologic cycle simulated by SWAT is based on the following water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw} \qquad \text{(Eq. 2.2)}$$

Where: SW_t is the final soil water content, SW_0 is the initial soil water content on day i, t is the time (days), R_{day} is the amount of precipitation on day i, Q_{surf} is the amount of surface runoff on day i, E_a is the amount of evapotranspiration on day i, w_{seep} is the amount of water entering the vadose zone from the soil profile on day i, and Q_{gw} is the amount of return flow on day i. All variables are computed in mm H_2O (Neitsch, et al., 2005).

In SWAT, a watershed is divided into multiple subwatersheds, which are then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, slope, management, and soil characteristics. The overall hydrologic balance is simulated for each HRU, including canopy interception of precipitation, partitioning of precipitation, snowmelt water, and irrigation water between surface runoff and infiltration, redistribution of water within the soil profile, evapotranspiration, lateral subsurface flow from the soil profile, and return flow from shallow aquifers (Gassman, et al., 2007).

Climatic variables provide the moisture and energy inputs that control the water balance. As weather input variables SWAT requires at least daily precipitation, maximum and minimum temperature and solar radiation. If measured data is completely or partially unavailable for one of these variables, values can be generated using the WXGEN Weather Generator Model (Sharpley, et al., 1990) incorporated in SWAT. Based on observed input average monthly values, this model generates daily values for each subbasin independently. Generated values are thus not spatially correlated and keep the same statistical properties as monthly inputs.

For the present study the only one generated variable was solar radiation. The procedure used is based on a weekly stationary generating process (Matalas, 1967) which firstly generates serially correlated daily residuals, then multiplies these values by the monthly standard deviation and adds the monthly average. Finally, these values are adjusted for clear/overcast conditions for each day, based on the presence or absence of rain, by using a continuity equation and assuming that the average wet day solar radiation is a fraction of the average dry day solar radiation.

3.3.4.2. The land phase of the hydrologic cycle

Simulation of the water cycle is partitioned into two major divisions. The first is the land phase, which controls the amount of water and loadings to the main channel in each subbasin. The second division, the routing phase, comprises the movement of water through the channel network to the watershed's outlet (Gassman, et al., 2007; Neitsch, et al., 2005).

As rain falls water may follow many pathways. It can be intercepted by the vegetation canopy or fall to the soil surface, from where it will infiltrate of flow overland as runoff, quickly reaching a stream channel and contributing to short-term stream response. Infiltrated water may be held in the soil and later evapotranspired or may slowly reach the surface-water system via underground paths. Canopy storage is taken into account when using the Curve Number method (CN) to compute surface runoff (see following section). Infiltration rate depends on the initial moisture of the soil, and its final value is equivalent to the saturated hydraulic conductivity of the soil. The amount of water infiltrated is calculated as the difference between the amounts of rainfall and runoff (Neitsch, et al., 2005).

Water infiltrated after precipitation or irrigation keeps moving through the soil profile when infiltration ceases, until its inner distribution is uniform. Percolation occurs when field capacity of a soil layer is exceeded and the layer below is not saturated. The flow rate is governed by the saturated hydraulic conductivity of the soil layer. Redistribution is also affected by soil temperature. Daily average soil temperature, which also affects the decay rate of residue in the soil, is calculated at the soil surface and at the centre of each soil layer (Neitsch, et al., 2005).

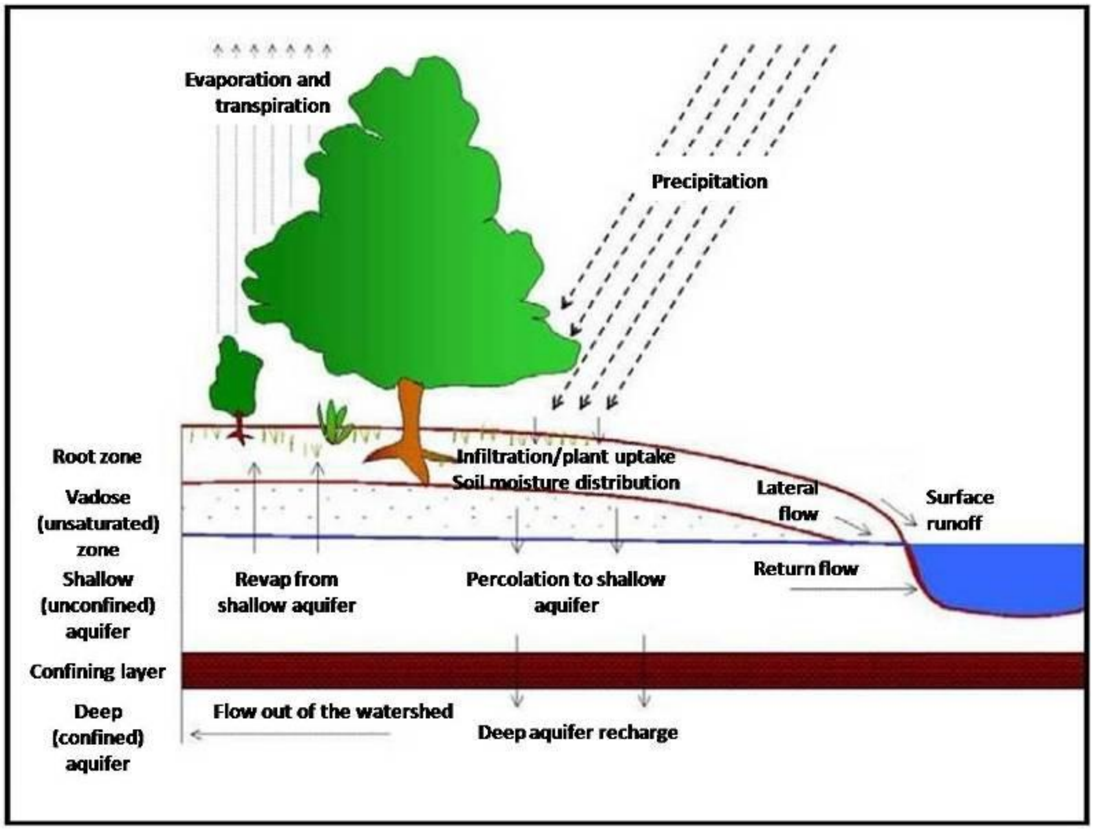

Figure 2.3. Representation of the hydrologic cycle as conceptualized in SWAT (Neitsch, et al., 2011).

Lateral subsurface flow, or interflow, is streamflow contribution which originates below the surface but above the zone where rocks are saturated with water (0 – 2 m). It is calculated simultaneously with redistribution. The model accounts for variation in conductivity, slope and soil water content. Surface runoff volume is computed using a modification of the SCS Curve Number method (USDA Soil Conservation Service, 1972 – see following section) or the Green & Ampt infiltration method (Green & Ampt, 1911). Peak runoff predictions are made with a modification or the rational method, which is based on the idea that, if a rainfall of intensity i begins instantaneously and continues indefinitely, the rate of runoff will increase until the time of concentration (T_c), when all of the subbasin is contributing to flow at the outlet (Neitsch, et al., 2005).

Return flow, or baseflow, is the volume of stream flow originating from groundwater. SWAT partitions groundwater into a shallow unconfined aquifer, which contributes return flow to streams, and a deep confined aquifer, which contributes return flow to streams outside the watershed. Water stored in the shallow aquifer may also replenish moisture in the soil profile in very dry conditions or be directly removed by plants or by pumping. SWAT also allows a water balance within reservoirs to be estimated. Resulting outflow can be directly input as measured records or be simulated by specifying water release rates for small uncontrolled reservoirs or by specifying monthly target volumes for larger ones (Gassman, et al., 2007; Neitsch, et al., 2005).

Surface runoff

Surface runoff occurs whenever the rate of water application to the ground surface exceeds the infiltration rate. In this case, surface depressions begin to fill, and if the application rate continues to be higher than infiltration rate once all surface depressions have filled, surface runoff will commence (Neitsch, et al., 2005). The method used to simulate this process is the USSCS Curve Number (CN) method, which is an empirical model that came into common use in the 1950s, being the result of more than 20 years of studies involving rainfall-runoff relationships from small rural watersheds across the United States (Neitsch, et al., 2005). It takes the following form:

$$Q_{surf} = \frac{\left(R_{day} - I_a\right)^2}{\left(R_{day} - I_a + S\right)} \qquad \text{(Eq. 2.3)}$$

Where Q_{surf} is the accumulated runoff or rainfall excess, R_{day} is the rainfall depth for the day, I_a are the initial abstractions which include surface storage, interception and infiltration prior to runoff, and S is the retention parameter. S varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content. It is defined as:

$$S = 25.4 \left\{\frac{1000}{CN} - 10\right\} \qquad \text{(Eq. 2.4)}$$

Where *CN* is the curve number for the day. Initial abstractions (I_a) are commonly approximated as 0.2*S*, and thus equation 2.3 becomes:

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} + 0.8S\right)} \qquad \text{(Eq. 2.5)}$$

All variables are computed in mm H_2O. Runoff will only occur when $R_{day} > I_a$ (Neitsch, et al., 2005).

The curve number is a function of the soil's permeability, land use and antecedent soil water conditions. It varies non-linearly with the soil moisture content of the soil, dropping as the soil approaches the wilting point and increasing to near 100 as the soil approaches saturation. Tables containing typical curve numbers for the different soil moisture conditions, land covers and soil hydrologic groups are found in the literature. Soil hydrologic groups are constituted by soils with similar runoff potential under similar storm and cover conditions, according to a classification made by the U.S. Natural Resource Conservation Service (NRCS). Runoff potential is influenced by depth to seasonally high water table, saturated hydraulic conductivity (K_s) and depth to very slowly permeable layer (Neitsch, et al., 2005).

Soils classified as A have low runoff potential and high infiltration rates even when thoroughly wetted. They are deep, well drained to excessively well drained sands or gravels. Soils classified as

B show moderate infiltration rates when thoroughly wetted, being moderately deep to deep that have moderately fine to moderately coarse textures. C soils have slow infiltration rates when thoroughly wetted. Usually they present a layer that impedes downward movement of water or have moderately fine to fine textures. Finally, D soils have high runoff potential, consisting mainly of clay soils with high swelling potential, or a permanent water table, a clay pan or a clay layer at or near the surface, or shallow soils over nearly impervious material (Neitsch, et al., 2005).

Antecedent soil moisture conditions are classified into 3 categories: I – dry (wilting point), II – average moisture, and III – wet (field capacity). Condition I curve number is the lowest value that the daily CN can assume. The retention parameter varies with the soil profile water content and with accumulated evapotranspiration. Finally, the curve numbers have to be adjusted for the slope, given that typical values are for 5% slopes. This adjustment is done with an equation developed by Williams (1995) (Neitsch, et al., 2005).

Evapotranspiration

Estimation of Evapotranspiration (ET) is achieved through first estimating Potential Evapotranspiration (ET_P) and then Actual Evapotranspiration (ET_A). ET_P concept was originally introduced by Thornthwaite in 1948 and then redefined by Penman in 1956. It is understood as "the amount of water transpired by a short green crop, completely shading the ground, of uniform height and never short of water. It is also referred to as Reference Evapotranspiration (ET_0). SWAT includes three methods to estimate ET_P: the Penman-Monteith method (Penman, 1956; Monteith, 1985), the Priestly-Taylor method (Priestly, et al., 1972) and the Hargreaves-Samani Method (Hargreaves, et al., 1985).

The Penman-Monteith method has proved to be the most accurate one (Campos-Aranda, 2005) and is recommended by FAO (Allen, et al., 1998). However, besides solar radiation and air temperature, this method requires relative humidity and wind speed measured values, which are not available at the meteorological stations of the Valles River Basin. Priestly-Taylor method does not require wind speed data but needs relative humidity (Neitsch, et al., 2005). Therefore, the Hargreaves-Samani method, which is an empirical model requiring only temperature data, was chosen. This method was tested for Mexico's conditions against the Penman method and the Makkink and Turc equations by Campos-Aranda (2005), who analyzed 31 meteorological observatories, located around the country and found that it reproduced better the results obtained with the Penman method for dissimilar environments along the year. The Hargreaves-Samani equation used by SWAT is (Neitsch, et al., 2005):

$$\lambda E_0 = 0.0023 \text{ x } H_0 \text{ x } (T_{mx} - T_{mn})^{0.5} \text{ x } (\bar{T}_{av} + 17.8) \qquad \text{(Eq. 2.6)}$$

Where λ is the latent heat of vaporization (MJ/kg), E_0 is the potential or reference evapotranspiration, H_0 is the extraterrestrial radiation (MJ/m^2/day), T_{mx} is the maximum air temperature for a given day (°C), T_{mn} is the minimum air temperature for a given day (°C), and $\bar{T}_{av}$ is the mean temperature for a given day.

Soil water, ground water and baseflow

Water infiltrated into the soil profile may take one of three pathways. It can be taken up by plants, percolate through the vadose zone to the aquifers or contribute to streamflow by moving as lateral flow. Most of the volume of water takes the first path. Additionally, if surface runoff occurs, the model allows to simulate bypass flow in soils with vertic properties (formation of cracks due to drying of soils with high swelling-clays content), which are very significant in the study area. Bypass flow, which is the vertical movement of free water along soil macropores through unsaturated soil horizons, occurs when the rate of rainfall or irrigation exceeds the vertical infiltration rate. A volume of water equal to the volume of cracks in the soil may enter the profile as bypass flow (Neitsch, et al., 2005).

Percolation, which is the downward movement of water in the soil, is calculated for each layer in the soil profile. It occurs only if the water content exceeds the field capacity of the layer and if the layer below is not saturated. Lateral flow, on the other hand, is significant in shallow soils with high hydraulic conductivity in surface layers. The amount of water that moves downward from one layer to the underlying layer is calculated in SWAT using a storage routing technique, while the lateral subsurface flow is calculated through a kinematic wave storage model (Neitsch, et al., 2005).

Regarding groundwater, SWAT simulates the existence of a shallow unconfined aquifer and a deep confined aquifer. Volume of water available in shallow aquifer depends on the recharge from the soil profile, the amount of water contributed to the main channel of the subbasin as baseflow, the upward movement into the overlying unsaturated zone and percolation into the deep aquifer. On the other hand, water content in the deep aquifer is a function of inputs from the shallow aquifer through percolation and the quantities extracted by pumping. This water is assumed to be lost by the system, contributing to streamflow somewhere outside the watershed (Neitsch, et al., 2005).

Baseflow contribution from shallow aquifer to the main channel occurs when the amount of water stored in the shallow aquifer exceeds a threshold value specified by the modeller. The steady-state response of groundwater flow to recharge is (Neitsch, et al., 2005):

$$Q_{gw} = \frac{8000 \text{ x } K_{sat}}{L_{gw}^2} \text{ x } h_{wbtl} \qquad \text{(Eq. 2.7)}$$

Where Q_{gw} is the groundwater flow or baseflow into the main channel on day i (mm H_2O), K_{sat} is the saturated hydraulic conductivity of the aquifer (mm/day), L_{gw} is the distance from the ridge or subbasin divide for the groundwater system to the main channel (m), and h_{wbtl} is the water table height (m) (Neitsch, et al., 2005).

3.3.4.3. The routing phase of the hydrologic cycle

Once the model determines the contributions of water and loadings to the main channel of each subbasin, the routing phase of the hydrologic begins, simulating several in-stream processes. As water flows along the channels, a portion may be lost due to evaporation and transmission through the bed of the channel, and additionally due to removal for consumptive use. Flow may be supplemented by the fall of rain directly on the channel and/or addition of water from point source discharges. Manning's equation for uniform flow is used to determine rate and velocity of flow in a channel's segment for a given time step. Flow is routed through the channel using a variable storage coefficient method developed by Williams (1969), which is a variation of the kinematic wave approach and is based on the continuity equation (Neitsch, et al., 2005).

3.3.5. SOME OTHER HYDROLOGIC MODELS

This section provides a brief description of some few of the most popular models currently available, according to Refsgaard, et al. (2010) and Cunderlik (2003).

3.3.5.1. The SHE model

In 1969 Freeze & Harlan published a call for development of distributed physically-based catchment models. This was a paradigm shift as compared to the lumped conceptual models such as the Stanford Watershed Model. The first hydrological model code that was developed to meet this concept was the Système Hydrologique Européen (SHE), a collaborative venture initiated in 1976 between the Danish Hydraulic Institute, the British Institute of Hydrology and the French consulting company SOGREAH (Refsgaard, et al., 2010) and funded by the European Commission. The objective in building SHE was to produce a catchment-scale, physically based, two-dimensional hydrological and hydraulic model, to be used for simulating water budgets and flows across a wide range of physiographic and climatic conditions, and under different types of land cover and land management (Odoni, et al., 2010).

The SHE model was built with a strong physical basis, in order to give it the widest ranges of applicability. It was therefore built in modular form, to comprise a set of linked components, based on spatial and temporal scales appropriate to each of the system components being modelled, and incorporating physical and empirical formulations. It was intended that the model's sophistication and general applicability could, over time, be enhanced through updating one or more of the modules as and when necessary (or indeed, convenient), but without changing the underlying rules and procedures for linking and combining the modular output (Odoni, et al., 2010). Today, two codes exist based on the original SHE model: the MIKE SHE code further developed by DHI and the SHETRAN code further developed by University of Newcastle. In both MIKE SHE and SHETRAN, the basic process descriptions have in various ways been modified and extended to include alternative or new process descriptions and numerical solution techniques (Refsgaard, et al., 2010).

According to DHI (2003) the couple MIKE SHE/MIKE 11 is the most widely used hydraulic modelling system in the world and has been approved for use by regulatory authorities in many countries including USA, Australia and UK. The transformation of the SHE into the MIKE SHE began in the late 1980s and focused on developing a graphical user interface (Refsgaard, et al., 2010). It is a physically-based, integrated, distributed and deterministic model (Xu, 2002) applicable to spatial scales ranging from single soil profiles (for infiltration studies) to regional watershed studies. It includes all of the processes in the land phase of the hydrologic cycle: precipitation (rain or snow), evapotranspiration, interception, overland sheet flow, channel flow, unsaturated sub-surface flow and saturated groundwater flow. Evapotranspiration is calculated using the Kristensen and Jensen method. Overland flow component includes a 2D finite difference diffusive wave approach using the same 2D mesh as the groundwater component. MIKESHE includes a traditional 2D or 3D finite-difference groundwater model. It has three options for calculating vertical flow in the unsaturated zone: the full Richards equation, a simplified gravity flow procedure, and a simple two-layer water balance method for shallow water tables (Cunderlik, 2003).

3.3.5.2. The TOPMODEL

The TOPMODEL is a physically-based semi-distributed model developed by the University of Lancaster (Refsgaard, et al., 2010; Xu, 2002). It is one of the most widely used precipitation runoff model codes in the research community (Refsgaard, et al., 2010). TOPMODEL is a TOPography based hydrological MODEL, meaning that predictions in it are based on an analysis of basin topography. Its development was initiated at the School of Geography of the University of Leeds, and further developed by Keith Beven at the Lancaster University (Cunderlik, 2003). Since 1974 there have been many variants of TOPMODEL but never a "definitive" version. This has been intentional because TOPMODEL is not intended to be a traditional model package of general applicability, but is more a set of conceptual tools that can be used to simulate hydrological processes in a relatively simple way where they are considered as appropriate by the modeller (Beven, 1997; Beven, et al., ND).

TOPMODEL simulates explicit groundwater/surface water interactions by predicting the movement of the water table, which determines where saturated land-surface areas develop and have the potential to produce saturation overland flow. It is a variable contributing area conceptual model in which the dynamics of surface and subsurface saturated areas is estimated on the basis of storage discharge relationships established from a simplified steady state theory for downslope saturated zone flows. The theory assumes that the local hydraulic gradient is equal to the local surface slope and implies that all points with the same value of the topographic index *a/tan B* will respond in a hydrologically similar way. This index is derived from the basin topography, where *a* is the drained area per unit contour length and *tan B* is the slope of the ground surface at the location (CSDMS, 2011). The use of this index greatly simplifies catchment dynamics, and therefore the model should be used with care and perhaps be modified to suit particular circumstances. The model code allows its structure to be changed to reflect modeller's perceptions of the hydrological response of the particular system, if there is a perception that the equations of the model do not adequately reflect the processes (Beven, 1997).

The model allows basins to be divided into a set of subbasins. Evaporation is estimated by using the Penman-Monteith method. Surface runoff is computed based on variable saturated areas. The subsurface flow is calculated using an exponential function of water content in the saturated zone. Channel routing and infiltration excess are calculated using the Beven and Kirkby method. The spatial component requires a high quality DEM without sinks (Cunderlik, 2003). A correct estimation of evaporation is critical for model performance. Evaporation is most frequently estimated by using the Penman-Monteith methods. Time scale and resolution constraints can vary from 1 to 24 hours (CSDMS, 2011). Calibration parameters are relatively few in number and have obvious physical interpretations. TOPMODEL can be applied most accurately to catchments that do not suffer from excessively long dry periods and have shallow homogeneous soils and moderate topography. Model results are sensitive to grid size, and grid size <=50 m is recommended (USGS, 2008).

3.3.5.3. The HBV model

The HBV model is a conceptual and deterministic daily rainfall-runoff model developed at the Swedish Meteorological and Hydrologic Institute (SHMI). It is named after the abbreviation of Hydrologiska Byråns Vattenbalansavdelning (Hydrological Bureau Water balance-section), which was the former section at SMHI where the model was originally developed. It has a lumped conceptual process description at its core, but has been extended with discretization into hydrological response units. Therefore it is sometimes regarded as lumped and sometimes as semidistributed. The basin can be disaggregated into sub-basins, elevation zones, and land-cover types. It is a general-purpose model designed to run on a daily time step (shorter time steps are available as an option) and to simulate river runoff in river basins of various sizes (Koponen, et al., 2010; Cunderlik, 2003; Xu, 2002).

Input data include precipitation, air temperature (if snow is present), monthly estimates of evapotranspiration, runoff (for calibration) and basin geographical information. The treatment of snow accumulation and melt in HBV is based on a simple accounting (degree-day) algorithm. The existence and amount of snowfall is predicted using meteorological input data extrapolated to the mean elevation of each sub-area of the basin. A simple model based on bucket theory is used to represent soil moisture dynamics. There is a provision for channel routing of runoff from tributary basins, using a modified Muskingum method. Outflow from lakes is usually specified by a stage-discharge rating curve but can be given by a lookup table to allow for power station operating rules. The HBV model can be linked with real time weather information and river monitoring systems (Cunderlik, 2003).

The HBV model was originally developed in the early 70´s to assist hydropower operations. The aim was to create a conceptual hydrological model with reasonable demands on computer facilities and calibration data. It is now used for several purposes, such as flood forecasting, warning and risk assessment, spillway design floods simulation, water resources evaluation, hydropower, irrigation and climate change. The HBV approach has proven flexible and robust in solving water resource problems and applications now span a broad range. It has been applied in more than 40 countries worldwide; to basins with such different climatic conditions such as Sweden, Zimbabwe, India and Colombia, and for spatial scales ranging from lysimeter plots to the entire Baltic Sea drainage basin. It is now the standard forecasting tool in Sweden, where some 45 catchments are calibrated for the national warning services (mainly in small and unregulated rivers), and in nearly 200 basins throughout Scandinavia (Koponen, et al., 2010).

3.3.5.4. The HEC-HMS

HEC-HMS is the result of about 30 years is the Hydrologic Modelling System (HMS) of the Hydrologic Engineering Centre (HEC) of the US Army Corps of Engineers. This is a multipurpose physically-based, distributed and deterministic model designed to simulate the precipitation-runoff processes of dendritic watershed systems. It may be used to perform both event and continuous simulation over long periods of time, and computes runoff using grid-cell depiction of the watershed (HEC, 2010; Cunderlik, 2003). HEC-HMS comprises a Graphical User Interface, but a GIS interface has been developed to operate the model under the ArcGIS software (Environmental Systems Research Institute, Inc. - ESRI). This interface is called the Geospatial Hydrologic Modelling Extension (HEC-Geom.) (US-ACE, ND).

Different methods are available to simulate infiltration losses. Options for event modeling include initial constant, SCS Curve Number (CN), gridded SCS CN and Green & Amp, among others. Seven methods are available for transforming excess precipitation into surface runoff (direct runoff) including Unit Hydrograph methods such as Clark, Snyder and SCS technique. An implementation of the kinematic wave method is also included. Five methods are available for representing baseflow, such as the recession method (exponentially decreasing baseflow), the constant monthly method and the nonlinear Bossiness method. Six routing methods can be used to simulate open channel flow, including a lag method for no attenuation modeling, the Muskingum and the straddle stagger methods for simple approximations of attenuation (HEC, 2010).

One limitation of the model is to be time stationary, meaning that all mathematical submodels use constant parameter values. This implies that change and trends in parameter values cannot be modeled during long time simulations. There is a limited capability to break a long simulation into smaller segments and manually change parameters. Additionally, all mathematical models in the program are uncoupled. The program first computes evapotranspiration and then infiltration, when they should be simulated simultaneously. Errors due to this are minimized as much as possible by using a small time interval for calculations (HEC, 2010).

3.3.5.5. Other models

There are many other mathematical models available and suitable for different purposes, with plenty of differences among them. Some of them are free source, some are lumped-conceptual, some are physically-based distributed, and some can be operated under GIS frameworks, for instance. This is a list of some of them (Cunderlik, 2003):

- WATBAL: Integrated lumped water balance model developed for climate change impact assessment of river basin runoff.
- HSPF (Hydrologic Simulation Program-Fortran): Is the model of the US Environmental Protection Agency (US-EPA) and has its origin in the Stanford Watershed Model. It is a conceptual, semidistributed and continuous watershed model designed to simulate all water quantity and quality processes that occur in a watershed.
- PRMS: The US Geological Survey (USGS) PRMS (Precipitation-Runoff Modeling System) model is a modular-design, deterministic and semidistributed model developed to evaluate the impacts of various combinations of precipitation, climate, and land use on streamflow, sediment yields, and general basin hydrology.
- WATFLOOD: Is a distributed hydrologic model for real time flood forecasting and continuous simulation developed at the University of Waterloo. The emphasis of the WATFLOOD system is on making optimal use of remotely sensed data.

3.4. LAND USE / LAND COVER AND WATERSHED HYDROLOGY

3.4.1. LAND USE AND LAND COVER DEFINITIONS

There are several ways to understand the concept of *Land Use*, which are greatly determined by the purpose of its application and the context within it is employed. They are also related to the prior definition of *Land*, which is differently conceptualized by the various fields of knowledge. Although these definitions may be similar, they vary according to the priority given to the several attributes that characterize the land. Natural sciences, for instance, start from the natural characteristics of land, while the social sciences, more specifically economics, start from the mere element of space and refer more abstractly to the natural features of a segment of space (Briassoulis, 2000).

For the purposes of the present study a proper definition of *Land* is considered that given by FAO (1995, cited in Briassoulis, 2000): "*Land is a delineable area of the earth's terrestrial surface, encompassing all attributes of the biosphere immediately above or below this surface, including (among others) those of the near-surface climate, the soil and terrain forms, the surface hydrology, the plant and animal populations, the human settlement pattern and physical results of past and present human activity*".

While *Land Cover* refers to the "*biophysical state of the earth's surface and immediate subsurface*" (Turner *et al*. 1995, cited in Briassoulis, 2000), *Land Use* denotes "*the human employment of land*" (Meyer, et al., 1994), or more extensively defined "*the way in which, and the purpose for which, human beings employ the land and its resources*" (Meyer, 1995, cited in Moser, 1996). FAO (1995, cited in Briassoulis, 2000) adds that land use "*can be defined as the human activities which are directly related to land, making use of its resources or having an impact on them*". The description of land use usually involves specifying the mix of land use types, the particular pattern of these land use types, the areal extent, the intensity of use associated with each type, and the land tenure status (Bourne 1982, Skole 1994, cited in Briassoulis, 2000).

Finally, the concept of *change* in Land Use / Land Cover has to be defined. At a very elementary level, land use (and also land cover) change means quantitative changes in the areal extent (increases or decreases) of a given type of land use (or land cover, respectively). However, *land use change* may involve two different forms of change: a *conversion* from one type of use to another or a *modification* of a certain type of land use. The latter involves changes in its characteristic qualities or attributes, as may be intensification, extensification, marginalization and abandonment in the case of agricultural land use (Briassoulis, 2000). For the present purposes, we are restricting the definition to the first one.

The approach taken for the analysis of land use/land cover change is critically determined by the analyst's objectives. These define the conceptualization, the classification system and the models employed (if any). In this sense, and to navigate within the broad range of approaches, a useful classification is made by Briassoulis (2000), who discriminates among several major categories according to the purposes of analysis:

- *Descriptive studies* constitute the indispensable first step, documenting changes (be *conversion* or *modification*) over a given time period and within a given spatial entity. The level of detail in detection and measurement of changes depends on the spatial scale of the analysis and the availability of required data.
- *Explanatory studies* attempt to address the question of "why" these changes have occurred or are occurring and to uncover the factors or forces that directly or indirectly bring about these changes.
- *Predictive studies* try to foresee future changes in land use. They may be trend extrapolations or alternative scenarios derived from different assumptions.

- *Impact assessment* studies try to assess different kinds of environmental or socio-economic effects of changes in land use.
- *Prescriptive* studies seek to address the question of "what should be" or to prescribe land use configurations that ensure the achievement of particular goals.

As the objective of this study is to assess the impacts of land use/land cover change on the hydrology of a watershed, it's considered to be comprised within the fourth category mentioned above.

With the advent of Earth Observing satellites, the task of characterizing the state of the Earth's land cover (and through it the land use) over large areas has obtained the possibility to yield more precise and reliable results. Up until recent times, land cover maps were necessarily restricted to local coverage, affected by aerial and field survey, or to gross generalizations, both spatially and thematically. Beginning in the early 1970's, satellite remote sensing techniques have been successfully applied to the mapping of local, national, continental and even of global land cover (Mayaux, et al., 2008). This evolution has fundamentally altered the capacity to observe and monitor land change. Local to regional emphases have generated detailed land use classifications and land change assessments are increasingly ''targeted'' to specific problems (Reenberg, et al., 2007). Although not applied directly, this study takes advantage of this technical advances through the use of a land use/land cover classification based on the use of Remote Sensing and Geographic Information Systems, as will be described in the methodology chapter.

3.4.2. LAND USE AND LAND COVER INFLUENCE ON WATERSHED HYDROLOGY

A great deal of what is currently known about the influence of land cover (change) on catchment runoff comes from experimental studies, mainly carried out under a paired catchments experimental design. This method presents the advantage of avoiding the climatic variability and the most meaningful differences between watersheds (Andréassian, 2004). The direct measuring of various hydrological variables, whether or not under this experimental design, has enabled significant progress in understanding the hydrologic effects of land cover and land use. The impacts of urbanization and the conversion from forests to crop fields or pastures have been the main study objects of these studies, but there is little information about other types of transformations like from crops to pastures or vice versa. This empirical knowledge has been poured into the design of many different hydrological models, which afterwards became a much more practical tool to gain knowledge about hydrologic processes at local contexts.

3.4.2.1. Influence of the forests

Some aspects of the effects of deforestation seem very clear while others appear to vary significantly according to the context. In order to gain a better understanding of the role of the forests and land covers in general it is important to distinguish between the effects of the land cover and those of the soil water content capacity, and between the total water offer and the seasonal distribution of the flows. Each of them is related with the balance among four mechanisms: the interception by the canopy, infiltration, water consumption and evapotranspiration (Bruijnzeel, 2004).

It seems scientifically well established that the removal of forests almost invariably results in increases of the total annual volumes of the streams. However, the actual increase depends on numerous factors such as the associated past or new land cover, the forest type, rainfall regime, soil type, soil depth and topography. Another important aspect of the response, which also depends on the mentioned factors, is the variation in terms of peak and base flows. The first ones are related mostly to the behaviour of the surface flow. These are the two possibilities by which the increase in the annual volumes can take place, thus changing differently the distribution of flow throughout the year (Andréassian, 2004; Bruijnzeel, 2004; Bosch, et al., 1982).

Forest removal brings higher values of rain reaching the soil and an important reduction of the evapotranspiration, due to the reduction of leave area and of the consumption of water from the soil. Nevertheless, the reduction in transpiration can be strongly compensated by the increase of the direct evaporation from the soil and of the evapotranspiration from herbaceous vegetation, due to the higher incident radiation. The removal of vegetation and litter causes infiltration decrease and hence the increase of surface flow, causing in turn the increase in total volume to express as peak flows. The infiltration reduction may also be due to compaction caused by some common practices such as overgrazing (Fu, et al., 2005; Andréassian, 2004; Bruijnzeel, 2004; Costa, et al., 2003; Putuhena, et al., 2000).

On the other hand, the increase can be primarily as base flow. Following Andréassian (2004), it’s almost a rule that deforestation of more than 25% of the biomass will lead to increased base flows due to reduced water consumption. When soil disturbance is minimal the effect is enhanced due to increased infiltration thanks to the conservation of the litter layer (Fu, et al., 2005; Bruijnzeel, 2004; Costa, et al., 2003). Considering these two possibilities, the seasonal variation in the flow levels can be different for each context. For example, according to Lorup, et al. (1998), most of the catchment studies made in Africa, like in Tanzania and South Africa, indicate that the dry season flow is lower from catchments with indigenous forests than from other types of land cover, like traditional smallholder cultivation. However, there are numerous reports about streams dried during summer after deforestation processes (Fu, et al., 2005; Bruijnzeel, 2004; Costa, et al., 2003; Putuhena, et al., 2000).

The variability in these aspects of the hydrological response to land cover changes has prompted the differentiation of two main forms to interpret such effects. The "traditional" position is the basis of the concept of "water regulation", according to which the soil-root-litter system in the forest acts like a sponge, absorbing water during the rainy season and releasing it slowly during the dry season. As the disruption of this system is more intense the effect "a lot of water in winter and very little in summer” is increased, and thus floods and droughts can be eliminated by large-scale reforestation (Bruijnzeel, 2004).

A more modern position emphasizes the prevailing influence of the soil and the geological substrate on the base flow, and thus the existence of a threshold of intensity and duration of storms beyond which these exceed the capacity of soil water storage, which permits floods. This position also argues that forests perform a greater consume of water, and therefore deforestation causes increases in the annual volumes and peak and base flows, while reforestation brings reductions (Bruijnzeel, 2004).

The importance of the soil properties, specially its depth, is high. Deep soils can lead to increases in base flow after deforestation, while shallow soils may bring increases in the form of surface runoff (Cornish, et al., 2001). In this regard, Andréassian (2004) establish as a condition to detect the hydrologic influence of the forests that the watershed have deep enough soils for the forests to have advantage over the rest of land covers with shallower root systems. Another condition is the presence is that the climate has seasonal variations, so there are temporary deficits and also allows recharging of the aquifer reserves.

A special mention must be made about the hydrologic influence of cloud forests, which correspond to what is known as “Mesophyll Mountain Forest” in this investigation. What is special in this kind of forests is their ability to capture moisture from the fog through its condensation over the leaf surfaces, a process known as ‘horizontal precipitation’. This is the result of this kind of vegetation being frequently covered by fog or mist. This process has important implications for this forest’s hydrology, which is considered quite unique and different from other forest covers (García Coll, et al., 2004; Bruijnzeel, 2004; Castro Schmitz, 1995). There are few measurements of such contributions. For tropical conditions, Holder (2006) speaks about additional inputs of between 5 and 20% of normal precipitation, and may be greater during the dry season. García Coll *et al* (2004) mention an average of 11 mm/per foggy day input by this way.

These "extra" inputs and low rates of evapotranspiration produce very high runoff coefficients and can substantially change the water balance of these forests. For example, in some forests with high levels of horizontal rain, the water reaching the ground is higher than the incident rainfall (Weaver, 1972, cited in Cavelier, et al., 1997). In a forest of Colombia Cavelier and Goldstein (1989, cited in Holder, 2006) found that 48% of annual inflows to the ground due to horizontal precipitation.

Although deforestation of tropical forests usually results in increased total runoff, the conversion of cloud forests to pastures is probably the exception to the rule. Although there are only a few studies on the effects of such conversion in Latin America, there is growing evidence that conversion to pasture may lead to decreased base flows in summer. The result of this transformation is a negative balance caused by the loss of the extra inputs, as demonstrated Ataroff and Rada (2000, cited in Bruijnzeel, 2004) in Venezuela. However, the influence of these forests depends on their proportionality in relation to the area of the basin, which is usually too small to be significant (Bruijnzeel, 2004).

3.4.2.2. Impacts of urbanization

Urbanization is equivalent to the replacement of naturally vegetated areas of agricultural fields with impermeable surfaces. This process includes increasing surface area of road networks, fragmentation and drainage of wetlands and the reduction of floodplains areas, among others. (Shuster, et al., 2005). Regarding urbanization, the present study focuses on the effects of the impervious area increase, which brings shorter lag times between rainfall and subsequently higher runoff peaks and total volume of runoff in receiving waters (Shuster, et al., 2005).

As an area becomes dominated by impervious surfaces, a shift in the distribution of water occurs from partially subsurface flow processes to nearly all surface runoff, increasing the overall hydraulic efficiency of a catchment. This brings a substantially decreased capacity of infiltration, with a concomitant increase in the production of runoff, shorter times of concentration or lag times and decreased recharge of water tables with a corresponding decline in base flows. There is also some evidence that heavily urbanized areas have altered evapotranspiration regimes due to the removal of vegetation, as well as patterns in precipitation totals and intensity from 'heat island' effects (Jat, et al., 2009; Shuster, et al., 2005).

Smaller peak flows and associated higher-frequency precipitation events are more sensitive to changes in extent of impervious surface compared with events having longer recurrence intervals. As the impervious surfaces increase, the runoff response is amplified from increasingly smaller precipitation events. For example, Booth (2000) found that at a 10% level of effective impervious surface, runoff production increased to the extent that the post-development 2-year storm was found to yield the same amount of discharge as a 10-year pre-development storm. This relationship is more intense at commercial types of development, which tend to produce more concentrated and contiguous imperviousness. The extent, connectedness, location and geometry of a development are also likely to be important co-factors (Shuster, et al., 2005).

4. THE VALLES RIVER BASIN

The Valles River Basin embraces an area of 3690 km^2 located in north-central Mexico, in the north-western portion of the *Huasteca* region, a subhumid natural and socioeconomic region located between the Gulf of Mexico and the Eastern Mountain Range (*Sierra Madre* Oriental). This region is comprised by six states: Tamaulipas, Veracruz, San Luis Potosi, Hidalgo, Querétaro and Puebla. Most of the Valles River Basin is within the *Huasteca Potosina,* the portion of this region which belongs to the San Luis Potosí state. It is a 11409 km^2 region representing 18.3% of the State's area (Algara Siller, et al., 2009; Bassols Batalla, et al., 1977). 73.9% of the watershed corresponds to San Luis Potosí state, while the other 26.1% is in the Tamaulipas state (see figure 3.1). It comprises portions of 9 municipalities: Tula, Ocampo, Nuevo Morelos and Antiguo Morelos in Tamaulipas, and El Naranjo, Tamasopo, Ciudad Valles, Ciudad del Maíz and Aquismón in San Luis Potosí.

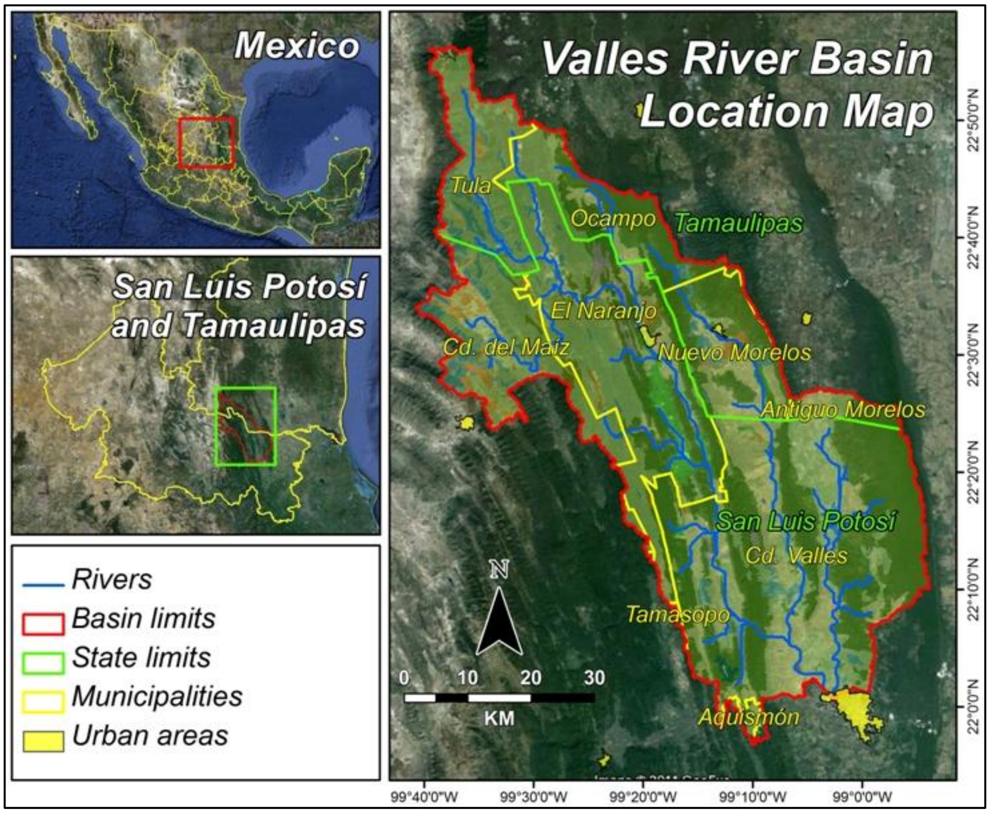

Figure 3.1: Location of the Valles river basin. Own elaboration with Google Earth images and INEGI data.

4.1. HYDROGRAPHY

According to INEGI (2011a) the VRB is not recognized as a unit within the official hydrographical delineation system. It is formed by four subbasins of the Tamuín basin, which is the largest basin of the 26th Hydrological Region (Pánuco River), with an area of 30,450.3 km^2. The Pánuco Hydrological Region, in turn, has an area of 84,956 km^2 and delivers its waters to the Gulf of Mexico. It represents 4% of the country surface, comprising portions of the states of México, Querétaro, Hidalgo, Guanajuato, San Luis Potosí, Veracruz, Tamaulipas and Nuevo León, and 5% of the national water potential, with a mean annual runoff of 18 Mm^3 (Santacruz de León, 2007).

The four subbasins by which the Valles River Basin is constituted[7] are shown in figure 3.2. First and largest one is *El Salto* subbasin (also known as *Rio Los Naranjos* subbasin), which embraces 58.4% of the watershed's area. The second, *Los Gatos* subbasin, comprises 19.1% of the total area. The third one is called *Rio Puerco*, and covers 19.9% of the total area. The *Valles* subbasin is the fourth one, comprising only 2.5% of the total area. This last one is only partially taken into account in this study, because of the location of the Santa Rosa hydrometric station, which is taken as the watershed outlet.

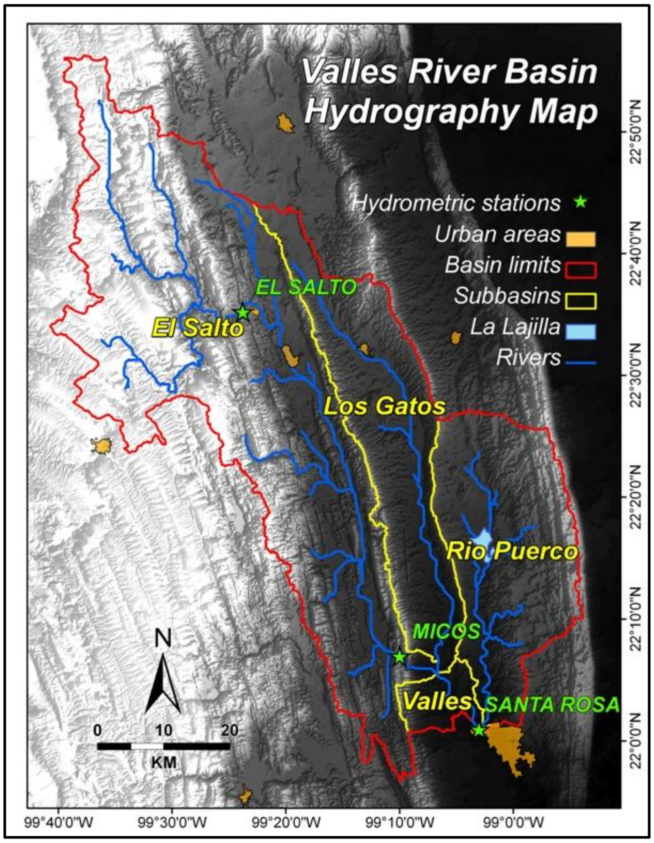

Figure 3.2: Hydrography of the Valles River basin.
Own elaboration with INEGI data.

The upper watershed is located in Tamaulipas. There, El Salto River, the main affluent of the Valles River is born at 8 km southeast from the city of Tula, at 1600 masl. At the beginning this river is known as 'El Salto', since it passes by a village named 'Salto de Agua', but then it takes the name of 'El Naranjo' after running through the town of the same name. From there, it flows downstream, passing through the 'Micos' hydrometric station to finally converge with 'Los Gatos' river. The latter is born also in Tamaulipas, in the municipality of Nuevo Morelos. It runs downstream through the municipality of the same name and through Ciudad Valles, until reaching the waters of El Naranjo to form the Valles River. This river receives the contribution of the Río Puerco River, which is born in the municipality of Ciudad Valles, just before the Santa Rosa hydrometric station. Afterwards, it passes through the city of Ciudad Valles, which is the main urban area of the *Huasteca Potosina* region. Finally, the river gives it waters to the river Tamuín or Tampaón, being its main affluent (Santacruz de León, 2007).

Altitudes of the watershed range between 70 and 1955 metres above sea level. Figures 3.3 and 3.4 show the longitudinal and cross-sectional profiles of the watershed. They show the noticeable abruptness of the relief. 72.7 % of the basin area is below 1000 masl, but only 3.9% is below 300 masl and 7.46% is above 1600 masl. In addition, 74% of the watershed has a slope lower than 25%.

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[7] They receive different names, according to Santacruz de León (2007) and INEGI (2011a).

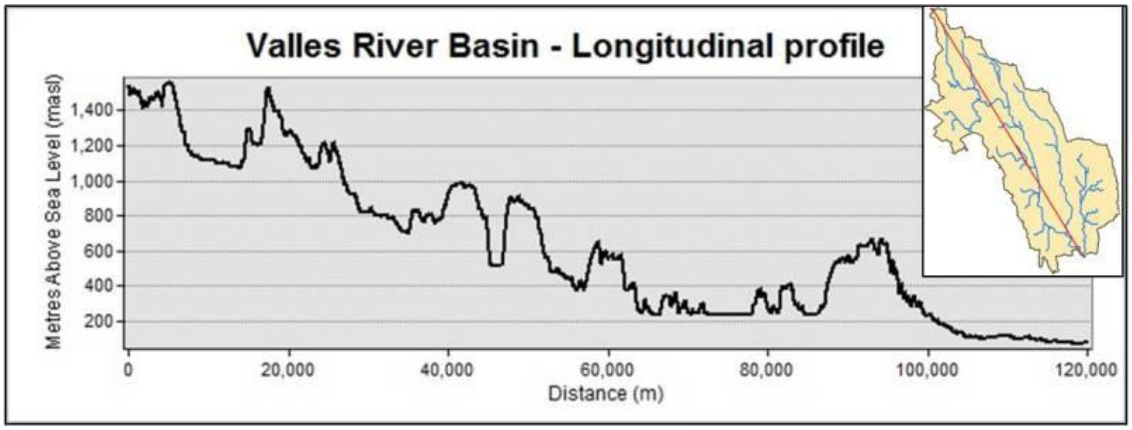

Figure 3.3: Longitudinal profile of the Valles River basin. Own elaboration from INEGI data.

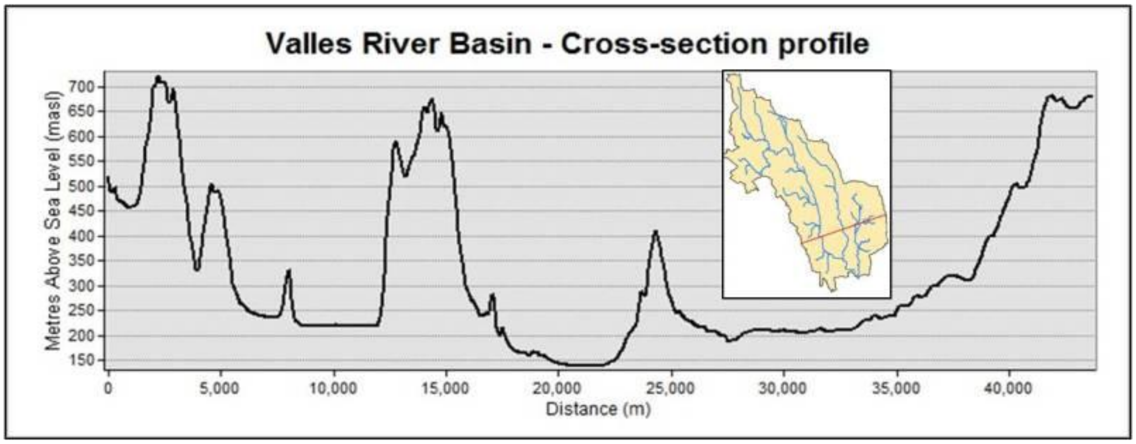

Figure 3.4: Cross-sectional profile of the Valles River basin. Own elaboration from INEGI data.

4.2. SOCIOECONOMICAL CONTEXT

4.2.1. POPULATION

According to the results of the 2010 Population and Housing Census (INEGI, 2010), the total population living within the limits of the basin is of 46221 inhabitants, with a density of 12.52 inhab/km^2. To have an overview of the demography and social conditions within the Valles River Basin, the table 3.1 shows some basic indicators obtained from INEGI (2010). Values are disaggregated by state (within the VRB), subbasin and municipality.

AGGREGATION	% AREA	POPUL	% BAS	EAP	HSRH	HOUS	% BAS	P.W.	SANIT	DRAIN
SAN LUIS POTOSÍ	73.9	39420	85.28	33.35	74.83	12501	85.3	63.54	76.40	55.21
TAMAULIPAS	26.1	6801	14.71	31.02	81.52	2153	14.69	68.14	77.10	47.19
Sub. El Salto	58.45	33770	73.06	33.56	76.03	10670	72.81	66.62	76.72	55.26
Sub. Los Gatos	19.11	5408	11.70	31.68	76.63	1790	12.21	59.89	74.53	53.18
Sub. Río Puerco	19.88	4512	9.76	29.63	72.23	1429	9.75	46.26	74.74	57.59
Sub. Valles	2.52	2531	5.47	34.57	77.56	765	5.22	74.38	81.44	32.29

El Naranjo	22.05	20489	44.32	35.84	75.90	6613	45.12	72.42	75.70	65.73
Cd. Valles	40.04	14186	30.69	31.08	71.03	4408	30.08	60.34	76.77	48.23
Cd. del Maíz	11.13	4138	8.95	28.93	83.42	1304	8.89	26.53	77.07	28.83
Aquismón	0.52	606	1.31	32.67	69.14	175	1.19	84.57	89.14	30.29
N. Morelos	8.20	3381	7.31	33.01	85.18	1158	7.90	69.17	72.63	61.49
A. Morelos	1.82	494	1.06	22.06	77.73	147	1.00	32.65	78.91	79.59
Tula	8.53	1272	2.75	32.94	92.06	381	2.60	56.43	83.20	10.24
Ocampo	7.53	1660	3.59	28.07	66.81	469	3.20	85.93	82.30	31.56
BASIN TOT / AV	100	46221	100	33.01	75.82	14654	100	64.21	76.50	54.03

Table 3.1: Demographical and social indicators of the VRB. %BAS: % of the basin population; EAP: % Economically Active Population; HSRH: % Health Services Right Holders; HOUS: Total of houses; P.W: % houses with piped water service; SANIT: % houses with toilet; DRAIN: % houses with drainage service. Own elaboration with INEGI (2010) data.

It may be observed that San Luis Potosí has the largest share of the population and houses of the basin (both 85%). El Salto is the principal subbasin with 73% of the population and the houses. In terms of municipalities, El Naranjo, Ciudad Valles and Ciudad del Maíz are the greatest contributors with 44.3%, 30.7% and 8.9% of the population and with 45%, 30% and 8.9% of the houses, respectively. Perhaps the numbers that say more about the social conditions are those related to the services coverage. 76% of the basin population has insured medical services, 64% of the houses have access to the piped water system, 76% has a toilet and only 54% is connected to a drainage system. These numbers reflect that the social conditions of the basin correspond to a rural environment, unlike the conditions found in big cities, where the coverage of these services can even reach 100%.

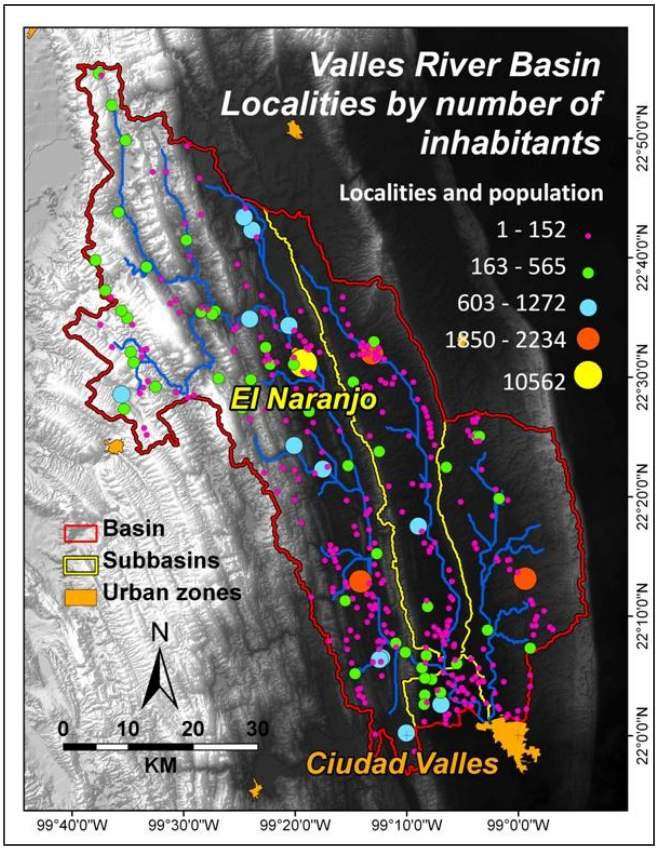

Figure 3.5: Localities in the VRB by population size. Own elaboration with INEGI (2010) data.

It is important to mention that numbers in table 3.1 don't take into account the 124644 people reported for the urban area of Ciudad Valles. This is the most important city of the region, with an area of 34.3 km^2, but is technically outside the watershed. Of the 382 localities within the basin delineation obtained in this study, the largest human concentration corresponds to the urban area of El Naranjo, with an area of 4.9 km^2 and 10562 inhabitants, while the second largest is Nuevo Morelos, with 2.04 km^2 and 2234 inhabitants. There are other important urban areas, like Ciudad del Maíz (10391 inhab.), Tula (10043 inhab.) and Ocampo (5095 inhab.), which nevertheless are not comprised within the VRB. Figure 3.5 shows the spatial distribution of the localities of the VRB according to the size of their population. It is possible to observe that localities are found mainly along the water streams. It is also observable that the largest human concentrations are within the subbasin of El Salto, and that's why this subbasin, with 58.5% of the basin's area, comprises 73% of its population. The most densely populated subbasins are the Valles and El Salto subbasins, with 27.11 and 15.65 inhab/km^2 respectively, while Los Gatos and Río Puerco subbasins have only 7.66 and 6.15 inhab/km^2 respectively. It may be assumed, thus, that the greatest pressure on natural resources, including water, is exerted within the Valles and El Salto subbasins, especially by the urban areas of El Naranjo and Ciudad Valles. The latter, although not technically inside the VRB, exerts the greatest demand of resources, goods and services from the basin. For instance, its water supply system have an installed capacity to treat more than 400 lps of water extracted from the Valles River, and operating at 95% of its capacity, is supplies about a million cubic metres by month (INAFED, 2010). Thus, the 124644 inhabitants of the urban area of Ciudad Valles add to the population demanding water from the VRB.

In terms of municipalities, Ciudad Valles comprises the largest proportion of the VRB (40%), being this area the 61.02% of the municipality. El Naranjo is 99.15% within the VRB, contributing with 22.05% of the basin's area. The third largest municipality is Ciudad del Maíz, with 11.13% of its area, which corresponds to 13.04% of the municipality. These numbers, along with population and housing numbers, reflect that these tree municipalities, especially El Naranjo and Ciudad Valles, are the most representative of the watershed. This is important because most of the available information about socioeconomical aspects is aggregated by municipality. Ciudad Valles is the second most important city of San Luis Potosí and the economical, social and political centre of the *Huasteca Potosina*. The municipality of El Naranjo, in turn, corresponds to a former part of Ciudad del Maíz, until it was separated to create a new entity in 1994. Table 3.2 shows how the population has grown in these three municipalities.

Year	Ciudad Valles	AGR (%)	El Naranjo	AGR (%)	Ciudad del Maíz	AGR (%)
1970	77,444	-	-	-	34,044	-
1980	105,625	2.39	-	-	43,841	2.52
1990	130,939	2.17	-	-	45,823	0.44
1995	143,277	1.81	18,255	-	30,268	-7.95
2000	146,604	0.46	18,998	0.84	30,603	0.22
2005	156,859	1.39	18,454	-0.57	29,855	-0.48
2010	167,713	1.38	20,495	2.21	31,323	0.98

Table 3.2: Population growth in the main 3 municipalities of the VRB. AGR: mean Annual Growth Rate. *Elaborated with data from INEGI (2010) for the year 2010 and with data compiled by INAFED (2010) from the past national population censuses for the previous years.

The table shows that the population in these municipalities keeps growing, although with a decreasing growth rate, which reflects the impact of migration to other parts of the state, to other states or to other countries, especially by young people (AYUNTAMIENTO DE CIUDAD VALLES, 2004).

4.2.2. ECONOMICAL ACTIVITIES

Table 3.3 shows the percentage of the occupied economically active population in the year 2000 by sector of the economy. It is noticeable that the primary sector (agricultural) is the most important in El Naranjo and Ciudad del Maíz, which are more rural municipalities, while the tertiary (services) is the main sector of the economy in Ciudad Valles, where the influence of a main city is of primary importance. The importance of the primary sector for most of the population of the basin is a reflection of the pressure exerted on the natural resources of the basin.

	Ciudad Valles	El Naranjo	Ciudad del Maíz
Primary sector	15.97	38.38	51.66
Secondary sector	19.96	24.12	15.53
Tertiary sector	61.96	34.87	29.87

Table 3.3: Percentages of jobs generated by each of the economy sectors in the main municipalities of the VRB in the year 2000. Source: INAFED (2010).

In Ciudad Valles, for the year 2000, the trade sector was the most important contributor with 19.65% of the generated jobs. Agriculture, stockbreeding, forestry and fishing, altogether, generated 15.97% of the jobs, while the manufacturing and construction industries generated 10.7% and 8.3% of the jobs.

Regarding agriculture, most of the arable land in Ciudad Valles is devoted to the culture of sugar cane for refined sugar production, which is sold at the national market. Sugarcane agribusiness is the base of the economy of Ciudad Valles. Crops following in importance are corn and beans, but sorghum, coffee and fruits like orange, lemon, mango and papaya are also cultivated. Some of these products are mainly for the local consumption, with surpluses sold at the local and regional markets. Livestock farming, in turn, includes cattle, pigs, sheep, bees and poultry breeding. Please refer to the section 3.5.2 to see a better description of the agricultural activities. Other important branches of the primary sector are the forestry and mining (INAFED, 2010; AYUNTAMIENTO DE CIUDAD VALLES, 2004).

4.3. CLIMATE

Figure 3.6 shows the spatial distribution of the climate units of the VRB according to INEGI's 1:1'000.000 climatic classification (INEGI, 2011b), which is based on the world classification of climates developed by Wladimir Köppen in 1936 and modified for Mexico by Enriqueta García in 1964. Most of the climatic units are comprised within the group of warm humid climates (A), whose mean temperature of the coldest month is higher than 18 °C. There are also small areas belonging to the semi-dry climates (BS), and to temperate subhumid climates (C), with a mean annual temperature between 12 and 18° C (INEGI, 2005c). Table A1.1 in Annex 1 presents the description of these climate units. It is worth to mention the existence of a more detailed climate classification for the area, elaborated by Hernández Cerda (2007), who also followed the classification developed by Köppen and modified by García, and applied it to the *Huasteca Potosina* region using the records from 1960 to 2005of 119 meteorological stations. However, this classification covered only the portion of the VRB corresponding to San Luis Potosí (see figure 3.7).

Description of the climate units identified in this classification is presented in table A1.2 of the annex 1.

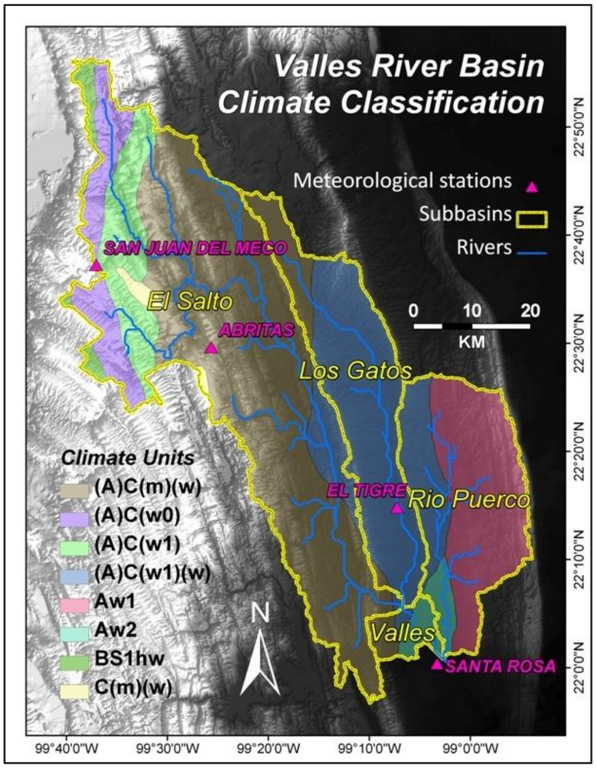

Figure 3.6. Climate units of the Valles River basin according to INEGI (2011b).

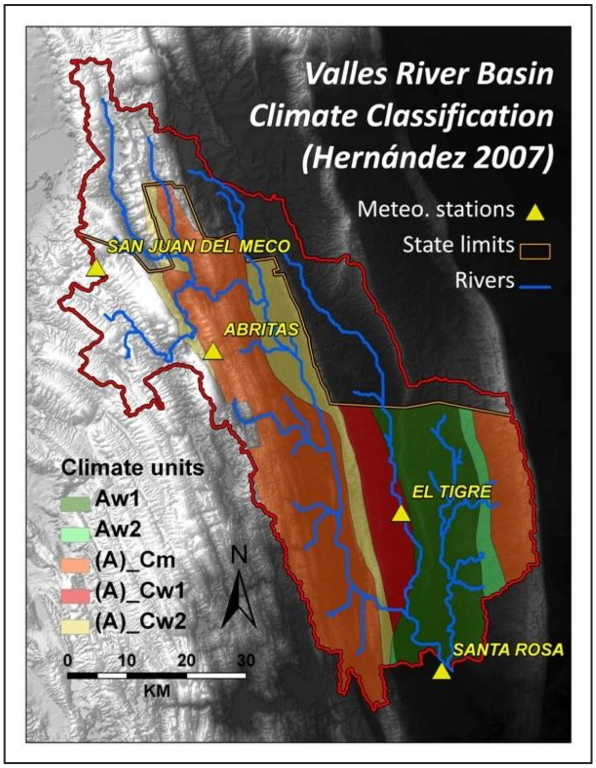

Figure 3.7: Climate units of the Valles River basin according to Hernández (2007).

Abra Tanchipa and *Colmena* mountain ranges, among others, give shape to the Valles River Basin. They are part of the Eastern Mountain Range (*Sierra Madre Oriental*), which acts as an orographic barrier where the air masses coming from the Gulf of Mexico collide and deliver its humidity. This condition is one of the main climatic factors in the region (Santacruz de León, 2007). Precipitations at the lower parts are between 1000 and 1200 mm/year, while at the higher altitudes of the Eastern Mountain Range they exceed 3000 mm/year. In most of the *Huasteca Potosina* mean annual rainfall ranges between 1200 and 2000 mm (Algara Siller, 2009). In this study, a weighted estimation of areal rainfall was done, through the Thiessen polygons method, yielding an average value of 1330 mm/year for the VRB. Figures 3.8 to 3.11 show the climatic diagrams of 4 meteorological stations within the VRB, according to their *normal*[8] values for periods of 38-40 years, taken from INIFAP (2005). It can be observed in figures 3.6 and 3.7 that these stations correspond to different climate units and are located at different altitudes.

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[8] Average values of meteorological elements (temperature, humidity, precipitation, evaporation, etc.) calculated with data collected over a long period, typically 30 years (SMN, 2011).

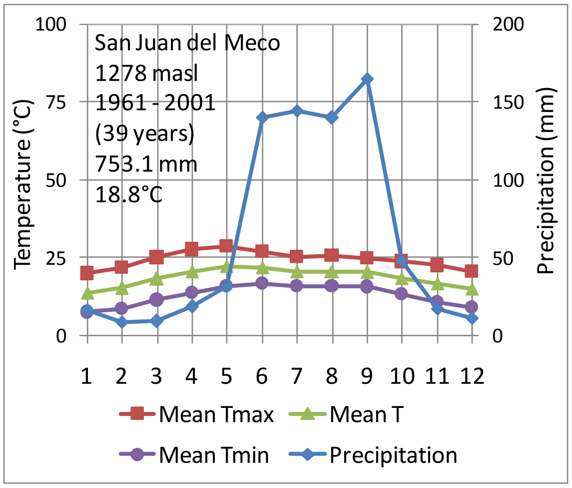

Figure 3.8. Climatic diagram of San Juan del Meco station. Own elaboration with data from INIFAP (2005).

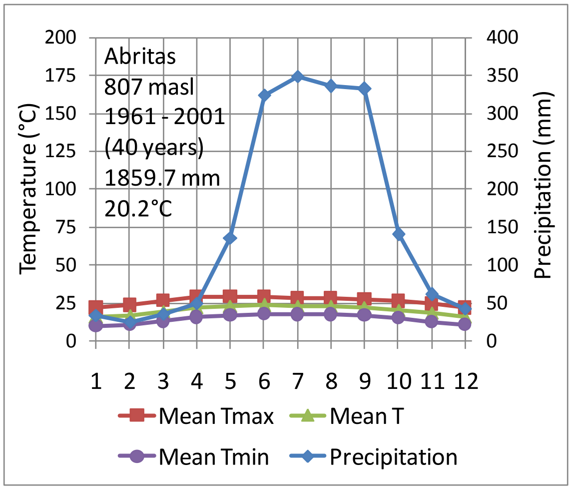

Figure 3.9: Climatic diagram of Abritas station. Own elaboration with data from INIFAP (2005).

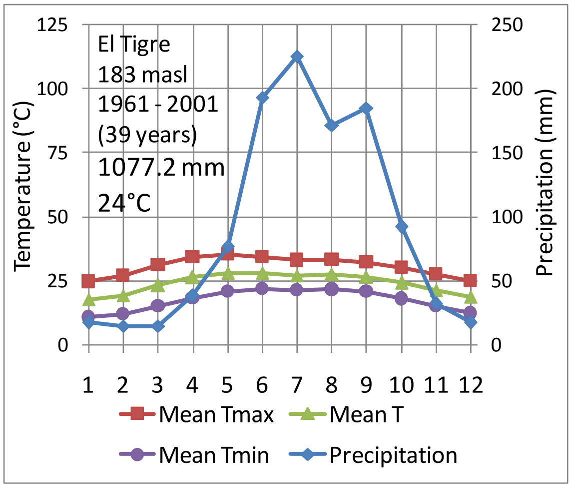

Figure 3.10: Climatic diagram of El Tigre station. Own elaboration with data from INIFAP (2005).

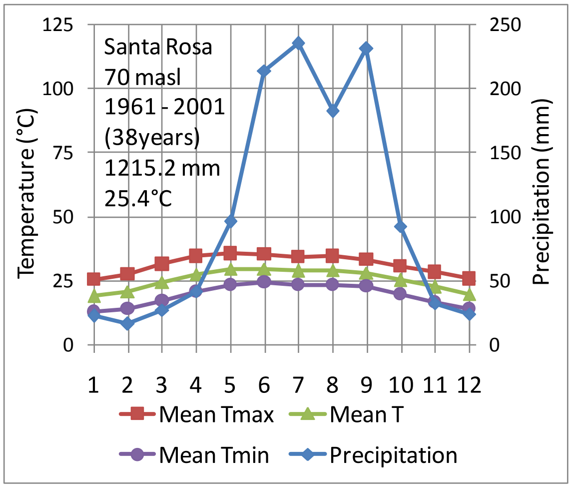

Figure 3.11: Climatic diagram of Santa Rosa station. Own elaboration with data from INIFAP (2005).

The four stations exhibit a summer rainfall regime, meaning that the month with the highest temperature is between May and October, and that the rainfall value of this month is at least 10 times the rain fallen in the month with the lower mean value (INEGI, 2005c). It may also be observed, in figures 3.10 and 3.11, that an aestival drought occurs in August. According to Santacruz de León (2007) this is a characteristic of the type of climates present in the region. In more general terms, the diagrams show similar patterns in the normal distribution of the precipitation along the year. In the four diagrams the period from May to October can be considered as relatively humid since precipitation is above mean temperature. By the contrary, the period between November and April can be considered as relatively dry, since temperature lines are below precipitation.

At the national level, precipitation is concentrated during the months from May to November, which is considered as the rainy season, and is mostly associated to the entrance of moisture from the oceans through meteorological systems such as tropical cyclones, detachments from the Intertropical Zone of Convergence and cold fronts. Following the graphs, the rainy season in the VRB can be considered to be from May/June to October. According to Algara Siller, et al. (2009) 80% of the annual precipitation in the *Huasteca Potosina* falls between June and September. The percentages found here are lower (71% - 78%) but still show the strong concentration of the rainfall along the summer. It is difficult to assign the origin of the rainfalls to a particular phenomenon, because they coexist in space and time. However, the maximum rainfalls are mainly associated with cyclonic activity, especially in hilly areas near the oceans (Prieto González, et al., 2010), such as the VRB.

Tropical cyclones are an important climatic factor in the *Huasteca*, which is exposed to tropical storms and hurricanes coming from the Atlantic Ocean (Santacruz de León, 2007). This region is considered as part of the typical trajectories of these phenomena (Blanco Loredo, 2011). The season of cyclonic activity is comprised between the months of June and October, being August the most active one. According to Blanco Loredo (2011), 19 tropical cyclones directly affected the *Huasteca Potosina* between 1970 and 2008. However, when reviewing other sources it became evident that they don't coincide completely in the records and the information reported. Table 3.4 shows the tropical cyclones, from tropical depressions to hurricanes, which affected the *Huasteca Potosina* between 1970 and 2007. The National Meteorological System (SMN, ND) reports more cyclones affecting San Luis Potosí and Tamaulipas. However, in this study were considered only those whose effects could be verified with the newspapers revisions by (Blanco Loredo, 2011) or (SAGARPA, 2004a), or whose trajectories were verified as close to the *Huasteca Potosina* according to the NOAA (2010) and UNYSIS (2010) databases.

Name	Period	Impact date	Category when impacting	Source
Greta	Sep 26 - Oct 5 1970	04/10/1970	Tropical depression	1, 2, 3, 4, 5
Caroline	Aug 24 – Sep 1 1975	31/08/1975	Hurricane 3	3, 6
Anita	Aug 29 - Sep 3 1977	02/09/1977	Hurricane 1	1, 2, 3, 4, 5
Cosme	Jun 18 - 23 1989	21/06/1989	Tropical depression	1, 3
Diana	Aug 4 - 9 1990	07/08/1990	Tropical storm	1, 2, 3, 4, 5
Tropical depression 2	Jul 5 - 7 1991	01/07/1991	Tropical depression	1, 4, 5
Gert	Sep 14 - 21 1993	20/09/1993	Tropical storm	1, 2, 3, 4, 5
Tropical depression 5	Aug 29 - 31 1994	31/08/1994	Tropical depression	1, 3
Tropical depression 6	Aug 5 - 7 1995	07/08/1995	Tropical depression	1, 3, 4, 5
Gabrielle	Aug 9 -12 1995	11/08/1995	Tropical storm	1, 2, 3, 4, 5
Dolly	Aug 19 - 24 1996	23/08/1996	Hurricane 1	1, 2, 3, 4, 5
Tropical depression 2	Jul 2 - 3 1999	03/07/1999	Tropical depression	1, 4
Keith	Sep 28 - Oct 6 2000	03/10/2000	Tropical storm	1, 2, 3, 4, 5
Bret	Jun 28 - 30 2005	29/06/2005	Tropical depression	1, 2, 3, 4, 5
Gert	Jul 23 - 25 2005	24/07/2005	Tropical depression	1, 2, 3, 4, 5

Table 3.4: Tropical cyclones impacting the *Huasteca Potosina* between 1970 and 2007. Sources: 1) SMN, ND; 2) UNYSIS, 2010; 3) NOAA, 2010; 4) Blanco Loredo, 2011; 5) AGENDA AMBIENTAL, ND; 6) SAGARPA, 2004a.

Regional and local hydrometeorological patterns are affected by tropical cyclones mainly through the large amounts of water contributed by torrential rains concentrated during a few hours or days. In many regions of Mexico these cyclonic rainfall events are determinant for the socioeconomical welfare because they constitute an important mechanism of humidity transport from the ocean to the central semiarid high plateaus. Even if a region is not directly impacted by a cyclone, the cloudy bands of the cyclones passing nearby may cover it and leave a trail of wind and rain (Prieto González, et al., 2010; Blanco Loredo, 2011). The benefits produced may extend for several years, due to the subsequent recharge of aquifers and the filling of reservoirs, where they exist (Agenda Ambiental, ND). However, tropical cyclones also constitute a threat to the population, in part because they can trigger pluvial and fluvial floodings.

Cold fronts constitute another source of water, especially during winter. A cold front is a zone of interaction between two air masses that origins when a cold air mass advances towards lower latitudes and its leading edge introduces between the earth and the hot air mass. This phenomenon can bring sudden and heavy rains and even snowfalls if the temperature goes too low (SMN, 2011). The velocity of the cold front is such that there is an effect of sudden temperature decrease is in a few hours. In absence of humidity, cold fronts cause frosts, especially in the mountain ranges. The cold fronts season is considered to be from November to March, but they are more frequent between December and February and sometimes occur also before the season, in September, or afterwards, in April. These phenomena originate from extratropical cyclonic systems in mid latitudes, with a trajectory from northwest to southeast, coming from North America (CENAPRED, 2011).

The frequency of the fronts is very variable and depends on their origin. Depending on the time of year and geographical location, cold fronts can occur in intervals of 5 to 7 days. Some of them come from the Pacific Ocean, others from the north and others have an arctic continental origin. When the polar masses cross the Gulf of Mexico, they give rise to the “northers”, which are cold fronts accompanied by strong winds coming from the north, which produce storms and intense rains (CENAPRED, 2011). Northers from the Gulf of Mexico blow violently and continuously for two or three days over the coastal plain of the Gulf, mainly affecting the states of Tamaulipas, Veracruz, Tabasco, Campeche and Yucatán (Pereyra, et al., 1992). During *El Niño* years the number of Northers tends to increase, although it does not necessarily reflect on precipitation levels (Magaña Rueda, 2004). Since the 90s the National Meteorological service maintains a record of cold fronts in order to produce annual statistics (CENAPRED, 2011). However these statistics are not easily available and couldn’t be obtained.

On the other hand, when the dry period (November – April) becomes longer and more intense than the *normal* conditions it is considered a meteorological drought. Meteorological drought is a temporal anomaly defined as a deficit in precipitation (relative to the normal conditions) over a long period of time, usually a season or even longer periods. It is related to the moment of occurrence (the delay in the onset of the rainy season, for instance) and its intensity (rainfall intensity, rainfall events, etc) (Montero Martínez, et al., 2007). In the *Huasteca Potosina*, including the VRB, seasonal droughts are recurrent events that may last from 5 to 9 months, but are more usual and more intense between January and April (Algara Siller, et al., 2009) when water surpluses from rainfall season are finished and there are about four months of low or even null rainfall left.

Algara Siller (2009) analyzed the phenomenon of meteorological drought in the *Huasteca Potosina.* This author applied a Drought Severity Index (DSI) to meteorological records of 92 stations throughout the region. This index expresses the difference between measured precipitations and the normal values as a percentage for a given period, identifying up to 7 levels of drought severity: absent (0 to - 0.2), slight (-0.2 to -0.35), strong (-0.35 to -0.4), very strong (-0.4 to -0.5), severe (-0.5 to -0.6), very severe (-0.6 to -0.8) and extremely severe (<-0.8). Figure 3.12 shows the evolution of the DSI in the region year by year from 1960 to 2000 according to this study.

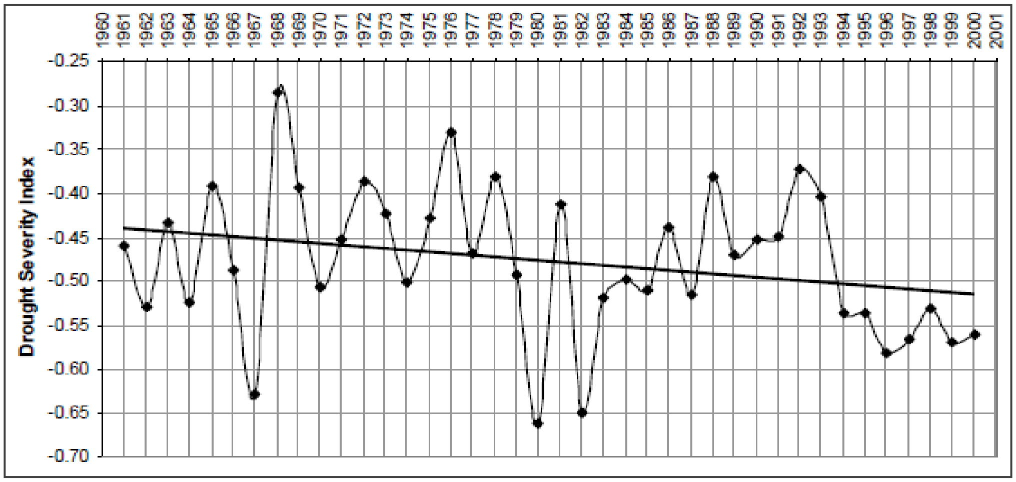

Figure 3.12. Evolution of the Drought Severity Index in the *Huasteca Potosina* (Algara Siller, et al., 2009).

Both frequency and tendency of the phenomenon may be observed. Regarding the former, there was a seasonal drought (<-0.2) in every year of the period. There were three years of very severe droughts in 1967, 1980 and 1982. Very strong and severe droughts presented consistently. In second term, there is an increasing tendency of the severity along the period, identified by the tendency line. Regarding the spatial distribution of the drought, this study found that for the entire study period (1961 – 2000) the VRB can be regarded as a zone subject to very strong meteorological droughts (Algara Siller, et al., 2009).

El Niño Southern Oscillation (ENSO) exerts another important and recurrent influence on the regional and local hydrometeorological patterns. The occurrence of *El Niño* and *La Niña* does not follow periodic intervals (Magaña Rueda, 2004) although it is accepted that can occur every 2 to 7-8 years. In the Mexican context, El Niño brings decreases in rainfall and increases in temperature when occurring in summer, because the Intertoprical Zone of Convergence is closer to the Ecuador and farther from Mexico. Thus, during summer El Niño can bring very severe droughts to the Mexican territory. During winter, El Niño brings lower temperatures and a greater incidence of cold fronts and higher rainfalls in northern and central Mexico, (like in the winters of 82-83, 86-87, 91-92 and 97-98, for instance). In general, the opposite occurs under the influence of La Niña (Jiménez Cisneros, 2009; Magaña, et al., 2004).

In his study of the drought phenomenon in the *Huasteca Potosina*, Algara Siller (2009) concluded that, as for all the Mexican territory, El Niño alters the atmospheric circulation pattern and diminishes the amount of rainfall. This author, for instance, found a reduction of 25% of the adjusted mode of the precipitation in 44 stations of the region during the event of El Niño that took place from April 1982 to July 1983. There is also a clear relationship between the ENSO and the occurrence of tropical cyclones, which has been found to be statistically significant. There is a reduction of the number of hurricanes affecting Mexico's Atlantic Coast during El Niño years. On the contrary, the probability of hurricanes enhances during La Niña years (Blanco Loredo, 2011; Magaña, et al., 2004).

Finally, it is worth to mention what is known about the observed and expected trends in the climate of the region. At the national level, precipitation patterns throughout the year have changed so that there are higher summer rainfall levels and a higher variability. There has also been an increase in the frequency of extreme events during the last twenty years, although the average annual rainfall has dropped by an average annual rate of 0.4% between 1960 and 2007 (Jiménez Cisneros, 2009). At the level of the *Huasteca Potosina*, the aforementioned study of Algara Siller (2009) can be considered as evidence of a change tendency in the climatic patterns of the region. This author found an increasing trend in the severity of the meteorological drought associated to the decline in average rainfall and average temperature increase in 40 years, and besides correlations between loss of vegetation and the area subject to drought and changes in the climate types of the region.

Simulations performed with General Circulation Models (GCM) at the global scale are consistent in projecting precipitation decreases in some subtropical and mid-latitude regions (Jiménez Cisneros, 2009). In Mexico, several projection studies have been made by institutions like the Mexican Water Technology Institute (IMTA) and the Centre of Sciences of the Atmosphere (CCA-UNAM), based on different scenarios of greenhouse effect gasses emission. They are consistent in projecting increases in mean temperature for the rest of the century, especially for the north and northeast of the country. Increases are projected to be larger in maximum temperatures and during summer (Montero Martínez, et al., 2010; Ojeda Bustamante, et al., 2010; Jiménez Cisneros, 2009; INE, 2000).

Regarding precipitation, Ojeda Bustamante, et al. (2010) assure that a decrease is projected by the end of the century, and Montero Martínez, et al. (2010) found a projected reduction for the whole century, especially for winter precipitations. However, Jiménez Cisneros (2009), who did a thorough review of the investigations regarding climate change at the national level, and INE (2000) state that results of projections are not so conclusive and show a great dispersion in the expected behaviour of this variable. Studies are clear to say that variation in precipitation patterns will enhance drought and flooding risks. The projected enhanced flooding risk is also based on an anticipated increase in the occurrence of extreme events like tropical storms, hurricanes and on the intensification and more frequent incidence of El Niño phenomenon (Jiménez Cisneros, 2009; INE, 2000).

Montero Martínez, et al. (2010) report the results of the implementation by the IMTA of a statistical downscaling technique applied for Mexico to the projections obtained by the 23 Coupled GCMs that took part of the 4th IPPC Evaluation Report, using the SRES-A2 emission scenario. For the *Huasteca Potosina*, this work reports projected reductions of up to 15% in winter precipitation and of 10% in summer precipitation for the period 2010-2039 in comparison to the 1961-1990 period. In terms of temperature, increases of up to 1°C are projected in the minimum winter temperature and up to 2.5°C in maximum summer temperature. Prieto González, et al. (2010), in turn, report the application of the A1B GHGs emission scenario under the Japanese High

Resolution Climate Model (20 km resolution), to simulate future changes in precipitation during the rainy and cyclonic seasons (May – November) in Mexico for the period 2015-2039, with respect to 1979-2003. For most of the *Huasteca Potosina* and the VRB, the results show a decrease of 0 to 50 mm.

Finally, Mendoza, et al. (2004) report the results of the models GDFL30 (Fluid Dynamics Laboratory in Princeton), CCCM (Canadian Climate Centre) and MTC (Centre of Sciences of the Atmosphere-UNAM) for each of the 12 hydrologic regions of Mexico and for the year 2050. This study took into account population growth projections provided by the Country Studies Program Support for Climate Change Studies (Aguilar, 1994). For the Panuco hydrological region, the most populated zone in the country and in which the VRB is comprised, an increase of 67.8% in population was estimated for the year 2050 since 1995. For this region a reduction of 2.2% in the runoff per inhabitant was projected by the GDFL30 model, while the CCM model projected a reduction of 49.6% and the MTC projected a 46.8%.

4.4. GEOLOGY

According to INEGI (2011b) the Valles River Basin is comprised between the *Sierra Madre Oriental* (Eastern Mountain Range) and the Northern Gulf Coastal Plain physiographic provinces. The *Sierra Madre Oriental* originated at late Cretaceous and early Tertiary, due to an orogenic process that folded the Mesozoic sedimentary base, forming narrow alpine-style anticlines and synclines. At the low parts there are inter-montane plains and valleys of fluvial and alluvial origin limited by high mountain ranges with steep slopes. This physiographic province is represented in the Valles River Basin by the *Gran Sierra Plegada* physiographic subprovince, whose area corresponds to 92% of the watershed (see figure 3.13).

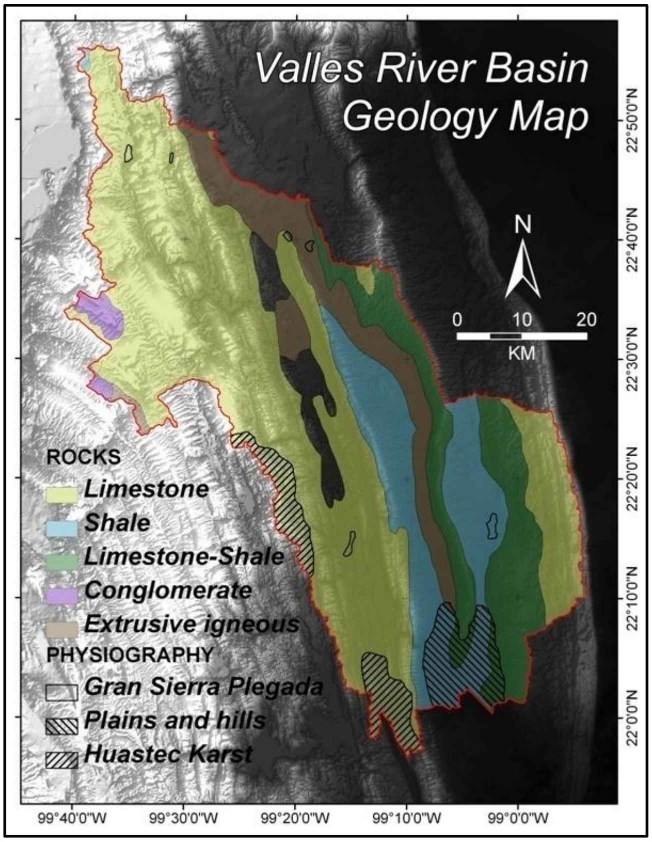

Figure 3.13: Geology map of the Valles River basin. Own elaboration with INEGI (2011b) data.

The Northern Gulf Coastal Plain, in turn, is a sedimentary plain whose origin is tightly related to the regression of the Atlantic Ocean. It is represented in the Valles River Basin by the *Llanuras y lomeríos* (Plains and hills) subprovince, which comprises 4% of the watershed. Altitudes range from 15 to 100 masl, and is characterized by extensive plains and valleys with a monotone topography and a gentle slope towards the Gulf coast (INEGI, 2007; Agenda Ambiental, ND). The remaining 4% of the watershed corresponds to a physiographic discontinuity called *Carso Huasteco* (Huastec Karst), which is one of the most extensive karsts regions in Mexico. It's dominated by limestone, which originates wells, sinkholes and caves when diluted by water (Sánchez Orta, 2010).

The predominant rock type in the watershed is sedimentary, which corresponds to 86.6% of the watershed, while basic extrusive igneous rocks area is 10.1%. Among sedimentary rocks limestone covers the largest area, corresponding mainly to *El Salto* subbasin, and shale is the second most common, present mostly in *Los Gatos* and *Río Puerco* subbasins.

4.5. VEGETATION AND LAND USE

Figure 3.14 shows the spatial configuration of natural vegetation covers and land uses in the watershed in 2003, according to the 1:250.000 map by (INEGI, 2005a). This section provides a description of both components, separately.

4.5.1. VEGETATION

Vegetation types existing within the Valles river basin are Oak Forest, *Juniperus* Forest, Cloud Forest (Mesophyll mountain forest), Low Deciduous Tropical Forest, Semi-evergreen Tropical Forest, Rosetofilous Desert Shrubland, Sub-montane Shrubland, Mesquite Shrubland and Palm Groves. As it can be observed in figure 3.14, the dominant vegetation types, which are equivalent to vegetative formations (Rzedowski, 2006) are the Oak forest and the Low deciduous tropical forest. The following section describes briefly each of these categories, focusing on their physiognomy and structure.

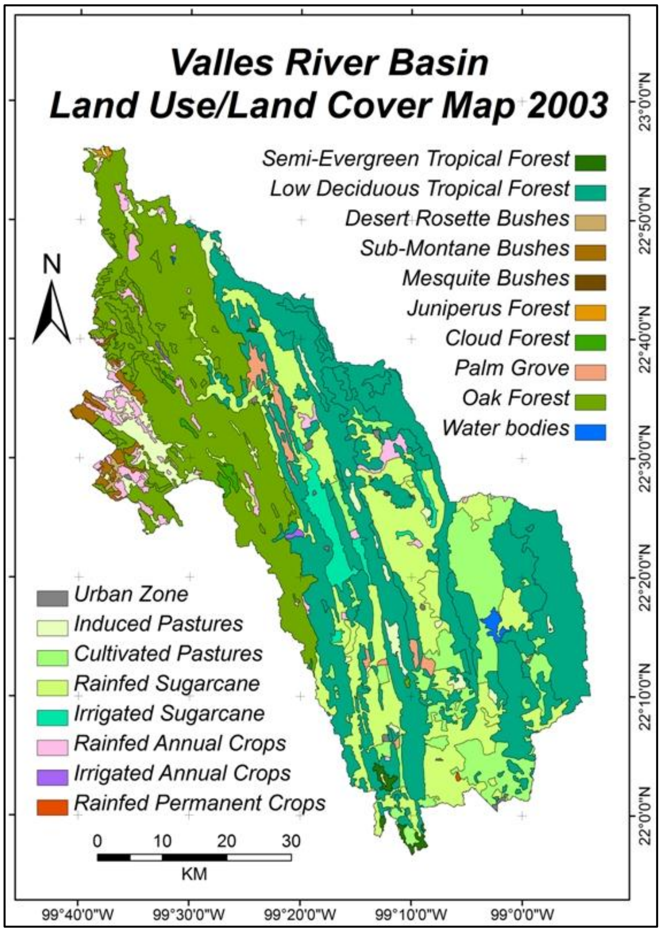

Figure 3.14. Land Use and Land Cover map of the Valles River basin (2003). Own elaboration with INEGI (2005a)

4.5.1.1. Oak Forests

Oak forests are plant communities formed by different species of the genus *Quercus* (almost 200 in Mexico). They are generally found in mountainous zones as a transition between coniferous forests (which are closely related to) and tropical forests, and develop under diverse ecological conditions. Along with the pine forests, which they tend to form mix forests with, they constitute most of the vegetative cover of the template and semihumid climates in the country (Rzedowski, 2006; INEGI, 2005b).

Many of the oak species are deciduous, and therefore such is the behaviour of the communities they dominate. However, the leaves-loss period of these species is short, often less than a month and not always matched one to another, so a forest in which dominance is shared between various species of oak can always keep a portion of greenery and even appear as an evergreen community. Typically the soils under oak forests are covered with plenty of litter and organic matter in the surface horizon and often deeper (Rzedowski, 2006; INEGI, 2005b).

The physiognomy and structure of these forests may vary between several tendencies. For example, there is no clear separation between oak scrub bushes and trees formations. A certain species of oak may behave either as tree or shrub. Oak individuals can be 4 to 30 m height, and the forests are usually very dense, although is not difficult to find sparse ones. The highest forests can exhibit two or three arboreal strata, while the low ones only show one. There are also two or three usually well developed arbustive strata. The herbaceous stratum varies its significance, being more important within open forests. Although the oak forests are sometimes called 'Broadleaved forests', the size of the leaves varies, especially according to the climate, ranging from small leaves in the driest zones, to broad leaves in the most humid climates, and to very broad leaves in intermediate or relatively dry zones (Rzedowski, 2006; SEMARNAT, 2005).

Oak forests are the prevailing vegetation of the Eastern Mountain Range (*Sierra Madre Oriental)*, particularly over its eastern slope. In San Luis Potosí portion of this mountain range, a dense oak forest, 10 to 25 m tall, covers a large area above 600 masl. There, the most abundant species are *Q. prinopsis, Q. laeta, Q. polymorpha* and *Q. sartorii* (Rzedowski, 2006). For the oak forests of the *Huasteca Potosina* region, which are referred to as 'S*clerophyllous Forest',* Puig (1991) discriminates among several groups: the hygrophilous, the meso- hygrophilous and the mesophylous. The one present at the Valles River basin is the mesophylous group, which is found in the less humid zones, located between Tamaulipas and the north of the *Huasteca Potosina*, between 700 and 1400 masl. It's constituted almost entirely by oak species, which form 10 to 20 m height dense forests with only one tree stratum, and lose their leaves for two months during the dry season (Puig, 1991).

This kind of forests has been locally very exploited for the extraction of wood for charcoal production and tables for domestic use (INEGI, 2005b). Because its associated soils are usually very fertile, agricultural activities are common in them (SEMARNAT, 2005).

4.5.1.2. Low Deciduous Tropical Forest

This type of vegetation develops under subhumid and semidry warm climates, with a mean annual temperature above 20° C and an annual precipitation between 600 and 1200 mm, having a well-marked dry season which can last up to 7 or 8 months and can be very severe. It's found from 0 to 1900 masl, normally below 1500 masl and over slopes with a good drainage. A very important factor to its distribution is the extreme minimum temperature, normally not below 0° C, being the mean annual temperature between 20 and 29° C. Another important factor is the unequal distribution of the humidity throughout the year, with very well defined rainy and dry seasons. The number of consecutive dry months ranges from 5 to 8, and the annual rainfall varies between 600 y 1200 mm (Rzedowski, 2006; INEGI, 2005b).

It is an easy-to-recognize vegetative formation, due to its peculiar phenology, physiognomy, composition and ecological requirements. It forms a dense community with a height ranging more usually between 8 and 12 m, although sometimes it may reach 15 m. Generally, its foliage is light green, easily distinguishable from the evergreen forest. The leaves are predominantly compound and small. More than 75% of the species lose their foliage during the dry season, although not simultaneously, for 5 to 8 months (INEGI, 2005b; Rzedowski, 2006).

Regarding its structure, the low deciduous tropical forest has usually only one arboreal stratum, although there may be two. Some of the most important species are *Bursera simaruba* (chaka), *Bursera* spp. (copal), *Lysiloma* spp. (tepeguaje); *Jacaratia mexicana* (bonete); *Ceiba* spp. and others. The arbustive stratum development varies as a function of the arboreal one. In a non-disturbed condition, the herbaceous stratum is poorly developed and is total absence is not rare. Reeds are abundant and epiphytes are represented only by small plants of the Bromeliaceae family. The thorny individuals in the non-disturbed communities are usually not significant, but the succulent life forms, like species from the genus *Agave* and *Opuntia*, are very frequent (INEGI, 2005b; Rzedowski, 2006).

In San Luis Potosi the reported dominant species are *Bursera simaruba, Lysiloma divaricat* and*, Phoebe tampicensis*, while *Acacia coulteri, Beaucarnea inermis, Cedrela mexicana, Lysiloma acapulcensi,* and *Piscidia piscipula* are frequent. When this formation is highly disturbed usually gives place to bushes or palm groves. It's estimated that in this state only a 30% of the remaining low deciduous tropical forest is mature forest and the rest corresponds to secondary vegetation (Rzedowski, 2006). This kind of vegetation is frequently subjected to migrant agriculture and extensive grazing although the associated soils are usually shallow and stony, not the best for agriculture. From the standpoint of forestry, although the size and shape of its trees have not desirable characteristics for trade, locally they are exploited for lack of better materials. In San Luis Potosí, the introduction of pastures in previously deforested terrains for grazing is frequent (SEMARNAT, 2005).

4.5.1.3. Semi-evergreen Tropical Forest

According to Rzedowski (2006) this type of vegetation corresponds (in part) to the 'Sub-deciduous Tropical Forest'. It is found in Mexico under warm and humid/subhumid climates, with mean temperatures of 20 – 28° C and total annual rainfall of 1000 – 1600 mm. It seems that a limiting factor to its distribution is the minimum temperature, which can be lower than 0° C. The difference between the mean temperatures of the warmest and coldest months is usually less than 5° C. It can be found from 0 to 1300 masl, over moderate slopes with good drainage or more dry plain zones, and usually karst zones. The distribution of rainfall along the year seems to be a very important distribution determinant, since typically there is a long drought of 5 to 7 months, which is only compensated by the high atmospheric humidity within the forest (Rzedowski, 2006; INEGI, 2005b).

This type of vegetation groups a series of plant communities with physiognomic characteristics and ecological requirements that are intermediate between the evergreen tropical forest and the deciduous tropical forest. Thus, many of its characteristics correspond to these vegetative formations or are halfway between the two. Its phenology is closer to that of the deciduous tropical forest. About 50% of the trees lose their leaves during the dry season, although they only facultatively deciduous. Thus, the intensity and length of the dry season determinates the defoliation degree and period, which ranges between 1 and 4 months (Rzedowski, 2006).

On the other hand, its physiognomy and structure resemble those of the evergreen forest. Its height varies between 25 and 35 metres and it shows three different arboreal strata: a lower from 4 to 12 m, a middle one from 12 to 22 m and the upper one from 25 to 35 m. Included in the lower two are the palms. Important species are *Lysiloma latisiliquum, Brosimum alicastrum, Bursera simaruba, Manilkara zapota*, *Lysiloma* spp. and *Vitex gaumeri*. During most of the year the gloomy conditions at the bottom of the forest are not favorable for the growth of the underforest. Generally the upper stratum forms a uniform canopy. Leaves are predominantly dark green and medium-sized, although there are legumes with small leaves. Thorny plants are not abundant within the climax community, and neither are the palms at the upper stratum. Woody climbers can be very abundant, especially from the Bignoniaceae family. Bromeliads and orchids stand out among the epiphytes, which generally are not so abundant (Rzedowski, 2006; INEGI, 2005b).

4.5.1.4. Cloud Forest or Mesophylous Mountain Forest

The cloud forest is part of the group of vegetative formations of mountain zones, which occupies more humid places than those occupied by *Quercus* and *Pinus* forests. The lower altitudinal limit is around 600 masl in San Luis Potosi, but it's usually found between 800 and 2400 masl. This altitudinal distribution is mainly determined by the humidity, which is why this type of vegetation is more usually found on mountain slopes protected from strong winds and excessive insolation, where fog or mists are frequent throughout the year. This is the most characteristic feature of this kind of vegetation, and it compensates the rainfall deficits during the dry season (Rzedowski, 2006; INEGI, 2005b).

In Mexico, annual mean precipitation is never less than 1000 mm, usually more than 1500 and sometimes exceeds 3000 mm. Number of dry months varies between 0 and 4. The distribution of these forests in the Eastern Mountain Range sometimes is clearly determined by the influence of the cold fronts coming from the north, known as "Northers", during the coldest period of the year, during which frosts are frequent at the higher altitudes. The mean annual temperature is 12 – 13° C (Rzedowski, 2006)

This is a dense and exuberant, usually 15 – 35 m height mesophylous forest. Most of its species are evergreen, but deciduous are common too. The period of foliage loss is usually brief, during the coldest months (Rzedowski, 2006). The most frequent species are *Liquidambar styraciflua*, *Engelhardtia mexicana*, C*arpinus caroliliana*, *Ouercus* spp., *Pinus* spp., *Clethra* spp.), *Podocarpus* spp., *Styrax* spp., *Junglans* spp., *Eugenia* spp., Meliosma spp. Usually there are several arboreal and one or two arbustive strata. The herbaceous stratum is not greatly developed within the well-preserved forests. Climbers, lianas and epiphytes are abundant, due to the high atmospheric humidity and abundant rainfall. An important part of this forest's flora is endemic (INEGI, 2005b; SEMARNAT, 2005).

The cloud forests of San Luis Potosí are referred to as *'Deciduous Humid Mountain Forests"* by Puig (1991). There, these forests are characterized by the dominance of deciduous species (80%), which lose their leaves for about three months, between December and February. *Liquidambar*, a deciduous species, is the evident dominant in these forests (Puig, 1991). Due to the climatic conditions of the zones occupied by these forests, they are frequently used for migrant or shadow coffee agriculture, and sometimes for the introduction of pastures. Besides, some trees (*Quercus, Juglans, Liquidambar*, etc.) are extracted for wood, which are of good quality (Rzedowski, 2006; SEMARNAT, 2005).

4.5.1.5. *Juniperus* Forest

These forests are largely dominated by trees from the genus *Juniperus*, which in Mexico are known as 'Táscate'. They belong to the group of the conifers and have a height of 8 – 15 metres. These forests locate in semi-warm, template and semi-cold zones, always in contact with the oak forests, mix (pine/oak) forests, low deciduous tropical forests and arid zones bushes. Most common species are *Juniperus flaccid*a, *J. deppeana, J. monosperma* and some species of *Quercus* and *Pinus* (INEGI, 2007; INEGI, 2005b). Puig (1991) adds that these forests are located on the western slope of the Eastern Mountain Range, and are usually open forests with a coverage coefficient of less than 50%. They are described by this author as transition forests between the high altitude tropical forests and the bushes of the semiarid zones.

4.5.1.6. Palm Groves

Palm groves are plant communities dominated by species of the Arecaceae (Palmae) family. The distribution of these in Mexico is highly determined by the human activities, prospering as a function of fires or other types of disturbances, although many times their presence is determined by the characteristics of the soils, which tend to be deep and waterlogged, resembling savannas. Usually they are secondary communities which substitute the evergreen or deciduous tropical forests. Apparently they don't represent a climatic climax (Rzedowski, 2006), but they grow mainly in warm and humid/semihumid climates. They are distributed forming patches, sometimes very isolated, most usually below the 300 masl (Rzedowski, 2006; INEGI, 2005b).

In most of the cases one species is the dominant and even the only representative of its life form (Rzedowski, 2006). In the *Huasteca* Potosina the dominant species are *Sabal Mexicana* (guano)*, Scheelea liebmannii* (corozo) and *Acrocomia Mexicana,* but most of the palm groves are dominated by the former, and are found next to oak and tropical forests. Structure of these formations can vary between a community and another, but in the region they usually exhibit one 8 - 15 m height (exceptionally 20 m) dense arboreal stratum and one dense herbaceous stratum. On the palms the epiphytes are abundant (INEGI, 2005b; Puig, 1991).

Palms are exploited in Mexico since long time ago. Fruits and seeds of many native species are edible and some others are exploited for the grease and soap industry. Besides, Palm Groves are frequently utilized as grazing areas by pastures introduction (Rzedowski, 2006).

4.5.1.7. Xerofilous Shrublands

Rosetofilous Desert Shrubland, the Sub-montane Shrubland and Mesquite shrublands, three of the vegetation categories employed in this study, are comprised within what Rzedowski (2006) calls "Xerofilous Shrublands", the most extended vegetation in the country according to SEMARNAT (2005). They correspond to the physiognomically diverse plant cover of the arid and semiarid zones, which are, however, floristically and ecologically similar. Apart from the mentioned formations are included some others like the 'Chaparral'. Climate for these vegetations varies from very warm at the coastal plains to relatively fresh at the highest altitudes of the high plateau, where it climbs even up to 3000 masl (Rzedowski, 2006).

The mean annual temperature ranges between 12 and 26° C. In general its associated climate is extreme, particularly during the day, when the termal oscillation is about 20° C. Insolation is usually very intense and atmospheric humidity low, causing evaporation and transpiration values to be high. Annual mean precipitation is generally below 700 mm and usually between 100 and 400 mm. Besides scarce, rainfall is usually irregular, showing strong differences from year to year. Dry months can vary from 7 to 12, and even to 18 months without appreciable rains. The xerofilous flora of Mexico is characterized by a large number of life forms adapted to the arid conditions. Succulent plants, small leaves and thorns are frequent, as well as leaves-loss during the less favorable season (Rzedowski, 2006).

This group of plant formations include some of the most economically important species of the arid and semiarid regions, such as *Agave lechuguilla* (Lechuguilla), *Euphorbia antisiphylitica* (Candelilla), *Parthenium argentatum* (Guayule), *Yucca carnerosana* (Palma samandoca) and others. Due to the scarcity of water and the shallow poor soils, agriculture is practiced on a small scale, except where irrigation is possible. By contrast, livestock is extremely widespread and very large xeric shrub areas are overgrazed, being goats the most common animals in this environment. In general, however, xerofilous shrublands are among the plant communities less affected by the man, as a consequence of the associated climatic conditions (Rzedowski, 2006).

Rosetofilous Desert Shrubland

This vegetative formation is dominated by species whose leaves form rosettes, with or without thorns, and without apparent stem. It's usually found on hillsides Xerosols of sedimentary origin (INEGI, 2005b). The most characteristics elements of this formations are species of the genus *Agave, Hechtia* and *Dasylirion*, which form a subarbustive thorny and evergreen stratum, usually very dense due to the vegetative reproduction of its components. Typically there are one or two more arbustive strata. In San Luis Potosi the dominant species are A*gave lechuguilla, A. striata* and *Hechtia glomerata*, and *Yucca carnerosa* is very frequent (Rzedowski, 2006).

Sub-montane Shrubland

This is an arbustive community, sometimes very dense, formed mostly by unarmed species but also thorny ones, which lose their leaves for a brief period each year. It develops under semiarid climates of 450 – 900 mm of annual rainfall and mean annual temperature over 23° C, between the arid shrublands and oak forests or low deciduous tropical forests, between 1500 and 1700 masl, mainly on the low hillsides of the Eastern Mountain Range. Soils are frequently rocky and shallow, sometimes covered by a thin layer of litter, of sedimentary origin (Rzedowski, 2006; INEGI, 2005b).

Physiognomy of this shrub land is given by its upper arbustive stratum, whose height varies between 2.5 and 5 metres and coverage reaches 70%. Lower stratum is less than 0.5 m height and very diverse in its composition. However, *Agave lechuguilla*, *Euphorbia antisyphilitica* and some species of the genus Bouteloua*, Tridens* and *Aristida* are the most important elements (INEGI, 2005b). In San Luis Potosí the shrub land formed by *Helietta parvifolia* is the most common, mostly on the high plateau (Rzedowski, 2006).

Mesquite Shrubland

This is a plant community dominated by species of the genus *Prosopis* (mesquites), which develop as thorny small-leaved trees 5 to 10 m height in the most humid conditions, but as shrubs under the driest conditions. They remain green during the dry season, since they are capable to reach deep water through their long roots. This is why they are frequently found over alluvial deep soils, which are relatively good for agricultural purposes (INEGI, 2005b; SEMARNAT, 2005).

4.5.2. LAND USE

4.5.2.1. Agriculture

From the very beginning of the 16th century, the Huasteca region played a role as an exchanging area of people, plants, and animals between New Spain and the Antilles, and therefore, between the New and the Old World. This commercial trade brought the introduction of cattle and sugarcane, among others. At this time the most common activities in this region were the agriculture and trade, with corn as the central element. Other crops, such as chilli, beans, tomato, papaya and pineapple were cultivated. By 1532 sugar trade was already established, although it's not clear if sugarcane as cultivated or sugar was imported from the Antilles. Sugarcane was one of the introduced species which spread more rapidly throughout the *Huasteca*, especially thanks to the adoption by indigenous population, who appreciated it as food and trading good (Ruvalcaba Mercado, 1996).

Nowadays the *Huasteca* remains an agricultural and livestock region. The most important cultivated species in the *Huasteca* are beans, corn, sorghum, chilli, tobacco, sugarcane, coffee and a variety of fruits such as citrus (orange, tangerine, lemon, etc), mango, avocado, papaya, pineapple, etc citrus, among others. However, it is possible to divide the *Huasteca* region into two agricultural subregions, according to specialized crops, production modes, land tenure, irrigation schemes and other aspects (Ruvalcaba Mercado, 1996; Bassols Batalla, et al., 1977).

Ciudad Valles and the Valles River basin are comprised within a subregion characterized by its specialization in certain cultures like sugarcane and citrus, mainly. This is a zone of large fields of rainfed crops and some irrigated crops, where volumes of agricultural production are considerable. Here is where industrialization and mechanization of agriculture is most advanced, being the sugarcane the most important culture, which has led to the consolidation of four sugar refineries. Another important crop is that of the citrus, which consolidated the establishment of juice processing plants. Although corn and beans are small scale crops, they are worth to be mentioned since they are cultivated throughout the entire region (Bassols Batalla, et al., 1977).

Table 3.5 shows surface planted with the main annual and perennial crops in the principal agricultural municipalities in the Valles River basin. It can be observed that beans and corn are by far the main annual crops during the summer cycle, beans and sorghum during the winter cycle, and sugarcane and cultivated pastures all along the year. Additionally, table 3.6 shows the number of hectares for both rainfed and irrigated crops. Ciudad Valles presents the larger are of irrigated fields, which in every case are much less than rainfed ones.

Sugarcane is the most important crop in the watershed. It is cultivated mainly in the foothills and plains areas of the zone, for the production of sugar and derivatives. Currently there are three sugar mills located within the Valles River basin: 'Plan de Ayala' (founded in 1963), 'San Miguel del Naranjo' (founded 1974) and 'Plan de San Luis' (founded 1980). There is a fourth sugar refinery in the zone, named 'Alianza Popular', but it doesn't fall within the VRB according to the delimitation done for this study. This four sugar refineries absorb almost all the sugarcane produced in the watershed, and have the capital and investment capacity to control all aspects of sugarcane cultivation (Bassols Batalla, et al., 1977). The San Miguel del Naranjo and the Plan de San Luis refineries have a bigger milling capacity than Plan de Ayala, with 7000 ton/24h vs 6000 ton/24h. Just to have an idea of the dimensions of the production, table 3.7 shows some numbers related to each refinery for the year 2002.

Planted surface per cycle (ha) in 2007						
Annual Crops: Spring-Summer						
	Oats	**Beans**	**Corn**	**Sorghum**	**Others**	
Ciudad del Maíz	184,8	3069,7	15250,2	60,0	804,2	
Ciudad Valles	2,2	457,5	3860,0	6,3	319,4	
El Naranjo	0,9	130,2	746,3	4,9	12,3	
Annual Crops: Fall-Winter						
	Oats	**Beans**	**Corn**	**Sorghum**	**Chickpea**	**Others**
Ciudad del Maíz	550,4	182,1	110,6	1174,3	14,7	180,0
Ciudad Valles	2,2	254,1	-	180,4	7,7	67,0
El Naranjo	0,9	23,9	-	4,7	-	2,4
Perennial crops						
	Alfalfa	**Coffee**	**Sugarcane**	**Orange**	**Cultivated grass**	**Others**
Ciudad del Maíz	306,4	-	168,4	0,4	3814,9	944,7
Ciudad Valles	-	190,5	32503,7	466,5	15042,4	2505,8
El Naranjo	0,0	21,8	13226,9	51,0	1199,9	29,8

Table 3.5. Sown surface with principal crops in 2007 for each cycle and for the main agricultural municipalities of the Valles River basin. Own elaboration with INEGI (2009) data.

Agricultural surface (ha) 2007		
	Irrigated	**Rainfed**
Ciudad del Maíz	1636,0	29550,4
Ciudad Valles	10459,3	52610,6
El Naranjo	1416,5	15195,6

Table 3.6. Surface according to the possibilities of irrigation for the main agricultural municipalities of the Valles River basin. Own elaboration with INEGI (2009) data.

The *Huasteca Potosina* region is an important sugar producer in Mexico. It has a great development potential. However, during the last decade the four sugar refineries present in the zone has shown a considerable deceleration in their productivity indicators, and currently are facing low profitability. At the national level, the productivity in the state, which corresponds to the production level in the *Huasteca Potosina*, is ranked as medium/low. Regarding the productivity at the level of industrial processes the indicators are acceptable, but the productivity of the sugar cane fields is low. These considerations are important, especially for the municipality of El Naranjo, which has a high dependence on sugar cane (Aguilar Rivera, 2011).

	Plan de Ayala	Plan de San Luis	San Miguel del Naranjo
Milled sugarcane (tons)	934.460	802.982,99	1’024.500,82
Produced sugar (tons)	101.058	99.852,15	129.234,94
Tons of sugarcane per ha	49,5	62,785	59,6
Milling capacity	6000 ton/24h	7000 ton/24h	7000 ton/24h
Producers suppliers	2.657	1.823	2966

Table 3.7. Some production numbers of the sugar refineries of the Valles River basin in 2002. Own elaboration with data from Cía. Editora del Manual Azucarero (2003).

4.5.2.2. Stockbreeding

Stockbreeding has been also one of the principal activities in the *Huasteca* since the 16th century. By 1550 there were already established ranches breeding mules, horses and cows, but the important development of this activity came afterwards. Some large agricultural and stockbreeding ranches were created through royal distribution of lands during colonization and survived to the Mexican Revolution until present. Livestock arrived at this time through two main processes: the exchange of slaves and animals coming from the Antilles, and the pacification and evangelization processes (Ruvalcaba Mercado, 1996; Bassols Batalla, et al., 1977).

Bassols Batalla *et al* (1977) state that stockbreeding is not a homogenous activity in the *Huasteca* and therefore they classified it into three categories: the extensive stockbreeding, the tech capitalist stockbreeding and the (traditional) smallholders’ stockbreeding. Moreover, FIRA (2011) identifies three subregions within the *Huasteca Potosina*, according to their climates, orography and vegetation, which also present differences regarding the characteristics of the stockbreeding production systems. Size of the properties, for example, is larger in the lower region, where these are usually private. Here is included Ciudad Valles, the municipality with more pastures areas in the Valles River Basin. The opposite happens in the upper zone, where the municipality of El Naranjo is included.

Municipality	P.U.	Heads	Free and controlled grazing		Intensive and Semi-Intensive	
			Prod. Units	Heads	Prod. Units	Heads
Cd. del Maíz	1729	20226	949	16907	107	1131
Cd. Valles	1779	72769	1084	68158	121	2896
El Naranjo	344	5732	203	4641	38	723

Table 3.8. Production units and cattle stock according to the 2007 Agricultural and Livestock INEGI (2009) Census in the three municipalities with the largest agricultural fields of the Valles River basin.

According to FIRA (2011), the mandatory practices are extensively applied, but those practices involving inputs and services expenses (such as fodder conservation and pasture fertilization) are practiced only by a small portion of the producers. Traditional stockbreeding is widely prevalent in the region (see table 3.8). This is a low-budget system, which employs a minimum of technology, labour and inputs and present very low yields, and hence is just profitable enough to save some incomes for necessary cases. However, there are systems which utilize better grass species, mechanical milking and other improved practices, and there are also intensive systems which employ high quantities of inputs and capital, producing high pasture and livestock yields (FIRA, 2011).

4.5.2.3. Protected areas

It is important to mention the existence of a Natural Protected Area in the area of the Valles River Basin. Its name is '*Sierra del Abra Tanchipa*' and is categorized as a Reserve of the Biosphere (RBSAT). It is located between the municipalities of Ciudad Valles and Tamuín, in San Luis Potosí. It is a federal natural protected area, and constitutes a part of the Sierra Madre Oriental. Is the only reserve of the biosphere in San Luis Potosí, and has a total area of 21464 hectares, including a core area of 16758 ha. It is hydrographically divided into two basins. The northern part corresponds to the Guayalejo River Basin, while the central and southern parts are within the VRB (see figure 3.15). The importance of the RBSAT lies on being one of the last redoubts of fauna and flora with neotropical characteristics in northwest Mexico, on the uniqueness of its ecosystems and on its diversity of endemic, threaten and in-danger fauna and flora. It is the northern limit of the medium evergreen tropical and low deciduous forests, which explains its extraordinary biodiversity (Vargas Mergold, 2010; Diario Oficial de la Federación, 1994).

Figure 3.15. Location of the *Sierra del Abra Tanchipa* Natural Protected Area. Own elaboration with data from CONANP (2011) on Google Earth.

The purposes of its declaration as natural protected area were to preserve the natural habitats of the region and the most fragile ecosystems, to conserve the genetic diversity of the fauna and flora species of the zone and to ensure the sustainable use of its natural resources, among others. The execution of public or private works, as well as the establishment of new human settlements, is forbidden within the reserve. The communities within the reserve zone and its area of influence have a high marginalization level. Their economical activities are mainly associated to the primary sector. Therefore, the area has been subject to land use changes, mainly the establishment of pastures and rainfed agriculture. There are different perturbation levels within it, especially in the central and southern parts, being the northern ones the best conserved due to its low accessibility, where most of the semi-evergreen and deciduous tropical forests are distributed. Besides the deforestation in the lower parts, environmental issues within the reserve are mainly, the extraction of wood for post elaboration, its fragmentation by the road from Ciudad Valles to Tampico, and the extraction of materials for construction. However, despite these problems, its protection has not been a priority, since there is not even an official management plan. The elaboration of this has not been possible and has been resumed only in 2008, 14 years after the creation of the reserve (Vargas Mergold, 2010; Diario Oficial de la Federación, 1994).

4.5.3. LAND USE / LAND COVER CHANGES

Table 3.9 shows area changes found for the land cover/land use categories defined in this study (see methodology chapter).

LULC	1976		1993		2003		Change 76-93		Change 93-03	
	Km^2	%WSH	Km^2	%WSH	Km^2	%WSH	Km^2	%	Km^2	%
ANCR	109.50	2.97	108.41	2.94	101.85	2.76	-1.09	-0.99	-6.56	-5.99
DCMF	14.13	0.38	13.72	0.37	13.89	0.38	-0.40	-2.86	0.17	1.21
DCTF	1779.64	48.23	1347.27	36.51	1315.72	35.66	-432.37	-24.30	-31.55	-1.77
HALV	10.54	0.29	0.28	0.01	-	-	-10.26	-97.31	-	-
IRSC	63.10	1.71	71.30	1.93	69.51	1.88	8.20	13.00	-1.79	-2.84
JUNF	3.96	0.11	3.30	0.09	2.90	0.08	-0.66	-16.67	-0.40	-10.18
OAKF	820.39	22.23	820.41	22.23	829.04	22.47	0.02	0.00	8.63	1.05
PALM	87.31	2.37	41.87	1.13	41.87	1.13	-45.44	-52.04	0.00	0.00
PAST	373.04	10.11	482.67	13.08	442.43	11.99	109.63	29.39	-40.24	-10.79
PMCR	0.63	0.02	1.05	0.03	0.71	0.02	0.43	68.15	-0.34	-54.40
RFSC	230.63	6.25	563.97	15.28	645.13	17.48	333.34	144.53	81.16	35.19
SSVB	176.08	4.77	200.78	5.44	190.49	5.16	24.70	14.03	-10.28	-5.84
SETF	12.02	0.33	17.39	0.47	15.67	0.42	5.37	44.63	-1.72	-14.31
URML	-	-	7.83	0.21	11.04	0.30	7.83	-	3.22	41.12
WATR	9.12	0.25	9.83	0.27	9.83	0.27	0.71	7.82	0.00	0.00

Table 3.9. Land use/land cover changes found for the VRB. ANCR: Annual Crops; DCMF: Deciduous Mountain Forest; DCTF: Deciduous Tropical Forest; HALV: Halophile Vegetation; IRSC: Irrigated Sugarcane; JUNF: *Juniperus* Forest; OAKF: Oak Forest; PALM: Palm Grove; PAST: Pastures; PMCR: Permanent Crops; RFSC: Rainfed Sugarcane; SSVB: Secondary Shrubby Vegetation and Bushes; SETF: Semi-Evergreen Tropical Forest; URML: Urban zones; WATR: Water bodies. Own elaboration with data from INEGI (2001) and (INEGI, 2005a).

The first thing to notice is that the most important covers in terms of area, in the three years, are the deciduous tropical forest and the oak forest. Regarding agricultural covers, pastures and rainfed sugarcane have been the most extensive. Most noticeable area changes occurred between 1976 and 1993. Largest one is the reduction of the deciduous tropical forest by an amount of 24.3% of the initial area (432.4 km^2)[9]. The increase of the rainfed sugar cane fields in 333.3 km^2 (144.5%) is the second largest one. It is also worth to notice that along this period the area devoted to pastures and to sugar cane under irrigation conditions increased in 29.4% and 13% respectively. Between 1993 and 2003 the changes were less considerable, which is understandable

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[9] This result is supported by some authors. According to (Algara Siller, et al., 2009), by 1959 Alderete and Rivera spoke of the Huasteca as a forested place of large trees, but by 1991 Dirzo and Miranda said that the *Huasteca* became a degraded region which lost its tropical forests in twenty years. Additionally, Vázquez-Yanes and Orozco-Segovia (1992, cited by Algara Siller, et al., 2009) said that high tropical rain forest, which covered from the Gulf of Mexico to San Luis Potosí, reduced its area to only 10% of its original size.

if we take into account that it is a shorter period (10 years) compared to the previous one (16 years). In this period the most noticeable change occurred was an increase of 41% (3.22 km^2) in the urban area. There was also an important increase of 81.1 km^2 in the area cultivated with rainfed sugar cane.

It is also necessary to highlight the absence of urban areas in the 1976 classification. This fact is understandable if two things are taken into account. First, the main urban area within the VRB is El Naranjo, but this municipality was not created until 1994. It can be assumed thus that in 1970 its urban area was not consolidated. Second, Ciudad Valles had in 1976 about half of the population that it registered in 2003, and thus its urban area may be expected to be totally outside the watershed. On the other hand, the total absence of halophile vegetation in 2003 seems to follow a reduction pattern. Finally, according to the data the semi-evergreen topical forest increased its area between 1976 and 1993. This is information seems not trustable, especially because it contradicts the strong reduction trend that took place in the area of deciduous tropical forest in the same period. No studied or reports were found about the reliability of the land use/land cover classification maps used in this study. A possible form to check them would be to perform a thorough analysis of land use change which includes exchanges between LULC categories.

The reduction rate of the deciduous tropical forest area decreased between 1993 and 2003. Only 31.5 km^2 were lost, in comparison to the 432.4 km^2 lost between 1976 and 1993. A decreasing trend is also observed along the three years in the area cultivated with annual crops. However, these crops occupy only a 3% of the watershed, and its hydrological influence may be insignificant. The noticeable increase trend in area cultivated with sugar cane is confirmed by Aguilar Rivera (2011). Figure 3.16 shows the historical growth of this surface according to this author.

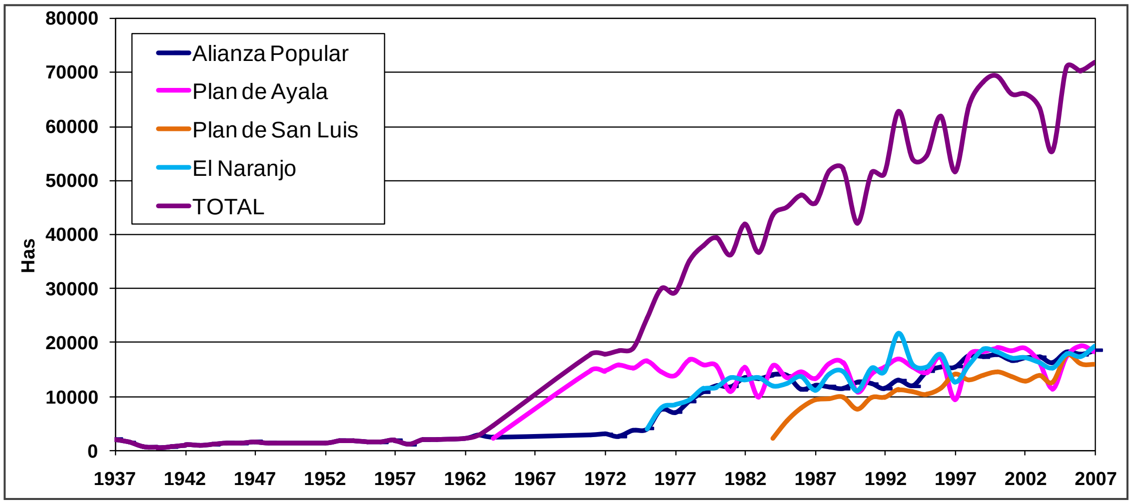

Figure 3.16. Growth of surface planted with sugarcane in the *Huasteca Potosina* (Aguilar Rivera, 2011).

According to Santacruz de León (2007) sugarcane crop fields experienced an important expansion during the last half of the 20th century. The Plan de Ayala sugar refinery received the sugarcane production from 2854 ha in 1964, and this surface grew to 16964 ha in 2005, meaning a 596.27% increase in 41 years. The San Miguel del Naranjo refinery went from 3989 ha in 1975 to 18228 ha in 2005, an increment of 457% in 30 years. Finally, the Plan de San Luis refinery had an increase of 859.4% in 20 years, going from 2137 ha in 1984 to 18366 ha in 2005. Aguilar Rivera (2011) adds that the four sugar mills in the *Huasteca Potosina* (including the Alianza Popular refinery) show the highest annual average growth rate of surface planted with sugar cane in the country, with 3.1% for the period 1998 – 2008.

4.6. SOILS

Figure 3.17 shows a 1:250.000 classification of the soils of the Valles River basin according to the World Reference Base for Soil Resources (1999) classification system, adapted for Mexico by INEGI in 2000. It can be observed that Lithosols are the predominant soils, as shown also in table 3.10. This kind of soils covers half of the watershed. They are followed in dominance by Regosols and Vertisols.

	Cambisols	Gleysols	Kastanozems	Lithosols	Luvisols	Phaeozems	Regosols	Rendzinas	Vertisols
km^2	69.83	3.55	3.63	1834.71	44.34	208.60	592.95	398.78	524.65
%	1.9	0.1	0.1	49.7	1.2	5.7	16.1	10.8	14.2

Table 3.10: Areas and percentages covered by each soil type. Own elaboration with INEGI data.

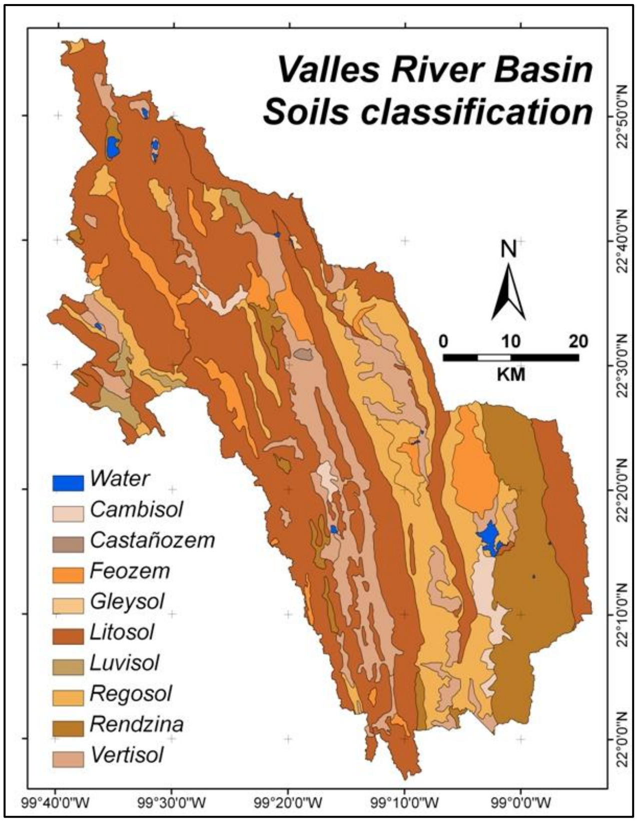

Figure 3.17. Soils map of the Valles river basin. Own elaboration with INEGI data.

4.6.1. LITHOSOLS

Lithosols are also the most abundant soils in the country (22%). They are found under every climate and varied vegetations, in all of the mountain ranges and some plain terrains. Their depth is less than 10 cm, limited by the presence of rock or a hardpan. Fertility and susceptibility to erosion is very variable depending on other environmental factors. The use of these soils depends mainly on the vegetation cover, and they can be devoted to agriculture, especially for corn or nopal (INEGI, 2004).

4.6.2. REGOSOLS

Regosols form a taxonomic remnant group containing all soils that could not be accommodated in any of the other categories. These are very weakly developed mineral soils in unconsolidated materials. Hence they don't exhibit well differentiated horizons. Generally they are light-coloured or poor in organic matter, closely resembling the original rock. They are the second most abundant soils in Mexico too (19.2%), located in very diverse climates, vegetation and reliefs. They are frequently associated with Lithosols and rocky outcrops or hardpans. Usually they are shallow and have a variable fertility. Their productivity is conditioned by their depth and stone presence. Many Regosols correlate with the Entisols of the American taxonomy (FAO, 2006; INEGI, 2004).

4.6.3. VERTISOLS

Vertisols are heavy clay soils with a high proportion of swelling clays. These soils form deep wide cracks from the surface downward when they dry out, which happens in most years. The name Vertisols (from Latin vertere, to turn) refers to the constant internal turnover of soil material. Their most common colour is black or dark grey. Vertisols are found under temperate and warm climates, especially in zones with very marked seasonal variations in precipitation. Natural vegetation ranges from low tropical forest to shrublands and pastures. Their agricultural use is very extended, varied and productive. They are very fertile but their hardness hinders tillage. On these soils is produced most of the sugarcane, cereals, vegetables and cotton. They have low susceptibility to erosion and high salinization risk (FAO, 2006; INEGI, 2004).

4.6.4. RENDZINAS

The name of this kind of soils is connotative of shallow soils which produce noise during plow due to their high stone content. They are present in semiarid, tropical or temperate climates. They're characterized by a surface layer rich in organic matter and very fertile, over limestone or lime-rich material. Generally rendzinas are shallow – under 25 cm depth - clay soils, but they get to sustain high evergreen forests. In general they present a moderate susceptibility to erosion (INEGI, 2004). This category is a modification of the WRB classification (FAO, 2006), in which they correspond to the *Leptosols*. These are very shallow soils over continuous rock and soils that are extremely gravelly and/or stony, and particularly common in mountainous regions (FAO, 2006; INEGI, 2004).

4.6.5. PHAEOZEMS

The name of this kind of soils comes from the Greek *phaeo*, which means brown. Phaeozems comprise soils of relatively wet grassland and forest regions in moderately continental climates. They are characterized by a superficial dark and soft layer, rich in organic matter and nutrients, and are similar to Chernozems and Kastanozems, but are leached more intensively and without the lime-rich layers. Consequently, they have dark, humus rich surface horizons that, in comparison with Chernozems and Kastanozems, are less rich in bases. Phaeozems may or may not have secondary carbonates but have a high base saturation in the upper metres of the soil. This type of soils can be found in any kind of relief and climate, except tropical rainy or very desert zones. They are the forth most abundant soils in the country. Depth of these soils is very variable. When deep they usually are in plain terrains and under agricultural use with high productivity. When shallower, they are located on slopes and are limited by rock or strong hardpans, yielding lower productivities and eroding more easily, although they can be used for grazing with acceptable yields. Optimal use of these soils depends on the characteristics of the terrain and especially on the water availability for irrigation (FAO, 2006; INEGI, 2004).

4.6.6. CAMBISOLS

These are young, poorly developed soils but at least with an incipient subsurface soil formation. They're characterized by slight or moderate weathering of parent material and by absence of appreciable quantities of illuviated clay, organic matter, Al and/or Fe compounds. They show a subsoil layer with lumps which show traces of the underlying rock, and may have small clay, calcium carbonate, iron or manganese accumulations. Transformation of parent material is evident from structure formation and mostly brownish discoloration, increasing clay percentage, and/or carbonate removal. They originate from medium- to fine-textured materials derived from a wide range of rocks. Are included here very thin soils directly lying over hardpans. They are very abundant and devoted to many uses, and may be found under any type of vegetation or climate except arid ones. Their productivity is variable, determined mostly by the climate. They have a moderate to high susceptibility to erosion. US Soil Taxonomy classifies most of these soils as *Inceptisols* (FAO, 2006; INEGI, 2004).

4.6.7. LUVISOLS

This word comes from the Latin *luo* which means to wash. These are soils with clay accumulations, with a higher content of clay in the subsoil than in the topsoil as a result of pedogenetic processes (especially clay migration) leading to an argic subsoil horizon. Luvisols have high-activity clays throughout the argic horizon and a high base saturation at certain depths. They are found more usually in temperate or tropical rainy zones, although sometimes in dryer climates. Associated vegetation is typically forest. Frequently red or yellow, although sometimes light brown. They are devoted meanly to agriculture with moderate yields. Under cultivated or induced pastures they can yield good incomes. These are very susceptible soils to erosion (FAO, 2006; INEGI, 2004).

4.6.8. KASTANOZEMS

These are alkaline soils found in semiarid or transitional zones to more rainy climates. Under natural conditions the associated vegetation is pastures and sometimes shrublands. Usually they are more than 70 cm deep and are characterized by an upper brown or reddish horizon, rich in organic matter and nutrients, with accumulation of loose or slightly cemented caliche in the subsoil. Kastanozems have a similar profile to that of Chernozems but the humus-rich surface horizon is thinner and not as dark as that of the Chernozems and they show more prominent accumulation of secondary carbonates. In Mexico these soils are used for extensive or intensive grazing through cultivated pastures. When used for agriculture they have high productivity, especially under irrigation, because they have a natural high fertility. Their susceptibility to erosion is moderate (FAO, 2006; INEGI, 2004).

4.6.9. GLEYSOLS

From the Russian *gley*, which means swamp. Gleysols are wetland soils that, unless drained, are saturated with groundwater for long enough periods to develop a characteristic gleyic colour pattern. This pattern is essentially made up of reddish, brownish or yellowish colours at ped surfaces and/or in the upper soil layer or layers, in combination with greyish/bluish colours inside the peds and/or deeper in the soil. They are usually under pastures and sometimes under mangroves. They have very variable textures but in Mexico clay ones predominate, which brings flooding problems during the rainy season. Frequently they present saltpetre accumulations. They are in Mexico used for cattle grazing with moderate to high yields. Sometimes they may be devoted to agriculture with good results, like in the case of sugarcane and rice, which require or tolerate floodings. Many of the WRB Gleysols correlate with the aquic suborders of the US Soil Taxonomy (FAO, 2006; INEGI, 2004).

4.7. DROUGHTS AND FLOODINGS IN THE VALLES RIVER BASIN

The analysis of the water management at the VRB made by Santacruz de León (2007; mentioned in chapter 1), which was focused on problems related to water use and availability, made no mention of the floodings that occur frequently in Ciudad Valles and other parts of the VRB. In this sense, the same author says that the relevance of an environmental problem is not necessarily a function of its magnitude, but also of the way that their effects are perceived and internalized by the society. A number of communities that live in localities under risk by water pollution, droughts and/or floodings don't internalize these risks because a lack of alternatives or because they have other priorities. However, floodings, likewise droughts, are recurrent events in the VRB, particularly in Ciudad Valles. The present study focuses on these two phenomena, since they can be directly reflected in the hydrological regime of the watershed.

According to the International Glossary of Hydrology (UNESCO, 2011), a flood is a "relatively high flow as measured by state height or discharge" or "rise, usually brief, in the water level of a stream to a peak from which the water level recedes at a slower rate". Flooding, on the other hand, is the "overflowing by water of the normal confines of a stream or other body of water, or accumulation of water by drainage over areas which are not normally submerged". According to their duration floods can be classified as flashy, typical of mountainous watersheds, or slow floods, which are gradual rises in the flow level. According to their generation mechanism floodings can be fluvial, caused by the overflowing of a river, or pluvial, which are produced by the accumulation of water precipitated over a particular area, due to both intense short or moderate long rainfall events (Agenda Ambiental, ND).

Table 3.11 shows the records of floodings in the area of Ciudad Valles and the VRB from 1970 to 2007 obtained from to SAGARPA (2004a) and Agenda Ambiental (ND). Monthly maximums in the stream flow records obtained from IMTA-CONAGUA (2010) were also checked to identify the events when the Valles River surpassed the critical scale of 5.5 metres at the Santa Rosa station, the level at which the river overflows and starts to inundate Ciudad Valles. In table 3.11 these cases are identified as source 3.

Year	Months	Source	Origin	Source	Affected
1973	**Jul**	1			Ciudad Valles
1974	**Jun-Oct**	1, 2, 3			Ciudad Valles
1975	**May-Sep**	1	Hurricane Caroline	1	Ciudad Valles
1976	**May-Jul**	1, 2, 3	Stationary front	2	Ciudad Valles
1977	**Sep**	1, 2, 3	Hurricane Anita	2	Ciudad Valles
1979	**Jun-Sep**	1			Ciudad Valles
1984	**May-Oct**	1			Ciudad Valles

1988	**Aug-Sep**	1, 2, 3			Ciudad Valles
1989	**Aug**	1			Ciudad Valles
1990	**Aug**	1, 2, 3	Hurricane Diana	1, 2	Ciudad Valles
1991	**Jul**	1, 2, 3	Tropical Depression 2	2	Ciudad Valles
1992	**Jul**	2, 3			Ciudad Valles
1993	**Jun - Sep**	1, 2, 3	Hurricane Gert	1, 2	Cd.Valles, El Naranjo
1996	**Aug**	1, 2	Hurricane Dolly	1	Ciudad Valles
1997	**Apr-Jun**	1			Ciudad Valles
2000	**Jun**	1			Cd.Valles, El Naranjo
2001	**Jun, Oct**	1			Cd.Valles, El Naranjo
2003	**Oct**	1			Ciudad Valles
2004	**Jun-Sep**	1			Cd.Valles, El Naranjo

Table 3.11: Record of floodings that affected Ciudad Valles and the VRB between 1970 and 2007. The first source column refers to the record of the flooding and the second refers to its association to a meteorological phenomenon. Sources: 1) SAGARPA (2004a), 2) (Agenda Ambiental, ND), and 3) this study.

It may be observed that some of these events have been caused by tropical cyclones. According to (Agenda Ambiental, ND), the others can be attributed to other meteorological phenomena such as convective storms and cold fronts. Some of these events represent fluvial floodings caused by the overflowing of rivers Valles, Los Gatos and Puerco, and some affluent creeks of the Valles River like *Las Cruces, Birmanía, El Macho* and *Las Garzas*, which directly impact the urban area of Ciudad Valles (Agenda Ambiental, ND). In the case of El Naranjo, floodings are mostly associated to long and intense rainfalls (pluvial floodings) (SAGARPA, 2004a). Overall they leave behind a trail of devastated crops, landslides, affected population, housing losses, economic losses, food shortages and many other calamities (SAGARPA, 2004a; Agenda Ambiental, ND).

Return period	Scale or level (m)
2	3.68
5	5.98
10	7.12
20	7.94
50	8.92
100	9.62

Table 3.12: Levels of the Valles River corresponding to several return periods. Taken from (Agenda Ambiental, ND).

In the Atlas of Natural Hazards of Ciudad Valles (Agenda Ambiental, ND) a probability analysis of the maximum levels recorded at the Santa Rosa station was carried out. The best fit was found with the Double Gumble distribution, based on which the maximum levels corresponding to several return periods (T) were calculated, and are shown in table 3.12. Interpolating the results it is obtained that the critical scale is equaled or exceeded every 4.2 years. In other words, the average frequency of the floodings in the lower parts of Ciudad Valles is 4.2 years[10]. The maximum level registered at the Santa Rosa station was 8.95 m (12/07/1976), which slightly exceeded the 50 years level (Agenda Ambiental, ND). Annex 2 shows the map of the urban areas subject to flooding for the 5 years return period, which corresponds to the recurrent scenario of

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[10] Table 3.11, however, shows a higher frequency of more than 1 flooding every two years. The analysis of Agenda Ambiental (ND) refers only to the overflowing of the Valles River at the Santa Rosa station, while the newspaper records from SAGARPA (2004a) refers to all kind of floodings, including pluvial floodings and those occurring in Ciudad Valles but downstream from the Santa Rosa station.

floodings, when the lower parts at the southwest of the city are inundated (taken from Agenda Ambiental, ND). Blanco Loredo (2011) presents a complete map of the areas of the *Huasteca Potosina* which are subject to floodings, including the rural areas that are not shown here.

The severity of meteorological drought in the zone has led to other types of drought with severe implications for the population, namely decreased agricultural production, unusual decreased levels of water bodies and even impacts on the health of the population (Algara Siller, 2009). In its compilation from newspaper records, SAGARPA (2004a) shows that the most recurrent impacts are losses in the production of sugarcane and other crops such as corn and citrus. Other frequent impacts are livestock deaths and forest fires. When droughts have extended or been more severe there are reports of dried rivers, reservoirs, and wells, water shortages for domestic use, dehydration and rural migration. Table 3.13 shows a summary of these records. In it, agricultural drought refers to the events when agricultural production has been damaged by the water scarcity and high temperatures, hydrological drought to the reports of considerable reduction in water levels of rivers and other water bodies, and social drought to the reports of impacts to the health of the population, namely dehydration and even food shortages.

Year	Meteo.	Agricul.	Hydro.	Social	Year	Meteo.	Agricul.	Hydro.	Social
1971	X	X	X	X	**1987**	X			
1973	X	X	X	X	**1988**	X	X	X	X
1974	X	X	X	X	**1989**	X	X		
1975	X	X	X	X	**1990**	X	X		X
1977	X		X		**1993**	X	X		
1978	X		X		**1994**	X	X		
1979	X		X		**1996**	X	X		
1980	X	X	X		**1997**	X	X		
1981	X	X			**1998**	X	X	X	
1982	X	X	X	X	**2001**	X	X	X	
1983	X	X	X		**2002**	X	X	X	X
1986	X	X			**2005**	X	X	X	X

Table 3.13: Different types of droughts occurred in the VRB according to newspaper records compiled by SAGARPA (2004a).

It may be seen that, there is almost a drought (at least meteorological) per year, which agrees with the already shown results from Algara Siller (2009). Agriculture is usually the first injured, since it is mostly rainfed. There are some cases in which hydrological drought is reported and agricultural drought is not. In this sense it has to be considered that these records are not conclusive and thorough evidence, but they are useful to have an idea of the frequency of the different effects of the meteorological droughts in the zone. On the other hand, if table 3.11 and 3.13 are compared, it may be seen that there are records of droughts and floodings occurring in the same year. Accordingly, in the newspaper records there were some cases in which floodings were reported immediately after the occurrence of a seasonal drought.

5. METHODOLOGY

In order to assess the suitability of the SWAT model, the methodological scheme shown in figure 4.1 was adopted. It is worth to say that a model's suitability for a given watershed has to be assessed in the light of a specific application, which in this case is the identification of land use/land cover change hydrologic effects.

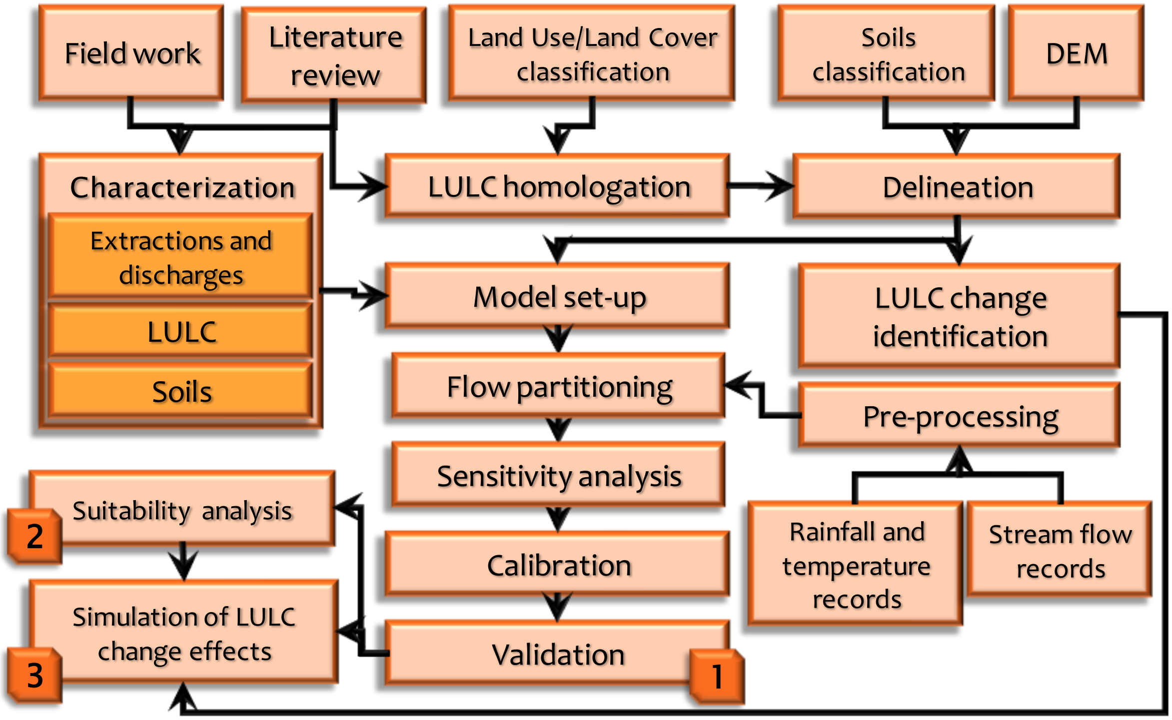

Figure 4.1. Methodological scheme showing the relations among main inputs, processes, outputs and specific objectives (numbers in squares).

In this study SWAT was applied through the ArcSWAT 2009 Graphical User Interface (GUI), which works as an extension within the ArcGIS software. In general terms, the application of the model begins by collecting data, which constitute the inputs for the model, and is followed by the spatial configuration and parameterization. After that comes the calibration and validation process, which is the basis to analyze the suitability of the model to the particular watershed of study. of the model, to finally apply it, in this case to simulate the hydrological effects of land use/land cover changes and analyze the applicability of the model as a water resources management tool for the Valles River Basin.

5.1. MORPHOMETRICS

To have a first idea of the hydrology of the Valles River Basin some shape indices or morphometrics were calculated. They reflect the topographical and hydrographical configuration of the watershed and hence are used to infer what can be expected from the watershed's hydrology. Indices calculated were:

- **Shape Coefficient (K_f):** It reflects the relation between the average width of the basin and the length of the longest stream (Monsalve Sáenz, 1995):

$$K_f = \frac{A}{L^2} \tag{Eq. 4.1}$$

Where A is Area and L is Length of the longest stream. A watershed with a small shape coefficient is less likely to present high runoff peaks (CEIFI & CRQ, 2003); Monsalve Sáenz, 1995).

- **Gravelius or Compactness Coefficient (K_c):** It indicates the relationship between the perimeter of the basin and the perimeter of a circle with the same area of the watershed and thus gives an idea of the regularity of its shape (Monsalve Sáenz, 1995):

$$K_c = 0.28\left(\frac{P}{A^{1/2}}\right) \tag{Eq. 4.2}$$

Where P is Perimeter and A is Area.

The lower this value the more regular is the basin's perimeter and the more prone to present high runoff peaks. When K_c = 1 the basin is round, and its centroid is closer to the streams. In this case a faster and bigger concentration of water during/after rainfall events can be expected (CEIFI & CRQ, 2003; Monsalve Sáenz, 1995).

- **Drainage Density (D_d):** This index gives a good idea of the complexity and development degree of the watershed's drainage system (CEIFI & CRQ, 2003). A rich drainage system has a greater water concentration capacity because water runs through less distance to the streams. Likewise, a poorer system gives place to higher infiltration values, and therefore lower and delayed flow peaks are expected. It is calculated as (Monsalve Sáenz, 1995):

$$D_d = {}^{L}\!/_{A} \tag{Eq. 4.3}$$

Where L is the water streams length and A is the drainage area. A 1:50.000 shapefile obtained from (INEGI, 2011a) to calculate this index.

- **Average slope:** Slopes has a direct relationship with infiltration and surface runoff, among others. A higher slope produces higher and faster runoff peaks. Average slope was determined through the surface analysis tools of ArcGIS for each of the subbasins.

- **Concentration Time (T_c):** It expresses the time elapsed since the beginning of the precipitation until the moment in which the total area of the watershed contributes to the runoff at the outlet. It also may be defined as the time that a water drop takes to travel from the farthest point in the watershed to the outlet. This parameter was calculated according to the equation of the U.S. Bureau of Reclamation (CEIFI & CRQ, 2003):

$$T_c = \left(\frac{0.886\,L^3}{H}\right)^{0.385} \qquad \text{(Eq. 4.4)}$$

Where L is the length of the main stream (in kilometres) and H is the altitudinal difference (in metres).

5.2. MODEL SET UP

This section describes the process by which the model was configured to simulate the hydrologic behaviour of the Valles River Basin, including some tasks common for calibration, validation and simulation. The first step was to pre-process data inputs such as land use/land cover maps, soil map and hydrometeorological records. Results of the corresponding pre-processing procedures are presented. After that came the process of parameterization, meaning the process by which specific values are assigned to the variables characterizing the watershed system, according to prior knowledge of the watershed. This process is called by Xu (2002) as "parameter specification", in contrast to the "parameter estimation" process which is regarded here as calibration.

Out of the total number of parameters used by SWAT, which includes parameters to model sediments, nutrients and pesticides transport, about 180[11] (see Annex 3) were relevant for the purposes of this modelling exercise and were modified thanks to information availability. Some of the spatial parameters were automatically configured by the ArcSWAT interface. Following sections also describe the parameterization process carried out for the main physical aspects of the Valles River Basin system.

5.2.1. DATA USED

SWAT model was applied through the ArcSWAT interface, which operates under the ArcGIS software. Spatial data were georreferenced under the Universal Transverse Mercator (UTM) Zone 14 projection (Datum WGS 1984). Overall, the principal input datasets were:

- ✓ **Digital Elevation Model (DEM):** A DEM from the Mexican statistics and geography institute (Instituto Nacional de Estadística y Geografía - INEGI), with a grid resolution of 50 m was used.
- ✓ **Land cover/land use maps**: Land use/land cover 1:250.000 classifications for the years 1976, 1993 and 2003 elaborated by INEGI were used.
- ✓ **Soils map:** A soil 1:250.000 classification elaborated by INEGI was used.
- ✓ **Precipitation and temperature:** Measured daily precipitation, maximum and minimum temperature datasets from 32 meteorological stations within and around the watershed were available, with record periods of 20 – 50 years.
- ✓ **Solar radiation:** As no measured solar radiation values were available, satellite derived monthly values for the city of San Luis Potosí calculated by Galindo, et al. (1991) were used to feed the weather generator.
- ✓ **Streamflow:** Daily records from the 'Santa Rosa' hydrometric station for the period 1958 – 2006 were available to calibrate the model. A 6 year (1966-1971) daily series of a station located at the El Salto hydropower plant outlet was utilized to know discharge levels from this

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[11] This number increases if the necessity of defining each of them for several soil and land cover classes and also for twelve months in the case of the weather input parameters is taken into account.

plant. These series were obtained from the surface water national data bank (BAnco Nacional de Datos de Aguas Superficiales) (IMTA-CONAGUA, 2010).

- ✓ **Water use**: Location of water extraction and wastewater discharge points was obtained from the public water rights register (Registro Público de Derechos de Agua – REPDA), along with right holders and allowed extraction and/or discharge amounts (CONAGUA, 2010) and complemented with information obtained from Soriano Pérez (2001) and Gonzalez Quilantan (1994).

Besides, during field visits interviews to some local experts were carried out to know the main aspects of land and water use, including aspects such as:

- **Sugarcane management**: Culture calendar, planting, tillage practices, tools, crop residues use, fertilization, irrigation, crop characteristics, etc.
- **Pastures management**: Most common management schemes, most common grasses, technology levels, irrigation, planting, fertilization, etc.
- **Reservoirs management**: A visit to the El Salto (Camilo Arriaga) hydropower plant was made to obtain information about technical characteristics and functioning of this plant as well as about Los Micos and Electroquímica hydropower plants. Another visit was made to the La Lajillas (Laguna del Mante) reservoir, to obtain corresponding information from its managers from Ejido Laguna del Mante.

5.2.2. WATERSHED DELINEATION

Valles River Basin was delimited based on INEGI's DEM through the flow direction and flow accumulation algorithms of the ArcSWAT module, taking the Santa Rosa hydrometric station as the watershed's outlet. The area contributing to a stream was defined to simulate a streams shapefile previously elaborated by INEGI, and following the recommendation of the ArcSWAT User's Manual (Winchel, et al., 2010) to incorporate more complexity into the model by generating a larger number of subbasins rather than more HRUs by subbasin. After an iterative delineation process a spatial configuration of 57 subbasins was obtained (see figure 4.2). Land Use/Land Cover was classified into 15 categories and soils into 10 classes. Slope had only one class. This

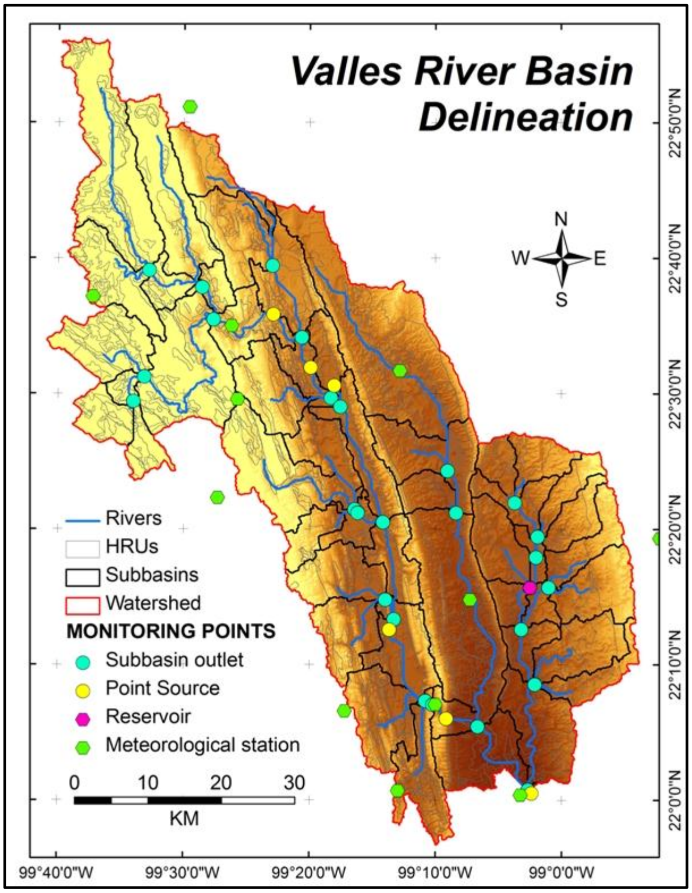

Figure 4.2. Watershed delineation for modelling in ArcSwat. Own elaboration.

configuration was chosen because focus was put on the effects of land covers. Indeed, no area threshold was introduced to discard small HRUs, since the overall effect of small changes might be important. Figure 4.2 shows the obtained delineation. A different HRU definition was done for each of the modelled years, according to the different land use/land cover configurations. 677, 724 and 705 HRUs were obtained for 1976, 1993 and 2003, respectively.

5.2.3. SOILS

5.2.3.1. Classification

Soil map used in this study is based on FAO's World Reference Base for Soil Resources (1999) classification system, modified by INEGI in 2000. Levels of classification were 10 types and 14 subtypes, and included information about physical and chemical phases. Original soil units (subtypes) were:

- Calcic cambisol
- Calcic kastanozem
- Luvic kastanozem
- Calcaric phaeozem
- Haplic phaeozem
- Luvic phaeozem
- Vertic gleysol
- Lithosol
- Cromic luvisol
- Ferric luvisol
- Calcaric regosol
- Pelic vertisol
- Rendzina

Because of computing constraints soil units had to be merged into 10 categories. Units were then equivalent to soil types.

5.2.3.2. Parameters specification

SWAT soils database includes data only for soils located in the United States, and its classification doesn't match FAO's WRB system. Modelled soil classes had to be created and 14 variables had to be defined for them, including 9 variables for each soil layer. Below are the definitions according to (Neitsch, et al., 2005) and the description of how each was obtained.

- **Soil hydrologic group**: Definition of this variable was presented in section 4.2.1.1. Values were defined according to the texture and depth, following the definition presented and given by Neitsch, et al. (2005).
- **Maximum rooting depth / Depth of soil profile:** These two variables were assumed to be equal. Data was obtained from INEGI (2002).
- **Maximum crack volume:** Is a fraction of the total soil volume, important to predict infiltration and runoff in areas dominated by Vertisols. Data obtained from Cerana, et al. (2005).
- **Soil albedo:** Is the ratio of the amount of solar radiation reflected by a body to the amount incident upon it, expressed as a fraction. Values were estimated based on texture, following Ten Berge (1986).
- **USLE K factor:** Is the soil erodibility factor of the Universal Soil Loss Equation (USLE), which expresses the soil ease to be eroded, independently from other factors. Data were obtained from Rojas (2009) based on texture classes.
- **Depth of layer**: Depth from soil surface to the bottom of layer. Data obtained from INEGI (2002).

- **Clay, silt and sand contents of layer:** Percent of soil particles corresponding to each size. Data obtained from INEGI (2002).
- **Rock content of layer:** Percent of the total weight with a size particle larger than 2 mm. Values were estimated based on the soil and diagnostic layers in FAO (2006).
- **Organic carbon content of layer**: Defined as a percentage of soil weight. Calculated by dividing values of organic matter obtained from INEGI (2002) by 1.72, following the equivalence mentioned in Neitsch, et al. (2005).
- **Moist bulk density of layer**: Expressed in gm/cm^3, this variable expresses the ratio of the mass of solid particles to the total volume of the soil. Values were estimated based on the texture of the layer, following Almorox Alonso (2010).
- **Soil available water capacity of layer (AWC)**: Is the plant available water, expressed in mm H_2O/mm soil, and is equivalent to the subtraction of the water present at permanent wilting point from that present at field capacity. Data were estimated based on layer's texture, following Burk, et al. (2008).
- **Saturated hydraulic conductivity of layer (K_{sat})**: Is a measure of the ease of water movement through the soil, expressed in mm/h. It was estimated based on the proportion of sand, after finding an exponential regression model which fitted the values included in the SWAT soil database.

5.2.4. LAND USE AND LAND COVER

5.2.4.1. Classification

To identify land cover/land use change effects three land cover classification maps elaborated by INEGI (see figure 3.14) and corresponding to the years 1976 (Series I), 1993 (Series II) and 2003 (Series III) were used. The first series was elaborated based on the interpretation of aerial photographs of the 70s decade, complemented with a review of literature about vegetation and land use and a process of field verification, including a botanical sampling. The second series was based on actualization of the information collected for the first series and the interpretation of Landsat TM images of the year 1993, print with a 4, 3, 2 (RGB) band combination. Finally, for the elaboration of the third series another actualization was carried out, and an identification of the changes with respect to the second series based on the interpretation of 2002 satellite images also based on updated information, followed by the corresponding field observation and verification (INEGI, 2009; INEGI, 2005a).

Due to computing constraints land cover categories included within INEGI's LULC classification were modified by merging some of them, taking into account similarities in physiognomy and their spatial significance (area). As mentioned in section 4.3.2, it's recommended that subbasins and HRUs in the watershed don't exceed a certain number. Thus, a homologation process between INEGI's vegetation categories and SWAT's database land cover categories was carried out, based on the definitions given by EPA (2007) and Anderson, et al. (1976) for the SWAT database and by Rzedowski (2006), INEGI (2009 and 2005b), SEMARNAT (2005) and Puig (1991) for local vegetation. Categories of Oak Forest, Cloud Forest, Low Deciduous Tropical Forest, Semi-evergreen Tropical Forest, *Juniperus* Forest and Palm Groves remained unchanged. Chaparral, Mesquite Shrublands, Sub-montane Shrublands and Rosetofilous Desert Shrubland were merged altogether with Secondary Vegetation into a new category named Secondary Shrubby Vegetation and Bushes.

Regarding land use, categories included within INEGI’s LULC classification were:

- Cultivated pastures
- Induced pastures
- Rainfed agriculture
- Irrigated agriculture
- Humidity agriculture

These categories are based on the humidity condition of the crops and the nature of the pastures. Humidity is not a determining factor of a land use, only an attribute. However, INEGI’s shape files included information about the seasonality of the agriculture, and this fact was taken advantage of to modify the classification and make it more similar to the LULC database included in SWAT, which comprises only land cover categories and not land use ones. Thus, a homologation for these categories was made too, also in order to avoid the necessity of finding values for each of the required parameters (many of them not available) for new land cover categories and to fit the classification to a more convenient one for the purposes of the study.

Taking information from Bassols Batalla, et al. (1977), the 1991 National Agricultural Census (INEGI, 1996; INEGI, 1994), and from the SIAP database (SIAP, 2010), the main crops in the zone for the model years were identified. INEGI’s semipermanent crops were identified as sugarcane crops, and due to the important area devoted to this crop in the watershed, the discrimination between rainfed and irrigated fields was maintained. The categories obtained were:

- Pastures
- Annual crops
- Rainfed sugarcane
- Irrigated sugarcane
- Permanent crops

Principal annual crops are corn, beans and sorghum. However, as they are cultivated under rotational schemes they couldn’t be spatially discriminated and remained as one class.

5.2.4.2. Parameters specification

An important component of the model is the land cover / plant growth sub-model, which is used to assess removal of water from the root zone, transpiration and biomass/yield production. It simulates plants’ potential growth as a function of intercepted energy (which in turn is a function of solar radiation and leaf area index) and plant’s efficiency in converting it to biomass, as well as actual evapotranspiration, as a function of potential evapotranspiration and water availability (Neitsch, et al., 2005).

A total of 42 variables had to be defined for SWAT’s land cover/plant growth database. As information for most of them for the conditions of the Valles River Basin was not available, default values were employed. It is important to mention that SWAT uses values of some land covers to simulate others. Equivalences used in this study are summarized in table 4.1. Variables taken by default are very specific values related to radiation use efficiency, leaf area and corresponding points of the plants’ development curve, fractions of biomass corresponding to nitrogen and phosphorus for several points of the development curve, C factor (crop management factor) for the Universal Soil Loss Equation (USLE), stomatal conductance and CN values for moisture condition II for each hydrologic group class (Winchel, et al., 2010). Values included in SWAT database for these variables were taken from several sources, most of them studies made in United States.

LAND USE/LAND COVER CLASS	SWAT HYDROLOGIC EQUIVALENT
Oak Forest	Forest-Deciduous (Oak)
Deciduous Mountain Forest	Forest-Deciduous (Oak)
Deciduous Tropical Forest	Forest-Deciduous (Oak)
Semi-Evergreen Tropical Forest	Forest-Evergreen (Pine)
Secondary Shrubby Vegetation and Bushes	Range-Brush (Little Bluestem)
Palm Grove	Oil Palm
Halophile Vegetation	Range-Brush (Little Bluestem)
Pastures	Pasture (Bermuda grass)
Annual Crops	Corn
Rainfed Sugarcane	Sugarcane
Irrigated Sugarcane	Sugarcane
Water	Water
Juniperus Forest	Forest-Evergreen (Pine)
Permanent Crops	Orchard (Apples)
Sorghum	Grain Sorghum
Beans	Pinto Beans

Table 4.1. Hydrologic equivalents used to simulate hydrologic behaviour of defined LULC classes.

These equivalences were defined during the homologation process described in the previous section, as well as with the information about pastures management obtained through interviews during field visits (Osmín Meraz, pers. Comm.). Nevertheless, some few variables were modified as information was available and in order to reflect, as much as possible, the characteristics of the Valles River Basin land uses and land covers. Modified variables were (Winchel, et al., 2010):

- **Harvest Index for land cover/plant (HVSTI)**: Is the fraction of aboveground biomass that is removed during harvest operations under optimal growing conditions, and is then unavailable to convert into residue and subsequent decomposition (0 – 1).
- **Lower limit of harvest index:** Is a value between 0 and HVSTI, which represents the lowest harvest index expected due to water stress.
- **Maximum canopy height:** Maximum canopy height of land covers in metres.
- **Optimal temperature of growth:** Temperature conditions under which the plants exhibit an optimal growth (°C)
- **Minimum temperature of growth:** Temperature conditions below which the plant stops to grow (°C).

5.2.5. HYDROMETEOROLOGICAL RECORDS

5.2.5.1. Selection of stations

Processing of hydrometeorological records began with the selection of the most appropriate series of daily maximum and minimum temperature and precipitation. A number of 12 stations were considered as a good compromise between representativeness for the watershed's area and the necessity to minimize computing requirements and processing time. The first selection was made for precipitation, and the first criterion was the extension of the series, which had to cover from 1970 to 2006 and have data for 1976, 1993 and 2003 (model years). 21 stations covered the three model years and also had at least 33 years of records (see figure 4.3 - step 1).

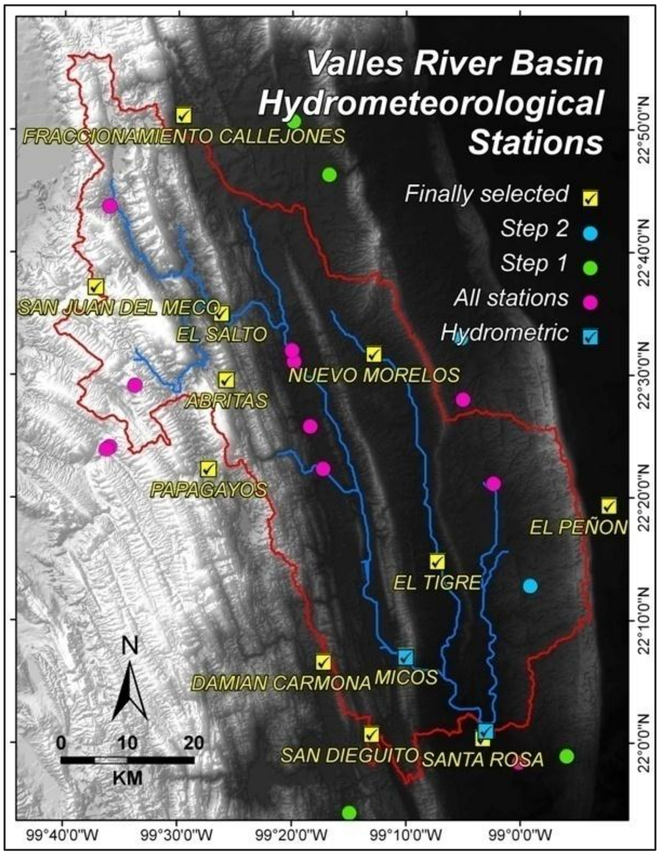

Figure 4.3. Selection process of meteorological stations. Own elaboration with INEGI data.

At this point, spatial distribution of stations was taken into account. The horizontal and altitudinal distribution of the partially selected meteorological stations was not uniform, and 7 stations were discarded because of this reason (step 2). Afterwards, an assessment of the missing data was made. The two stations with higher percentage (26.3% and 18.9%) of missing data were discarded. Among the rest, there was one station (Nuevo Morelos) with 21.1% of missing data in relation to the model years, but had only 6.7% in relation to the whole simulation period. It was decided to be kept within final selected stations because of its location, which was important for the spatial representativeness of the watershed. The rest of the stations had less than 5% of missing data. For temperature stations, the selection followed the same criteria and the 12 selected stations were the same than those selected for precipitation. In the case of the Santa Rosa hydrometric station, it had only one year of missing data each.

5.2.5.2. Outliers identification

After selecting the stations a quality assessment of the series was carried out. The first step was to find the outliers, which are values that grossly exceed the usual variation range of the analyzed variable. These values have to be verified, because they can be recording errors or true records of not common situations. In some cases it may not worth to find and adjust these values, but in this case was considered important to do so because they might affect the model calibration process. The most common causes of extraordinary temperature and precipitation records in Mexico are extreme events such as tropical cyclones and cold fronts coming from the north, which can cause very low temperatures and high rainfall values (Vásquez Aguirre, 2010).

There are several methods to evaluate this kind of errors, from those based on the use of percentiles and probability density function analyses, to multivariate and multidimensional techniques. In the case of this study, identification of outliers or suspicious values in precipitation and temperature daily series was based on comparison with climatic normal values[12] reported by INIFAP (2005) and the National Meteorological Service (SMN, 2011). Once identified, outliers were assessed by comparing with values of near stations that showed the highest linear correlation and by reviewing the information about the occurrence of El Niño phenomenon and tropical cyclones (table 3.4). No records or statistics were found for cold fronts. El Niño and La Niña years were identified through anomalies in sea surface temperature of the region 3.4 obtained from the National Oceanic and Atmospheric Administration (NOAA)[13]. For temperature analysis an additional step was introduced. Daily series of differences $(T_i - T_{i-1})$ were generated and higher differences were checked against occurrence of extreme phenomena. No adjustment of values was made. Values considered as errors were deleted from the series and left as missing values to be generated by the WXGEN generator. A total of 89 values were checked for maximum temperature, 26 of which were deleted. For minimum temperature 331 values were checked, 39 being erased. Precipitation presented 86 suspicious values, 42 of which were deleted.

In the case of streamflow records, outliers' identification was performed on the level records (scales) because they reflect more precisely when an overflow occurs (when surpassing the critical scale). The process was carried out on a monthly basis. A first step was to verify the coherence between average values and maximum values (i.e. average value being higher than maximum), and no incoherences were found. A second step was to verify the occurrence of the highest values by comparing them to the records of floods occurred in Ciudad Valles, according to Agenda Ambiental (ND) and SAGARPA (2004a) (see table 3.11). All values above the critical scale of the station could be verified according to the reports, and some of them could be associated to tropical cyclones (see figure 4.4).

5.2.5.3. Homogenization

Climate data series usually contain artificial shifts due to inevitable changes in observer, instruments, location, environment and observing practices/procedures taking place in the period of data collection. Data discontinuities also arise from the continuously evolving technology of climate monitoring. It is important to detect artificial changepoints in climate data series, because these artificial changes directly affect the possibility to recognize patterns or trends within a hydrometeorological series. In order to correct these changes, a homogeneity test is done. This kind of analysis is made in order to ensure that variations in records of a climatic variable are only a result of the climatic process and not errors or changes in the measurement conditions (Wang, et al., 2010b; Vásquez Aguirre, 2010).

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[12] Average values of the meteorological elements calculated with data recorded over long periods of time, usually 30 years (SMN, 2011).

[13] ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/sstoi.indices

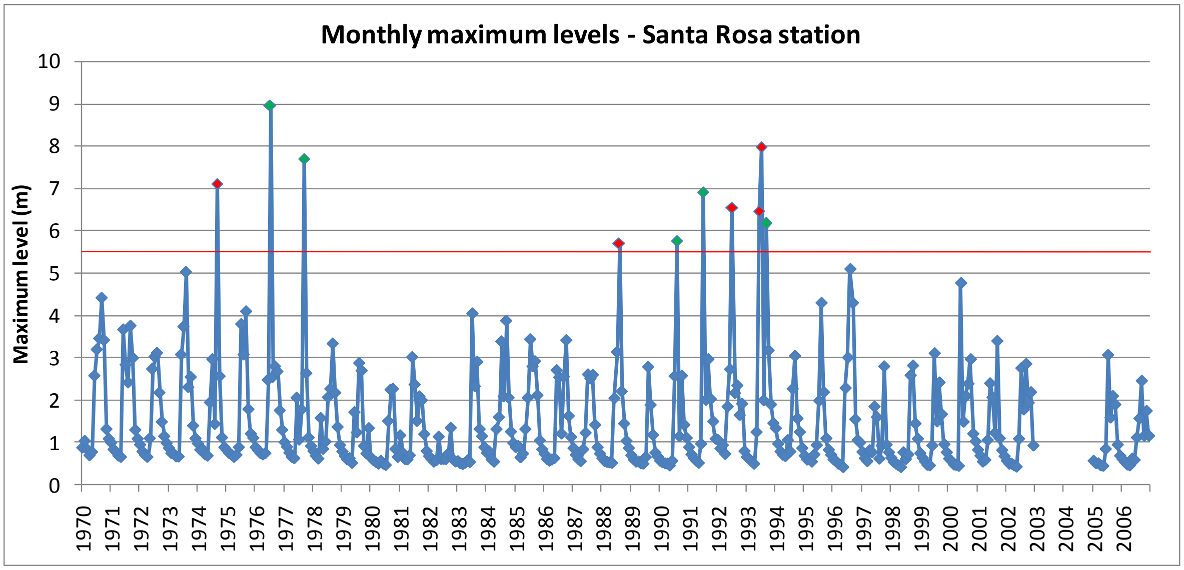

Figure 4.4. Monthly maximum level (scales) records obtained at Santa Rosa station. Red line represents the critical scale of the station. Green points are maximum values associated to tropical cyclones (and one stationary front). Red points are maximum values whose origin couldn't be identified in other sources. Own elaboration with data from IMTA-CONAGUA (2010).

As SWAT includes a weather generator for both missing unique values and gaps, no completion of series had to be made. Therefore, the following step in the quality assessment was the homogeneity test. Several methods to identify and adjust inhomogeneities had been developed. Most of them are applied to monthly series because they assume that the data are normally distributed. This assumption is often valid for temperature series and monthly rainfall series, but not for daily precipitation data and streamflow records (Wang, et al., 2010b; Vásquez Aguirre, 2010).

For the present study RHtestV3, a program recommended by the Expert Team on Climate Change Detection Indices (ETCCDI), was used. This software package can be used to detect, and adjust for, multiple changepoints (shifts) that could exist in a data series that may have first order autoregressive errors. It is based on the Penalized Maximal F test and makes it possible to detect changepoints also when a homogenous reference series is not available. The package includes algorithms to adjust inhomogeneous series according to the mean and according to quantiles (Quantile-Matching – QM) (Wang, et al., 2010a). As the test requires the series to have a Gaussian or normal distribution, and also to reduce computing and processing times, precipitation and temperature series were analyzed on a monthly basis, for the period 1970 - 2006. No inhomogeneities were found in rainfall series, but several temperature series showed one or several changepoints (table 4.2). Figure 4.5 shows an example of an inhomogenous maximum temperature series, and figure 4.6 shows the adjustment obtained for that series.

After identification of inhomogeneities (changepoints) in monthly series, it was possible to adjust daily series based on the performed analysis, using the QM adjustment procedure of the RHTest pack. It is applicable to whichever normally distributed series. Its objective is to adjust the series so that the empirical distributions of all segments of the de-trended base series match each other; the adjustment value depends on the empirical frequency of the datum to be adjusted (i.e. it varies from one datum to another in the same segment, depending on their corresponding empirical frequencies). As a result, the shape of the distribution is often adjusted (including, but not limited to, the adjustment to the mean). The QM adjustments can account for a seasonality of discontinuity (e.g., it is possible that winter and summer temperatures are adjusted differently because they belong to the lower and upper quartiles of the distribution, respectively). The trend component estimated for the base series is preserved in the QM adjustment algorithm (Wang, et al., 2010a).

	Precipitation	Max Temp	Min Temp
Abritas	0	0	2
Damian Carmona	0	3	0
El Peñon	0	1	1
El Salto	0	3	1
El Tigre	0	1	0
Fraccionamiento Callejones	0	0	0
Micos	0	0	1
Nuevo Morelos	0	4	3
Papagayos	0	2	4
San Dieguito	0	1	2
San Juan del Meco	0	2	0
Santa Rosa	0	0	1

Table 4.2. Number of changepoints identified during homogeneity tests.

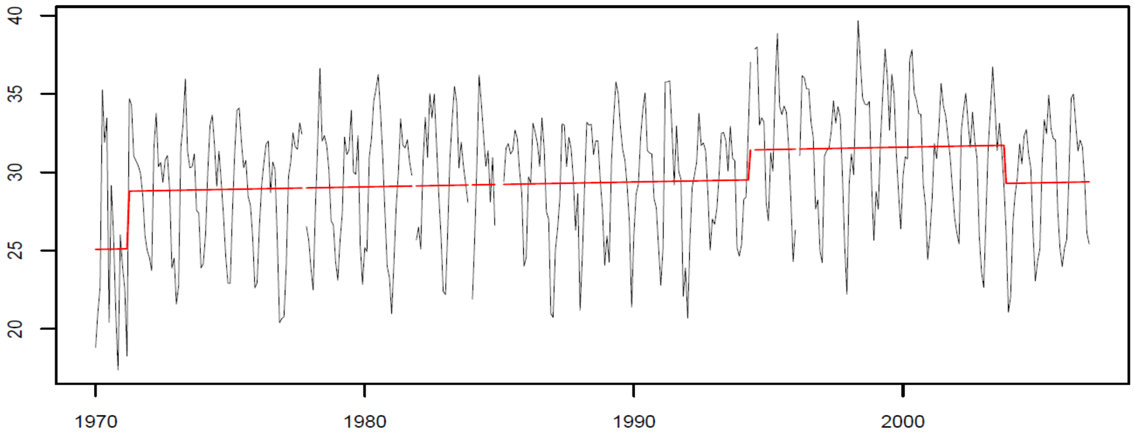

Figure 4.5. Maximum temperature series of Damian Carmona station and regression fit. Three changepoints can be observed in 1971, 1994 and 2003.

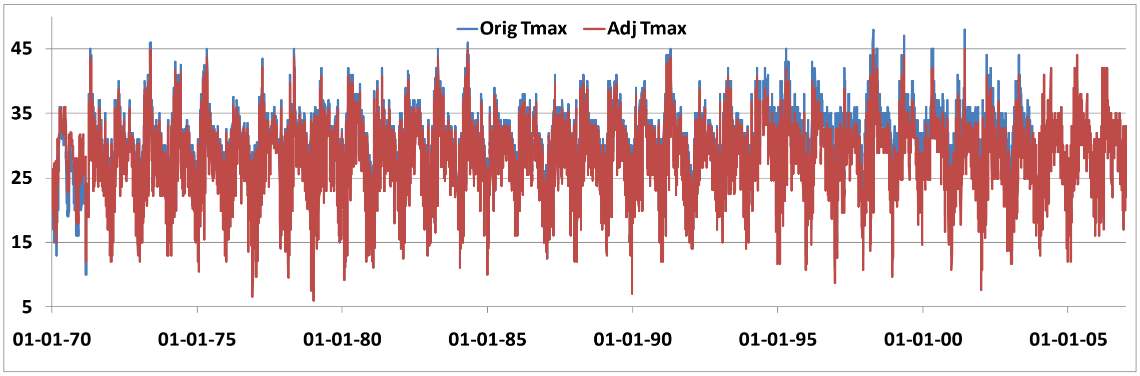

Figure 4.6. Original and adjusted maximum temperature series of Damian Carmona station. Last 3 years were baseline segment and therefore show no adjustment.

Stream flow record series are usually not normally distributed (Kundewicz, et al., 2004) homogeneity of these series was assessed through the daily precipitation testing and adjusting package of the RHTest software, which is also based on the Penalized Maximal F test but does not assume a normal distribution in input series (Wang, et al., 2010a). No changepoints were identified after applying this procedure to stream flow records.

5.2.6. WATER USE

The total granted water volume in the VRB is 89.85 hm^3/y, 89.2% of which is for agricultural use, 7.53% for agroindustrial use and 2.43% for urban public use. Most of the agricultural use is for irrigation of sugarcane, although for pastures irrigation too. There are three concession titles for hydropower generation (a non-consumptive use) for a total volume of 476523 hm^3/year, 276 titles for agricultural use for a volume of 86201 hm^3/year, and for urban public use exist 141 titles for a volume of 15312 hm^3/year (Santacruz de León, 2007). Table 4.3 shows the number of concession titles for the different uses of surface waters in the Valles River basin and table 4.4 shows the distribution of the granted water by use and subbasin

Water use	N° of concession titles	Percentage
Aquaculture	1	0.23
Agriculture	276	63.3
Hydropower	3	0.69
Industrial	6	1.38
Livestock	6	1.38
Public urban	141	32.34
Services	3	0.69
Total	436	100

Table 4.3 Water concession titles in the Valles River basin in 2008.
Taken from Comité de Cuenca del Río Valles (2008).

Table 4.4 shows that the major water concessions are for agriculture, even in the Valles subbasin, where public urban use is still only 1.67%, despite the presence of the largest urban centre of the region. In this subbasin two industries take 98.8% of the water for industrial use. It is also worth to mention that the totality of the industrial use in subbasin *El Salto* is made only by one user. In summary, *El Salto* subbasin presents the largest proportion of the granted water volume in the entire watershed (44%), and the largest number of concession titles (Santacruz de León, 2007).

	Granted water (hm^3y^{-1})	Agricultural (%)	Industrial	Public (%)	Other uses
El Salto	39.91	90	6	4	0
Los Gatos	8.34	91	0	0.73	8.27
Río Puerco	24.1*	99.03	0	0.97	0
Valles	17.15	73	25	1.67	0.33

Table 4.4. Distribution of the granted water by use and subbasin. *Excluding Antiguo Morelos. Source: REPDA records in Santacruz de León (2007).

SWAT allows to model agricultural water use for irrigation at the HRU level, as well as water extraction for consumptive use and wastewater discharge at the subbasin level[14]. Because the specific purpose of the modelling exercise was to assess the effects of land use changes, agricultural water use was modelled according to the identified irrigated crop fields, and not according to the REPDA database. The amounts of water modelled for this use are described in section 4.3.7. The model assumes extracted water other than irrigation to be lost from the watershed system. Removals are defined only by a monthly average, meaning that consumptive use from each subbasin can't be modelled to vary along time. Water disposal (point sources) is allowed to vary, even on a daily basis.

Table 4.5 shows individual water rights with the largest amounts granted within the VRB according to the REPDA database. These data were used to know the location and right holders of the principal extractions and discharges in the watershed.

CONCESSION HOLDER	VOL. GRANTED (m^3/y)	USE
Discharges		
Plan de San Luis sugar mill	1,854,000	Industrial
Plan de Ayala sugar mill	1,193,600	Industrial
San Miguel del Naranjo sugar mill	800,000	Industrial
Extractions		
Federal Electricity Commission (Electroquímica H.P.P.)	57'668,000	Hydropower
Federal Electricity Commission (Micos H.P.P.)	28,689,000	Hydropower
Municipality of Ciudad Valles (DAPA)	7,000,000	Public urban
Municipality of Ciudad Valles (DAPA)	7,000,000	Public urban
Plan de San Luis sugar mill	2'860,000	Industrial
Plan de Ayala sugar mill	1,200,000	Industrial
San Miguel del Naranjo sugar mill	830,000	Industrial

Table 4.5. Largest water concessions within the VRB, excluding those for agricultural use.
Own elaboration with data from CONAGUA (2010).

Some important uses, like the wastewater discharge from Ciudad Valles' urban area, are not included because they are located outside the VRB. Moreover, not all discharge and extraction

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[14] In this case *subbasin* refers to the 57 spatial units delineated by the model.

points could be modelled, due of several reasons: 1) agricultural uses were discarded due to the reasons aforementioned, 2) REPDA data correspond to water rights, not to actual amounts of water extracted and discharged, 3) only a few uses could be traced in time along the modelling period. Thus, for modelling purposes, only public urban and industrial uses whose actual amounts could be found or somehow estimated and traced in time were taken into account. Due to the third reason groundwater extractions were not modelled.

Water uses in table 4.5, plus the diversion of *El Salto* hydropower plant (for which no record was found at the REPDA database), were those selected to be modelled. Figure 4.7 shows the location of these points. The only one modelled extraction for public urban use was the diverting for the treatment plant of *Ciudad Valles*, located just one kilometre upstream from the Santa Rosa hydrometric station. Extraction values (see table 4.6) were obtained from Gonzalez Quilantan (1994). Wastewater treatment plant of *El Naranjo* came into operation just in 2010. It was not possible thus to model the return of water previously extracted for public urban use, and therefore this extraction point was discarded. In the case of *Nuevo Morelos* urban area, no wastewater treatment plant exists, and the same consideration was taken into account.

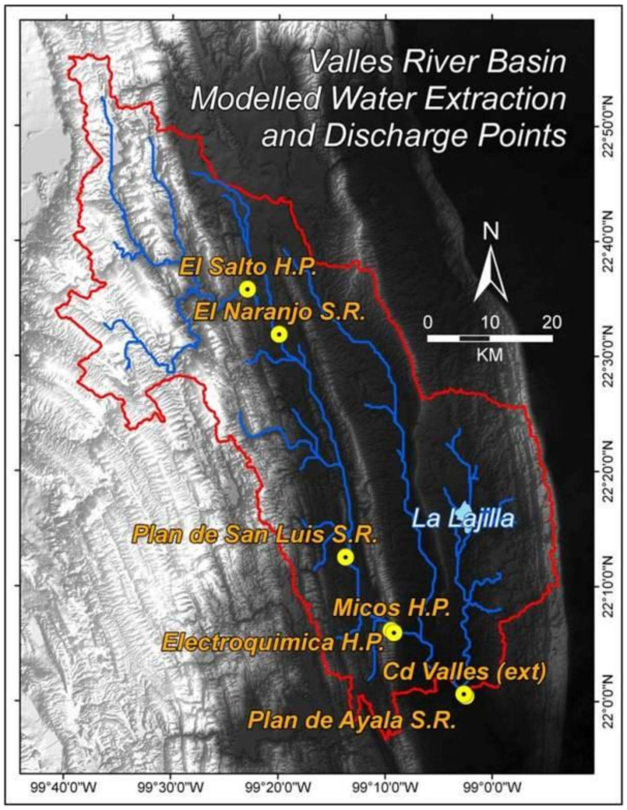

Figure 4.7. Modelled extraction and discharge points. Own elaboration with INEGI data.

The three concessions for hydropower generation obtain water through diversion dams, which means that no reservoir is located at the channel, but off the channel. This kind of water use was decided to be modelled as water extraction and discharge (return). Values for extraction and discharge at *El Salto* plant were obtained from the BANDAS database (IMTA-CONAGUA, 2010). Values for *Micos* and *Electroquímica* plants were not available and were inferred from technical characteristics of the plants. Tables 4.6 and 4.7 show values used to model water extraction.

EXTRACTION POINT	SUBBASIN	AV REMOVAL ($10^4m^3/d$)
San Miguel El Naranjo S.R.	11	9,1658
Plan de San Luis S.R.	48	8,076
Micos & Electroquímica H.P.P.	52	86,4
Plan de Ayala S.R.	55	9,0862
Ciudad Valles	55	2,4356

Table 4.6. Average water removal for modelled extraction points with annual data available.

EL SALTO H.P.P. - MONTHLY AVERAGE WATER REMOVAL ($10^4 m^3/d$)											
ENE	FEB	MAR	ABR	MAY	JUN	JUL	AGO	SEP	OCT	NOV	DIC
95,69	76,79	66,27	56,20	52,75	62,04	123,72	126,19	151,24	147,64	146,19	120,46

Table 4.7. Monthly average annual water removal in El Salto hydropower plant.

Regarding water use from the sugar mills, according to Gonzalez Quilantan (1994), an amount of 393 m^3 of water is needed to produce 1 ton of sugar, while 363 m^3 are returned as wastewater. The first value was multiplied by the annual production of sugar[15] achieved by each of the sugar mills to obtain water extraction values. The second value was subsequently used to calculate how much water was disposed as wastewater.

5.2.6.1. 'La Lajilla' reservoir

La Lajilla (see figures 4.2 and 4.7) is a reservoir built in 1964 by the *Banco Nacional de Crédito Agrícola* for flood control and irrigation and purposes at the *Ejido Laguna del Mante*, which was constituted in 1974. At the beginning irrigation was applied to pastures, but around 1980 land use was changed to 800 ha of sugar cane crops. Currently a citrus factory performs most of the irrigation with water obtained from this reservoir. However, this extraction was not modelled since irrigated agriculture was decided to be simulated according to INEGI's land use map. Values for parameters related to the reservoir were obtained from CONAGUA's technical archive, and are summarized in table 4.8. Reservoir was simulated as an uncontrolled one and simulation of its outflow was made as average annual release.

PARAMETER	VALUE	UNITS
Surface area when reservoir is filled to the spillway	989,28	ha
Volume of water needed to fill the reservoir to the spillway	41,5	hm^3
Spillway maximum flow	1930	m^3/s
Spillway elevation	203	masl
Crown elevation	209	masl
Spillway length	85	m

Table 4.8. Technical characteristics of the *La Lajilla* reservoir.
Data obtained directly from CONAGUA's technical archive.

5.2.7. CROP MANAGEMENT

As the specific application of the model was to identify impacts of land use changes on watershed hydrology, a great importance was paid to the modelling of crop management schemes, which are directly associated to land uses. As part of the crop management SWAT simulates crop growth and scheduled operations of planting, fertilization, tillage, irrigation and harvesting at an HRU scale. Biomass removal and manure deposition can be simulated for grazing operations. Residue and biological mixing are simulated in response to each tillage operation. Crop irrigation can be

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[15] Data obtained from Noé Aguilar Rivera, author of the article "La Agroindustria de la caña de azúcar en la *Huasteca Potosina*", published in *Espaciotiempo* magazine (3:5, 98-112), Autonomous University of San Luis Potosí, San Luis Potosí, Mexico.

simulated on the basis of alternative sources such as streams, reservoirs or aquifers (Gassman, et al., 2007; Neitsch, et al., 2005). Management was simulated for sugarcane (rainfed and irrigated), annual crops and pastures.

5.2.7.1. Sugar cane

Management practices of sugarcane crops at the study zone were known through interviews with local experts and reviewing of sources such as the *Manual Azucarero Mexicano* (Cía. Editora del Manual Azucarero, 2003), and technical manuals of INIFAP and the *Produce Foundation*, among others. Two agricultural calendars were designed for each rainfed and irrigated sugar cane crops, in order to simulate a certain asynchrony in harvests and other practices throughout the watershed. A calendar example for sugarcane under irrigation is shown in table 4.9.

YEAR	CYCLE	STAGE	OPERATION	DATE
1	Plant cane (17 months)	Field preparation	1st harrow	02-05
			Subsoiling	03-05
			1st plow	04-05
			2nd plow	05-05
			2nd harrow	06-05
			Levelling	06-06
			Furrowing	06-07
		Planting	Planting	07-05
			Fertilization	07-06
		Culture	1st cultivation	08-15
			2nd cultivation	09-25
			3rd cultivation	11-05
			1st irrigation	11-06
			2nd irrigation	12-06
2			3rd irrigation	02-05
			4th irrigation	03-05
			5th irrigation	04-05
		Harvest	Burn	12-04
			Harvest	12-05
	Ratoon (12 months)	Culture	Subsoiling	12-08
3-7			1st cultivation	02-05
			1st irrigation	02-06
			2nd irrigation	03-06
			2nd cultivation	04-05
			3rd irrigation	04-06
			Fertilization	04-07
		Harvest	Burn	12-04

			Harvest	12-05
		Field preparation	Subsoiling	12-08

Table 4.9. Sugar cane agricultural calendar 1 under irrigation conditions.

Most of the producers cultivate sugarcane in order to sell the yield to the sugar refineries. Crop management practices are pretty much defined by the refineries' standards, and therefore there is not much variation among producers, only small ones between the influence areas of the different refineries. Usually the crops stand on the field for up to 7 years along which about 5 harvests can be obtained. At the end of this period a new planting operation is made. Before planting the field has to be prepared, and this process is done between February and September. Field preparation usually includes two harrow passes (the second perpendicular to the first) to pulverize soil lumps, and then a subsoiler pass to remove soil to a depth of about 40 cm, aerate and incorporate organic matter. Afterwards, two disk- or mouldboard-plow passes are made to tear, remove, fragment and turn the soil surface layer, allowing for aeration and weathering and facilitating the plant's roots development. Finally, furrowing is carried out to get the soil prepared for planting.

A field superintendent plans the establishment of early, intermediate and late sugar cane varieties, in order to achieve a better coordination during the harvest period for the cane milling process, which usually lasts from November to May-June. Planting time is also determined by other factors among which the water availability stands out. Therefore, it's made usually from June to October, during the rainy season. Irrigation is needed during the dry season, from November-December to June. Consumptive use of water by sugar cane is about 5 mm/day, and irrigation is planned to fulfil these requirements, taking into account the efficiency of the irrigation method, which is predominantly by gravity or by sprinkler. During first cycle (plant cane) 2 irrigations are done during the first growth stage to help the crop to get established. Afterwards, during ratoon cycles, usually 3 irrigations are done along the dry season.

5.2.7.2. Pastures

Information about pasture management in the study zone was obtained during field visits and from sources such as Torres Espinosa, et al. (ND) and INIFAP technical manuals. Predominant stockbreeding in the zone is managed as extensive grazing over plain terrains and under rainfed conditions, although grazing at hillsides is also practiced. There is no tech stockbreeding in the watershed, and the principal purposes are breeding and fattening. Rotation of pasture lots is a common practice, done by about 80% of the farmers, but it's carried out without a proper scheduling. The average carrying capacity in the zone is between 0.5 and 1.08 Animal Units/year. Despite the presence of some introduced grasses such as the Brisanta (*Brachiaria brizantha*) or the Tanzania (*Megathyrsus maximus*), the most common grasses in the zone are the Bermuda grass (*Cynodon dactylon*) and the Star grass (*Cynodon plectostachyus*), and the Bermuda grass was chosen for modelling purposes. Fertilization of pastures is done only by 7% of producers.

Taking into account this information, two agricultural calendars with a difference of 7 days were designed to simulate pastures grazing and management allowing for certain asynchrony among HRUs. Basic data to model pastures management is summarized in table 4.10. As it was not possible to model grazing at the production system scale, parameters were adjusted for the HRU scale.

Type of grass	Bermuda grass
Number of consecutive days grazing takes place in the HRU	13.1 days
Dry weight of biomass consumed daily	24 kg/ha
Dry weight of biomass trampled daily	24 kg/ha
Dry weight of manure deposited daily	4.5 kg/ha

Table 4.10. Parameters and values used to model pastures management.

5.2.7.3. Annual crops

According to the land use classification process (section 4.3.3.1) the main annual crops in the watershed along the study period have been corn, beans and grain sorghum. Information about management practices was obtained only from literature review, mostly INIFAP technical manuals. The most common practice in the study zone is to rotate these crops (altogether with others, less representative) between the fall-winter and the spring-summer seasons, although the largest area is devoted to corn. Culture during fall-winter cycle is made under irrigation conditions, where water is available. To simulate crop rotations and reflect some asynchrony, two calendars were designed, and are shown in tables 4.8 and 4.9.

CYCLE	CROP	STAGE	OPERATION	DATE
Fall - Winter	BEANS	Sowing	Sowing	01-02
		Culture	1st cultivation	02-01
			2nd cultivation	02-11
			2nd Irrigation	02-16
		Harvest	Harvest and kill	04-26
Spring-Summer	CORN	Field preparation	Plow	05-02
			1st harrow	05-17
			2nd harrow	05-24
			Levelling	05-25
			Furrowing	05-26
		Sowing	Sowing	05-30
		Culture	1st fertilization	05-31
			Cultivation	06-20
			2nd fertilization	06-21
		Harvest	Harvest and kill	10-15
Fall - Winter	BEANS	Field preparation	Plow	11-23
			1st harrow	12-08
			2nd harrow	12-15
			Levelling	12-16
			Furrowing	12-17
			1st Irrigation	12-18

Table 4.11. Annual crops rotation calendar 1: Beans – Corn.

CYCLE	CROP	STAGE	OPERATION	DATE
Fall - Winter	CORN	Sowing	Sowing	01-01
		Culture	1st fertilization	01-02
			Cultivation	01-08
			2nd fertilization	01-09
			2nd irrigation	01-10
			3rd irrigation	02-09
			4th irrigation	03-11
		Harvest	Harvest and kill	05-27
Spring-Summer	SORGHUM	Field preparation	Plow	05-28
			1st harrow	06-23
			2nd harrow	06-30
			Levelling	07-08
			Furrowing	07-10
		Sowing	Sowing	07-18
		Culture	1st weeding	08-02
			2nd weeding	08-12
		Harvest	Harvest and kill	11-10
Fall - Winter	CORN	Field preparation	Plow	11-16
			1st harrow	12-02
			2nd harrow	12-20
			1st irrigation	12-21
			Levelling	12-22
			Furrowing	12-23

Table 4.12. Annual crops rotation calendar 2: Corn - Sorghum.

5.3. MODEL CALIBRATION

After model set-up, calibration process was carried out. This process is meant to ensure that the model is reproducing the observed (measured values) and thus the “real behaviour” of the watershed system. In order to achieve this, parameter values are varied until the differences between simulated values and measured values are minimized. Calibration was applied to an 8-year period, from 1989 to 1996. A calibration period of this length was considered as short enough to reflect the system behaviour associated to one land cover/land use configuration. Besides, this particular period was considered as optimum to capture temporal variation of the watershed’s hydrological behaviour and thus obtain a good calibration, given the presence of high stream flow peaks and relatively dry years. Measured daily values from the Santa Rosa station were employed for this purpose. A 2-year initial warm-up or equilibration period (1987 – 1989) was included to ensure that the hydrologic cycle was fully operational for the calibration. This section describes the general aspects of the calibration methodology and the details are described in the results chapter.

5.3.1. BASE FLOW FILTERING

A very useful technique usually employed to improve calibration results is the prior partitioning (called filtering) of stream flow into surface runoff and base flow. This is rather an inexact procedure which can be done through different methods. Recently, attempts have been made to automate traditional manual methods and thus remove their inherent subjectivity, allow for replicability and reduce time requirements. In this study, the base flow filter program developed by Arnold, et al. (1995) was employed. This program is based on an automated recursive digital filter technique originally used for signal analysis and processing, and on the respective analogies between high frequency signals and surface runoff, and between low frequency signals and base flow. The algorithm first computes surface runoff and then calculates base flow as the remaining fraction. Base flow is considered as the ground water contribution to stream flow (Arnold, et al., 1995). Lateral flow is included within surface runoff. Stream flow partitioning is made with the purpose of getting the volumes and proportions corresponding to each of its two components.

5.3.2. SENSITIVITY ANALYSIS

Physically-based distributed and semi-distributed models comprise a large set of parameters, some of which have a greater influence on some specific outputs. If these parameters are identified, calibration process can be focused on them and thus computing and time requirements may be reduced considerably. Sensitivity analysis is the process by which this identification is done, yielding a sensitivity rank, by determining the rate of change in model output with respect to changes in model parameters. At the same time, this process serves to diminish uncertainties intrinsically related to input parameter values, by leading to a better understanding of the system's functioning and to better estimated values (Souvignet, 2010; Moriasi, et al., 2007; Lenhart, et al., 2002; Van Liew, et al., ND).

Sensitivity is expressed by a dimensionless index, which is calculated as the ratio between the relative change of model output and the relative change of a parameter (Lenhart, et al., 2002). In other words, it reflects the impact that change to an individual input parameter has on the model response (Van Liew, et al., N.D.). There are different methods to perform a sensitivity analysis. The ArcSWAT interface includes a tool to perform this analysis, called the LH-OAT analysis, which combines the Latin Hypercube (LH) sampling method and the One-factor-At-a-Time (OAT) design (van Grievsen, et al., 2006).

Latin-Hypercube technique is a random sampling technique commonly applied in water quality modelling due to its efficiency and robustness. It is based on the Monte Carlo Simulation and allows performing a robust analysis but requiring not too many runs. It uses a stratified sampling approach that allows efficient estimation of the output statistics, subdividing the distribution of each parameter into N ranges, each with a probability of occurrence equal to 1/N. Random values of the parameters are generated such that each range is sampled only once. The model is then run N times with the random combinations of the parameters. The model results are analysed with multi-variate linear regression or correlation statistics methods (van Grievsen, et al., 2006).

With each loop of the LH sampling, a new set of parameter values is selected. That set of parameter values is used to run a baseline simulation for that unique area. Then, using the OAT technique, a parameter is randomly selected, and its value is changed from the previous simulation by a user-defined percentage. Thus, changes in the model's output can be attributed to the input parameter changed. As the effect of that unique parameter may also depend on the values assigned to the remaining parameters, the result is only a sample of the sensitivity of the parameter (i.e. partial effect). Therefore, the experiment is repeated for several sets of input parameters, or several LH loops. The final effect will then be calculated as the average of a set of partial effects, and the variance of such a set will provide a measure of how uniform the effects are (Souvignet, 2010; van Grievsen, et al., 2006; Van Liew, et al., N.D.). However, as only one parameter is varied at a time respectively, interactions between parameters are disregarded (Lenhart, et al., 2002).

Sensitivity analysis in ArcSWAT was performed assessing the response of an objective function, which is a quantitative measure of the fit of simulated values to observed values calculated after each parameter alteration. The objective function chosen to be minimized was the Sum of Square Residuals (SSQ), computed as:

$$SSQ = \sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim}\right)^2 \qquad \text{(Eq. 4.7)}$$

Where Y_i^{obs} is the i_{th} observed or measured value and Y_i^{sim} is the i_{th} simulated value and n is the total number of observations

5.3.3. CALIBRATION AND VALIDATION

Calibration is typically done for the streamflow hydrograph at the outlet of the watershed. For a proper evaluation of the model calibration, it is necessary to translate the overall calibration objective into more operational terms. The following objectives are usually considered (Xu, 2002):

1. A good agreement between the average of simulated and observed catchment runoff volume (i.e. a good water balance).
2. A good overall agreement of the shape of the hydrograph.
3. A good agreement of the peak flows with respect to timing, rate and volume.
4. A good agreement for low flows.

Calibration can be done manually or automatically. In this study both approaches were employed, first manual and then automated. In theory, this combined approach is convenient because the automated calibration benefits from the partial results of the manual calibration, which reduces the number of parameters to calibrate, their variation ranges and the time requirements for this process. Moreover, as outlined by Souvignet (2010) the variation range constriction may lead to minimizing the risk of equifinality (see chapter 6).

Manual calibration is a trial-error process of modifying parameter values. After each parameter adjustment is made, match between simulated and observed hydrographs is evaluated (see next section), usually through graphical and statistical techniques (Souvignet, 2010; Xu, 2002). As the model user chooses the parameter to vary and the values to assign, this process demands a good knowledge of the processes occurring within the watershed. When this knowledge is available, a realistic calibration can be achieved. Moreover, this process requires a good understanding of parameters and model structure. However, this understanding can be acquired in a good level through the calibration process itself.

Automated calibration, on the other hand, is a powerful, labour-saving tool that can be used to substantially reduce the frustration and uncertainty that often characterize manual calibrations (Van Liew, et al., N.D.). It consists of an automated iteration of mathematical search algorithms that seek to optimize (usually minimize) an objective function. There are several objective functions, and the chosen one in this case was the Sum of Squares of Residuals (SSQ), which is similar to the Mean Square Error method (MSE) (van Grievsen, et al., 2006; Van Liew, et al., N.D).

For automatic calibration, ArcSWAT includes an automated procedure called Parasol (PARAmeter SOLutions method), which is based on the Shuffled Complex Evolution Algorithm (SCE-UA). In a first step, the SCE-UA selects an initial population of parameters by random sampling throughout the feasible parameter space for *p* parameters to be optimized, based on given parameter ranges. The population is partitioned into several communities. Each community is made to evolve based on a statistical "reproduction process" to evaluate the objective function in a systematic way with regard to the progress of the search in previous iterations. At periodic stages in the evolution, the entire population is shuffled and points are reassigned to communities to ensure information sharing. As the search progresses, the entire population tends to converge toward the neighbourhood of global optimization, provided the initial population size is sufficiently large. The SCE-UA has been widely used in watershed model calibration and other areas of hydrology such as soil erosion, subsurface hydrology, remote sensing, and land surface modelling, and has generally been found to be robust, effective, and efficient (Van Liew, et al., N.D.).

After calibration, the model has to be validated. Validation of a rainfall-runoff model is the task of applying a calibrated model to different conditions than those employed for calibration, usually a different period (different weather conditions), in order to ensure that the model has captured the essence of the watershed's hydrological properties and hence is capable of reproducing an appropriate response according to the new conditions. In this study the selected periods for validation were 1972 – 1980 and 2000 – 2006, seeking to validate the model for the land cover/land use configurations and weather conditions corresponding to the years 1976 and 2003.

5.3.4. EVALUATION

Evaluation of the model is done to establish how well it is reproducing the measured data, during both calibration and validation. Ideally, the overall model performance should be assessed through a combination of graphical a numerical techniques (Souvignet, 2010). Graphical techniques are essential to appropriate model evaluation, and are usually the first approach, providing a visual comparison of simulated and measured constituent data and a first overview of model performance (Moriasi, et al., 2007). Numerical techniques, in turn, are more precise and consist of a set of goodness-of-fit criteria, which are defined as numerical indices of how well a model simulation fits the measured values (Beven, 2001, cited by Souvignet, 2010). There are many goodness-of-fit indicators, which according to Moriasi, et al. (2007) can be classified into standard regression statistics, dimensionless statistics and error indices.

It's recommended to employ several numerical indices simultaneously, since each of them has its own deficiencies and is affected by different factors. Hence, four indices were chosen to evaluate model's performance:

1) Pearson's Determination Coefficient (r^2)
2) Nash-Sutcliffe Efficiency (NSE)
3) Percent Bias (PBIAS)
4) Ratio of the Root Mean Square Error (RMSE) to the standard deviation of measured data (RSR)

Pearson's Coefficient was chosen because it's easily understandable, whilst the other three were recommended by Moriasi, et al. (2007), who, based on an extensive review of literature on model application, established guidelines for evaluation of stream flow models, including statistical and graphical techniques to be used and performance ratings to evaluate results. Pearson's r^2 and NSE are by far the most widely used statistics reported for hydrologic calibration and validation (Gassman, et al., 2007).

Pearson's Determination Coefficient (r^2) describes the degree of co linearity between simulated and measured data, indicating the proportion of the variance in measured data explained by the model. It follows the equation:

$$r^2 = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - \bar{Y}_{obs}\right)\left(Y_i^{sim} - \bar{Y}_{sim}\right)}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - \bar{Y}_{obs}\right)}\sqrt{\sum_{i=1}^{n}\left(Y_i^{sim} - \bar{Y}_{sim}\right)}}\right]^2 \qquad \text{(Eq. 4.8)}$$

Where $\bar{Y}_{obs}$ is the mean of observed values and $\bar{Y}_{sim}$ is the mean of simulated values. r^2 ranges from 0 to 1, with higher values indicating less error variance. It is a commonly used statistic, but is oversensitive to high extreme values (outliers) and insensitive to additive and proportional differences between model predictions and measured data (Moriasi, et al., 2007). The main drawback of this coefficient is its ability to return values close to one, even in cases where the model systematically over- or underestimate time series (Krause et al., cited in Souvignet, 2010).

The Nash-Sutcliffe Efficiency (NSE) is a dimensionless measure of the overall Root-Mean-Square Error (RMSE), normalized with respect to the variance of the observed hydrograph. It determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information"). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. It is computed as (Moriasi, et al., 2007; Xu, 2002):

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - \bar{Y}_{obs}\right)^2}\right] \qquad \text{(Eq. 4.9)}$$

NSE ranges between $-\infty$ and 1, with NSE = 1 being the optimal value. Values between 0.0 and 1.0 are considered to reflect unbiased models, with values closer to 1 indicating a better performance. In turn, values < 0 indicate that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance (Souvignet, 2010; Moriasi, et al., 2007).

The Percent Bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias. It calculated as (Moriasi, et al., 2007):

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) \text{ x } 100}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)}\right] \qquad \text{(Eq. 4.10)}$$

Where PBIAS is the deviation of data being evaluated, expressed as a percentage (Moriasi, et al., 2007).

The Root Mean Square Error (RMSE) is one of the commonly used error index statistics. To qualify what is considered a low RMSE based on the observations standard deviation, the RMSE-Observations Standard Deviation Ratio (RSR), standardizes RMSE using the observations standard deviation. RSR is calculated as (Moriasi, et al., 2007):

The Root Mean Square Error (RMSE) is one of the commonly used error index statistics. To qualify what is considered a low RMSE based on the observations standard deviation, the RMSE-Observations Standard Deviation Ratio (RSR), standardizes RMSE using the observations standard deviation. RSR is calculated as (Moriasi, et al., 2007):

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2}} \qquad \text{(Eq. 4.11)}$$

RSR varies from the optimal value of 0, which indicates zero RMSE or residual variation and therefore perfect model simulation, to a large positive value. A lower RSR means a lower RMSE and a better model performance. Finally, performance ratings for the three statistical indices are given in table 4.13, according to Moriasi, et al. (2007).

Performance rating	NSE	PBIAS	RSR
Very good	0.75 < NSE ≤ 1.00	PBIAS <± 10	0.0 ≤ RSR ≤ 0.5
Good	0.65 < NSE ≤ 0.75	± 10 ≤ PBIAS < ± 15	0.5 ≤ RSR ≤ 0.6
Satisfactory	0.50 < NSE ≤ 0.65	± 15 ≤ PBIAS < ± 25	0.6 ≤ RSR ≤ 0.7
Unsatisfactory	≤ 0.5	PBIAS ≥ ± 25	RSR ≥ 0.7

Table 4.13. Performance ratings for statistics employed (Moriasi, et al., 2007).

In general terms, PBIAS describes performance of simulation in terms of average magnitudes, NSE in terms of trends, and RSR reflects residual variation (Moriasi, et al., 2007).

5.4. SIMULATION OF LAND USE/LAND COVER CHANGE EFFECTS

After the model has been calibrated and validated, it can be applied to simulate the desired scenarios. Table 4.14 summarizes how simulations were designed to isolate the hydrological effects of land use/land cover changes through comparison with results from calibration. Outputs from simulation 1 and 2 will be compared to calibration outputs to obtain hydrological effects of changes between 1976 and 1993, and between 1993 and 2003, respectively.

Process	Period (model year)	Variable	1976	1993	2003
1 Calibration	1989 - (1993) - 1999	Weather		X	
		LULC		X	
2 Validation 1	1973 - (1976) - 1980	Weather	X		
		LULC	X		
3 Validation 2	2000 - (2003) - 2006	Weather			X
		LULC			X
4 Simulation 1	1973 - (1976) – 1980	Weather		X	
		LULC	X		
5 Simulation 2	2000 - (2003) - 2006	Weather		X	
		LULC			X

Table 4.14. Simulations designed to isolate LULC change effects.

6. RESULTS

6.1. MORPHOMETRICS

Shape Coefficient (K_f) value obtained for the Valles River Basin was 0.16, which tells about a watershed not prone to short concentration times. This is confirmed by the result of the Compactness Coefficient (K_c), which was 2.66 and indicated a not so regular watershed, not so prone to high runoff peaks. Drainage Density (D_d) calculated with a 1:50.000 stream network shapefile was 1.84 km/km^2. According to Monsalve Sáenz (1995), this index usually varies between 0.5 km/km^2 in poorly drained basins, to 3.5 km/km^2 in exceptionally well drained basins. Following this definition, the obtained value of 1.84 km/km^2 for the Valles River basin tells about a well developed drainage system. Calculated Average Slope values were 9° (15.5%) for the entire watershed, 11.7° for *El Salto* subbasin, 6.7° for *Los Gatos* subbasin, 3.5° for *Rio Puerco* subbasin, and 5.5° for *Valles* subbasin. Finally, for the calculation of Concentration Time (T_c) a value of 16.6 hours was obtained.

6.2. PRELIMINARY ANALYSIS OF THE WATERSHED'S HYDROLOGY

The following lines present a previous analysis of what can be expected from the hydrological behaviour of the Valles River Basin according to what is known about it, given the available information and the hydrometeorological data. The first insight can be obtained from the computed morphometrics. A noticeable trait is the elongated shape of the watershed and, specially, its subwatersheds (see figure 3.2), as confirmed by the shape coefficient. Taking into account the Concentration Time (T_c = 16.6 hours) and the average slope (9° or 15.5%), and even though having a well developed drainage system (1.84 km/km^2), this results tell of a watershed with a low to moderate tendency to present high streamflow peak rates. However, when looking at the hydrograph (see figure 5.1), these results seem to be invalidated by the evidence of high peak flows of up to 600 m^3/s and even up to about 1000 m^3/s.

There are several factors other than physiographic influencing the Valles River Basin hydrological behaviour. One of these factors, clearly the most important, is climate. As described in section 3.2, climate in the region is very particular, being characterized by several elements with a determining influence on stream flow's regime. First of all is the rainfall temporal distribution. According to climatic classification, 68.9% of the watershed area receives less than 5% of winter rainfall, while the entire watershed receives less than 10%. It means that of the 1330 mm of rain fall annually, about 1190 mm fall during the months of summer, and most of this falls between June and September. Thus, there is a very marked difference between dry and rainy seasons, enhanced by the high temperatures during summer, especially during the dry period between February and June (see figures 3.8 to 3.11).

As mentioned before, according to Prieto González, et al. (2010) maximum rainfalls are mainly associated with cyclonic activity, and therefore are expected to be the most important cause of the unequal temporal distribution of precipitation. A simple procedure was carried out to test this hypothesis. A comparison was made between the occurrence of tropical cyclones and the monthly maximum rainfalls of the 12 selected meteorological stations. The events which showed the greatest influence on the monthly precipitation were the tropical depression N° 2 of 1992, the combined effect of the tropical depression N°6 and the Gabrielle tropical storm in 1995, the hurricane Dolly in 1996 and the hurricane Gert in 1993. In average, 2.8 of the 10 highest values in a single station coincided with the occurrence of cyclones. The highest number of maximum values explained by these phenomena was 5, which was found in 2 stations. Thus, the importance of the tropical cyclones on the rainfall values was less than expected, speaking of the necessity of exploring other phenomena as generators of maximum precipitations in the basin.

One of these phenomena is the ENSO, or more precisely *El Niño* and *La Niña* phenomena. These are abnormal conditions in the temperature of the Pacific Ocean, which affect many climatic patterns around the globe. It is considered that *El Niño* is present when sea surface temperature is at least 0.5 °C higher than the normal value of the period 1950-1979 (Magaña Rueda, 2004). Figure 5.1 plots monthly anomalies in the Sea Surface Temperature from (SST) from the region El Niño 3.4 against monthly rainfall. SST anomalies between -0.5 and +0.5 reflect neutral conditions. Positive SST anomalies larger than 0.5 correspond to *El Niño* conditions, while negative values smaller than -0.5 indicate the occurrence of *La Niña* (Algara Siller, pers.comm.).

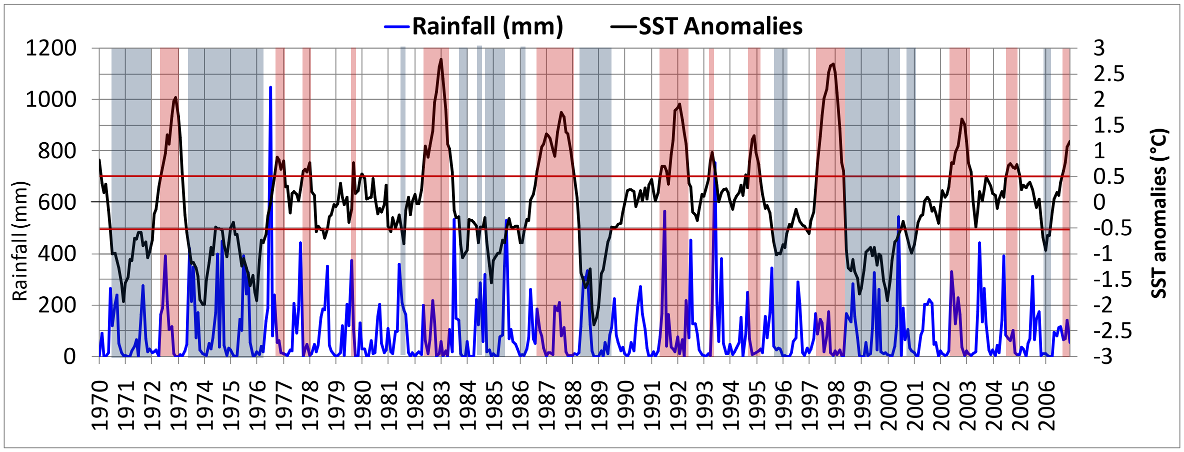

Figure 5.1. Total monthly rainfall values and SST monthly anomalies in *El Niño* region 3.4. Red horizontal lines form the central band for which ENSO behaviour is neutral. Red vertical bands correspond to the presence of *El Niño*, while blue ones correspond to *La Niña* conditions. Own elaboration with data from SMN (rainfall), IMTA-CONAGUA (stream flow) and NOAA (SST anomalies[16]).

The relation between the ENSO behaviour, reflected by the SST anomalies, and the rainfall behaviour doesn´t become clear with a simple visualization of the chart presented. Although the two strongest *El Niño* phenomena (1982-1983 and 1997-1998) seem to coincide with two of the lowest values for rainfall and stream flow, when performing a simple linear correlation between rainfall and ENSO anomalies, a value of 0.00092 was found for Pearson's r^2, meaning there is no correlation. However, a more thorough analysis is considered as necessary to elucidate the strength of the relation between these variables, but it is not within the objectives of the study. Nevertheless, it is known that *La Niña* leads to the increase of summer rainfall and to the decline of winter rainfall (Magaña, et al., 2004). Moreover, Algara Siller, et al. (2009) mention that abnormal droughts extending over a longer period than the dry season have shown a strong correlation with *El Niño* phenomenon in the region.

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[16] Source: [16] ftp://ftp.cpc.ncep.noaa.gov/wd52dg/data/indices/sstoi.indices.

Concerning soils, there is little information for the basin, especially about their hydraulic properties. However, based on the existing classification some things can be inferred. It is noticeable that 76.6% of the soils of the watershed (lithosols, regosols and rendzinas) are very shallow soils, with no more than 25 cm depth, usually limited by the presence of a hardpan or rock. They present high contents of rock and gravel. Among these, Lithosols, with no more than 10 cm depth, are the most common, covering 49.7% of the watershed's area, and especially abundant in *El Salto* subbasin, which presents the highest average slope. Another 5.7% corresponds to shallow soils (phaeozems), less than 50 cm depth. Only 17.4% of the soils (cambisols, vertisols and luvisols) are considered as deep (very deep indeed), reaching depths of more than 1 m. Thus, most of the soils in the watershed have a low total water content capacity and easily generate saturation overland flow, which is surface runoff generated after saturation of the soil profile (Ponce, et al., 1996), a process likely to occur at the end of the rainy season. In addition, the common presence of hardpans in these soils impedes the infiltration of water to deep layers.

On the other hand, 71.6% of the soils exhibit loamy textures, including loamy sands (phaeozems) and loamy clays (regosols). Medium size particles (silt) are the predominant content in these textures, and therefore these soils exhibit hydraulic properties intermediate between the clay and the sand. As a start, this kind of soils presents good infiltration capacities. Clay soils, which occupy a non-negligible 28.1% of the watershed, exhibit a larger volume of pores, thus having more water content capacity, but also higher adhesive forces, causing water to be more strongly retained by soil particles. Sands, in turn, exhibit the overall smallest pores volume and the lowest adhesive forces, usually showing the highest values of saturated hydraulic conductivity (K_{sat}). Thus, although they can't hold too much water because of their shallow profiles, water content in the predominant soils of the basin can move relatively more freely, whether to be taken up by plants, to run laterally or to percolate deeper in to the soil down to the aquifers, although the latter is not the most common process, as mentioned before.

Vertisols are a special kind of soils, covering 14.2% of the watershed. As described in section 3.5.3, these soils are characterized by its high content of expansive or swelling clays, which form deep wide cracks when they dry out. This behaviour gives way to preferential flow, a more free flow of water into the soil profile through the soil cracks. Thus, the infiltration rate is particularly high at the beginning of rainfall or irrigation, but declines rapidly as the macropores fill with water and shrinkage cracks close up (Brady, et al., 2001). Additionally, these soils have the highest contents of organic matter in the watershed, along with luvisols. Organic matter directly affects soil water content and flow, because it exhibits a higher available water holding capacity. Moreover, it exerts an indirect influence by stabilizing soil structure and total pore volume, increasing infiltration capacity and water holding capacity once again. In this respect, 65.8% of the basin's soils present organic matter contents between 2 – 4%, while 26.2% contain more than 4% and 7.7% less than 2%. Thus, in general terms the organic matter content of the basin's soils is moderately high.

According to the definition of hydrologic groups given in section 4.2.1.1 for the Curve Number surface runoff calculation method, 74.4% of the soils of the Valles River Basin are classified within hydrologic group D, which means soils with high runoff potentials, corresponding to shallow soils with presence of hardpans, or clay soils with high swelling potentials. Soils classified within hydrologic group C cover a 19.2% of the basin. These soils, including deep cambisols and luvisols, show slow infiltration rates given by their clay texture, or have not well developed structures such as the regosols. Only 5.8% of the soils have moderate infiltration rates, given by its moderately good depth and moderately coarse textures.

So far we have a watershed hydrographically not so prone to high streamflow peaks, but under the strong influence of a climate characterized by the occurrence of extreme meteorological phenomena such as tropical cyclones and *El Niño* phenomena, and conditioned by the hydrologic response of predominantly shallow soils with high surface runoff potential. Some other determining factors remain to be considered, such as land cover and human impacts. Especially important is the interaction between land cover and soils, influenced by crop management. Pastures and crops, especially sugarcane, are located mainly on the valleys and plains over vertisols and regosols. Annual crop fields are located in the upper part of the basin, mainly over regosols and vertisols, but also on Lithosols. On the hill slopes, lithosols predominate, generally under oak forests, deciduous forest and deciduous mountain forests as well.

Pastures, along with sugarcane, are the main crop in terms of area in the watershed. As mentioned before, prevailing management scheme for stockbreeding is the traditional extensive grazing, mainly over plains and valleys. Although the average carrying capacity of pastures is low (0.5 – 1.08 AU/year) and their rotation is a common practice, they are frequently overgrazed because carrying capacity is ignored and hence rotation schemes are not properly planned. As a consequence, soils under grazing systems are usually compacted. Soil compaction crushes many of the macropores and large micropores of soil into smaller pores, increasing its bulk density. Thus, not only total pore space decreases and soil hold less water at field capacity, but also the permanent wilting coefficient increases and so decreases the available water content (Brady, et al., 2001). These impacts may be dimmed by the fact that most of the pastures are located at plains and hence overland flow is not enhanced by slopes, although grazing at hillsides is also practiced. However, it affects infiltration rates and thus enhances saturation overland flow process, in soils such as vertisols and regosols, where it is already a quick process.

Sugarcane is the most important crop in terms of social and economical impacts. Cultivation of this crop is highly intensive and mechanized, and it has been so since the second half of the 20th century. It implies the use of fertilizers, herbicides, pesticides and heavy machinery such as tractor and complementary implements, like harrows and mechanical harvesters. As described in 4.3.7.1, tillage is performed in the traditional way. Harvest residues utilization is one of the few non-traditional practices implemented in a small proportion of the crops. It is done by cutting the tip and the straw, instead of burning, and aligning them in furrows, in a relation 2:1 (2 uncovered, 1 covered). Another non-traditional practice is the application of organic matter in the form of compost at the moment of planting. These practices improve soil organic matter content, structure and water content capacity. However, they are relatively new and still struggle against the deeply entrenched traditional cultivation habits.

Regarding water conservation, some efforts have been made to make irrigation schemes more efficient, moving away from the traditional irrigation by gravity and introducing new irrigation techniques, especially sprinklers, including large coverage ones known as ‘canyons’ that can be fixed or mobile. The sugarcane area irrigated through these methods has reached a 40% of the irrigated area, and there are some isolated cases of fertigation. Cultivation of annual crops, in turn, comprises the implementation of some conservation practices. One of them is conservation tillage, which implies making no tillage at all, especially to prevent erosion. Contour cultivation is also an implemented practice in slant crops (SAGARPA, 2004b). Nevertheless, these practices are present in a very small proportion of the watershed and hence their effects are presumably insignificant.

Another factor to be considered is the geological substratum. As mentioned in chapter 3, the main rock type in the watershed is limestone, covering 86.6% of the watershed. This kind of rock is prone to form karst environments. Although no reports were found about the effects of karst formations, besides the existence of the *Huastec Karst* covering a 4% of the basin, it is important to consider a possible influence from them, which is hydrologically very particular. A karst is defined as a terrain, generally underlain by limestone or dolomite, in which the topography is chiefly formed by the dissolving of rock, and is characterized by sinkholes, sinking streams, closed depressions, subterranean drainage and caves (Field, 2002). A wide range of closed surface depressions, a well-developed underground drainage system, and a strong interaction between circulation of surface water and groundwater typify karst (Bonacci, et al., 2009).

Water circulation in karst areas is very different from that in non-karst areas, which is the main reason for the strong differences between karst and non-karst hydrology. Interactions between surface and subsurface in karst environments are very strong. The varied and often spectacular surface landforms are only a guide to the presence of unpredictable conduits, fissures and cavities beneath the ground, which can exist even where surface karst landforms are completely absent. Karst underground features, such as caves and conduits, play a major role in water circulation and storage where present. Karst aquifers are some of the most complex and difficult systems to decipher. Their highly heterogeneous nature leads to the inability to predict groundwater flow. Circulation of groundwater within these environments is quite different from water circulation in other non-karst type aquifers. Their characteristic features are the conduits, which provide low resistance pathways for groundwater flow (Bonacci, et al., 2009).

Finally, direct human impact on water cycle within the watershed has to be taken into account. This impact is exerted in many ways, mainly water extraction and discharge, and stream flow regulation. Main water uses and wastewater discharges were already described. Regarding stream flow regulation, *La Lajilla* or *Laguna del Mante* reservoir exerts the main influence within the watershed. This reservoir was built for flood control and irrigation purposes. Its flood-controlling action is exerted during the rainy and cyclonic seasons, during which high stream flows are expected to occur, and during the rest of the year it supplies water for irrigation. Indeed, outflow from the reservoir is null during this period, a situation that certainly arises many complains by population located downstream (Santacruz de León, 2007). *El Salto, Micos* and *Electroquímica h*ydropower plants, in turn, exert a minimal impact on stream flow regulation, since they work through diversion dams and deliver back the diverted water some hundred meters downstream.

With all these factors interacting, hydrological behaviour of the Valles River Basin is certainly a complex system. An influence of each of these factors can be expected, but the magnitude of their effects and the results of their interaction remain unknown. An approach through hydrological modelling can shed some light on how this complex system works to yield the existent measured values, and on the magnitude of the land use/land cover influence.

6.3. MODEL CALIBRATION

6.3.1. STREAM FLOW FILTERING

Prior to calibration per se, partitioning of daily measured stream flow into surface runoff and base flow was carried out by applying the base flow filter program. A first output was an estimate of the base flow recession constant (called baseflow alpha factor in SWAT). Recession is the "period of decreasing discharge as indicated by the falling limb of a hydrograph starting from the peak" (UNESCO, 2011) or "the rate at which stream flow diminishes in the absence of recharge" (Arnold, et al., 1995). The baseflow recession constant describes the slope of the recession curve or stream flow decline following a recharge event (Arnold, et al., 1995), and thus, more than affecting the base flow volume, affects the shape of the streamflow hydrograph. When alpha factor is larger the slope of the recession curve is steeper, which is indicative of a rapid drainage and little soil storage. For the Valles River Basin a very low value of 0.0175 was obtained, meaning that a very flat recession curve has to be expected and simulated.

Base flow filtering showed an average 61% of the stream flow corresponding to base flow, while the remaining 39% corresponds to surface runoff. Figure 5.2 shows the separation of the base flow component from the stream flow. The remaining portion corresponds to surface runoff. A hydrologic regime dominated by base flow is expected for the watershed.

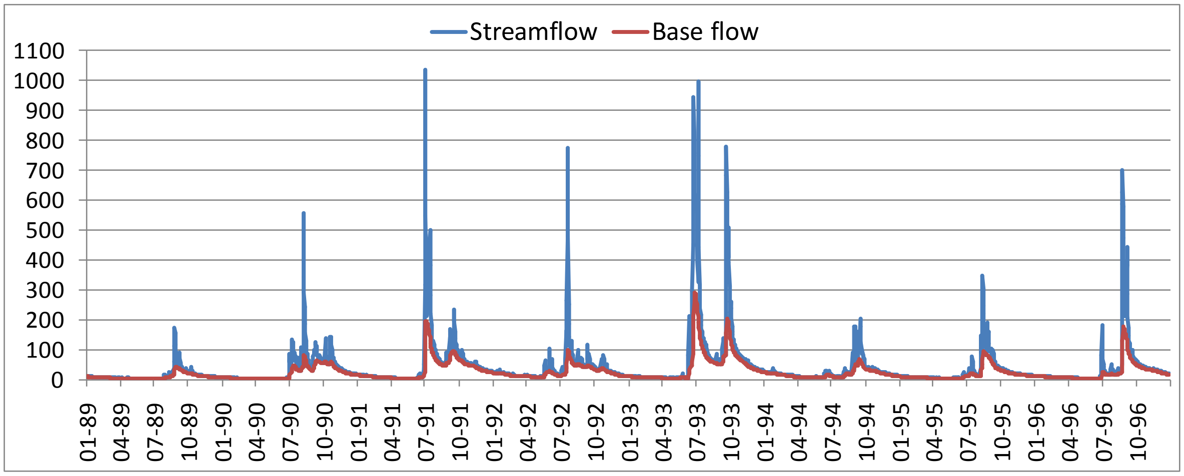

Figure 5.2. Separation of the base flow component from the observed stream flow by base flow filtering.

6.3.2. SENSITIVITY ANALYSIS

Sensitivity analysis was applied to parameters affecting stream flow for the calibration period (1987 – 1996) on a daily basis, to obtain a sensitivity ranking according to the response of the objective function (Sum of Square Residuals - SSQ) to changes in parameters. Table 5.1 shows the ranks obtained for the 20 parameters analyzed. The "very important" and "important" parameters are briefly explained in the following lines.

Parameter	Rank
(Main) Channel effective hydraulic conductivity	1
Manning's n value for main channel	2
Baseflow alpha factor	3
Initial SCS CN II value	4
Surface runoff lag time	5
Maximum canopy storage	6
Threshold water depth in the shallow aquifer for flow	7
Maximum potential leaf area index	8
Soil evaporation compensation factor	9
Groundwater delay	10
Groundwater "revap" coefficient	11
Threshold water depth in the shallow aquifer for "revap"	12
Soil depth	13
Available water capacity	14
Saturated hydraulic conductivity	15
Average slope steepness	16
Plant uptake compensation factor	17
Average slope length	18
Biological mixing efficiency	19
Moist soil albedo	20

Table 5.1. Sensitivity ranking for parameters affecting flow. 1: Very important; 2-7: Important; >7: Slightly important (van Grievsen, et al., 2006).

Results showed that the most important parameter was the channel hydraulic conductivity, which govern transmission losses through channel bed from the watershed's main stream. These losses occur only in ephemeral or intermittent streams which do not receive continuous contributions from groundwater flow. Second most important parameter, first of those classified as "important", was Manning's roughness coefficient for main channel flow, which controls channel flow rate and velocity. The larger this value, the slower is the flow velocity and the lower are the flow and peak rates.

The third most sensitive parameter was the baseflow recession constant, already explained before. Fourth and fifth parameters affect surface runoff. Curve number is an expression of the retention potential of the soil-vegetation system, as explained in chapter 2, while the surface runoff lag time is a coefficient included in SWAT to simulate a delay in the release of a portion of the surface runoff to the main channel, for watersheds with concentration times greater than 1 day. Maximum canopy storage is an absolute measure (mm) of the maximum volume allowed to be intercepted by the canopy of a vegetation cover, which is included as part of the initial abstractions when using the CN method to calculate runoff, and also affects evapotranspiration because all the intercepted rainfall is the first volume of water evaporated by SWAT to meet evaporative demand. Finally, the threshold water depth in the shallow aquifer for flow is an absolute measure (mm) of the amount of volume required as storage in the shallow aquifer for SWAT to begin to simulate groundwater contribution to stream flow.

6.3.3. CALIBRATION

Stream flow filtering is made with the purpose of improving calibration by obtaining separate flow rates for surface runoff (SQ) and for base flow (BF). However, in this case it was not possible to calibrate flow rates, due to the following reason. Outputs of the model are given in two forms: water balance components (precipitation, surface runoff, groundwater flow, water yield, etc) are given in sheet units (mm), while stream flow is given in m^3/s. In order to directly calibrate observed and simulated surface runoff and base flow, equivalence has to be found between the simulated stream flow (m^3/s) and the simulated water yield (mm), which is equal to the sum of groundwater flow, lateral flow and surface runoff. Such equivalence was not found (differences were significant), and without it there was neither a correspondence between the respective components[17]. Therefore, only the SQ/BF ratio could be used for model calibration.

Being a trial-error process, calibration process comprised two attempts to get a good match between simulated and measured stream flow.

6.3.3.1. First calibration

First manual parameters changes were performed on annual stream flow averages, looking for a match between the observed and simulated SQ/BF ratio. However, annual stream flow values don't reflect the behaviour of these two components. Therefore, taking into account the observed extreme flow variations, it was decided to perform manual calibration on a daily time step, and thus be able to assess variations in each of the two components. At first SWAT was simulating an SQ/BF ratio of 80/20. The correct ratio of 39/61 was achieved by modifying the evapotranspiration weighting coefficient used to calculate the retention coefficient for daily curve number calculations, the maximum canopy storage, the initial curve number values, the manning's values for tributary and main channels, the effective hydraulic conductivity of tributary channels and the soil available water capacity.

While SQ/BF ratio was correct, the model was still overestimating values. Matching level was visually and statistically inspected at the same time. In addition to the aforementioned parameters, calibration was performed for the soil saturated hydraulic conductivity, the deep aquifer recharge fraction, the maximum leaf area index, the soil evaporation compensation factor, the groundwater delay and the groundwater "revap" coefficient. Through manual calibration the performance ratings shown in table 5.2 were achieved. This table includes the corresponding rating according to table 4.13. Figures 5.3 and 5.4 show a sample of the results.

	Pearson r^2	NSE	Rating	PBIAS	Rating	RSR	Rating
Annual	0.92	0.85	Very good	-27.94	Unsatisfactory	0.39	Very good
Monthly	0.89	0.72	Good	-27.94	Unsatisfactory	0.53	Good
Daily	0.55	-0.038	Unsatisfactory	-27.94	Unsatisfactory	1.02	Unsatisfactory

Table 5.2. Performance statistical indices obtained with manual calibration.

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[17] This difference couldn't be explained, even though all model outputs were checked and model developers at the Agricultural Research Service (ARS) of the USDA were consulted through the ArcSwat forum web site (http://groups.google.com/group/arcswat?pli=1).

Performance was satisfactory only for NSE and RSR at the annual and monthly level, and unsatisfactory for all the three indices at the daily level. Seeking to improve performance ratings, it was decided to run autocalibration for daily values at this point.

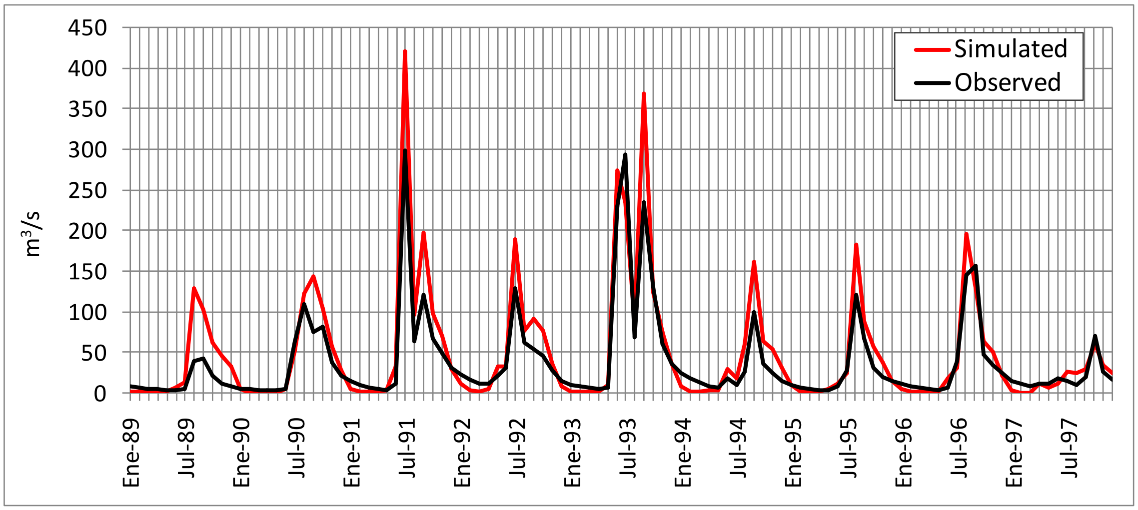

Figure 5.3. Observed average monthly stream flows Vs simulated values obtained through manual calibration.

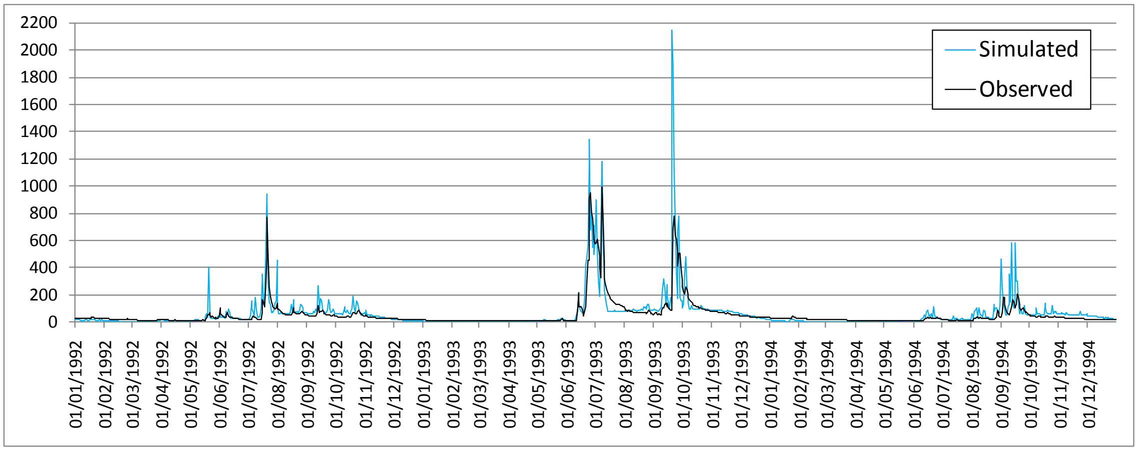

Figure 5.4. Sample of the observed average daily stream flow for the period 1992 – 1994 and corresponding simulated values obtained through first manual calibration.

According to Van Liew, et al. (N.D), a number of 3000 runs within autocalibration are recommended to perform a comprehensive process. However, due to time and computing resources constraints, autocalibration run comprised only 900 runs, which is considered only as a cursory autocalibration. The process was applied to a set of 12 parameters selected taking into account their supposed effect on the hydrograph and their sensitivity rank. These parameters were:

- Manning's n value for main channel
- Baseflow alpha factor (recession constant)
- Initial SCS Curve Number value

- Maximum canopy storage
- Surface runoff lag time
- Threshold water depth in the shallow aquifer for baseflow
- Soil evaporation compensation factor
- Groundwater "revap" coefficient
- Groundwater delay
- Soil available water capacity
- Soil saturated hydraulic conductivity
- Deep aquifer percolation fraction

Autocalibration process yielded very good results in terms of goodness-of-fit. Obtained indices were: NSE = 0.8 (very good), PBIAS = 20.32 (satisfactory) and RSR = 0.43 (very good). However, with this process base flow dropped to almost zero and surface runoff became 100% of streamflow.

6.3.3.2. Second calibration

With these unrealistic results, calibration process was approached once again giving priority to manual calibration, in order to achieve a better performance manually and leaving autocalibration only for fine-tuning. This new attempt was directly commenced on a daily time step, and this time every single parameter affecting stream flow was perturbed. The correct SQ/BF ratio could be only approximated, achieving 42/58. For this ratio performance indices obtained were NSE = 0.58 (satisfactory), PBIAS = -73.8 (unsatisfactory) and RSR = 0.65 (satisfactory). Figure 5.5 shows the corresponding comparison between observed and simulated hydrographs. Bad performance indicated by PBIAS is associated with incorrect absolute flow rate amounts, despite the satisfactory level achieved in NSE, RSR and SQ/BF ratio. By the contrary, very good PBIAS values (-6.17 and -8.81) were achieved only when SQ/BF ratio was 78/22 and 77/23 (too bad).

Because of the inability to get correct flow rates and SQ/BF ratio at the same time, a revision of the model setup was carried out, looking for alternatives to improve model performance. Solar radiation and precipitation values were successfully verified. Water stress values couldn't be checked due to an error in model outputs at the HRU level. Nevertheless, it was found that actual evapotranspiration (ET_A) values were too low. According to INEGI (2007), the Río Pánuco Hydrologic Region has an annual average ET of 77.7% of the precipitation; while the percentage corresponding to simulated ET was 44%. According to INEGI maps (INEGI, 2011b) ET in the watershed is between 600 and 1000 mm/year, while the annual average simulated value was 530 mm. Moreover, for the watershed a maximum runoff coefficient (percentage of the precipitation) reported for the watershed is 30% (INEGI, 2011c), while the simulated average coefficient was 50%. Based on these references, it was concluded that ET had to be boosted up in order to get a proper calibration. Additionally, a comparison between simulated ET_A and simulated potential evapotranspiration (PET) showed that ET_A was only 30% of the PET, which was considered too slow[18].

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[18] A previous estimation of the ET for the watershed obtained based on pan evaporation values and crop coefficients yielded annual ET/PET ratio values always above 0.8.

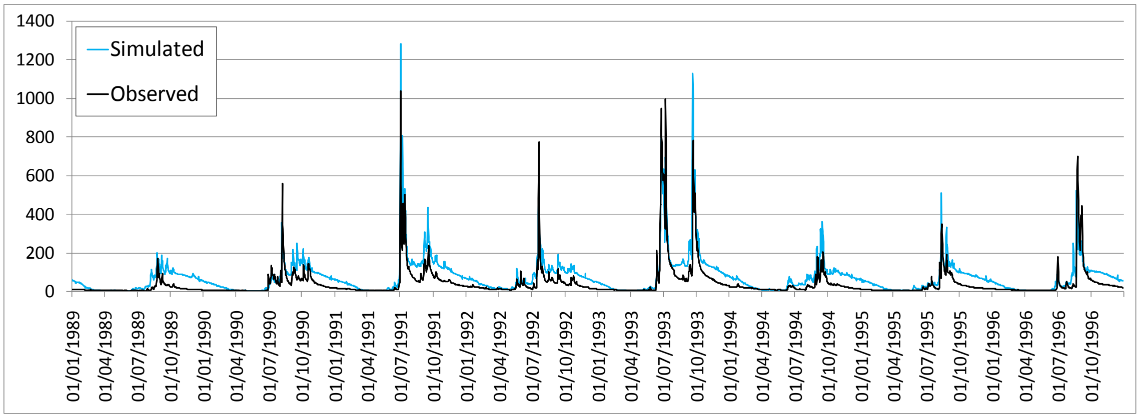

Figure 5.5. Observed average daily stream flow for the whole calibration period (1989 – 1996) and corresponding simulated values obtained through second manual calibration.

When looking for reasons to explain such low values for ET it was found that biomass production was too low. Oak forests showed an average of only 6346 kg ha^{-1} of biomass, palm groves 4706 kg ha^{-1}, brushes 4606 kg ha^{-1} and rainfed sugarcane 2210 kg ha^{-1}, just to give some examples. Adjustments were made to model setup in order to increase biomass yield, to parameters such as the maximum Leaf Area Index, the minimum temperature for growth, the number of years for a tree stand to reach maturity, the initial biomass, the target biomass, the amount of heat units necessary to reach maturity. However, it was not possible to test the new setup because of a bug in the program which couldn't be overcome. Thus, the calibration process had to be finished without a calibrated model, and hence subsequent processes of validation and simulation couldn't be performed.

7. ANALYSIS AND CONCLUSIONS

7.1. ANALYSIS AND DISCUSSION

7.1.1. SENSITIVITY ANALYSIS

Table 6.1 shows the parameters classified as “important” and “very important” according to the analysis. Among listed parameters in table 6.1, the baseflow alpha factor and the curve number are the ones most commonly reported as the most sensitive parameters (Gassman, et al., 2007).

Parameter	Rank	Directly affects
(Main) Channel effective hydraulic conductivity	1	Stream flow, peak rate
Manning's n value for main channel	2	Stream flow, peak rate
Baseflow alpha factor	3	Base flow
Initial SCS CN II value	4	Surface runoff
Surface runoff lag time	5	Surface runoff
Maximum canopy storage	6	Initial abstractions, ET
Threshold water depth in the shallow aquifer for flow	7	Base flow

Table 6.1. Most sensitive parameters according to the response of the objective function.

Sensitivity analysis shows which parameters can have a greater impact on model’s calibration, but is the task of the modeller, according to the existent data and knowledge of the watershed, to choose which parameters are more convenient to vary and how large the variation can be. Channel hydraulic conductivity, for instance, was the most influencing parameter according to sensitivity analysis. As explained before, this parameter governs transmission losses through channel bed from the watershed’s main stream. When making changes to the value of this parameter, which can vary from 0 to >130 mm/hr, stream flow response was clearly large. However, transmission losses occur only in ephemeral or intermittent streams which do not receive continuous contributions from groundwater flow.

Therefore, losses from the main channel were set to zero, and thus the influence of this variable was cancelled because no variation was allowed. Transmission losses from tributary channels, in turn, were allowed. Another example is the base flow alpha factor, which is commonly reported as a very sensitive parameter. In this case, with the reference value obtained from the base filter program, its variation was minimized. Thus, other parameters, for which less precise information[19] (or not at all), became more important when calibrating the model. Among these are the curve number, the maximum canopy storage, the soil available water capacity and the soil saturated hydraulic conductivity. In conclusion, in this study sensitivity analysis constituted mostly an initial guide to approach calibration, by indicating which parameters had the greatest influence on the objective function. After this, the sensitivity rank is not that important because all parameters have to be analyzed in order to perform a meaningful calibration process.

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[19] Many soil parameters had to be inferred or estimated from soil texture, for instance.

7.1.2. MODEL CALIBRATION

Calibration is a trial-error process which simultaneously demands and generates knowledge about the model's structure and the particular watershed of study. Performing an effective and efficient calibration process (especially manual calibration) demands a good knowledge of this type and experience. With these assets time requirements can be reduced considerably, but for the inexperienced and untrained modeller it can be a rather frustrating and time-consuming exercise, as recognized by Moradkhani, et al. (2009) and Xu (2002). The difficulty of this process has justified the development of automated calibration methods (Moradkhani, et al., 2009), but these are not a panacea. As evidenced with the first calibration attempt, automated calibration depends on a very good prior manual calibration; otherwise it can yield very unrealistic results.

Another factor that comes into play to perform an effective and efficient calibration is the experience of the modeller handling the corresponding model user interface, like was the ArcSWAT module in the present study. The modeller has to deal with many format issues, including those related to the handling of spatial data when using a Geographical Information System interface. Moreover, the task involves dealing with the frequent and unexpected software bugs, which can take a lot of time to be overcome, even with the proper technical assistance. This factor became a real obstacle for the present study, to the point that it didn't allow completion of the calibration.

A literature revision made by Borah, et al. (2003) found that the SWAT model has been found suitable for predicting annual flow volumes, sediment and nutrient loads. Monthly simulations are generally good, except for months having extreme storm events and hydrologic conditions. Daily simulations are usually not as good as monthly ones. This is understandable taking into account that yearly and monthly totals tend to smooth the data, increasing the NSE. Although some years has passed since publication of that work and many changes and improvements have been included within the model, this decreasing tendency in performance rating following the reduction of the time step could be evidenced with the results obtained, as may be observed in table 5.2.

According to Gassman, et al. (2007), many of the poorest calibration results can be attributed, in part, to inadequate representation of rainfall inputs, due to either a lack of adequate rain gauges in the simulated watershed or subwatershed configurations that were too coarse to capture the spatial detail of rainfall inputs. Inaccuracies in measured streamflow data and relatively short calibration and validation periods are also frequent factors affecting the quality of calibration results. Besides the modelling experience required, in the case of the present study, poor results are attributed also to a combination of another two factors. First of all, the established objective of simulating land use/land cover change effects required calibration and simulation to be performed on a daily time step, because part of the interest was put on the peak flows, which constitute a rapid response of the watershed to rainfall events. If a different goal had been set, such as predicting the annual water balance, requiring much less precision, probably the results had been better.

Alongside this, it is considered that data and information availability was not adequately enough to ensure a proper calibration at a daily scale. As mentioned in chapter 4, parameters can be adjusted to match the measured behaviour of the stream flow by two forms: parameter specification and parameter estimation. Ideally, parameter adjustment through their estimation is not necessary if all parameter correct values are known. However, this is a utopian scenario, because all models need at least some calibration, even if precise data for all parameters is available. Parameter estimation takes more and more importance when data are imprecise or unavailable. With each parameter that has to be estimated uncertainty and the effects of equifinality are amplified. A discussion on these concepts and others such as distributed modelling and complexity is presented in the following sections.

7.1.2.1. Uncertainty

Shirmohammadi *et al*. (2006, cited in Gassman, et al., 2007) defined uncertainty as “the estimated amount by which an observed or calculated value may depart from the true value”. A definition considered more appropriate is that given by Wechsler (2007) who, assigning the term “error” to the former definition, defined uncertainty as “a measure of what we don’t know about the error and its impact on subsequent processing of the data”. The truth is that error and uncertainty are tightly interrelated.

Physically-based distributed models try to simulate the processes through which precipitation converts into the other components of the water balance by introducing many physical and process parameters into the model’s structure. By doing this, the uncertainty associated to the input-output direct relation in conceptual models is disaggregated among the many elements of the model system. According to Liu, et al. (2007) these elements are: system boundary, inputs, initial states, parameters, structure, states, and outputs. Inputs and outputs are fluxes of mass and/or energy into and out of the system across the system boundary; states are time-varying quantities of mass and/or energy stored within the system boundary; and parameters are characteristic properties of the system that are assumed to remain constant over the time duration of interest (time-invariant). Model structure, in turn, is constituted by the nonlinear functional relationships between inputs and outputs, as defined by model’s equations (Liu, et al., 2007).

As states and outputs are obtained by running the model, the other five components (defined by modeller) can be considered the main sources of uncertainty. Moreover, as initial conditions and inputs are specified or estimated from direct observations, respective errors can be collectively regarded as observation or data errors, as also can errors in observations used to calibrate the model. In turn, errors in boundary conditions, as these are determined during the model conceptualization, can be considered as a source of structural uncertainty (Liu, et al., 2007).

Thus, uncertainty in hydrologic models can be disaggregated in basically three types according to the source: structural errors, parameter errors, and data errors. Structural uncertainty is related to the model´s equations and functional relations and can be enhanced by inappropriate approximations and omissions during model’s conceptualization and failures during translation of the conceptual model to a numerical model. Parameter-associated uncertainty derives from the not-easily-measurable nature of most of parameters, which generally must be estimated by indirect means. Finally, data-associated uncertainty derives from the observations of variables in situ or at lab, and is enhanced by possible errors in measurement. Structural errors are generally the most poorly understood and the most difficult to cope with, but their impacts on hydrologic simulations can be far worse than those of parameter errors and data errors (Moradkhani, et al., 2009; Liu, et al., 2007).

Many specific examples of error and uncertainty sources are available. For instance, observed system response (streamflow) is subject to error reflected in the rating curve inaccuracies at very high and very low flows, where the problem of heteroscedasticity (changing variance) of error (as opposed to homoscedasticity or constant variance of error) with respect to the magnitude of flow is manifested (Moradkhani, et al., 2009). Another example is the uncertainty associated to the use of Digital Elevation Models (DEM), which describe the topography that drives surface flow. They have become indispensable for hydrological modelling, and hence their associated uncertainty is of primary importance. This uncertainty is related to: DEM errors, topographic parameters frequently derived from DEMs, the spatial scale imposed by DEM's resolution, DEM interpolation, and terrain surface modification used to generate hydrologically viable surfaces (Wechsler, 2007).

In the case of the present study many sources of uncertainties can be identified. First of all is the uncertainty associated to the SWAT model structure, which means how is it spatially discretized, its subdivision into components or subsystems (climates, runoff, evapotranspiration, etc), which methods are used for each one (SCS CN method for runoff, Muskingum method for channel routing, Hargreaves method for ETP, etc), how are they interrelated, the equations involved, the parameters included and the interrelation functions between them, among other aspects. A thorough analysis of the model structure requires a deep understanding of the methods included in it, which have been developed during many years of hydrology practice. Only a discussion on the implications of the SCS CN method, which is one of the most important methods within SWAT's structure, is included (see section 6.1.2.4). However, some structural or conceptual issues in the model were identified and are presented here, not as error sources but as shortcomings whose overcoming might represent some improvement:

- Water extraction is not allowed to vary in time. This seems to be an important structural obstacle when performing historical studies where is important to model increases of water extraction due to the growth of population and/or industrial activities.
- Point discharges are allowed to be simulated only if they are into the channels. In the case of the present study, a point discharge outside the stream network in the municipality of El Naranjo was identified and couldn't be modelled.
- Soil compaction due to overgrazing can't be modelled. This process can be really important in watersheds with an important presence of pastures for stockbreeding, such as the VRB.
- It is not possible to model a pasture rotation management scheme.
- Climatic modelling is based on the use one single point data for each subbasin, using the same value for the whole area. The possibility to introduce extrapolated data might yield better results.
- The vegetation growth component includes an algorithm to simulate a dormancy period, where dormancy can be triggered only by the reduction of the photoperiod. In some places, like subtropical areas, leaf fall and dormancy is triggered by high temperatures and water scarcity.

Uncertainty related to parameters was important in this study. There are few available data for process parameters related, for instance, to interception and infiltration, and for physical parameters such as Leaf Area Index and soil hydraulic conductivity. This data lack has to be overcome by using references from other places and thus, despite similarity in conditions, uncertainty is introduced to the model. In this study many assumptions had to be made based on the few existing data. An important and representative example is related to soils. The reports of the most complete study of the soils in the local context (PRONAC, 2009) present only chemical and physical properties of the soils relevant for precision agriculture of sugarcane, but makes no mention of their hydraulic properties. Thus, soils properties were taken from a general characterization of Mexico's soils (INEGI, 2002), following soil types identified by INEGI's classification. Relevant physical variables included in this characterization were only clay, silt, sand and organic matter contents for each soil layer, as well as depth. Thus, all other parameters had to be inferred from these properties. Hydraulic conductivity, for instance, is a very important factor governing percolation and lateral flow, and although it has some relation to texture, this relation is not linear, and hence its values are not completely inferable from the available data.

The problem is enhanced by the form in which the parameters are designed within the model's structure. General (not local) data about biomass volume in a forest stand, for instance, may be used as an input for the model, but when it requires an amount of biomass produced per year the situation gets more complicated. SWAT has many parameters like this, such as the "Threshold water depth in the shallow aquifer for flow" and the "Threshold water depth in the shallow aquifer for revap". Additionally, it includes many empirical coefficients, which are usually fractions by which a certain variable or parameter is adjusted, such as the "Surface runoff lag time", the "Soil evaporation compensation factor" and the "Plant uptake compensation factor". These are calibration parameters (to be estimated, not specified) which increase uncertainty and reduce the "physically-based" character of the model.

In addition, quality of available data represents more uncertainty, and in the case of the VRB this quality is not the best. In the case of the land use/land cover classification maps, for instance, a smaller spatial scale is needed for some purposes, such as a land use change impact assessment. Moreover, comparing INEGI'S classification map to information obtained from another sources, clear incoherences became evident. One of them was the inexistence of crop fields irrigated with water from *La Lajilla* reservoir, which is known to be around 1800 ha of citrus (Melquiades De León, pers.comm.). Another example refers to permanent crops, whose area is a lot bigger in the statistics (SIAP, 2010) than that represented in the maps. These don't even include irrigated crops, which are reported for Ciudad Valles by SAGARPA & SEDARH (2010). Here the scale factor is of primary importance. Data was available only at a 1:250,000 scale. For a study like the present, a 1:50,000 would be the optimum.

Principles and techniques to approach modelling uncertainty have emerged in the last decades, but there are no unequivocal guidelines on how to implement them, and the issue remains a critical and challenging one. Some examples of frameworks for uncertainty analysis are the Generalized Likelihood Uncertainty Estimation (GLUE) methodology, the Bayesian Recursive Estimation technique (BaRE), and the Shuffled Complex Evolution Metropolis algorithm (SCEM). A classical way to quantify uncertainty is to represent the predictions in terms of a probability distribution, computed by performing probabilistic instead of deterministic prediction/modelling. By producing an ensemble of hydrologic predictions (instead of a single deterministic prediction), probabilistic prediction seeks to take into account uncertainties in the equations and/or parameters that are used to describe the physical system (Liu, et al., 2007). However, quantitative estimation of uncertainty was not considered in the present study.

7.1.2.2. Optimization and equifinality

Calibration, as established in chapter 4, is the process of matching the simulated and the observed values to ensure that the model is reproducing the behaviour of real system. In practice, this is achieved by modifying the values specified for input parameters until getting an “optimal” set of parameters, which reproduce best the measured values. Considerable effort has been expended in the past decades in the study of model calibration, to develop and improve techniques meant to efficiently (automatically) find the optimal parameters set. However, the concept of the optimum has been challenged due to the recognition of the nonlinearities and parameter interactions inherent in many hydrological models, which are increased within distributed models given the large number of parameters involved (Beven, 1993).

Another way to approach the problem is that presented by Moradkhani, et al. (2009), who explain the process of calibration as an ‘inverse problem’ (IP). A ‘forward problem’ (FP) is that where the relevant properties of the model are known, including initial and boundary conditions and also the parameters of the system. The model just has to be applied to straightforwardly predict the outputs. Thus, an ‘inverse problem’ “is a problem where the input and output observations and sometimes state variables are known, but not the model parameters”. In FP, effects are found from causes, in a relation of many-to-one, meaning many causes produce one output. By the contrary, in IP causes need to be found based on the effects and this relation is one-to-many, e.g. obtaining many causes from one output. Such a relation can yield many possible results. In other words, the same effects (streamflow) may be caused by different set of causes (parameters) (Moradkhani, et al., 2009).

This problem has been confirmed by numerous studies, which have shown that many different parameter sets or combinations may throw similar values for objective functions, meaning that several optimum solutions may exist for a problem. This problem is known as ‘equifinality’, and for catchment hydrological modelling, as outlined by Moradkhani, et al. (2009) implies that “there may be many possible representations of a watershed (many possible parameter sets) that may be equally capable of simulating the observed system response” (...) “despite the effectiveness, consistency and efficiency of some of the global optimization methods such as the Shuffled Complex Evolution Algorithm (SCE-UA)”. If the modeller is not aware of this issue, unrealistic results may wrongly be taken as good ones. Therefore, the maximum number of outputs must be taken into account to verify that the model is producing valid results, which also have to be evaluated through the validation process.

7.1.2.3. Distributed modelling and complexity

In last decades, development of increasingly complex distributed models has been prompted by the advances in technology and availability of data, including spatial data. Moreover, distributed models have gained popularity over the lumped models thanks to, as outlined by Moradkhani et al. (2009), “the possibilities of considering spatially variable inputs and outputs (...) and analyzing the hydrological response at ungauged basins”, and as stated by Xu (2002), “their potential to provide information about the flow characteristics at points within the catchments”. However, a parallel assessment of what these models can really achieve has taken place, based on the recognition of several issues, among which are the fundamental assumptions and algorithms used, the incompatibility of parameter measurement scales and the miss-perception of the models capabilities, among others (Xu, 2002).

Distributed and semi-distributed models are meant to reflect spatial heterogeneity of input variables, but information about this variation in the real world is in most cases very scarce, especially concerning variables such as infiltration capacity and other soil hydraulic properties. Therefore, it is commonly very difficult to incorporate this variability in hydrological models. Thus, a certain degree of aggregation or lumping is needed in every modelling task. For instance, a measurement of infiltration rate, as accurate it may be, can only describe the rate at the point of measure. As the scale increases to hundreds of hectares and tens of square kilometres, the practical inability to collect increasing amounts of infiltration data makes extrapolation necessary, which is equivalent to lumping. In fact, a lumped infiltration depth is a statement of a spatially and temporally averaged infiltration rate. Sooner or later, a certain amount of spatial (and temporal) averaging has to be introduced. Furthermore, considering that spatial averaging is implicit in the nature of rainfall measurements, it's unavoidable to think of lumping as a de facto modelling tactic (Ponce, et al., 1996).

These arguments can be extended to the nature of the equations. According to Beven (1993), who focus on the matter of soil properties, the nonlinear partial differential equations, for instance those describing subsurface flow based on Darcy's law and unsaturated flow based on Richards' equation, have shown to reproduce small-scale experiments when properly defining boundary conditions, but at the heterogeneous catchment scale those equations are not applicable. This is because they are continuum equations which require smooth variations in variables such as capillary potential and overland flow depths and therefore need the definition of those change gradients. Such requirements may be satisfied in small-scale soil cores but not at the element scale of a distributed model, because of the heterogeneity of a structured and macroporous soil system. These arguments led this author to radically state that distributed physically-based models are invalid, and that they are only considered successful because of a process of circular argument called parameter calibration (Beven, 1993).

There is a misperception that model complexity is positively correlated with confidence in the results and precision in simulations. It has been exacerbated by the development and use of distributed models, the lack of full and frank discussion on model's capabilities and limitations and the reticence to publish poor results (Xu, 2002). There is a limit in performance that cannot be passed even by the most complete physical description. It is important not to forget that models are simplified representations of the reality and thus inevitably imperfect approximations to it. Hence, a proper level of complexity and required precision has to be chosen according to the specific objectives established for the modelling exercise. For instance, according to Xu (2002), one of the most appropriate uses for physically-based distributed models is to improve our understanding of hydrological processes and to identify areas of poor understanding in our process descriptions. Bergstrom (1991), in turn, points out that physically-based, distributed models are normally more feasible as research tools for process studies in the small scale where physical parameters are well under control, and their variability is small, while lumped-conceptual models are more basin-oriented. Therefore, according to the study objectives, lumping may be, more than necessary, convenient to reduce the complexity of the model exercise.

The representation of the heterogeneity in an area of 3690 km^2 such as the VRB is a difficult task, and for such a spatial scale there will be always the necessity of some lumping when modelling, as mentioned before. SWAT includes a certain degree of lumping, since it is a semi-distributed model and not a fully distributed one. However, with the current availability of data about physical properties and processes in the VRB it seems not possible to fully take advantage of its spatial discretization level. In principle, the existence of DEMs, land cover/land use maps and soil maps allows to represent the spatial heterogeneity of the watershed in relation to these aspects. However, a real differentiation among land use/land cover categories and among soil units cannot be made beyond a few physical parameters, such as canopy height and optimal growth temperature in the first case, and texture and organic matter content in the second case.

Therefore, it seems rather unnecessary (and even unjustified) to undertake the complicated task of applying a complex model like SWAT to the VRB (keeping the purpose modelling LULC changes effects in mind), mostly because it is currently impossible to reflect the spatial variation of such a large amount of parameters included in SWAT. Maybe a conceptual semidistributed model, with fewer parameters and hence less data requirements, but with the capability to model some spatial variation in order to reflect LULC changes, can do sufficiently good.

7.1.2.4. The SCS Curve Number Method

As an example of the questions about the structural foundations of hydrological models, in this case the SWAT model, this section concerns the SCS[20] Curve Number method, which is one of the most important methods within SWAT's structure. A recognized critique to the indiscriminate use of this method was made by Ponce & Hawkins (1996). According to these authors, this method was fully supported by the US Soil Conservation Service since its inception in 1954, and thus, without being subject to the rigors of journal review procedures, quickly became established in hydrologic practice, with numerous applications in the US and other countries. It is a semi-empirical, conceptual hydrologic model of abstractions from storm rainfall, which estimates direct runoff depth from storm rainfall depth, based on a parameter known as the "curve number". It may be regarded also as an infiltration loss model, which also accounts for interception and surface storage losses through its initial abstraction component (Ponce, et al., 1996). Fennessey, et al. (2001) add that it was originally developed as a tool to estimate direct runoff generation in the context of traditional agricultural lands in the United States.

This method is widely used due to the following perceived advantages: (1) simplicity, (2) predictability, (3) stability, (4) its reliance on only one parameter, and mainly (5) its high sensitivity or responsiveness to major runoff-producing watershed properties, such as soil type, land use and management, surface condition and antecedent moisture condition. However, it has also some disadvantages which make it suitable only for certain purposes. First of all, it aggregates infiltration and other abstractive losses into a calculation of the total depth loss for a given storm event and drainage area, and thus doesn't take into account the spatial and temporal variability of these variables. Being a storm scale model, it's meant to account for short-term abstractions like infiltration (the most important) interception and surface storage. It is not intended to account for evaporation and evapotranspiration, which are long-term losses. Nevertheless, it is commonly

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[20] Known today as the National Resources Conservation Service (NRCS).

used as an abstraction term or loss model for both continuous and event simulations (Fennessey, et al., 2001; Ponce, et al., 1996).

Surface runoff is generated by a variety of surface and near-surface flow processes, mainly: (1) Hortonian overland flow, which is the process that takes place when rainfall rate exceeds infiltration capacity, (2) Saturation overland flow, which occurs after the soil profile has become saturated, and (3) Throughflow processes or quick interflow, which is not strictly direct runoff, but mostly lateral flow immediately below the ground, and occurs within the same time frame of surface runoff (Ponce, et al., 1996). The CN equation (Eq. 2.5) needs only one parameter, which is the Potential Retention (*S*), which characterizes the watershed's potential for abstracting and retaining storm moisture and therefore its runoff direct potential. As infiltration is the most important abstraction at the storm scale, it is certainly the most important component of *S*. This implies that the assumptions of the CN method simulate properly only saturation overland flow (Ponce, et al., 1996), but says nothing about hortonian flow. Moreover, these assumptions are almost never valid for non-extreme runoff events (Fennessey, et al., 2001).

Another argument against the formulation of the abstraction potential (*S*) is the fact that its relation to the initial abstractions was assumed to be linear, in order to avoid the necessity to estimate two parameters. This linear relationship is defined by a ratio (λ) whose value was standardized as 0.2, according to measurements carried out in watersheds less than 10 acres in size, where there was considerable scatter in the data and 50% of the data points threw values within the limits $0.095 \leq \lambda \leq 0.38$. For convenience in practical applications the *S* parameter is mapped into a dimensionless parameter CN, which theoretically varies in the range between 0 – 100, where CN=100 ($S = 0$) represents an impermeable watershed, and CN=0 ($S = \infty$) represents an infinitely abstracting watershed. As *S* is the only parameter in the equation, it's not surprising that the method's outputs are markedly sensitive to the CN (Ponce, et al., 1996).

The fact that the CN method does not take into account evaporation is overcome in SWAT with the inclusion of method for the estimation of evapotranspiration. Indeed, as mentioned before, a coefficient has been included in the model structure to reflect evapotranspiration in daily CN calculations. Thus, SWAT enables the CN method, at least to some degree, to be applied for long-term continuous simulations. The focus that the CN method puts on saturation overland flow may be suitable for shallow loamy soils in which this process is predominant, like in most of the VRB. However, the method still does not simulate hortonian flow properly, something that can be important for areas with predominance of heavy soils where the infiltration rates are slow, like in the 28% of the basin. Based on this points it is considered that the CN method has more pros than cons for its application, within SWAT, to the VRB.

However, according to (Ponce, et al., 1996), this method performs best when applied to agricultural areas, for which it was originally intended, and generally does poorly when applied to forest sites, which still occupy most of the VRB. This implies that the runoff curve number is better suited for storm rainfall-runoff estimates in streams with negligible baseflow, which is not the case of the Valles River. As a conclusion in relation to the CN method, it is considered that other methods should be tested and their performance compared to that of this method. The Green and Ampt (1911), Horton (1933) and Philip (1957) methods, for instance, describe instantaneous and/or local infiltration rates and thus are directly suited for distributed modelling (Ponce, et al., 1996). Among these, SWAT includes the possibility to apply the Green & Ampt method, which however requires subdaily precipitation records.

7.2. CONCLUSIONS AND RECOMMENDATIONS

7.2.1. CONCLUSIONS

Hydrologic models can be very useful tools for water resources management. However, in order to apply a model to a given watershed, its suitability for the particular context has to be proven, and the best way to do that is by calibrating and validating it for a specific simulation objective. Performing a meaningful, effective and efficient calibration requires experience in the modelling field and a good knowledge of and the particular watershed of study, besides technical skills to handle the corresponding software. With these assets time requirements can be reduced considerably, but for the inexperienced and untrained modeller it can be a rather frustrating and time-consuming exercise.

The Soil and Water Assessment Tool has proven to yield valid results in many contexts. However, its calibration to simulate land cover/land use change effects in the Valles River Basin was not possible, due to software bugs which couldn't be overcome within the project's time frame. Therefore, it was not possible to simulate the hydrological effects of changes in land use/land covers, and it is not possible to state conclusively whether the SWAT model is applicable to the Valles River Basin or not. However, some conclusions can be drawn from the performed setup and calibration processes, which, for instance, proved to be useful to discover information and data gaps.

A basic task of a hydrological model is to properly reproduce observed water balance at the chosen time-step. In this case a mismatch between simulation outputs prevented a proper calibration of groundwater and surface runoff flow rates, making it difficult to get a proper water balance. The SQ/BF ratio was a tool used as a methodological resource to tackle this obstacle, but couldn't prove to be useful due to the software bug which didn't allow calibration to be finished. Regarding the mismatch in model outputs, SWAT developers at the ARS recognized that this sort of mismatches is expected to occur sometimes.

The principal obstacle for calibrating the model was the evapotranspiration component. Potential evapotranspiration was proved to be well simulated, but there was a problem in the simulation of actual evapotranspiration values, whose roots were found in the biomass production. Input data for this submodel consisted mainly of general biomass volumes reported for different types of vegetation in the literature and harvested volumes reports for the crops. Even though, simulated biomass values were too slow, and the inability to correctly simulate them is attributed, in part, to a lack of clear guidance for vegetation growth, biomass production and crop management modelling. The model is focused on crop growth, but natural vegetation still covers the most extensive areas in many rural watersheds, such as the VRB.

The extreme hydrological behaviour of the Valles River Basin makes it not an easy task to successfully calibrate a hydrological model for it. The influence of several factors, such as the tropical cyclones, the *El Niño* Southern Oscillation, the shallow soils, the existence of a large reservoir and the presence of karst environments, makes the Valles River Basin a really complex hydrological system.

Sensitivity analysis is regarded as a useful tool to determine the most influencing parameters on the simulated stream flow. Accordingly, in this study this analysis constituted an initial guide to approach calibration. However, after this the sensitivity rank is not that important because all parameters have to be analyzed in order to perform a meaningful calibration process, and thus it results didn't help too much to obtain a good calibration. In conclusion, taking into account its computing requirements it is considered rather as dispensable, although not completely useless.

A proper selection of model's performance indices proved to be very useful to adequately evaluate model's outputs. In this case the PBIAS index was the only one to reflect a mismatch between measured and simulated values, thus invalidating the results validated by the other statistical indices. Likewise, base flow filtering proved to be necessary since its outputs, as PBIAS index did, invalidated results that otherwise could be regarded as valid.

Despite all efforts that have been made in the field of automated objective function-optimization techniques, automated calibration must be used carefully if the modeller seeks for valid results. The best way obtain such results is through manual calibration, where the modeller can apply its knowledge of the basin and the model. A good automated calibration depends on a very good prior manual calibration; otherwise it can yield very unrealistic results. Automated calibration is recommended only to fine-tune the model, a fine-tuning that sometimes may be unnecessary.

The selection of a model or/and the methods to model the components of the water balance depends, among other factors, on the data availability. An example from the present study is the selection of the Hargreaves method for estimating potential evapotranspiration, instead of the most precise Penman-Monteith method, due to the lack of relative humidity and wind speed records. Thus, model's flexibility allows it to be implemented, but at the expense of greater uncertainty and lower quality of the results.

Although not quantified, many sources of uncertainty were identified in this modelling exercise. A first group is related to the model structure. Among these, the inclusion of many empirical coefficients, which don't have a physical basis and have to be calibrated, stand out. Uncertainty related to parameters was also important, since available data were few and once again enhanced the importance of calibration. Finally, data-associated uncertainty was also important, although some efforts were made, for instance, to check the quality of hydrometeorological records.

Lack of data makes that many physical and process parameters have to be inferred or indirectly estimated, thus enhancing the effects of equifinality during the calibration process. These effects are enhanced also by the many empirical coefficients included within the model structure. These coefficients increase the role played by the parameter estimation process (calibration) and reduce the physically-based character of the model.

The SCS Curve Number method was selected to model surface runoff in this study. Despite its wide use, it may be not appropriate for certain spatial and temporal scales. SWAT enables, at least to some degree, the use of this method for long-term continuous simulations. However, the nature of the method makes it more appropriate for contexts with predominance of agricultural lands, and not of forest lands such as the VRB. Despite this drawback, its use for modelling land use/land cover change effects at the VRB is not discarded, due to its advantages such as its simplicity and its high response to soil types and land uses.

It’s necessary to keep in mind that hydrologic models are only simplified representations of real world systems and are based on many assumptions to describe their most important components. As it is not feasible to obtain a perfect representation of the real system, the simplest model capable of closely reproducing its behaviour and achieving the established simulation goals has to be chosen. For some purposes simpler, maybe lumped-conceptual models, can be selected.

In this case the SWAT model was considered as convenient to simulate land cover/land use change effects, mainly due to the inclusion of several features that allow modelling land management more precisely. However, data scarcity proved to be an important obstacle for its application to the Valles River Basin, due to the important data requirements of the model. Nevertheless, information availability for its application is not conclusively judged as insufficient for modelling at a daily scale, mostly because further calibration work is needed to draw that conclusion.

The expected benefits of applying SWAT to model land use/land cover change effects in the VRB were its semidistributed character, its physical basis and the features included within its structures to model land management. However, it was not possible to fully exploit these advantages due to the lack of data mentioned before. Thus, the application of a model with such a large amount of parameters may be unjustified in a context of low data availability such as the VRB. SWAT is not the most suitable model for the VRB. This is true even for simulations made at the annual and monthly levels, where satisfactory calibrations may be more easily attained.

7.2.2. RECOMMENDATIONS

Model setup was the longest part of the modelling exercise. It implied understanding model structure, requirements and parameters, as well as pre-processing and formatting maps and databases. Setup time requirements have to be properly considered when scheduling a chronogram for a modelling project with SWAT. In addition, unexpected software bugs have also to be taken into account, as they may extend time requirements considerably. Thus, a modelling project with SWAT may become inadequate for the time frame associated to a thesis work.

Although some parameter estimation (calibration) is always needed, its importance relative to parameter specification can be reduced with a very good knowledge of the watershed properties and hydrological behaviour. However, it is not easy to achieve such a level of knowledge, more even taking into account its interdisciplinary nature. Thus, the recommended way to approach the task within water resources management is to form a multidisciplinary team composed of experts in fields such as soil science, botany, agronomy, meteorology, hydrogeology and, of course, hydrology.

It is recommended to the model’s developers to elaborate more detailed user’s guide. So far they describe thoroughly the mathematical structure of the model, the meaning of the parameters (although not so clearly) and how to format input data. It would be convenient to give more details on how to configure the model, especially regarding the components of vegetation growth, biomass production and crop management. The model is focused on crop growth, but natural vegetation still covers the most extensive areas in many rural watersheds in developing countries.

It is also considered that the vegetation covers database lacks a proper description on what each category represents. The difficulties to calibrate biomass production in the present work are partially attributed to these issues.

It is necessary to improve data availability and quality if hydrological models like SWAT are to be implemented for IWRM in this VRB. There is a necessity of data about the hydraulic properties of the soils and about groundwater processes, for instance. Also, spatial information on soils and vegetation with a higher resolution is considered necessary in order to implement geographic information systems that allow the application of hydrological models for managing water resources on the "watershed committee” level.

Metadata about hydrometeorological data is required for the modeller to know the quality of the records and thus know which analyses have to be performed on them prior to their use in modelling exercises. Some inexact references were found for the meteorological records and none for the stream flow records. It is recommended that national institutions in charge of the management of these data improve metadata availability. In addition, hydrometric stations network need to be extended, mainly by installing gages at reservoir outlets, like *La Lajilla* in the Valles River Basin.

For future SWAT applications in the Valles River Basin, some improvements can be achieved in the results by taking into account some already existent possibilities that were not considered for the present study. SWAT allows, for instance, simulating up to ten elevation bands to account for variations in precipitation according to the altitude (orographic effect). Other improvements can be achieved by taking into account slope classes, which seem to be important in the VRB, by performing multi-gage calibration, including stream flow records measured at the Micos hydrometric station, and by simulating the existence of hardpans below the soils. It is also recommended, if possible to apply another surface runoff calculation method other than the SCS CN method, like the Green & Ampt infiltration method, to check which of the two yields better results.

For a thorough assessment of land use/land cover change impacts, it is recommended to perform a complete analysis of land use changes, identifying several aspects of the changes for each land cover/land use, such as persistent areas, gains, losses, net changes (gains – losses) and exchanges between covers, as proposed by (Pontius, et al., 2004). A new land use change module has been introduced into SWAT 2009 to introduce land use updates (Pai, et al., 2011), although it doesn´t allow to change HRU configuration, only to establish changes in the proportions occupied by the categories within a given HRU.

Finally, it is recommended to explore some other models as alternatives to apply to the VRB, especially conceptual semidistributed models with fewer parameters, and hence less data requirements, but with the capability to model some spatial variation in order to reflect LULC changes. It is worth to say that this exploration should be applied to find models suitable to simulate several types of scenarios like climate change, water consumption increases, water regulation policies for irrigation and ground water extractions, which are important scenarios in the context of the VRB.

REFERENCES

- **Agenda Ambiental. ND.** Atlas de peligros naturales de la Ciudad de Valles, San Luis Potosí. Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico.
- **Aguilar, A. G. 1994**. El cambio climático global y la vulnerabilidad de asentamientos humanos en México ante el cambio climático. Memorias del Primer Taller de Estudio de País: México (203-211). Cuernavaca, Morelos, Mexico.
- **Aguilar Rivera, Noé. 2011.** Competitividad de la agroindustria azucarera de la Huasteca México. PhD Thesis on Environmental Sciences. Autonomous University of San Luis Potosi, San Luis Potosí, Mexico.
- **Aguilar Rivera, Noé. 2010.** La caña de azúcar y sus derivados en la Huasteca, San Luis Potosí, México. Diálogos, revista electrónica de historia de la Escuela de Historia de la Universidad de Costa Rica, 2010. Vol. 11: 81-110.
- **Aguilar Rivera, Noé; Galindo Mendoza, Guadalupe; Fortanelli Martínez, Javier; Contreras Servin, Carlos. ND.** Uso de técnicas de agricultura de precisión en la agroindustria azucarera de la Huasteca Potosina. San Luis Potosí, Mexico.
- **Algara Siller, Marcos. 2009.** Propuesta metodológica para medir el impacto del fenómeno de la sequía en la Huasteca potosina y propuesta general de manejo. PhD Thesis on Environmental Sciences, Autonomous University of San Luis Potosi. San Luis Potosí, Mexico.
- **Algara Siller, Marcos; Contreras Servin, Carlos. 2009.** Drought and Climate Change on the Huasteca Region, San Luis Potosí, México. Environmental Engineering and Management. Theophanides, Michael; Theophanides, Theophile (Eds).
- **Algara Siller, Marcos; Contreras Servín, Carlos; Galindo Mendoza, Guadalupe; Mejía Saavedra, José de Jesús. 2009.** Implicaciones territoriales del fenómeno de la sequía en la Huasteca Potosina. Espaciotiempo, Vol. 4: 56-67. San Luis Potosí, Mexico.
- **Allen, Richard G; Pereira, Luis S; Raes, Dirk; Smith, Martin. 1998.** Crop Evapotranspiration - Guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56. Rome, Italy.
- **Almorox, Alonso Javier. 2010.** Estimación de la densidad aparente.
- **Anderson, James R; Hardy, Ernest E; Roach, John T; Witmer, Richard E. 1976.** A Land use and land cover classification system for use with remote sensor data. Geological Survey Professional Paper 64.
- **Andréassian, Vazken. 2004.** Water and forests: from historical controversy to scientific debate. Journal of Hydrology, 291: 1–27.
- **Arnold, J.G; Allen, P.M; Muttiah, R.; Bernhardt, G. 1995.** Automated base flow separation and recession analysis techniques. Ground Water journal. Vol. 33 (N° 6): 1010-1018.
- **AYUNTAMIENTO DE CIUDAD VALLES. 2004.** Plan Municipal de Desarrollo de Ciudad Valles, San Luis Potosí 2004 - 2006. Ciudad Valles, San Luis Potosí, Mexico.
- **Bassols Batalla, Angel; Rentería Romero, Santiago; Ortiz Wadgymar, Arturo; Hernández A., Remedios; Bustamante Lemus, Carlos; Sosa F., Patricia. 1977.** Las huastecas en el desarrollo regional de México.
- **Bergstrom, Sten. 1991.** Principles and confidence in hydrological modelling. Nordic Hydrology, Vol. 22: 123-26.
- **Beven, Keith. 1997**. TOPMODEL: A critique. Hydrological Processes, Vol. 11: 1069-1085.

- **Beven, Keith. 1993.** Prophecy, reality and uncertainty in distributed hydrological modelling. Advances in Water Resources, Vol. 16: 41-51.
- **Beven, Keith; Quinn, Paul; Romanowicz, Renata; Freer, Jim; Fisher, James; Lamb, Rob. ND.** TOPMODEL. A user's guide to the distribution version for DOS (95.02). Lancaster University. Lancaster, UK.
- **Blanco Loredo, Hugo G. 2011.** Vulnerabilidad de la Huasteca Potosina ante el impacto de huracanes. Thesis on Geography degree, Autonomous University of San Luis Potosi. San Luis Potosí, Mexico.
- **Bonacci, Ognjen; Pipan, Tanja; Culver, David C. 2009.** A framework for karst ecohydrology. Environmental Geology, Vol. 56: 891-900.
- **Borah, Deva K; Bera, Maitreyee. 2003.** SWAT model background and application reviews. ASAE 2003 Annual International Meeting.
- **Bosch, J.M; Hewlett, J.D. 1982.** A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology, 55: 3–23.
- **Brady, Nyle C; Weil, Ray R. 2001.** The nature and properties of soils.
- **Briassoulis, Helen. 2000.** Analysis of Land Use Change: Theoretical and Modeling Approaches. Lesvos, Greece.
- **Bruijnzeel, L.A. 2004.** Hydrological functions of tropical forests: not seeing the soil for the trees? Agriculture, Ecosystems and Environment, 104: 185 – 228.
- **Burk, L; Dalgliesh, N.P. 2008.** Estimating water available capacity - A methodology. CSIRO Sustainable Ecosystems.
- **Campos-Aranda, Daniel F. 2005.** Estimación empírica de la ETP en la República Mexicana. Ingenieria Hidráulica en México, Vol. 20 (N° 3): 99-110.
- **Castro Schmitz, Mauricio. 1995.** Andean Forest Restoration and Management for Watershed Conservation in Colombia. MSc Thesis on Geoinformatic Systems for Rural Applications, Wageningen Agricultutal University & Internacional Aerospace Survey and Earth Sciences. - Wageningen/Eschende, Netherlands.
- **Cavelier, Jaime; Jaramillo, María; Solís, Daniel. 1997.** Water balance and nutrient inputs in bulk precipitation in tropical montane cloud forest in Panama. Journal of hydrology, 193: 83 - 96.
- **CEIFI & CRQ. 2003.** Modelación de corrientes hídricas superficiales en el departamento del Quindío, Fase II: Informe final de la Modelación del Río Quindío. Centro de Estudios e Investigaciones de la Facultad de Ingeniería (CEIFI) de la Universidad del Quindío & Corporación Autónoma Regional del Quindío (CRQ). Armenia, Colombia.
- **CENAPRED. 2011.** Frente frío. Centro Nacional de Prevención de Desastres. Online: http://www.cenapred.gob.mx/es/Investigacion/RHidrometeorologicos/FenomenosMeteorologicos/FrenteFrio/.
- **Cerana, Jorge; Wilson, Marcelo G; Pozzolo, Oscar; De Battista, Juan José; Rivarola, Silvia; Arias, Norma; Banchero, Ana Carina. 2005.** Determinación de las condiciones físicas de los vertisoles, orientadas al manejo sustentable con la siembra directa. Seminario Internacional de Indicadores de Calidad de Suelo.
- **Cía. Editora del Manual Azucarero. 2003.** Manual azucarero mexicano 2003. Mexico City, Mexico.
- **Comité de Cuenca del Río Valles. 2008.** Plan de Gestión Integral de la Cuenca del Río Valles. Ciudad Valles, San Luis Potosí, Mexico.

- **CONAGUA. 2010.** Registro Público de Derechos de Agua. Comisión Nacional del Agua. Online: http://www.conagua.gob.mx/Contenido.aspx?id=ada36b70-b1c1-4bc5-92ab-7635941bc171|%20%20%20Registro%20P%C3%BAblico%20de%20Derechos%20de%20Agua%20%28REPDA%29|0|37|0|0|0.
- **CONANP. 2011.** Cobertura de las Áreas Naturales Protegidas Federales de México. Comisión Nacional de Áreas Naturales Protegidas. Morelia, Mexico.
- **Cornish, P.M; Vertessy, R.A. 2001.** Forest age-induced changes in evapotranspiration and water yield in a eucalipt forest. Journal of Hydrology, 242: 43 - 63.
- **Costa, Marcos Heil; Botta, Aurélie; Cardille, Jeff. 2003.** Effects of large scale changes in land cover on the discharge of the Tocatins River, Southeasthern Amazonia. Journal of Hydrology, 283: 206 - 217.
- **CSDMS. 2011.** TOPMODEL. Community Surface Dynamics Modeling System. University of Colorado. Online: http://csdms.colorado.edu/wiki/Model:TOPMODEL.
- **Cunderlik, Juraj.2003.** Hydrologic model selection for the CFCAS project: Assessment of the water resources risk and vulnerability to changing climatic conditions. Project report I.Department of Civil and Environmental Engineering, University of Western Ontario.
- **DHI. 2003.** DHI software. Modelling the world of water. Danish Hydraulic Institute. Online: http://www.dhisoftware.com/index.htm.
- **Diario Oficial de la Federación. 1994.** Decreto por el que se declara como Area Natural Protegida, con el carácter de reserva de la biosfera, la región conocida como Sierra del Abra Tanchipa. Mexico City, Mexico.
- **Dorge, Jesper; Windolf, Jorgen. 2003.** Implementation of the water framework directive: ¿can we use models as a tool in integrated river basin management? River Basin Management International Journal, Vol. 1 (N° 1): 165–171.
- **Dourojeanni, Axel. 2001.** Water management at the river basin level: Challenges in Latin America. Economic Commission for Latin America and the Caribbean. Santiago de Chile, Chile.
- **Dourojeanni, Axel; Jouravlev, Andrei; Chávez, Guillermo. 2002.** Gestión del agua a nivel de cuencas: Teoría y práctica. Economic Commission for Latin America and the Caribbean. Santiago de Chile, Chile.
- **ECLAC/UNEP. 1990.** El Reto ambiental del desarrollo en América Latina y el Caribe. Programme, United Nations Economic Commission for Latin America and the Caribbean/United Nations Environmental. Chile. Santiago de Chile.
- **EPA. 2007.** NLCD 2001 Land Cover Class Definitions. United States Environmental Protection Agency. Online: http://www.epa.gov/mrlc/definitions.html#1992.
- **FAO. 2006.** World reference base for soil resources 2006. Rome, Italy.
- **Fedra, K. 1995.** Decision support for natural resources management: Models, GIS and expert systems. AI Applications, Vol. 9 (N° 3): 3-19.
- **Fennessey, Lawrence A.J; Hawkins. Richard H. 2001.** The NRCS Curve Number, a New Look at an Old Tool. Proceedings of the 2001 Pennsylvania Stormwater Management Symposium. Pennsylvania, USA.
- **Field, M.S. 2002.** A lexicon of cave and karst terminology with special reference to environmental karst hydrology. USEPA. Washington D.C, USA.
- **FIRA. 2011.** Escala mínima de ganadería bovina sostenible en la Huasteca Potosina. Informative bulletin.

- **Fu, Bo-Jie; Zhao, Wen-Wu; Chen, Li-Ding; Liu, Zhan. 2005.** Eco-Hydrological Effects of Landscape Pattern Change. Landscape Ecological Engineering, 1: 25–32.
- **Galindo, I; Castro, S; Valdes, M. 1991.** Satellite dervied solar irradiance over Mexico. Atmósfera, Vol. 4: 189-201.
- **García Coll, I.; Ramírez Soto, A.; Niño Cruz, A.; Juan Rivas, A.; Domínguez Barrada, L. 2004.** La relación agua-bosque:Delimitación de zonas prioritarias para pago de servicios ambientales hidrológicos en la cuenca del río Gavilanes, Coatepec, Veracruz. El manejo integral de cuencas en México. Estudios y reflexiones para orientar la política ambiental. Cotler Ávalos, Helena (Ed.).
- **Gassman, P.W.; Reyes, M. R.; Green, C. H.; Arnold, J. G. 2007.** The Soil and Water Assessment Tool: Historical development, applications and future research directions. Transactions of the ASABE, Vol. 50 (N° 4): 1211-1250.
- **Gonzalez Quilantan, Liliana. 1994.** Impacto de la contaminación por aguas residuales domésticas e industriales en el río Valles, San Luis Potosí. Universidad Autónoma de San Luis Potosí. San Luis Potosí, Mexico.
- **GWP. 2008.** GWP IWRM Toolbox. Global Water Partnership. Online: http://www.gwptoolbox.org/.
- **GWP. 2000.** Integrated Water Resources Management. Global Water Partnership. Stockholm, Sweden.
- **Haberlandt, U. 2010.** From hydrological modelling to decision support. Advances in Geosciences, Vol. 27: 11-19.
- **Hargreaves, G.H; Samani, Z.A. 1985**. Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture, 108: 96-99.
- **HEC. 2010.** Hydrologic Modeling System (HEC-HMS) User's manual Version 3.5. Davis,USA.
- **Hernández Cerda, María E. 2007.** Clasificación climática para la Huasteca Potosina. Propuesta de una metodología para identificar zonas vulnerables a la sequía y a las plagas que afectan a las actividades agropecuarias en la Huasteca Potosina, apoyada en imágenes de satélite, sistemas de información geográfica, análisis multivariado un modelo de simulación climática. SAGARPA Project: SAGARPA-2004-C01-186/A-1.
- **Hernández Guzmán, Rafael; Ruiz Luna, Arturo; Berlanga Robles, César Alejandro. ND.** Cambios de cobertura y usos del terreno de la sub-cuenca río San Pedro (Nayarit, México) y su efecto sobre los humedales costeros.
- **Holder, Curtis D. 2006**. The hydrological significance of cloud forests in the Sierra de las Minas. Geoforum, 37: 82 - 93. Guatemala.
- **IMTA-CONAGUA. 2010.** Banco Nacional de Datos de Aguas Superficiales (BANDAS). Instituto Mexicano de Tecnología del Agua - Comisión Nacional del Agua. Online: http://www.imta.gob.mx/index.php?Itemid=145&option=com_wrapper&view=wrapper.
- **INAFED. 2010.** Enciclopedia de los municipios y delegaciones de México. Instituto para el Federalismo y el Desarrollo Municipal. Online: http://www.inafed.gob.mx/wb2/ELOCAL/EMM_sanluispotosi
- **INE. 2000.** México: una visión hacia el siglo XXI. El cambio climático en México. Gay García, Carlos (Ed.). National Ecology Institute and National Autonomous University of Mexico. Mexico City, Mexico.

- **INEGI. 2011a.** Simulador de Flujos de Agua de Cuencas Hidrográficas – SIATL. Instituto Nacional de Estadística, Geografía e Informática. Aguascalientes, Mexico. Online: http://antares.inegi.org.mx/analisis/red_hidro/SIATL/#.
- **INEGI. 2011b.** Productos y servicios: Datos vectoriales escala 1:1000000 (descarga). Instituto Nacional de Estadística y Geografía. Aguascalientes, Mexico. Online: http://www.inegi.org.mx/geo/contenidos/recnat/clima/InfoEscala.aspx.
- **INEGI. 2011c.** Mapa digital de México V5.0. Instituto Nacional de Estadística y Geografía. Aguascalientes, Mexico. Online: http://gaia.inegi.org.mx/mdm5/viewer.html.
- **INEGI. 2010.** Censo de Población y Vivienda 2010: Principales resultados por localidad (ITER). Instituto Nacional de Estadística y Geografía. Aguascalientes, Mexico. Online: http://www.inegi.org.mx/sistemas/consulta_resultados/iter2010.aspx?c=27329&s=est.
- **INEGI. 2009.** Censo Agropecuario 2007: VIII Censo Agrícola, Ganadero y Forestal. Instituto Nacional de Estadística y Geografía. Aguascalientes, Mexico.
- **INEGI. 2007.** Estudio hidrológico del Estado de San Luis Potosí. Instituto Nacional de Estadística y Geografía. Aguascalientes, Mexico.
- **INEGI. 2005a.** Conjunto de datos vectoriales de la Carta de Uso del Suelo y Vegetación, Escala 1:250,000, Serie III. Instituto Nacional de Estadística y Geografía. Aguascalientes, Mexico.
- **INEGI. 2005b.** Guía para la interpretación de cartografía: Uso del suelo y vegetación. Instituto Nacional de Estadística y Geografía. Aguascalientes, Mexico.
- **INEGI**. **2005c.** Guía para la Interpretación de Cartografía Climatológica. Instituto Nacional de Estadística, Geografía e Informática. Aguascalientes, Mexico.
- **INEGI. 2004.** Guía para la interpretación de cartografía: Edafología. Instituto Nacional de Estadística y Geografía. Aguascalientes, Mexico.
- **INEGI. 2002.** Síntesis de información cartográfica del Estado de San Luis Potosí. Instituto Nacional de Estadística, Geografía e Informática. Aguascalientes, Mexico.
- **INEGI. 2001.** Conjunto de Datos Vectoriales F1405 de la Carta de Uso del Suelo y Vegetación, Escala 1:250,000, Serie II (CIUDAD MANTE). Instituto Nacional de Estadística y Geografía. Aguascalientes, Mexico.
- **INEGI**. **1996.** San Luis Potosí: Indicadores básicos censales. VII Censos Agropecuarios. Instituto Nacional de Estadística, Geografía e Informática. Aguascalientes, Mexico.
- **INEGI. 1994.** Panorama agropecuario. VII Censo Agropecuario 1991. Instituto Nacional de Estadística, Geografía e Informática. Aguascalientes, Mexico.
- **INIFAP. 2005.** Estadísticas climatológicas básicas del Estado de San Luis Potosí (Periodo 1961 - 2001). Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias. Mexico City, Mexico.
- **Jat, Mahesh K; Khare, Deepak; Garg, P. K. 2009.** Urbanization and its impact on groundwater: A remote sensing and GIS-based assessment approach. Environmentalist, Vol. 29: 17 - 32.
- **Jiménez Cisneros, Blanca. 2009.** Cambio climático y recursos hídricos: Desarrollo de una política nacional de investigación y desarrollo tecnológico. Mexico City, Mexico.
- **Koponen, Jorma; Lauri, Hannu; Veijalainen, Noora; Sarkkula, Juha. 2010.** HBV and IWRM watershed modelling user guide. Helsinki, Finland.
- **Kundewicz, Zbigniew W; Robson, Alice J. 2004**. Change detection in hydrological records: A review of the methodology. Journal of Hydrological Sciences, Vol. 49 (N° 1): 7-19.

- **Landa, Rosalba; Carabias, Julia. 2008.** Los recursos hídricos y la gestión de cuencas en México. Gestión de cuencas y servicios ambientales: Perspectivas comunitarias y ciudadanas. Paré, Luisa; Robinson, Dawn; González, Marco Antonio. SEMARNAT-INE. Mexico City, Mexico.
- **Lenhart, T.; Eckhardt, K.; Fohrer, N.; Frede, H-; Frede, H.G. 2002.** Comparison of two different approaches of sensitivity analysis. Physics and Chemistry of the Earth, Vol. 27: 645-654.
- **Liu, Yuqiong; Gupta, Hoshin V. 2007.** Uncertainty in hydrologic modeling: Toward an integrated data assimilation framework. Water Resources Research, Vol. 43.
- **Lorup, Jens Kristian; Refsgaard, Jens Christian; Mazvimavi, Dominic. 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.
- **Magaña Rueda, Víctor. 2004.** Los impactos del niño en México. Centro de Ciencias de la Atmósfera, Universidad Nacional Autónoma de México. Mexico City, Mexico
- **Magaña, V; Méndez, JM; Morales, R; Millán, C. 2004.** Consecuencias presentes y futuras de la variabilidad y el cambio climático en México. Cambio climático: Una visión desde México. Martínez, Julián; Fernández, Adrián. Secretaría de Medio Ambiente y Recursos Naturales (SEMARNAT), Instituto Nacional de Ecología (INE). Mexico City, Mexico.
- **Matalas, N.C. 1967.** Mathematical assessment of synthetic hydrology. Water Resources, Vol. 3 (N° 4): 937-945.
- **Mayaux, Philippe; Eva, Hugh; Brink, Andreas; Achard, Frédéric; Belward, Alan. 2008.** Remote Sensing of Land-Cover and Land-Use Dynamics. Earth Observation of Global Change. Chuvieco, Emilio (Ed.). Alcalá de Henares, Spain.
- **Melone, F; Barbetta, S; Diomede, T; Peruccacci, S; Rossi, M; Tessarolo, A; Verdecchia, M. 2005.** Review and selection of hydrological models – Integration of hydrological models and meteorological inputs. RISK-Advanced Weather forecast system to Advise on Risk Events and management.
- **Mendoza, Manuel; Bocco, Gerardo; López Granados, E. 2002.** Implicaciones hidrológicas del cambio de la cobertura vegetal y uso del suelo: una propuesta de análisis espacial a nivel regional en la cuenca cerrada del lago de Cuitzeo, Michoacán. Boletín del Instituto de Geografía UNAM. N° 49: 92-117.
- **Mendoza, Víctor M; Villanueva, Elba E; Maderey, Laura E. 2004.** Vulnerabilidad en el recurso agua de las zonas hidrológicas de México ante el cambio climático global. Cambio climático: Una visión desde México. INE-SEMARNAT. Martínez, Julia; Fernández Bremauntz, Adrián (Eds.). Mexico City, Mexico.
- **Meyer, William B; Turner II, B.L. 1994.** Changes in land use and land cover: A global perspective. Cambridge University Press. Cambridge, UK.
- **Monsalve Sáenz, Germán. 1995.** Hidrología en la Ingeniería. Escuela Colombiana de Ingeniería. Bogota, Colombia.
- **Monteith, J.L. 1985.** Evaporation from land surfaces: Progress in analysis and prediction since 1948. National Conference on Advances in Evapotranspiration, Society of Agricultural Engineering, pp. 4-12. Chicago, USA.
- **Montero Martínez, Martín José; Martínez Jiménez, Jessica; Castillo Pérez, Nadia Itzel; Espinoza Tamarindo, Brisia Edit. 2010.** Escenarios climáticos en México proyectados para el siglo XXI: precipitación y temperaturas máxima y mínima. Atlas de vulnerabilidad hídrica en México ante el cambio climático. IMTA. Martínez Austria, Polioptro F; Patiño Gómez, Carlos (Eds.). Morelos, Mexico.

- **Montero Martínez, Martín José; Sánchez Sesma, Jorge; Ojeda, Waldo. 2007.** Determinación de periodos de sequía y lluvia intensa en diferentes regiones de México ante escenarios de cambio climático. Mexico City, Mexico.
- **Moradkhani, Hamid; Sorooshian, Soroosh**. **2009.** General review of Rainfall-Runoff modeling: Model calibration, data assimilation and uncertainty analysis. Hydrological Modelling and the Water Cycle.
- **Moriasi, D.N.; Arnold, J.G.; Van Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. 2007.** Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE, Vol. 50 (N° 3): 885-900.
- **Moser, Susane C. 1996.** A partial instructional module on global and regional land use/cover change: assessing the data and searching for general relationships. GeoJournal, Vol. 39 (N° 3): 241-283.
- **Neitsch, S.L; Arnold, J.G; Kiniry, J.R; Williams, J.R 2011.** Soil and Water Assessment Tool Theoretical Documentation Version 2009. USDA Agricultural Research Service.
- **Neitsch, S.L; Arnold, J.G; Kiniry, J.R; Williams, J.R. 2005.** Soil and Water Assessment Tool theoretical documentation version 2005. USDA Agricultural Research Service.
- **NOAA. 2010.** Tropical Cyclone Rainfall Data. National Oceanic and Atmospheric Administration. Online: http://www.hpc.ncep.noaa.gov/tropical/rain/tcrainfall.html.
- **Odoni, Nicholas A; Lane, Stuart N. 2010.** Knowledge-theoretic models in hydrology. Progress in Physical Geography. Vol. 34 (2): 151-171.
- **Ojeda Bustamante, Waldo; Íñiguez Covarrubias, Mauro; González Camacho, Juan Manuel**. **2010.** Vulnerabilidad de la agricultura de riego en México ante el cambio climático. Atlas de vulnerabilidad hídrica en México ante el cambio climático. IMTA. Martínez Austria, Polipoptro F; Patiño Gómez, Carlos (Eds.). Mexico City, Mexico.
- **Ortiz Rivera, Alberto. 2010.** Implementación del modelo hidrológico SWAT: Modelación y simulación multitemporal de la variación de la escorrentía en la cuenca del lago Cuitzeo. MSc thesis on Environmental Geography. Morelia, Michoacán, Mexico.
- **Pai, N; Saraswat, D. 2011.** SWAT2009_LUC: a tool to activate land use change module in SWAT 2009. Transactions of the ASABE.
- **Palafox Juárez, Erika Betzabeth. 2008.** Propuesta de un modelo de simulación de impacto y vulnerabilidad ambiental en la Cuenca del Río Valles. MSc Thesis on Environmental Sciences. Autnomous University of San Luis Potosí. San Luis Potosí, Mexico.
- **Penman, H.L. 1956**. Evaporation: An itroductory survey. Netherlands Journal of Agricultural Science, Vol. 4: 151-153.
- **Pereyra, D; Palma, B; Zitacuaro, I. 1992.** Correlation between northers of Gulf of Mexico and frosts at Las Vigas, Veracruz, Mexico. Atmósfera, Vol. 5: 109-118. Xalapa, Mexico.
- **Ponce, Victor M; Hawkins, Richard H. 1996.** Runoff Curve Number: Has it reached maturity? Journal of Hydrologic Engineering.
- **Pontius, R.G; Shusas, E; McEachern, M. 2004.** Detecting important categorical land changes while accounting for persistence. Agriculture, Ecosystems and Environment, 101: 251—268.
- **Priestly, C.H.B; Taylor, R.J. 1972.** On the assessment of surface heat fluxes and evapotranspiration using large scale parameters. Monthly Weather Review, 100: 81-92.
- **Prieto González, Ricardo; Ramírez Villa, Roberto; Cortés Hernández, Virginia Edith; Maya Magaña, Maria Eugenia. 2010.** Impacto del cambio climático en la temporada de lluvias y

ciclones tropicales en México. Atlas de vulnerabilidad hídrica en México ante el cambio climático. IMTA. Martínez Austria, Polioptro F; Patiño Gómez, Carlos (Eds.). Morelos, Mexico.

- **PRONAC. 2009.** Proyecto: Digitalización del campo cañero de México para alcanzar la agricultura de precisión de la caña de azúcar. SAGARPA.
- **Puig, Henri. 1991.** Vegetación de la Huasteca, México. Mexico City, Mexico.
- **Putuhena, William M; Cordery, Ian. 2000.** Some hydrological effects of changing forest cover from eucalypts to Pinus radiata. Agricultural and Forest Meteorology, 100: 59 - 72.
- **Reenberg, A; Turner, B.L; Lambin, E.F. 2007.** The emergence of land change science for global environmental change and sustainability. Proceedings of the National Academy of Sciences, 104: 20666–20671.
- **Refsgaard, Jens Christian; Storm, Borge; Clausen, Thomas. 2010.** Système Hydrologique Européen (SHE): review and perspectives after 30 years development in distributed physically based hydrological modelling. Hydrology Research, Vol. 41 (5): 355-377.
- **Reyes Hernández, Humberto; Aguilar Robledo, Miguel; Aguirre Rivera, Juan Rogelio; Fortanelli Martínez, Javier. 2008.** Spatial configuration of land-use/land-cover in the Pujal-Coy project area, Huasteca Potosina region, Mexico. AMBIO, Vol. 37 (N° 5).
- **Rodríguez, M; Espinoza, G. 2003.** Gestión ambiental en América Latina y el Caribe: Evolución, tendencias y principales prácticas. Banco Interamericano de Desarrollo.
- **Rojas, Rafael.** Hidrología aplicada al manejo de cuencas.
- **Ruvalcaba Mercado, Jesús. 1996.** Vacas, mulas, azúcar y café: Los efectos de su introducción en la Huasteca, México. Revista Española de Antropología Americana, Vol. 26: 121 - 141.
- **Rzedowski, Jerzy. 2006.** Vegetación de México. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO). 1st digital edition.
- **SAGARPA & SEDARH. 2010**. Plan rector del sistema producto cítricos. Estado de San Luis Potosí.
- **SAGARPA. 2004a.** Propuesta de una metodología para identificar zonas vulnerables a la sequía y a las plagas que afectan a las actividades agropecuarias en la Huasteca Potosina. Project: SAGARPA-2004-C01-186/A-1.
- **SAGARPA. 2004b**. OEIDRUS - Oficina Estatal de Información para el Desarrollo Rural Sustentable San Luis Potosí. Sistema Producto San Luis Potosí. Online: http://www.sistemaproductoslp.gob.mx.
- **Sánchez Orta, Santiago. 2010.** Caracterización morfométrica y simulación del balance hídrico de la cuenca "Tres Valles", S.L.P. MSc thesis on Hydroscience, Colegio de Posgraduados. Montecillo, Mexico.
- **Santacruz de León, Germán. 2007.** Hacia una gestión integral de los recursos hídricos en la cuenca del río Valles, Huasteca, México. PhD Thesis on Environmental Sciences, Autonomous University of San Luis Potosi. San Luis Potosí, Mexico.
- **Schuurmans, J.M. 2008.** Hydrological now- and forecasting. PhD thesis, Faculty of Geosciences, Utrecht University. Utrecht, Netherlands.
- **SEMARNAT. 2005.** Informe de la situación del medio ambiente en México - Compendio de estadísticas ambientales. Mexico City, Mexico.
- **Sharpley, A.N; Williams, J.R. 2005.** EPIC - Erosion Productivity Impact Calculator. Model documentation. Tech. Bull. 1768, Agricultural Research Service, USDA.

- **Shuster, W.D; Bonta, J; Thurston, H; Warnemuende, E; Smith, D.R. 2005.** Impacts of impervious surface on watershed hydrology: A review. Urban Water Journal, Vol. 2 (N° 4): 263 - 275.
- **SIAP. 2010.** Servicio de Información Agroalimentaria y Pesquera. Online: http://www.siap.gob.mx/.
- **SMN. 2011.** Normales climatológicas por estación. Servicio Meteorológico Nacional. Online: http://smn.cna.gob.mx/index.php?option=com_content&view=article&id=42&Itemid=75.
- **SMN. ND.** Ciclones tropicales que impactaron a México de 1970 a 2008. Servicio Meteorológico Nacional. Online: http://smn.cna.gob.mx/index.php?option=com_content&view=article&id=38&Itemid=46.
- **Snellen, A.V; Schrevel, A. 2004.** IWRM for sustainable use of water. 50 years of international experience with the concept of integrated water management. Background document to the FAO/Netherlands Conferences on Water for Food and Ecosystems. Wageningen, Netherlands.
- **Soriano Pérez, Teresa de Jesús. 2001.** Modelado matemático de evolución de contaminantes en sistemas fluviales. PhD Thesis, Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos, University of Cantabria. Santander, Spain.
- **Souvignet, Maxime. 2010.** Climate Change impacts on water resources in mountainous arid zones: A case study in the central Andes, Chile. PhD Thesis, Leipzig University. Cologne, Germany.
- **Ten Berge H.F.M. 1986.** Heat and water transfer at the bare soi surface. Aspects affecting thermal imagery. PhD. Thesis, Agricultural University Wageningen. Wageningen, Netherlands.
- **Torres Benites, Elibeth; Fernández Reynoso, Demetrio; Oropeza Mota, José Luis; Mejía Saenz, Enrique. 2004.** Calibración del modelo hidrológico SWAT en la cuenca "El Tejocote", Atlacomulco, Estado de México. TERRA Latinoamericana, Vol. 22 (N° 4).
- **Torres Benites, Elibeth; Mejía Sáenz, Enrique; Cortés Becerra, José; Palacios Vélez, Enrique; Exebio García, Adolfo. 2005.** Adaptación de un modelo de simulación hidrológica a la cuenca del Río Laja, Guanajuato, Mexico. Agrociencia, Vol. 39: 481-490.
- **Torres Espinosa, Blanca; Tamez Martinez, Xochitl; Betancourt Enriquez, Ana Diana; Velásquez Turrubiartes, José Antonio; Orta Flores, Sara Berenice; Martínez González, Pablo. N.D.** Diagnóstico de la actividad ganadera en el municipio de Ciudad Valles, San Luis Potosí 2000 - 2005.
- **UNEP. 2002.** Global Environmental Outlook 3 (GEO 3): Past, present and future perspectives. United Nations Environment Programme. Nairobi, Kenya.
- **UNESCO. 2011.** International Glossary of Hydrology. Online: http://webworld.unesco.org/water/ihp/db/glossary/glu/aglo.htm.
- **UNW-DPC. 2010.** Integrated Water Resources Management. Capacity Pool. UN-Water Decade Programme on Capacity Development, 10: 14-17. Bonn, Germany.
- **UNYSIS. 2010.** Atlantic Tropical Storm Tracking by Year. Unisys Weather. Online: http://weather.unisys.com/hurricane/atlantic/index.html.
- **US-ACE. ND.** HEC-GeoHMS. US Army Corps of Engineers - Hydrologic Engineering Center. Online: http://www.hec.usace.army.mil/software/hec-geohms/index.html.
- **USGS. 2008.** TOPMODEL. Surface Water and Water Quality Models Information Clearinghouse. US Geological Survey. Online: http://smig.usgs.gov/cgi-bin/SMIC/model_home_pages/model_home?selection=topmodel.

- **Valencia Vargas, Juan C; Díaz Nigenda, Juan J; Ibarrola Reyes, Héctor J. 2004.** La gestión integrada de los recursos hídricos en México: Nuevo paradigma en el manejo del agua. El manejo integral de cuencas en México: Estudios y reflexiones para orientar la política ambiental. INE-SEMARNAT. Cotler, Helena (Ed.). Mexito City, Mexico.
- **van Grievsen, A.; Meixner, T; Grunwald, S; Bishop, T; Diluzio, M; Srinivasan, R. 2006.** A global sensitivity analysis tool for the parameters of multi-variable catchment models. Journal of Hydrology, Vol. 324: 10-23.
- **Van Liew, Michael W; Veith, Tamie L. ND.** Guidelines for using the sensitivity analysis and auto-calibration tools for multi-gage or multi-step calibration in SWAT.
- **Vargas Mergold, Angélica Violeta. 2010.** La Reserva de la Biósfera Sierra Abra Tanchipa: Las ANP de lo internacional a lo local. MSc thesis on Environmental Sciences, Autonomous University of San Luis Potosí. San Luis Potosí, Mexico.
- **Vásquez Aguirre, Jorge Luis. 2010.** Guía para el cálculo y uso de índices de cambio climático en México. Instituto Nacional de Ecología (INE). Mexico City, Mexico.
- **Viessman, Warren; Lewis, Gary L. 2003.** Introduction to hydrology. Pearson Education Inc.
- **Wang, Xiaolan L; Feng, Yang. 2010a.** RHtestsV3 User Manual. Ontario, Canada.
- **Wang, Xiaolan L; Hanfeng, Chen; Yuehua, Wu; Yang, Feng; Qiang, Pu. 2010b.** New techniques for detection and adjustment of shifts in daily precipitation data series. Journal of Applied Meteorology and Climatology.
- **Ward, R.C; Robinson, M. 2000.** Principles of Hydrology. Mc Graw Hill.
- **Wechsler, S. P. 2007.** Uncertainties associated with digital elevation models for hydrologic applications: A review. Hydrology and Earth System Sciences, Vol. 11: 1481-1500.
- **WHO/UNICEF. 2008.** Progress on drinking water and sanitation: Special focus on sanitation.
- **Winchel, LM; Srinivasan, R; Di Luzio, M; Arnold, J.** ArcSWAT Interface for SWAT 2009. USDA Agricultural Research Service.
- **World Bank Institute. 2006.** Integrated Water Resources Management (IWRM): Introduction to Principles and Practices. Africa Regional Workshop on IWRM. Oct. 29-Nov. 2006. Nairobi, Kenya.
- **Xu, Chong-yu. 2002.** Textbook of hydrologic models. Uppsala University. Uppsala, Sweden.

ANNEX 1

CLIMATIC CLASSIFICATIONS OF THE VALLES RIVER BASIN

Climate	Description	Km^2	%
Semi-warm subhumid (the driest) $[(A)C(w_0)]$	(A): Mean temperature of the coldest month is higher than 18 °C. (C): Mean annual temperature higher than 18°C. (w): Subhumid with summer rainfall and winter dry season. 5 - 10.2% of winter rainfall. (0): Ratio Total Annual Precipitation/Mean Annual Temperature less than 43.2.	31.59	6.28
Semi-warm subhumid (medium humidity) $[(A)C(w_1)(w)]$	(A): Mean temperature of the coldest month is higher than 18 °C. (C): Mean annual temperature higher than 18°C. ((w)(w)): Subhumid with summer rainfall and winter dry season. Less than 5% of winter rainfall. (1): Ratio Total Annual Precipitation/Mean Annual Temperature between 43.2 and 55.3.	887.40	24.05
Semi-warm humid [(A)C(m)(w)]	(A): Mean temperature of the coldest month is higher than 18 °C. (C): Mean annual temperature higher than 18°C. ((m)(w)): Humid with intense summer rainfall which compensates winter dryness. Precipitation of the driest month less than 60 mm. Less than 5% of winter rainfall.	1,627.28	44.10
Semi-warm subhumid (medium humidity) $[(A)C(w_1)]$	(A): Mean temperature of the coldest month is higher than 18 °C. (C): Mean annual temperature higher than 18°C. (w): Subhumid with summer rainfall and winter dry season. Winter rainfall between 5 and 10.2%. (1): Ratio Total Annual Precipitation/Mean Annual Temperature between 43.2 and 55.3.	257.37	6.97
Warm Subhumid (medium humidity) $[Aw_1]$	A: Mean temperature of the coldest month is higher than 18 °C. Mean annual temperature higher than 22°C. w: Subhumid with summer rainfall and winter dry season. Winter rainfall between 5 and 10.2%. 1: Ratio Total Annual Precipitation/Mean Annual Temperature between 43.2 and 55.3.	506	13.71
Warm Subhumid (the most humid) $[Aw_2]$	A: Mean temperature of the coldest month is higher than 18 °C. Mean annual temperature higher than 22°C. w: Subhumid with summer rainfall and winter dry season. Winter rainfall between 5 and 10.2%. 2: Ratio Total Annual Precipitation/Mean Annual Temperature higher than 55.3.	100.54	2.72
Semidry Semiwarm $[BS_1hw]$	BS_1: Ratio Total Annual Precipitation/Mean Annual Temperature higher than 22.9. h: Semi-warm with fresh winter. Mean annual temperature higher than 18° C. Temperature of the coldest month lower than 18° C. w: Summer rainfall. % of winter rainfall between 5 and 10.2	51.88	1.41

Climate	Description	Km^2	%
Temperate Humid [C(m)(w)]	(C): Mean temperature of the coldest month between -3 and 18°C. Mean annual temperature between 12 and 18°C. (m): Humid with intense summer rainfall compensating winter dryness. (w): Precipitation of the driest month less than 40 mm. Less than 5% of winter rainfall.	27.94	0.76

Table A1.1: Description of the climate units of the VRB identified by INEGI (2011b). Own elaboration with information taken from INEGI (2005b).

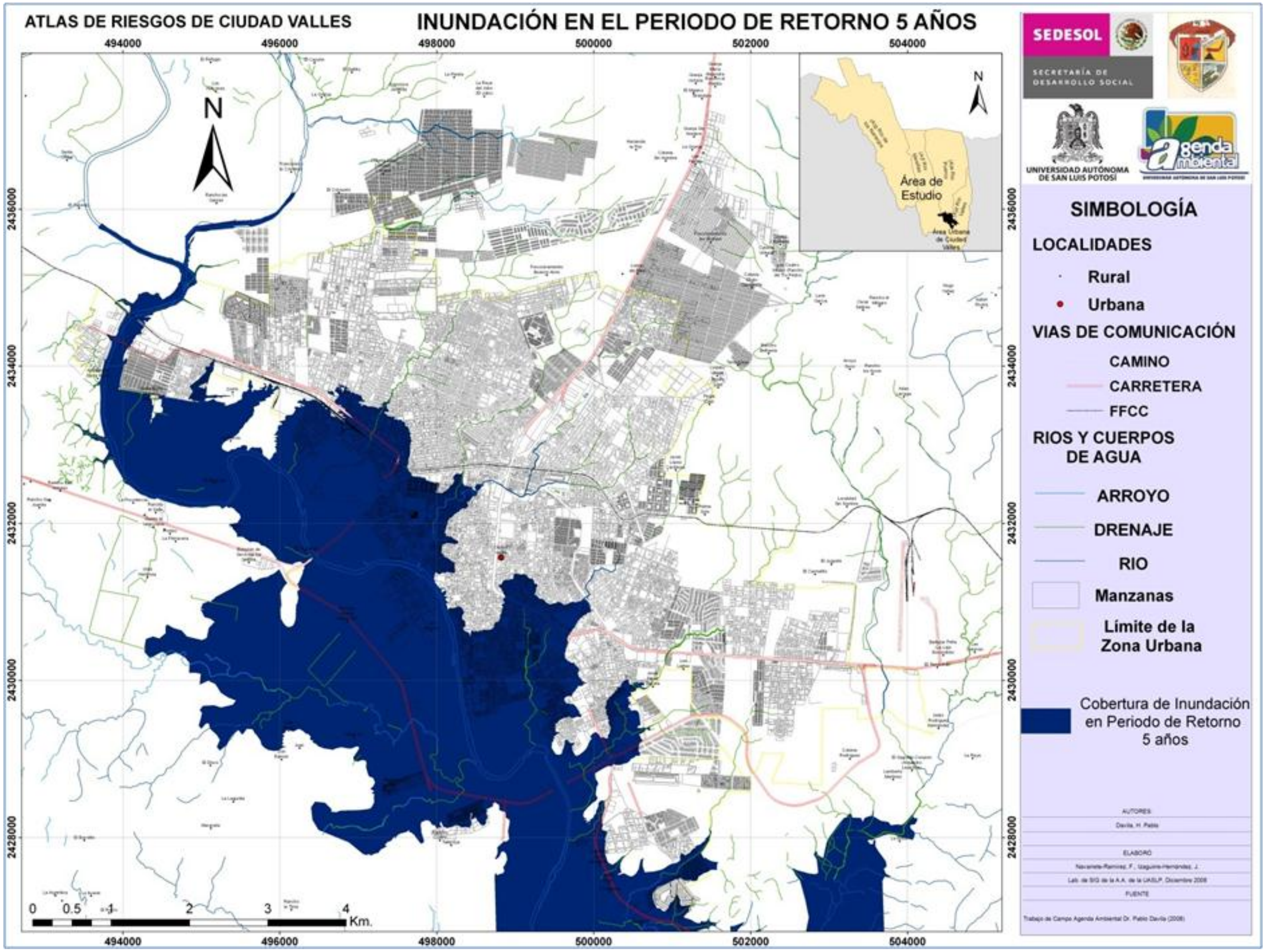
Climate	Description
Semi-warm Humid [(A)Cm]	(A): Mean temperature of the coldest month higher than 18 °C. C: Mean Annual Temperature higher than 18°C. m: Humid with intense summer rainfall compensating winter drought. Precipitation of the driest month lower than 60 mm. Winter rainfall between 5 and 10.2%.
Semi-warm Subhumid (medium humidity) [(A)C(w_1)]	(A): Mean temperature of the coldest month higher than 18 °C. C: Mean annual temperature higher than 18°C. (w): Subhumid with summer rainfall and winter dry season. Winter rainfall between 5 and 10.2%. (1): Ratio Total Annual Precipitation/Mean Annual Temperature between 43.2 and 55.3.
Semi-warm Subhumid (the most humid) [(A)C(w_2)]	(A): Mean temperature of the coldest month higher than 18 °C. C: Mean annual temperature higher than 18°C. (w): Subhumid with summer rainfall and winter dry season. Winter rainfall between 5 and 10.2%. (2): Ratio Total Annual Precipitation/Mean Annual Temperature higher than 55.3.
Warm Subhumid (medium humidity) [Aw_1]	A: Mean temperature of the coldest month is higher than 18 °C. Mean annual temperature higher than 22°C. (w): Subhumid with summer rainfall and winter dry season. Winter rainfall between 5 and 10.2%. (1): Ratio Total Annual Precipitation/Mean Annual Temperature between 43.2 and 55.3.
Warm Subhumid (the most humid) [Aw_2]	A: Mean temperature of the coldest month is higher than 18 °C. Mean annual temperature higher than 22°C. (w): Subhumid with summer rainfall and winter dry season. Winter rainfall between 5 and 10.2%. (2): Ratio Total Annual Precipitation/Mean Annual Temperature higher than 55.3.

Table A1.2: Description of the climate units of the VRB identified by Hernández (2007). Own elaboration with information taken from INEGI (2005b).

ANNEX 2

MAP OF THE URBAN AREA OF CIUDAD VALLES SUBJECT TO FLOODS CORRESPONDING TO A 5 YEARS RETURN PERIOD

[TAKEN FROM THE ATLAS OF NATURAL HAZARDS OF CIUDAD VALLES: AGENDA AMBIENTAL, ND]


ATLAS DE RIESGOS DE CIUDAD VALLES
INUNDACIÓN EN EL PERIODO DE RETORNO 5 AÑOS
494000
496000
498000
500000
502000
504000
2436000
2434000
2432000
2430000
2428000
N
Área de Estudio
Área Urbana de Ciudad Valles
0
0.5
1
2
3
4
Km.
SEDESOL
SECRETARÍA DE DESARROLLO SOCIAL
UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ
agenda ambiental
SIMBOLOGÍA
LOCALIDADES
Rural
Urbana
VIAS DE COMUNICACIÓN
CAMINO
CARRETERA
FFCC
RIOS Y CUERPOS DE AGUA
ARROYO
DRENAJE
RIO
Manzanas
Límite de la Zona Urbana
Cobertura de Inundación en Periodo de Retorno 5 años
AUTORES
Davila, H. Pablo
ELABORÓ
Navarrete-Ramirez, F., Izaguirre-Hernández, J.
Lab. de SIG de la A.A. de la UASLP, Diciembre 2008
FUENTE
Trabajo de Campo Agenda Ambiental Dr. Pablo Davila (2008)

ANNEX 2

PARAMETERS RELATED TO STREAM FLOW CALCULATIONS IN THE SWAT MODEL

ABBR.	FULL NAME	UNITS	¿REQUIRED?	ABBR.	FULL NAME	UNITS	¿REQUIRED?
Weather generator inputs							
WLATITUDE	Latitude of weather station	Degrees	Yes	WLONGITUDE	Longitude of weather station	Degrees	Yes
WELEV	Elevation of weather station	m	Yes	RAIN_YRS	Number of years of maximum monthly 0.5 h rainfall data used to define values for RAIN_HHMX 1 - 12		Yes
TMPMX (M)	Mean daily maximum air temperature for month	°C	Yes	TMPMN (M)	Mean daily minimum air temperature for month	°C	Yes
TMPSTDMX (M)	Standard deviation for daily maximum air temperature in month	°C	Yes	TMPSTDMN (M)	Standard deviation for daily minimum air temperature in month	°C	Yes
PCPMM (M)	Mean total monthly precipitation	mm H_2O	Yes	PCPSTD (M)	Standard deviation for daily precipitation in month	mm H_2O	Yes
PCPSKW (M)	Skew coefficient for daily precipitation in month		Yes	PR_W1 (M)	Probability of a wet day following a dry day in the month		Yes
PR_W2 (M)	Probability of a wet day following a wet day in the month		Yes	PCPD (M)	Average number of days with precipitation in month		Yes
RAINHHMX (M)	Maximum 0.5 hour rainfall in entire period of record for month	Mm H_2O	Yes	SOLARAV (M)	Average daily solar radiation in month	$MJ/m^2/day$	Yes
DEWPT (M)	Average daily dew	°C	No	WNDAV (M)	Average daily wind speed	m/s	No

ABBR.	FULL NAME	UNITS	¿REQUIRED?	ABBR.	FULL NAME	UNITS	¿REQUIRED?
	point temperature for month				in the month		
Watershed level inputs							
SFTMP	Snowfall temperature	°C	Yes	SMTMP	Snowmelt temperature	°C	Yes
ESCO	Soil evaporation compensation factor	Fraction	Yes	EPCO	Plant uptake compensation factor	Fraction	Yes
EVLAI	Leaf area index at which no evaporation occurs from water surface	cm^2/cm^2	No	FFCB	Initial soil water storage expressed as a fraction of field capacity	Fraction	No
DEP_IMP	Depth to impervious layer for modelling perched water tables	mm	No	CNCOEF	Plant ET Curve Number coefficient	0.5 - 2	Yes
SURLAG	Surface runoff lag coefficient	1 - 12	Yes	TRNSRCH	Fraction of transmission losses from main channel that enter aquifer	Fraction	Yes
EVRCH	Reach evaporation adjustment factor	Fraction	Yes				
Subbasin level inputs							
HRUTOT	Numbers of HRUs modelled in the subbasin		Yes[1]	SUB_KM	Area of the subbasin	Km^2	Yes[1]
SUB_LAT	Latitude of subbasin	Degrees	Yes[1]	SUB_ELEV	Elevation of subbasin	m	Yes[1]
PLAPS	Precipitation lapse rate	mm H_2O/km	No	TLAPS	Temperature lapse rate	°C/km	No
SNO_SUB	Initial snow water content	mm H_2O	No	CH_L(1)	Longest tributary channel length in subbasin	km	Yes[1]
CH_S(1)	Average slope of tributary channels	m/m	Yes[1]	CH_W(1)	Average width of tributary channels	m	Yes[1]
CH_K(1)	Effective hydraulic conductivity in tributary channel	mm/hr	Yes	CH_N(1)	Manning's n value for tributary channels		Yes

ABBR.	FULL NAME	UNITS	¿REQUIRED?	ABBR.	FULL NAME	UNITS	¿REQUIRED?
	alluvium						
Reservoir inputs							
MORES	Month the reservoir became operational	0-12	Yes	YRES	Year the reservoir became operational	AAAA	Yes
RES_ESA	Surface area when reservoir is filled to the emergency spillway	ha	Yes	RES_EVOL	Volume of water needed to fill the reservoir to the emergency spillway	$10^4 m^3$	Yes
RES_PSA	Surface area when reservoir is filled to the principal spillway	ha	Yes	RES_PVOL	Volume of water needed to fill the reservoir to the principal spillway	$10^4 m^3$	Yes
RES_VOL	Initial reservoir volume	$10^4 m^3$	Yes	RES_K	Hydraulic conductivity of the reservoir bottom	mm/hr	Yes
EVRSV	Lake evaporation coefficient	Fraction	Yes	RES_RR	Average daily principal spillway release rate	m^3/s	Yes
Soil parameters							
HYDGRP	Soil hydrologic group	A - D	Yes	SOL_ZMX	Maximum rooting depth of soil	mm	Yes
ANION_EXCL	Fraction of void space from which anions are excluded	Fraction	No	SOL_CRK	Maximum crack volume of the soil profile	Fraction	Yes (Vertisols)
SOL_Z (layer)	Depth from soil surface to bottom of layer	mm	Yes	SOL_CBN (layer)	Organic carbon content of layer	% soil weight	Yes
SOL_CLAY (layer)	Clay content of layer	% soil weight	Yes	SOL_SILT (layer)	Silt content of layer	% soil weight	Yes
SOL_SAND (layer)	Sand content of layer	% soil weight	Yes	SOL_ROCK (layer)	Rock fragment content of layer	% total weight	Yes
SOL_K (layer)	Saturated hydraulic conductivity of layer	mm/hr	Yes	SOL_BD (layer)	Moist bulk density of layer	g/cm^3	Yes
SOL_AWC (layer)	Available water capacity of layer	mm H_2O/mm soil	Yes	SOL_ALB	Moist soil albedo	Fraction	Yes
USLE_K	Soil erodibility factor		Yes				

ABBR.	FULL NAME	UNITS	¿REQUIRED?	ABBR.	FULL NAME	UNITS	¿REQUIRED?
	(K) for USLE equation						
Land cover/plant parameters							
IDC	Land cover / plant classification	Legumes, trees, annuals, etc	Yes	BIO_E	Radiation-use efficiency	(kg/ha)/(MJ/m^2)	Yes[2]
HVSTI	Harvest index for optimal growing conditions	Fraction	Yes	BLAI	Maximum potential Leaf Area Index	cm^2/ cm^2	Yes
FRGRW1	Fraction of the plant growing season corresponding to the 1st point on the optimal leaf area development curve	Fraction	Yes[2]	LAIMX1	Fraction of LAI corresponding to the 1st point on the optimal leaf area development curve	Fraction	Yes[2]
FRGRW2	Fraction of the plant growing season corresponding to the 2nd point on the optimal leaf area development curve	Fraction	Yes[2]	LAIMX2	Fraction of LAI corresponding to the 2nd point on the optimal leaf area development curve	Fraction	Yes[2]
DLAI	Fraction of growing season when leaf area begins to decline	Fraction	Yes[2]	CHTMX	Maximum canopy height	m	Yes
RDMX	Maximum root depth[2]	m	Yes	T_OPT	Optimal temperature for plant growth	°C	Yes
T_BASE	Minimum temperature for plant growth	°C	Yes	CNYLD	Normal fraction of Nitrogen in yield	Kg N/kg yield	Yes[2]
CPYLD	Normal fraction of Phosphorus in yield	Kg P /Kg yield	Yes[2]	BN1	Normal fraction of N in plant biomass at emergence	Kg N/Kg biomass	Yes[2]
BN2	Normal fraction of N in plant biomass at	Kg N/Kg biomass	Yes[2]	BN3	Normal fraction of N in plant biomass at maturity	Kg N/Kg biomass	Yes[2]

ABBR.	FULL NAME	UNITS	¿REQUIRED?	ABBR.	FULL NAME	UNITS	¿REQUIRED?
	50% maturity						
BP1	Normal fraction of N in plant biomass at emergence	Kg P/Kg biomass	Yes^2	BP2	Normal fraction of P in plant biomass at 50% maturity	Kg P/Kg biomass	Yes^2
BP3	Normal fraction of P in plant biomass at maturity	Kg P/Kg biomass	Yes^2	WSYF	Lower limit of harvest index	(kg/ha)/(kg/ha)	Yes
USLE_C	Minimum value of USLE C factor for water erosion		Yes^2	GSI	Maximum stomatal conductance at high solar radiation and low vapour pressure deficit	m/s	Yes^2
VPDFR	Vapour pressure deficit at the second point of the stomatal conductance curve	KPa	Yes^2	FRGMAX	Fraction of the maximum stomatal conductance corresponding to the 2nd point on the stomatal conductance curve	Fraction	Yes^2
WAVP	Rate of decline in radiation use efficiency per unit increase in vapour pressure deficit		Yes^2	CO2HI	Elevated CO_2 atmospheric concentration	µL CO_2/L air	Yes^2
BIOEHI	Biomass-energy ratio corresponding to the 2nd point on the radiation use efficiency curve	(kg/ha)/(MJ/m^2)	Yes^2	RSDCO_PL	Plant residue decomposition coefficient		Yes^2
ALAI_MIN	Minimum LAI for plant during dormant period	m^2/m^2	Yes	BIO_LEAF	Fraction of biomass accumulated each year that is converted to residue during dormancy (for trees)	Fraction	Yes
MAT_YRS	Years required by tree species to reach full development		Yes	BMX_TREES	Maximum biomass for a forest	(metric tons/ha)	Yes

ABBR.	FULL NAME	UNITS	¿REQUIRED?	ABBR.	FULL NAME	UNITS	¿REQUIRED?
EXT_COEF	Light extinction coefficient		Yes[2]	BM_DIEOFF	Biomass die-off fraction	Fraction	Yes[2]
Water use							
WURCH (M)	Average daily water removal from the reach for the month	$10^4 m^3$/day	Yes	These values are specified at the subbasin level			
Main channel parameters							
CH_W(2)	Average width of main channel at top of bank	m	Yes[1]	CH_D	Depth of main channel from top of bank to bottom	m	Yes[1]
CH_S(2)	Average slope of main channel along the channel length	m/m	Yes[1]	CH_L(2)	Length of main channel	km	Yes[1]
CH_N(2)	Manning's value for the main channel		Yes	CH_K(2)	Effective hydraulic conductivity in main channel alluvium	mm/hr	Yes
CH_COV1	Channel erodibility factor/Channel bank vegetation coefficient	0 - 1	Yes	CH_COV2	Channel cover factor/Channel bed vegetation coefficient	0 - 1	Yes
CH_WDR	Channel width-depth ratio	m/m	No	ALPHA_BNK	Baseflow alpha factor for bank storage	days	No
CH_SIDE	Change in horizontal distance per unit vertical distance	0 - 5	Yes	CH_BNK_BD	Bulk density for channel bank sediment	g/cm^3	Yes[2]
CH_BED_BD	Bulk density for channel bed sediment	g/cm^3	Yes[2]	CH_BNK_KD	Erodibility of channel bank sediment	cm^3/N-s	No
CH_BED_KD	Erodibility of channel bed sediment	cm^3/N-s	Yes[2]	CH_BNK_D50	D50 median particle size diameter of channel bank sediment	µm	Yes[2]
CH_BED_D50	D50 median particle size diameter of channel bed	µm	Yes[2]	CH_BNK_TC	Critical shear stress of channel bank	N/m^2	Yes[2]

ABBR.	FULL NAME	UNITS	¿REQUIRED?	ABBR.	FULL NAME	UNITS	¿REQUIRED?
	sediment						
CH_BED_TC	Critical shear stress of channel bed	N/m^2	Yes[2]				
HRU level inputs							
HRU_FR	Fraction of subbasin area contained in HRU	km^2/km^2	Yes[1]	SLSSUBBSN	Average slope length	m	Yes[3]
HRU_SLP	Average slope steepness	m/m	Yes[3]	OV_N	Manning's value for overland flow		Yes
LAT_TIME	Lateral flow travel time	days	No	SLSOIL	Slope length for lateral subsurface flow	m	No
CANMX	Maximum canopy storage	mm H_2O	Yes	RSDIN	Initial residue cover	kg/ha	No
Groundwater parameters							
SHALLST	Initial depth of water in shallow aquifer	mm H_2O	No	DEEPST	Initial depth of water in deep aquifer	mm H_2O	No
GW_DELAY	Groundwater delay time	days	Yes[2]	ALPHA_BF	Base flow alpha factor or baseflow recession constant	Fraction of a day	Yes
GWQMIN	Threshold depth of water in the shallow aquifer required for return flow to occur	mm H_2O	Yes	GW_REVAP	GW 'revap' coefficient	0.02 – 0.2	Yes[2]
REVAPMN	Threshold depth of water in the shallow aquifer for 'revap' or percolation to deep aquifer to occur	mm H_2O	Yes[2]	RCHRG_DP	Deep aquifer percolation fraction	Fraction	Yes
Land and water management parameters							
LAI_INIT	Initial Leaf Area Index of cover when already growing at beginning of	cm^2/cm^2	Yes	BIO_INIT	Initial dry weight biomass of cover when already growing at beginning of simulation	Kg/ha	Yes

ABBR.	FULL NAME	UNITS	¿REQUIRED?	ABBR.	FULL NAME	UNITS	¿REQUIRED?
	simulation						
PHU_PLT	Number of heat units needed to bring plant to maturity when already growing at beginning of simulation		Yes	HEAT UNITS	Total heat units for cover/plant to reach maturity		Yes
CN2	Initial SCS runoff curve number for moisture condition II		Yes	CNOP	SCS curve number for moisture condition II – Operation update		No
BIOMIX	Biological mixing efficiency		Yes[2]	NROT	Number of years of rotation		Yes
USLE P	USLE equation support practice factor	0 – 1	Yes	IRRSC	Irrigation source code	0 - 5	Yes
IRRNO	Irrigation source location		Yes	FLOWMIN	Minimum in-stream flow for irrigation diversions	m^3/s	No
IRR_AMT	Depth of irrigation water applied on HRU	mm	Yes	IRR_EFF	Irrigation efficiency	Fraction	Yes
IRR_SQ	Surface runoff ratio	Fraction	Yes	DIVMAX	Maximum daily irrigation diversion from reach	mm or $10^4 m^3$	No
FLOWFR	Fraction of available flow that is allowed to be applied to the HRU	Fraction	No	BIO_TARG	Biomass (dry weight) target	Metric tons/ha	No
HI_TARG	Harvest index target	(kg/ha)/(kg/ha)	No	CURYR_MAT	Current age of trees when transplanting		Yes
FERT_ID	Fertilizer applied		Yes	FRT_KG	Amount of fertilizer applied to HRU	Kg/ha	Yes
FRT_SURFACE	Fraction of fertilizer applied to top 10 mm of soil	Fraction	No	TILL_ID	Tillage practice/implement applied		Yes

ABBR.	FULL NAME	UNITS	¿REQUIRED?	ABBR.	FULL NAME	UNITS	¿REQUIRED?
EFFMIX	Mixing efficiency of tillage operation	Fraction	Yes	DEPTIL	Depth of mixing caused by the tillage operation	mm	Yes
IHV_GBM	Grain or biomass harvest code	0 / 1	Yes	HARVEFF	Harvest efficiency	Fraction	Yes
HI_OVR	Harvest Index Override	(kg/ha)/(kg/ha)	No	GRZ_DAYS	Number of consecutive days grazing takes place in the HRU		Yes
BIO_MIN	Minimum plant biomass for grazing	Kg/ha	Optional	BIO_EAT	Dry weight of biomass consumed daily by grazing	Kg/ha/day	Yes
BIO_TRMP	Dry weight of biomass trampled daily by grazing	Kg/ha/day	Yes	MANURE_ID	Manure identification code		Yes
MANURE_KG	Dry weight of manure deposited daily	Kg/ha/day	Yes				

[1]Automatically configured by ArcSwat. [2]Set by default.[3]Automatically configured by ArcSwat but calibrated.