SENSITIVITY AND UNCERTAINTY ANALYSIS OF TOPMODEL FOR THE HYDROLOGICAL SIMULATION OF THE GRISE RIVER CATCHMENT

By

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To my family and the memory of my brother, Pierre Jonas Beneche
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# TABLE OF CONTENTS

| ACKNOWLEDGMENTS | .............................................. | 4 |
| LIST OF TABLES | .............................................. | 8 |
| LIST OF FIGURES | .............................................. | 9 |
| LIST OF ABBREVIATIONS | .............................................. | 11 |
| ABSTRACT | .............................................. | 12 |

## CHAPTER

1 INTRODUCTION .......................................................................................................................... 14

Problem Statement .................................................................................................................. 14
Objectives .............................................................................................................................. 17

2 LITERATURE REVIEW ............................................................................................................. 18

Hydrological Modeling .......................................................................................................... 18
Model Classification .............................................................................................................. 18
  - Deterministic Versus Stochastic Models ........................................................................ 18
  - Lumped Versus Distributed Models .............................................................................. 19
Runoff Generation Mechanisms ............................................................................................ 19
  - Infiltration Excess Overland Flow ................................................................................ 20
  - Spatial Area Infiltration Excess Overland Flow .......................................................... 20
  - Saturation Excess Overland Flow .................................................................................. 20
  - Subsurface Stormflow .................................................................................................... 21
Hydrological Response Process .............................................................................................. 21
  - Characterization of the Hydrological Response ............................................................ 21
  - Transformation of Rainfall in Hydrograph .................................................................... 22
    - Production function ..................................................................................................... 22
    - Transfer function ........................................................................................................ 24
Sensitivity Analysis in Hydrological Modeling ...................................................................... 27
  - Sensitivity Analysis Method .......................................................................................... 28
    - Local SA (LSA) ............................................................................................................ 28
    - Global sensitivity analysis (GSA) ............................................................................... 29
Uncertainty Analysis in Hydrological Modeling .................................................................... 31

3 WATERSHED PRESENTATION ................................................................................................ 35

Watershed Location ................................................................................................................ 35
Physical Characteristics of the Watershed ............................................................................. 36
  - Hydrology and Hydrogeology ......................................................................................... 36
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1</td>
<td>Slope classification in the watershed</td>
<td>39</td>
</tr>
<tr>
<td>3-2</td>
<td>Soil properties in the catchment based on ASCE (American Society of Civil</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Engineers)</td>
<td></td>
</tr>
<tr>
<td>3-3</td>
<td>Saturated Hydraulic Conductivity classified by USDA Soil Texture (Rawls,</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>1998)</td>
<td></td>
</tr>
<tr>
<td>5-1</td>
<td>Summary statistics of CD (cm) parameter for various soil types</td>
<td>71</td>
</tr>
<tr>
<td>5-2</td>
<td>TOPMODEL parameters and their values for GSA</td>
<td>72</td>
</tr>
<tr>
<td>5-3</td>
<td>TOPMODEL parameters and their values for LSA</td>
<td>73</td>
</tr>
<tr>
<td>6-1</td>
<td>Three (3) hours sensitivity Indexes for the Morris Analysis</td>
<td>95</td>
</tr>
<tr>
<td>6-2</td>
<td>Three (3) hours sensitivity Indexes for the FAST First-Order Analysis</td>
<td>96</td>
</tr>
<tr>
<td>6-3</td>
<td>Three (3) hours sensitivity Indexes for the FAST Total-Order Analysis</td>
<td>97</td>
</tr>
<tr>
<td>6-4</td>
<td>Uncertainty analysis statistics for probability distributions obtained from</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>the FAST results</td>
<td></td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>2-1</td>
<td>Hydrological response of a catchment (Musy, 2001)</td>
<td>33</td>
</tr>
<tr>
<td>2-2</td>
<td>Land Use and Hydrological response. From Sauchyn (s. d.)</td>
<td>34</td>
</tr>
<tr>
<td>2-3</td>
<td>Hydrological response of a catchment (Musy, 2001)</td>
<td>34</td>
</tr>
<tr>
<td>3-1</td>
<td>Grise River catchment location</td>
<td>42</td>
</tr>
<tr>
<td>3-2</td>
<td>Towns overlapped by the catchment</td>
<td>43</td>
</tr>
<tr>
<td>3-3</td>
<td>Grise River in dry season view</td>
<td>44</td>
</tr>
<tr>
<td>3-4</td>
<td>Hydrographic network</td>
<td>45</td>
</tr>
<tr>
<td>3-5</td>
<td>River Grise left bank</td>
<td>46</td>
</tr>
<tr>
<td>3-6</td>
<td>Grise River catchment land use</td>
<td>47</td>
</tr>
<tr>
<td>4-1</td>
<td>The relation between topography, topographic index and soil moisture deficit</td>
<td>58</td>
</tr>
<tr>
<td>5-1</td>
<td>Decrease of the hydraulic conductivity with average depth</td>
<td>74</td>
</tr>
<tr>
<td>5-2</td>
<td>Derivation of an estimate of parameter m using recession curve analysis</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>under exponential transmissivity profile assumption (Beven, 2001)</td>
<td></td>
</tr>
<tr>
<td>5-3</td>
<td>Recession curve for the third week of December, 2011</td>
<td>75</td>
</tr>
<tr>
<td>5-4</td>
<td>Recession curve for the first two weeks of January, 2012</td>
<td>76</td>
</tr>
<tr>
<td>5-5</td>
<td>Bridge of Croix des Missions in dry seasons</td>
<td>76</td>
</tr>
<tr>
<td>5-6</td>
<td>Bridge of Croix des Missions in rainy seasons</td>
<td>77</td>
</tr>
<tr>
<td>5-7</td>
<td>Shape of the channel at the stages gauge</td>
<td>77</td>
</tr>
<tr>
<td>5-8</td>
<td>Distribution of the channel velocity inside the catchment</td>
<td>78</td>
</tr>
<tr>
<td>6-1</td>
<td>DEM of the River Grise catchment</td>
<td>99</td>
</tr>
<tr>
<td>6-2</td>
<td>Map of the area processed by R-TOPMODEL</td>
<td>100</td>
</tr>
<tr>
<td>6-3</td>
<td>Areal distribution of the Topographic Index</td>
<td>101</td>
</tr>
<tr>
<td>6-4</td>
<td>OAT sensitivity of the parameters for the minimum flows</td>
<td>102</td>
</tr>
<tr>
<td>No.</td>
<td>Section</td>
<td></td>
</tr>
<tr>
<td>-----</td>
<td>---------</td>
<td></td>
</tr>
<tr>
<td>6-5</td>
<td>OAT sensitivity of the parameters for the Median flows</td>
<td>102</td>
</tr>
<tr>
<td>6-6</td>
<td>OAT sensitivity of the parameters for the Average flows</td>
<td>103</td>
</tr>
<tr>
<td>6-7</td>
<td>OAT sensitivity of the parameters for the Maximum flows</td>
<td>103</td>
</tr>
<tr>
<td>6-8</td>
<td>OAT sensitivity of the parameters for the Total flows</td>
<td>104</td>
</tr>
<tr>
<td>6-9</td>
<td>Morris Sensitivity Index of the parameters for the minimum flows</td>
<td>105</td>
</tr>
<tr>
<td>6-10</td>
<td>Morris Sensitivity Index of the parameters for the Median flows</td>
<td>105</td>
</tr>
<tr>
<td>6-11</td>
<td>Morris Sensitivity Index of the parameters for the Average flows</td>
<td>106</td>
</tr>
<tr>
<td>6-12</td>
<td>Morris Sensitivity Index of the parameters for the Maximum flows</td>
<td>106</td>
</tr>
<tr>
<td>6-13</td>
<td>Morris Sensitivity Index of the parameters for the Total flows</td>
<td>107</td>
</tr>
<tr>
<td>6-14</td>
<td>FAST Sensitivity for the Total order indexes of the parameters</td>
<td>108</td>
</tr>
<tr>
<td>6-15</td>
<td>FAST Sensitivity for the First order indexes of the parameters</td>
<td>108</td>
</tr>
<tr>
<td>6-16</td>
<td>FAST Sensitivity for the interactions of the parameters</td>
<td>109</td>
</tr>
<tr>
<td>6-17</td>
<td>Probability distribution of the minimum flows</td>
<td>110</td>
</tr>
<tr>
<td>6-18</td>
<td>Probability distribution of the median flows</td>
<td>110</td>
</tr>
<tr>
<td>6-19</td>
<td>Probability distribution of the average flows</td>
<td>111</td>
</tr>
<tr>
<td>6-20</td>
<td>Probability distribution of the maximum flows</td>
<td>111</td>
</tr>
<tr>
<td>6-21</td>
<td>Probability distribution of the total flows</td>
<td>112</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
<td></td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
<td></td>
</tr>
<tr>
<td>ASCE</td>
<td>American Society of Civil Engineers</td>
<td></td>
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<tr>
<td>ASCII</td>
<td>American Standard Code for Information Interchange</td>
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</tr>
<tr>
<td>ASTER</td>
<td>Advanced Spaceborne Thermal Emission and Reflection Radiometer</td>
<td></td>
</tr>
<tr>
<td>CD</td>
<td>Capillary Drive</td>
<td></td>
</tr>
<tr>
<td>CDF</td>
<td>Cumulative Distribution Frequency</td>
<td></td>
</tr>
<tr>
<td>CN</td>
<td>Curve Number.</td>
<td></td>
</tr>
<tr>
<td>CNIGS</td>
<td>Centre Nationale de l'Information GeoSpatiale</td>
<td></td>
</tr>
<tr>
<td>DEM</td>
<td>Data Elevation Model</td>
<td></td>
</tr>
<tr>
<td>FAO</td>
<td>Food and Agriculture Organization</td>
<td></td>
</tr>
<tr>
<td>FAST</td>
<td>Fourier Analysis Sensitivity Test</td>
<td></td>
</tr>
<tr>
<td>GDEM</td>
<td>Global Digital Elevation Model</td>
<td></td>
</tr>
<tr>
<td>HWSD</td>
<td>Harmonized World Soil Database</td>
<td></td>
</tr>
<tr>
<td>MARNDR</td>
<td>Ministere de L'Agriculture des Ressources Naturelles et du Developpement Rural</td>
<td></td>
</tr>
<tr>
<td>MOE</td>
<td>Ministere de L’Environnement</td>
<td></td>
</tr>
<tr>
<td>NARR</td>
<td>North American Regional Reanalysis</td>
<td></td>
</tr>
<tr>
<td>OAT</td>
<td>One at a time</td>
<td></td>
</tr>
<tr>
<td>PDFs</td>
<td>Probability Density Function</td>
<td></td>
</tr>
<tr>
<td>SA</td>
<td>Sensitivity Analysis</td>
<td></td>
</tr>
<tr>
<td>SCS</td>
<td>Soil Conservation System</td>
<td></td>
</tr>
<tr>
<td>TI</td>
<td>topographic index</td>
<td></td>
</tr>
<tr>
<td>TWI</td>
<td>Topographic Wetness Index</td>
<td></td>
</tr>
<tr>
<td>UNESCO</td>
<td>United Nations Educational Scientific and Cultural Organization</td>
<td></td>
</tr>
<tr>
<td>USDA</td>
<td>United State Department of Agriculture</td>
<td></td>
</tr>
</tbody>
</table>
This study aimed at simulating the hydrological behavior of the Grise River watershed which is one of the most vulnerable watersheds in Haiti. TOPMODEL was used to perform the simulation. This is a semi-distributed model essentially based on topography that divides the catchment into contributing areas.

Five years (1999-2002) time series of 3 hours rainfall and potential evapotranspiration, obtained from the North American Regional Reanalysis (NARR) project, were used for the simulation. Soil data was obtained from the Food and Agriculture Organization (FAO) and other studies realized in this catchment. A 30m DEM was obtained from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM).

Both global (FAST and Morris Methods) and Local(OAT) sensitivity analyses were performed and revealed that the decay of the decrease of transmissivity with depth (m), the logarithm of the transmissivity, the hydraulic conductivity (ks), the Sr\text{Max} and the channel flow parameter (vr) influenced the application of TOPMODEL in the River Grise catchment in regards to different type of flows. Other parameters such as capillary drive (CD) influence also the response of the watershed but on a smaller scale.
Ranges of variation of different types of flows were also determined in this study. However measured data is necessary to confirm the performance of TOPMODEL in the watershed.
CHAPTER 1
INTRODUCTION

Problem Statement

Scientific evidence based on long-term observations showed that climate change and climate variability have influenced the natural resources particularly Water resources around the world (Olivier and Hidore, 2002; Brekke, et al., 2009). Spatial and temporal variability of rainfall and, consequently, streamflow regimes have obviously changed. In most of the United States for example, precipitation and streamflow have increased for the second half of the 20th century (Lettenmaier, et al., 2008). Rainfall in West Africa has indicated a continuous decrease since 1960s while recursive anomalies have been observed in East and North East of Africa (Moreda, 1999).

As a result of the climate variability and climate change, problems related to water have increased. Water shortages, poor water quality and flood damages have been increasingly observed all over the world. Parallel, population growth, agricultural expansion to meet the food needs and industrial growth have increased the demand on freshwater. Agriculture itself consumes 70% of the worldwide freshwater. Despite the fact that about one third of the world’s population is actually living in either areas where there is scarcity or shortage of water, scientific research has predicted that climate change and variability and population growth will increase this number to one half of humanity (United Nations Humans Development report, 2006)

Problems related to water can even be more remarkable on a watershed scale. In addition to the global effect, local practices can have large impacts on streamflow. Land cover and land-use changes such as residential and commercial development,
deforestation, reforestation, and wildfires over time can result in changes to basin runoff patterns, which could change flood peaks, flood storage, and other uses.

Since land-use and land cover have varied and the climate change and variability issue has become more flagrant, the integrated management and allocation of the water resources to satisfy the needs of different sectors are the challenges decision-makers have been facing (Simonovic, 2002). It has become urgent to link research with improved water management. The allocation of water resources in a more efficient way among competing needs requires a better monitoring, assessment, and forecasting of the resources.

In this context, scientists have been looking for more efficient ways to assess the hydrological processes within the watersheds. As a result, many hydrologic models, which have become an essential tool for water resources planning, development, and management, have been built to model watershed responses. Spatially distributed rainfall–runoff models have been generated for analyzing the impact of land cover and climate changes on streamflow regimes and surface water bodies (Harrison and Whittington, 2002; Eckhardt and Ulbrich, 2003).

The Haitian Watersheds for example are known as some of the most vulnerable in the world due to human activities. While only less than 30 % of the land is suitable for farming activities (Delusca, 1998) more than 60 % of the population has lived in rural areas using traditional farming practices that have led consequently to a drastic decrease in water infiltration and increase in surface runoff (Dautrebande, et al., 2006). Agricultural activities have been practicing on unsuitable steep lands.
Moreover, Haiti’s geographical location renders it more vulnerable. Indeed, located on the primary pathway of tropical storms that initiate in the Atlantic and strike Caribbean islands during hurricane season, Haiti has long been vulnerable to tropical storms and hurricanes. However a significant increase in severe natural disasters such as floods, hurricanes, landslides has been observed for the last decade. Flash floods have been the most important problems the eroded watersheds have faced leading to enormous loss of human life.

In Haiti, scientific investigation and measurement in the watersheds remain extremely rare. This is mainly due to the scarcity of hydrologic data necessary to conduct studies. There is been a lack of instruments capable to generate the data. The few existing hydrologic stations enable to collect these data were installed very recently. Some studies have been conducted to roughly estimate flood risk in some watersheds, but there is no description of the hydrological processes that intervene in generating the floods.

The watershed of Cul-de-Sac which encompasses the River Grise basin remains one of the most priority Haitian watersheds, based upon the population density, the flood risk and the vulnerability of the infrastructures (Timyan, 2006). Other authors such as Smucker et al. (2007) and Smith et al. (2008) have confirmed this conclusion. However none of these studies was able to quantify the hydrological processes happening in the watershed.

Thus, this research aims to assess the hydrological response of the River Grise basin using the TOPMODEL.
Objectives

The simulation of the hydrological response in this watershed with TOPMODEL aims at determining appropriate soil and catchment factors needed to improve flood estimation methods.

The specific objectives are:

1. Simulating the hydrological behavior of the catchment using R TOPMODEL
2. Identifying the controlling parameters of the hydrologic processes in the River Grise catchment
3. Predicting the stream discharges in the watershed
CHAPTER 2
LITERATURE REVIEW

Hydrological Modeling

As an important tool for hydrological system investigation, a hydrological model is a mathematical representation of the different components of the hydrologic cycle. They describe mathematically the elements of the water system. They have been applied on different scales. They can be local to global; they can be more or less complex based on the scale they are designed to address. Rainfall-runoff models have been developed for more than thirty years based upon different concepts and perceptions. However, the applicability of some widely accepted models may be limited by the complexity of hydrological measurement techniques and lack of measurements in space and time.

Model Classification

There have been several ways to classify hydrological models. The two generic classes are the deterministic versus stochastic models and the lumped versus distributed models.

Deterministic Versus Stochastic Models

Deterministic models represent the hydrological processes based on physical laws. They take into account no uncertainties in prediction. The variables are free from random variation and have no probability distribution. In nature, a deterministic model is one where the model parameters are known or assumed. On the contrary, stochastic models account for uncertainty in model predictions due to uncertainty in input variables, boundary conditions and/or parameter values. Instead of dealing with only one possible reality of how the process evolves over time, stochastic models can
capture the indeterminacy in its future evolutions described by probability distributions. This is also called a probabilistic model.

**Lumped Versus Distributed Models**

In lumped models the watershed is treated as a single unit while distributed models divide the watershed in several units (each considered as lumped) that have their own characteristics. In lumped models, the parameters represent the average value over the catchment area. Such models are calibrated using actual discharge data and usually use measured or calculated parameters. Lack of measured discharge data thus limits the application of lumped models.

Some assumptions are made when using lumped models. For instance rainfall is considered being uniformly distributed over a watershed basin both spatially and temporally over a given time period. In reality, that never happens. (Smith et al., 2004b) (Reed et al., 2004)

For the so called models of distributed parameters, the units are more homogenous than the whole watershed. The watershed response is a composite of the responses of the units. Distributed hydrologic modeling is a developing field around the world and there are many types, philosophies, and lines of work. As an example, one type of distributed hydrologic model is that which tries to integrate the units in order to represent the spatiality of the variables in a simple way. TOPMODEL (Corral, 2004) is such a model.

**Runoff Generation Mechanisms**

Runoff is one of the most important outputs of all hydrological models. The occurrence of runoff in a basin can be explained inclusively by several theories:
**Infiltration Excess Overland Flow**

Also called Horton overland flow, this mechanism is more likely to be significant in areas of low vegetation cover and high rainfall intensity. Horton (1933) stated that runoff occurs when rainfall intensity exceeds infiltration or storage capacity. However, Kirkby (1969) and Freeze (1972) remarked that in humid temperate regions covered with vegetation infiltration capacities of soils are usually higher than normal rainfall intensities.

**Spatial Area Infiltration Excess Overland Flow**

The properties of the soil vary spatially over the watershed. As a result, the infiltration capacity of the soil is more likely to be different from one point to another. Moreover, due to spatial variability of surface water inputs, infiltration excess runoff does not always occur over the entire basin during a rainfall event. Betson (1964) stated that the area contributing to infiltration excess runoff may only be a small portion of the drainage basin.

**Saturation Excess Overland Flow**

This mechanism of runoff occurs when in locations where the soil profile becomes completely saturated. In these locations, rainfall intensity does not necessarily exceed infiltration capacity. Once complete saturation of the soil occurs at a location all further rainfall becomes overland flow runoff (Cappus, 1960).

The complete saturation of the soil usually results in raising the water table near the surface making stream areas susceptible to saturation from below. These areas vary seasonally and are referred to as variable source areas (Beven 2000).
**Subsurface Stormflow**

Over relatively impermeable bedrock, water flows downslope after satisfying some initial depression storage. This situation was pointed out by Dunne and Black in 1979. As a result, when both the soil is deep enough and the capacity of infiltration is high, the streamflow is dominated by the subsurface flow (Beven, 2000).

**Hydrological Response Process**

The hydrological response is defined as the reaction of the basin when it is subjected to precipitation (Musy, 2005). The watershed is the basic hydrologic unit within which all measurements, calculations and predictions are made in hydrology. The characteristics of the watershed and the precipitation involve in expressing the hydrological response of the watershed. It is usually measured by the amount of water that flows at the outlet. The hydrological response can be graphically represented by the plot of discharge in the channel versus time called a hydrograph or by the plot of the water level versus time which is limnograph.

In fact, establishing the relationships between the physical attributes of the catchment and the behavior of the stream or river leaving a watershed has been one of the most important problem hydrologists have faced in watershed hydrology.

**Characterization of the Hydrological Response**

The hydrological response as represented in the Figure 2-1 can be characterized in several different ways. The hydrological response can be either null or positive. This is the case when subjected to the precipitation the stream or the river leaving the watershed does not change. The hydrological response is, on the contrary, positive when under the climatic stimuli the flow regime is modified.
As expressed in Figure 2-2 the hydrological response varies with land use. When the hydrological response is positive, it can be fast, delayed, total or partial (Musy, 2005).

1. Fast: when the response occurs within a relatively short period of time after the catchment has been subjected to the solicitation. It is more important in case of surface flow.

2. Delayed: when the lag time is relatively long the response is considered to be delayed. It occurs when the contribution of the subsurface is more important in the runoff generation process.

3. The hydrological response is thought of as total when it is composed of both the surface and subsurface flow.

4. The hydrological response is considered as partial when it results from either the surface flow or subsurface flow.

**Transformation of Rainfall in Hydrograph**

The transformation of rainfall into hydrograph is obtained by applying successively two functions referred to as production function and transfer function as indicated in the Figure 2-3.

**Production function**

The description of the hydrological response of the watershed solicited by climatic stimuli requires first the understanding and the estimation of flows at the interface soil-vegetation-atmosphere. This estimation consists in determining the total losses which is the collective term given to the various processes that act to remove water from the incoming precipitation before it leaves the watershed as runoff (McCuen et al., 2002). These processes are evaporation, transpiration, interception, infiltration, depression storage, and detention storage.
Several techniques have been proposed for estimating the amount of rainfall lost as abstraction form the effective rainfall that contributes to runoff. The SCS curve number and the phi-index methods are the most frequently used.

1. The SCS method accounts for abstractions as the difference between the volumes of rainfall and runoff. It relates runoff depth to rainfall depth. The Equation (2-1) expresses the Runoff as computed by SCS.

\[ R = \frac{(P - Ia)^2}{P - Ia + S} \]  

\[ (2-1) \]

R and P are respectively the runoff and the precipitation depth; and the maximum watershed retention S is given in Equation (2-2).

\[ S = \left( \frac{1000}{CN} \right) - 10 \]  

\[ (2-2) \]

CN is a runoff index called the runoff curve number.

The total loss is separated into two parts: the initial abstraction \( I_a \) and the retention. The initial abstraction is related to CN by the empirical equation as shown in Equation (2-3).

\[ Ia = 0.25 \]  

\[ (2-3) \]

2. The phi-index method assumes a constant rate of abstraction over the duration of the storm. These total abstraction methods simplify the calculation of storm runoff rates (McCuen et al., 2002). Mathematically the phi-index method for modeling losses is described by (Theodore et al., 1987) in the Equations (2-4) and (2-5).

\[ f(t) = I(t) \text{ for } I(t) < \phi \]  

\[ (2-4) \]

\[ f(t) = \phi \text{ for } I(t) \geq \phi \]  

\[ (2-5) \]
where \( f(t) \) is the loss rate; \( I(t) \) is the storm rainfall intensity; \( t \) is the time; and \( \phi \) is the calibration constant, called the phi index.

**Transfer function**

The transformation of the flows generated from different parts of the watershed into a hydrograph at the outlet is referred to the process called Transfer function (Hingray et al., 2009). This contribution accounts for both overland flow and interflow (Bedient et al., 2008). There are several methods to compute the hydrograph.

1. **Rational method**: The Rational formula is one of the simplest formulas that compute the prediction of peak flow. It is obtained as mentioned in the Equation (2-6) (Bedient et al., 2008).

\[
Q_p = C_i A \text{ (cfs)}
\]

where \( C \) is the runoff coefficient. It varies with land use, \( i \) is intensity of rainfall of chosen frequency for a duration equal to time of concentration \( t_c \) (in. /hr.) \( t_c \) is equilibrium time for rainfall occurring at the most remote portion of the watershed to contribute flow at the outlet, \( A \) is catchment area (acres).

As we can see the previous formula computes the peak flow \( Q_p \). It does not necessarily present the conversion of the excess flow into a hydrograph.

2. **Time–area methods**: One of the interesting ways to understand how rainfall excess is converted into hydrograph is the time–area histogram. The assumption made in this method is that the outflow hydrograph results from pure translation of direct runoff to the outlet at uniform velocity, ignoring any storage effects in the watershed. This method is given by the Equation (2-7) (Bedient et al., 2008).

\[
Q_n = R_i A_1 + R_{i-1} A_2 + \ldots + R_1 A_j
\]
where \( Q_n \) = hydrograph ordinate at time \( n \) (cfs), \( R_i \) is excess rainfall ordinate at time \( i \) (ft/s) and \( A_j \) is time–area histogram ordinate at time \( j \) (ft\(^2\)).

**3. Unit hydrograph method:** A unit hydrograph is defined as the hydrograph that results from 1-inch (or meter) of excess precipitation (or runoff) spread uniformly in space and time over a watershed for a given duration.

Several assumptions inherent to the Unit Hydrograph Method tend to limit its application to any given watershed (Johnstone and Cross, 1949):

1. The duration of direct runoff is always the same for uniform-intensity storms of the same duration, regardless of the intensity
2. The direct runoff volumes produced by two different excess rainfall distributions are in the same proportion as the excess rainfall volume
3. The time distribution of the direct runoff is independent of concurrent runoff from antecedent storm events
4. Hydrologic systems are usually nonlinear due to factors such as storm origin and patterns and stream channel hydraulic properties
5. Despite this nonlinear behavior, the unit hydrograph concept is commonly used because, although it assumes linearity, it is a convenient tool to calculate hydrographs and it gives results within acceptable levels of accuracy
6. The alternative to UH theory is kinematic wave theory and distributed hydrologic models

**4. Snyder’s Synthetic Unit Hydrograph:** The basin lag is given in the following Equation (2-8).

\[
 tp = C(LL)^{0.3} 
\]  
\ (2-8) 

\( C_l \) is a coefficient ranging from 1.8 to 2.2, \( L \) is the length of the basin outlet to the basin divide, \( L_c \) is the length along the main stream to a point nearest the basin centroid.

The Equation (2-9) expresses the peak discharge as followed

\[
 Q_p = \frac{640CpA}{t^p} 
\]  
\ (2-9)
where 640 will be 2.75 for metric system, $C_p$ is a storage coefficient ranging from 0.4 to 0.8 where larger values of $C_p$ are associated with smaller values of $C_t$, $A$ is the drainage area.

The time base is given by the Equation (2-10).

$$T_b = 3 + \frac{t_p}{8}$$

(2-10)

However, for small watershed the time is obtained by multiplying $t_p$ by a value ranging from 3 to 5

The duration is given by the Equation (2-11).

$$D = \frac{t_p}{5.5}$$

(2-11)

For other rainfall excess duration, the Equation (2-12) expresses the adjusted basin lag as followed

$$t_{p'} = t_p + 0.25 (D' - D)$$

(2-12)

The width expressed in the Equations (2-13) and (2-14) respectively for 50% and 75% of $Q_p$ are where 770 and 440 should be replaced with 2.14 and 1.22 when the metric unit system is used

$$W_{50} = 770\left(\frac{Q_p}{A}\right)^{\frac{1}{2}} - 1.08$$

(2-13)

$$W_{75} = 440\left(\frac{Q_p}{A}\right)^{\frac{1}{2}} - 1.06$$

(2-14)

5. SCS method: The hydrograph calculated in the Equation (2-15) is a triangle with a rainfall duration $D$, time of rise $T_r$, time fall $B$ and peak flow. The direct runoff is obtained as stated in the Equation (2-16).
\[ \text{Vol} = \frac{QpTr}{2} + \frac{QpB}{2} \]  

(2-15)

\[ Qp = \frac{2 \text{vol}}{Tr + B} \]  

(2-16)

From the analysis of historical streamflow data, B is usually equal to 1.67 Tr. So the peak discharge is calculated as stated by the Equation (2-17)

\[ Qp = \frac{0.75 \text{vol}}{Tr} \]  

(2-17)

**Sensitivity Analysis in Hydrological Modeling**

Sensitivity analyses consists of determining qualitative or quantitative variation induced in the model outputs by varying one or multiple inputs factors of the model (Saltelli et al., 2000). Hydrologic models that are mathematical or empirical descriptions of the watershed response to rainfall are based on conceptualization, assumptions and hypotheses. Model inputs are subject to multiple sources of uncertainty including errors of measurements, spatial and temporal limitations, and poor or partial understanding of the processes involved. Accordingly, the outputs of these models can also present imperfections that have been incorporated through hypothesis, structures, quantity and quality of input data, and parameter estimates (Gupta et al., 1999; Saltelli et al., 2000, Muletha and Nicklow, 2005). As a result, sensitivity analyses are conducted to determine:

1. The resemblance of the model to the system it represents
2. The factors that most influence the outputs and that particularly required stronger knowledge.
3. Parameters that are insignificant
4. Region in space where the model variation is maximum
5. The optimal regions within the space of input factors for use in a subsequent
calibration study.

6. Factors that interact with others if there is any (Satelli et al., 2000)

   The sensitivity analysis process involved following four particular steps that are:
   1. Determination of probability distribution functions (PDFs) of input parameters
   2. Generation of input samples
   3. Model simulations to calculate desired outputs/decision variables
   4. Statistical analysis that generates sensitivity indices and parameter rankings
      (Saltelli et al., 2000)

**Sensitivity Analysis Method**

Several methods of sensitivity analysis (SA) exist that have their own strengths
and weaknesses. The choice can be difficult and depends on the problem under
investigation, the characteristics of the model and the computational cost. The methods
can be generally classified into two that are the local SA methods and the global
methods

**Local SA (LSA)**

Local sensitivity analysis (LSA) that is usually carried out by computing partial
derivatives is mostly concentrated on the local impact of the factors of the model. Local
analysis addresses sensitivity relative to point estimates of parameter values. The local
derivative of the desired output variable is calculated around a certain value of one input
parameter while holding other input parameters constant at their mean values. It is less
helpful when being used to compare the effect of various factors on the output.

One-At-A-Time (OAT) is one of the experiment designs of the local sensitivity
analysis (LSA). Simplest class of screening designs; it uses nominal or standard values
per factor often obtained from the literature. Two extreme values are usually used for
the range of likely values of each factor. The mean value of the factor which is usually calculated or found in the literature is midway between the two extremes. A comparison is then made between the magnitudes of the differences between the outputs for the extreme inputs and the mean or standard value to find the factors that impact the most the model results (Satelli et al., 2002).

Daniel (1973) classified the OAT designs into five categories:

1. Standard OAT designs that vary one factor from the standard value
2. Strict OAT designs that one factor from the standard value of the preceding experiment
3. Paired OAT designs that produce two observations and hence one simple comparison at a time
4. Free OAT designs that make each new run under new conditions
5. Curved OAT designs that produce a subset of results by varying only one-easy-to-vary factor

Global sensitivity analysis (GSA)

Global sensitivity analysis is studies how the variation in the output of a model can be apportioned to different sources of variation, quantitatively or qualitatively in the model inputs. Unlike LSA, Global Sensitivity Analysis methods estimate the effect of a factor while all other factors are varied simultaneously. This variation of the other factors accounts for interactions between variables without depending on the stipulation of a nominal point. It describes the probability distribution function that covers the factors ranges of existence by examining sensitivity with regard to the entire factor distributions.

Some of the global sensitivity analysis methods are the Morris Method, which is a screening method, the Fourier Analysis Sensitivity Test method and the Sobol method which are variance-based methods.
1. The Morris Method: The Morris method (Morris, 1991) tends to determine which factors may have negligible, linear and additive or non-linear or interact with other factors. The Morris experiment is composed of individually randomized one-factor-at-a-time experiments (Saltelli et al., 2004). The Morris method is considered as a global sensitivity method because it covers the entire space over which the factors can vary. Morris computes a number \( r \) of local measures at different points and averages these points. Morris is computationally more efficient than other methods of global sensitivity analysis since it requires few simulations and can be interpreted easily (Saltelli et al., 2005).

The entire domains of the factors are randomly sampled to obtain finite distributions of elementary effects (\( F_i \)). High influence of the factors on the output results in high mean of the distribution, whereas high standard deviation reveals there is either interaction within factors or a non-linear effect exists (Morris, 1991; Saltelli et al., 2004).

However, the Morris method cannot give a quantitative measure about the percentage of total output uncertainty caused by uncertainty of each parameter. The number of simulations (\( N \)) to perform in the Morris is obtained by multiplying the sampling size for search trajectory (\( r \)) to the number of factors (\( k \)) increased by one unit (\( r^*(k+1) \)).

2. Fourier Amplitude Sensitivity Test Method (FAST): This method has been developed for the uncertainty and sensitivity analysis (Cukier et al., 1973, 1975, 1978). It allows the estimation of the expected value and variance of the output variable and the contribution of the individual input factor to the variance (Saltelli et al., 2000).
The Fourier Amplitude Sensitivity Test Method (FAST) presents two types of computations. The first one is the classical FAST that computes the first-order indices which are numbers indicating the primary effects of the factors. The second one is the Extended FAST. It was proposed by Saltelli et al. (1999b) and measures the total effect of the factors. It adds up the impacts of each factor and their interactions. In Extended FAST, (Saltelli et al., 1999), the total effect is evaluated by search curve that scans the space of the input factors in such a way that each factor is explored with selected integer frequency.

The simulation in the FAST is obtained at of cost $M^*k$ runs, where $M$ is a number between 500 and 1000 and $k$ is the number of factors.

3. **The Sobol’ Method**: The Sobol’ method is usually used to obtain quantitative measures on how the uncertainty in model outputs can be apportioned to uncertainty in individual input variables (Saltelli et al., 2000). The main idea behind the Sobol’ approach is to decompose the function into summands of increasing dimensionality (Saltelli et al., 2000). The main difference between FAST and Sobol’s method is the approach by which the multidimensional integrals are calculated. Whereas Sobol’s method uses a Monte Carlo integration procedure, FAST uses a pattern search based on a sinusoidal function.

Sobol can provide all the orders of indices from first to total. The number of simulations ($N$) to perform in the Sobol’ is obtained by multiplying $M$ (a number between 500 and 1000) by the number of factors ($k$)

**Uncertainty Analysis in Hydrological Modeling**

While the sensitivity analysis tries to determine the change in model output values that induces by changes in model input values, the uncertainty analysis attempts to
describe the entire set of possible outcomes. An uncertainty analysis consists in randomly choosing input values resulting from model simulation to obtain statistical measures of the distributions of the outputs. It is useful to determine ranges of potential outputs of the system and probabilities associated with them. It also estimates the probability that the output will exceed a target value. In any uncertainty analysis some assumptions are made. Statistical distributions for the input values are considered to be correct and the model is assumed to good enough to describe the processes taking place in the system.

Morgan and Henrion (1992), Haan (2002), and Shirmohammadi et al. (2006) provide extensive review of uncertainty analysis methods applied to environmental models. First-Order-Approximation (FOA) (Morgan and Henrion, 1992) and the Monte Carlo Simulations (MCS) are two methods for generating the general probability distributions of the output variables of interest, which is the best method to quantify model uncertainty (Haan 2002). In the first method, the expected value of the output is obtained based on the variance and covariance of the input parameters and their local absolute sensitivity indices. The second method is carried out by performing three different steps: first, a random sampling of the multivariate input distribution is performed; second the model simulations are run with the sampled values to produce estimates of model output values; and finally a PDF is produced by combining these output values. The procedure requires lot of computations.
Figure 2-1. Hydrological response of a catchment (Musy, 2001)
Figure 2-2. Land Use and Hydrological response. From Sauchyn (s. d.).

Figure 2-3. Hydrological response of a catchment (Musy, 2001)
CHAPTER 3
WATERSHED PRESENTATION

Watershed Location

This study was carried out in one of the watersheds of the metropolitan area as presented in Figure 3-1. The River Grise basin is varied and complex basin for its geography and its land use. This basin presents an important interest and has been pointed out as one of the most vulnerable watersheds in the country. The inundation risk in this catchment is really important and has been aggravated by agricultural practices, land use and unplanned urbanization.

The study area presents three more or less different defined zones: a rural zone lies in the upper part of the catchment; the middle part of the basin is an urban area; and the downstream area has both urban and sub-urban areas which have been more and more densely populated for the last decades.

The region is represented by the River Grise basin. Located in the southeastern of Port-au-Prince, it is bordered to the south by the summit of the Massif de la Selle, to the west by the hills and Calabasse and Gelin, to the east by the hills Mare Réseau et Pays-Pourri, and to the north by the hills Dumay and Chacha (Georges, 2008). The watershed straddles six municipalities as indicated in Figure 3-2 which are, in the upper part, Kenscoff and Croix-des-Bouquets; in the middle, the Petion-Ville and Croix-des-Bouquets; and in the lower part, Tabarre, Cite Soleil, the biggest shantytown in the country, Delmas and Croix-des-Bouquets. The catchment covers an area of 392 km² and is itself part of another wider watershed, Cul-de-Sac.
Physical Characteristics of the Watershed

The multiple interactions that have occurred in the watershed over time influence its hydrological behavior. Occurring at the interface between the lithosphere and the atmosphere, these interactions can be geological, climatological and meteorological etc. Also they influence in many ways the geomorphologic factors, the soil characteristics and the vegetation particularities, and to some extent determining the hydrology of the catchment.

Hydrology and Hydrogeology

Several streams and springs are encountered in the River Grise catchment. However most of them are perennial. The main river is the so called River Grise (Figure 3-3). Its name is due to the nature of the pebbles found in its bed which are from arising basalt and limestone formations eroded in the upstream. It presents an average flow of 3.93 m$^3$/s (MARNDR/MOE 2000).

With a wide bed and a low average flow, the River Grise is generally passable with light vehicles or on foot most of the time. However, in rainy seasons, flooding of the River Grise is devastating for crops and surrounding habitats. Nevertheless the regime of the River Grise has seriously evolved over time due to deforestation. In dry periods, the flow decreases significantly while devastating floods are becoming more frequent in rainy seasons. It is alimented by various ravines that drain the foothills of the Massif de La Selle. A network of ravines drains rainwater from the southern part of the watershed. These ravines flow, for some, into the River Grise (Figure 3-4). For the others on the contrary, the water is scattered in residential areas and roads due to lack of continuity in this natural system to the nearby river.
The River Grise represents an important source of recharge for the aquifer of Cul-de-Sac which is the main source of fresh water for the metropolitan area. Groundwater is typically found in layers of sand and gravel with a thickness of 1 to 8 meters separated by layers of silt and clay (Knowles et al., 1999).

**Climatology**

Depending on whether it is the lowland or the mountain, the climate of the Grise River catchment varies. In Port-au-Prince, the annual rainfall averages 1300 mm while it is around 946 mm in Croix-des-Bouquets. However, the climate is rather humid in the upstream part of the catchment. Windward and mountainous, the annual rainfall varies from 1450 mm in Petion-ville to 2000 mm in Kenscoff (Sergile, 1998; Holly, 1999).

Two rainy seasons are observed over the year in the study region: the first goes from April to May and the second, from September to November. Both rainy seasons are followed by a dry season (Holly, 1999).

**Geomorphology and Soils**

The geology of the region reflects the history of the island (MacFadden, 1986). In general, five major types of soil can be observed in the vicinity of Port-au-Prince. From oldest to later, there are massive limestone of the Eocene, sandy and marl limestone of Miocene, Pliocene sequence, basalts and Quaternary deposits. However, two types of geological materials are more likely to be observed: The Eocene limestone which is mainly karst forms the mountains that limit the plain of Cul-de-Sac and constitutes 51 % of the geology of the River Grise basin (Projet Interuniversitaire Ciblé, 2008). Generally they are white with a content of calcium carbonate that often exceeds 90% (Figure 3-5); Basalts (volcanic) rocks which count for 35% and the deposit materials for the remaining (AgroConsult, 2009).
Alternating beds of gray marl and limestone give the formation of the Grise River. The thickness of the formation is variable but is estimated to several hundred meters in average (Projet Interuniversitaire Ciblé, 2008).

This catchment rather presents a mountainous configuration. In the upstream, the altitude varies from 200 m to 2250 m with very steep slope as up to 60%. According to CNICS, 60% of the area has a slope higher than 35% while less than 20% has a slope between 0 % and 12 % as indicated in the Table 3-1.

Soils in the River Grise basin are a mosaic on the historical geology of the bedrock and terrain originated from basalt, limestone and alluvium (Georges, 2008). The Harmonized World Soil Database (HWSD) which is the soil database of the FAO presents the properties of the soils encountered within the watershed. Cambisol is predominant with a predominant texture of clay loam both in the topsoil and the subsoil. The depth of the soil is an approximate of 1.25m.

Richard et al. (2004), Lalonde et al. (1977) and HWSD found approximately the same classes of soil ranked in the Table 3-2.

**Vegetation and Land Use**

The vegetation varies with the difference existing in the topography of the basin from mountain to lowland ecosystems as indicated in the Figure 3-6. The flora is very diverse: Pine forest, hardwood forest, dry forests, humid forest of lowland etc. (Swartley et al., 2006). This watershed had presented one of the most interesting vegetation of the Caribbean region in terms of botany (Ekman 1926, Judd 1987, Holdridge 1947). However, the deforestation’s effect has affected significantly the vegetation.

Agriculture remains the main use of the land of the Grise River catchment. About 42 % of the land is allocated to agriculture which can be observed almost everywhere.
on the catchment. Savannah zones and pastures occupy respectively about 30 % and 15 % of the catchment. More or less dense forests account for 8 %.

Table 3-1. Slope classification in the watershed

<table>
<thead>
<tr>
<th>Class (%)</th>
<th>Area km²</th>
<th>Percentage of the catchment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-12</td>
<td>75.78</td>
<td>19.29</td>
</tr>
<tr>
<td>12-25</td>
<td>50.55</td>
<td>12.86</td>
</tr>
<tr>
<td>25-35</td>
<td>26.25</td>
<td>6.68</td>
</tr>
<tr>
<td>&gt; 35</td>
<td>240.35</td>
<td>61.17</td>
</tr>
<tr>
<td>Total</td>
<td>392.93</td>
<td>100.00</td>
</tr>
</tbody>
</table>

Source: CNIGS
Table 3-2. Soil properties in the catchment based on ASCE (American Society of Civil Engineers)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Texture class</th>
<th>Total porosity $\phi$ (cm$^3$/cm$^3$)</th>
<th>Residual water content $\theta$ (cm$^3$/cm$^3$)</th>
<th>Effective porosity $\phi_e$ (cm$^3$/cm$^3$)</th>
<th>Bubbling pressure $\psi_b$</th>
<th>Pore size distribution $\lambda$</th>
<th>Water etained at -33 kPa (cm$^3$/cm$^3$)</th>
<th>Water retained at 1500 kPa (cm$^3$/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-28</td>
<td>clay</td>
<td>$\mu$ 0.475 $\delta$ 0.048 $\mu$ 0.09 $\delta$ 0.075 $\mu$ 0.385 $\delta$ 0.116 37.3 22.51 $\mu$ 0.165 $\delta$ 0.128 0.396 $\mu$ 0.07 $\delta$ 0.272 0.064</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28-64</td>
<td>Clay loam</td>
<td>$\mu$ 0.464 $\delta$ 0.055 $\mu$ 0.075 $\delta$ 0.051 $\mu$ 0.39 $\delta$ 0.111 25.89 20.09 $\mu$ 0.242 $\delta$ 0.192 0.318 $\mu$ 0.068 $\delta$ 0.197 0.082</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>64-125</td>
<td>Sandy clay loam</td>
<td>$\mu$ 0.398 $\delta$ 0.066 $\mu$ 0.068 $\delta$ 0.067 $\mu$ 0.33 $\delta$ 0.095 28.08 29.87 $\mu$ 0.319 $\delta$ 0.24 0.255 $\mu$ 0.069 $\delta$ 0.148 0.063</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\mu$: average value  
$\delta$: standard deviation
Table 3-3. Saturated Hydraulic Conductivity classified by USDA Soil Texture (Rawls, 1998)

<table>
<thead>
<tr>
<th>USDA Soil Class</th>
<th>Texture</th>
<th>Saturated Hydraulic conductivity $^1$ (k0) (in/hr)</th>
<th>Range saturated Hydraulic Conductivity $^2$ (k0) (in/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>Sand</td>
<td>5.3</td>
<td>10.3 - 3.6</td>
</tr>
<tr>
<td>Fine</td>
<td>Fine Sand</td>
<td>4.8</td>
<td>8.7 - 4.2</td>
</tr>
<tr>
<td>Loamy</td>
<td>Fine Sand</td>
<td>2.6</td>
<td>5.6 - 1.4</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>Fine Loam</td>
<td>2.3</td>
<td>4.8 - 1.4</td>
</tr>
<tr>
<td>Sandy</td>
<td>Loam Sand</td>
<td>0.9</td>
<td>2.7 - 0.4</td>
</tr>
<tr>
<td>Fine loam</td>
<td>Sandy Loam</td>
<td>0.5</td>
<td>1.1 - 0.2</td>
</tr>
<tr>
<td>Loam</td>
<td>Loam Silt</td>
<td>0.2</td>
<td>0.8 - 0.11</td>
</tr>
<tr>
<td>Silt</td>
<td>Loam Clay</td>
<td>0.3</td>
<td>0.9 - 0.14</td>
</tr>
<tr>
<td>Sandy Loam</td>
<td>Clay</td>
<td>0.14</td>
<td>0.6 - 0.04</td>
</tr>
<tr>
<td>Clay</td>
<td>Loam Silty</td>
<td>0.05</td>
<td>0.28 - 0.01</td>
</tr>
<tr>
<td>Silty clay</td>
<td>Loam Sandy</td>
<td>0.17</td>
<td>0.5 - 0.09</td>
</tr>
<tr>
<td>Sandy</td>
<td>Clay</td>
<td>0.04</td>
<td>0.12 - 0.01</td>
</tr>
<tr>
<td>Silty clay</td>
<td>Clay</td>
<td>0.06</td>
<td>0.28 - 0.02</td>
</tr>
<tr>
<td>Clay</td>
<td></td>
<td>0.07</td>
<td>0.027 - 0.03</td>
</tr>
</tbody>
</table>

$^1$ Geometric mean value from k0 database

$^2$ 25% and 75% percentile values from k0 database
Figure 3-1. Grise River catchment location
Figure 3-2. Towns overlapped by the catchment
Figure 3-3. Grise River in dry season view
Figure 3-4. Hydrographic network
Figure 3-5. River Grise left bank
Figure 3-6. Grise River catchment land use
CHAPTER 4
MODEL PRESENTATION

Model Scope

First developed in 1979 by Beven and Kirkby, TOPMODEL is a semi-distributed model in which the predominant factors affecting the watershed response to precipitation are derived from the topography of the catchment and the soil transmissivity. The topography influences many aspects of the hydrologic system. It defines the movement of water in the watershed under the effect of gravity (Wolock and Price, 1994).

Divided into grid cells, the topography of the catchment is represented by means of a topographic-soil index, \( \ln \left( \frac{\alpha}{T_0 \tan \beta} \right) \), where \( \alpha \) is the area draining through the grid square per unit length of contour; \( T_0 \) is the transmissivity of the soil, \( \beta \) is the local gradient of ground surface and \( \tan \beta \) is the average outflow gradient from the square. When the spatial variability of the soil transmissivity is neglected, the index becomes the topographic index \( \ln \left( \frac{\alpha}{\tan \beta} \right) \) (Quinn et al., 1991). The topographic index reflects the spatial distribution of the soil moisture, surface saturation and runoff generation process (Zang and Montgomery, 1994). It assigns the same index to every point hydrologically similar. It is computed using topographic data such as DEM (Data Elevation Model). TOPMODEL allows at most thirty (30) discrete increments of the index. The transmissivity is computed as function of a saturated hydraulic conductivity which decreases exponentially with the depth.

The surface runoff computation in TOPMODEL includes both saturation excess and infiltration excess runoff (Montesinos-Barrios and Beven, 2004) using the variable source area concept of stream flow based on the topographic Index.
TOPMODEL is also considered as a physically based model (Beven and Kirby, 1979, Beven et al., 1984). Its parameters can be derived based on physical laws. Some parameters can also be measured in situ.

**Basic TOPMODEL Equations**

Total flow computed by TOPMODEL in the contributing area concept is measured as the sum of the saturation overland flow and the subsurface flow. It is expressed in the Equation (4-1).

\[ q_{\text{total}} = q_{\text{overland}} + q_{\text{subsurface}} \]  

(4-1)

Where \( q_{\text{total}} \) [L/T] is the total flow per unit area, \( q_{\text{overland}} \) [L/T] is the saturation overland flow per unit area, \( q_{\text{subsurface}} \) [L/T] the subsurface flow per unit area. Saturation overland flow is estimated as the sum of direct rainfall on the saturated areas and return flow as defined by the Equation (4-2).

\[ q_{\text{overland}} = q_{\text{direct}} + q_{\text{return}} \]  

(4-2)

Where \( q_{\text{direct}} \) [L/T] is direct precipitation on saturated areas, and \( q_{\text{return}} \) is return flow.

In TOPMODEL, the volume of water entering the soil is equivalent to the quantity of water leaving this particular column of soil (steady-state conditions). Also, it is assumed that the water table is recharged at a spatially uniform rate (R). The model derives expressions to compute the flows at some location \( x \) by using the Darcy’s Law and the continuity Equation (4-3):

\[ A_x R = T_x \tan \beta_x C_x \]  

(4-3)

where \( \tan \beta_x \) is the hydraulic gradient at \( x \), \( A_x \) [L^2] is the area upslope from \( x \) that drains past the location, \( T_x \) [L^2/T] is the transmissivity of the saturated thickness at the location \( x \), and \( C_x \) [L] is the contour width at \( x \) traversed by subsurface flow.
Beven and Kirkby (1979) assume that soil transmissivity at the saturated thickness $x$ is a function of the hydraulic conductivity, which decreases exponentially with depth. The soil surface is generally permeable because aggregations create flow pathways. Mathematically, the diminution of the transmissivity with depth is written as in the Equation (4.4).

$$T_x = \frac{K_0}{f} \left( e^{-f z_{wt}} \right)$$

(4-4)

Where $z_{wt}$ is the depth to the water table and $K_0$ the hydraulic conductivity at the soil surface and $f$ is the decay parameter for the decrease of hydraulic conductivity with depth.

By substituting $T_x$ in equation (4-3) and dividing by $C_x$, $z_{wt}$ is integrated to obtaining the average depth to the water table as expressed in the Equation (4-5).

$$z_{wt}(x) = z_{wt} + \frac{1}{f} \left( \lambda - \ln \left( \frac{a}{T_0 \tan B} \right) \right)_x$$

(4-5)

Then $\lambda$, $a_x$ and $T_0$ are respectively obtained in the Equations (4-6), (4-7) and (4-8)

$$\lambda = \frac{1}{A} \int \ln \left( \frac{a}{T_0 \tan B} \right)_x dA$$

(4-6)

$$a_x = \frac{C_x}{A_x}$$

(4-7)

$$T_0 = \frac{K_0}{f}$$

(4-8)

TOPMODEL's equations can be usually expressed in terms of saturation deficit ($S$) which is the product of the depth to the water table and readily drained soil porosity ($\theta$). By multiplying the Equation (4-5) by $\theta$ we obtain the Equation (4-9):

$$S_x = S + m(\lambda - \ln \left( \frac{a}{T_0 \tan B} \right)_x$$

(4-9)

And $m$ is obtained in the Equation (4-10)
Equation 4-9 states that the saturation deficit at any location $x$ is determined by the watershed average saturation deficit ($S$) and the difference between the mean of the $\lambda$ and the value of $\ln\left(\frac{a}{T_0 \tan B}\right)$.

The location $x$ in the watershed where $S_x \leq 0$ is considered as saturated and can generate saturation overland flow; any location where $S_x < 0$ produces return flow. The value of $q_{direct}$ is obtained by adding the products of the saturated areas $a_x$ by the precipitation intensity, $i$, and dividing by the watershed area, $A$, as presented in the Equation (4-11).

$$q_{direct} = \frac{\sum a_x i}{A} \quad \text{(4-11)}$$

Where $S_x \leq 0$.

The value of $q_{return}$ is computed by summing the products of the saturated areas and the absolute value of their saturation deficits which are negative, divided by the total area as indicated in the Equation (4-12):

$$q_{return} = \frac{\sum a_x |S_x|}{A} \quad \text{(4-12)}$$

Where $S_x < 0$.

Subsurface flow, $q_{subsurface}$, is computed by combining Darcy’s Law for saturated subsurface flux ($q_x$), (the right-hand side of equation 4-3 divided by $C_x$) with equation 4-4, the expression for transmissivity of the saturated thickness, along the derived values of $z_{wl}$ and $m$ to obtain the Equation (4-13):

$$q_x = (T_0 \tan B)_x e^{-\frac{S_x}{m}} \quad \text{(4-13)}$$
By integrating the previous equation along the length of all stream channels we obtain the Equation (4-14).

$$q_{\text{subsurface}} = \int L\left(T_0 \tan \beta\right) \frac{e^{-S_m}}{A} \, dL$$ (4-14)

**Assumptions**

The structure of the TOPMODEL is underpinned by some basic assumptions:

Steady-state is assumed to estimate the dynamics of the saturated zone

1. The hydraulic gradient of the saturated zone can be estimated by the local surface topographic slope, $\tan \beta$; and groundwater table and saturated flow are parallel to the local surface slope.
2. The transmissivity decreases with depth as an exponential function of storage deficit or depth to the water table.
3. Hydraulic similarity is assigned to the grid cells with the same topographic index.

**Differences of TOPMODEL’s Versions**

Initiated by Professor Mike Kirkby at the School of Geography at the University of Leeds in 1974, TOPMODEL has been varied in different versions with varying levels of complexity. Some versions of TOPMODEL compute snowmelt and snow-accumulation (Wolock and others, 1989) whereas others do not (Wood and others, 1988). All the different versions of TOPMODEL do not include all the concepts of streamflow generation. For example, while some computes both infiltration excess overland flow and the variable-source-area of streamflow generation (Wolock, 1993), evapotranspiration estimation can vary from one version to another. Evapotranspiration is estimated in some versions based on empirical computations whereas others use physically based methods to compute evapotranspiration (Famiglietti, 1992).
It is also noticeable that the level of spatial complexity and aggregation of the input and processes simulation differ from among the versions of TOPMODEL.

**Model Applicability**

TOPMODEL was first generated for the simulation of humid catchments in the United Kingdom (Beven and Kirkby, 1979; Beven et al., 1984, Quinn and Beven, 1993), in the eastern part of the United States of America (Beven and Wood, 1983, Homberger et al., 1985) and Scotland (Robson et al., 1993). The model has performed well for flow rates simulations and spatially distribution of saturations.

However, for the last decades several attempts have been made to simulate the hydrological responses of catchments located under more or less dry conditions. TOPMODEL was successfully applied to forecast flood in various Southern France catchments according to Durand et al., (1992), Sempere-Torres (1990) and Wedling (1992). TOPMODEL has also given good results for its applications to some Spanish basins (Piñol et al., 1997).

However, according to Seibert et al. (1997), TOPMODEL is not capable of producing the correct dynamics for groundwater, and consequently its ability to simulate runoff in shallow watersheds is reduced. In fact, the assumptions of spatial uniform recharge and steady flow rates are too simple. Measurements in different catchments showed that groundwater responses to storms can present wide spatial variations.

**Model Inputs**

Discharge and spatial soil water saturation pattern are simulated in TOPMODEL based on hydrological data time series and topographic information. The R implementation of TOPMODEL which is used in this study requires observed rainfall, potential evapotranspiration and the catchment topographic index map (Buytaert et al.,

53
The Topographic Index is generated from the Data Elevation Model (DEM) using such tools as GIS or other specific programs released with TOPMODEL.

However, in order to calibrate the simulation TOPMODEL observed discharge is also needed.

**TOPMODEL Parameters**

The quantity of parameters required to run TOPMODEL depends on the version of the model that is being used. All of the TOPMODEL versions use at least five parameters. Some versions however have up to twelve parameters.

The following are the parameters usually used in TOPMODEL and also the ones that are used in the R implementation:

1. **m**: Also named scaling parameter, it controls the decrease of transmissivity with depth and the shape of the hydrograph recession. Kinner and Stallard (1999) observed that 63% of the transmissivity is within 1m and 86% is within 2m. It has a length unit [L]

2. **Sr_{Max}**: is the maximum moisture deficit in the root-zone. It physically occurs when the canopy is dry and the soil is the wilting point. It has a length unit [L]

3. **td**: Unsaturated zone time delay per unit storage deficit. When water is added to the root-zone, the deficit decreases until zero, and then water is added to the unsaturated zone becoming unsaturated zone storage. It has a length unit [T/L]

4. **Sr**: initial root zone deficit. When it is null, evapotranspiration occurs at potential rates. It has a length unit [L]

5. **LnTe**: is the natural logarithm of the effective transmissivity of the soil. Its unit is [L^2/T].

6. **vch**: channel flow outside the catchment [m/h]
7. ks: Surface hydraulic conductivity [m/h]

Surface hydraulic conductivity (K0) [L] is an important parameter of TOPMODEL. It describes the rate at which water can move through a porous medium under a hydraulic gradient. It is a function of both the medium and the fluid properties. It reaches its maximum when the soil is saturated and decreases with decreasing water content or when the tension of the water increases.

8. CD: capillary drive, see Morel-Seytoux and Khanji (1974) [m]

9. vr : channel flow inside catchment [m/h]

10. dt : The time step [hours]

11. qs0: is the Initial subsurface flow

Some parameters of TOPMODEL such as ln(α/tanβ) or ln (α/T0tanβ) can be derived from the DEM of the watershed. However, for most of the parameters, it is always difficult to determine precisely their value. Calibration techniques are necessary to adequately quantify the parameters.

Beven (1997) has presented a review of the values that were used in TOPMODEL simulation.

**TOPMODEL Parameters Sensitivity**

Although initially designed to simulate the hydrological responses of catchments in humid areas based on the variable contributing area concept, TOPMODEL has been frequently modified to enlarge its application range (Pilar and Beven, 2004). Thus, many versions of TOPMODEL have been used to simulate hydrological watershed responses. Also, the Sensitivity analysis of the TOPMODEL parameters has been studied in many studies and for many versions of the model.
Fedak (1999) used the Windows 97 version of TOPMODEL which contains only five (5) parameters to simulate the hydrological behavior the Back Creek subwatershed of the Upper Roanoke River Watershed in southwest Virginia which is an urbanizing watershed currently dominated by forest and pasture. He found that by increasing the grid cell size from 15 to 120 meters, the watershed mean of the topographic index increases. However, hydrographs generated by TOPMODEL were not affected by this increase in the topographic index. The sensitivity analysis of the parameters reveals that the parameters that had the greatest effect on hydrographs generated by TOPMODEL were the m and lnTe parameters. Parameters such as the unsaturated zone time delay per unit storage deficit (td) and channel velocity are not sensitive.

Campling et al. (2002) used TOPMODEL to simulate the River Ebonyi headwater catchment (379 km2) which is humid catchment and is located on the western border of the Cross River Plains. He found that the most sensitive parameter was the m parameter. The transmissivity decay parameter (m) supports the observation that subsurface flow and local storage deficits are important contributors to the hydrological response of the catchment (Campling et al., 2002).

Arnbikadevi (2004) used TOPMODEL in Stillwater watershed and the model was sensitive towards the scaling parameter that controls the decrease of transmissivity with depth (m), the maximum moisture deficit in the root-zone (Srmax), the unsaturated zone time delay per unit storage deficit (td), the natural logarithm of the effective transmissivity of the soil (lnTe). Nourani et al. (2011) found that the sensitivity analysis indicates that m and lnTe parameters, which refer to the soil moisture condition, have the most effect on the results of rainfall-runoff simulation in the Ammameh watershed.
The study was conducted at different time scales using different terrain algorithms. The channel velocity was also sensitive in some extent.

In sum the parameters $m$, $\ln Te$, $t_d$, $S_{r_{\text{MAX}}}$, and $S_{r0}$, $v_r$ are the ones that have been usually found sensitive in watershed simulation were TOPMODEL has been used.

**Topographic Index**

Topography is usually considered as one of the most important factors that control the areal distribution of saturation in the soils, which in turn constitutes a key to understanding much of the variability in soils and the hydrological processes. The topographic index (TI) which is derived from the DEM has become a widely used tool to describe wetness conditions at the catchment scale Grabs et al. (2009), Beven. (1979).

The Topographic index represents the propensity of any point of the catchment to become saturated and to act as a source area that contributes surface runoff to the outlet. All points with the same value of the index are assumed to respond in a hydrologically similar way. High index values will tend to saturate first and will therefore indicate potential subsurface or surface contributing areas. High values of the topographic index are observed on shallow slopes. These locations represent high contributing areas. According to Trevor et al. (2005), low values occur on steep slopes resulting in small contribution of these areas in the in Runoff at the outlet. The Figure 4-1 shows a good relation between the topography, the topographic index and the soil moisture.

**Output of TOPMODEL**

The main output generated in TOPMODEL is the streamflow. However, any hydrological process can be simulated. Also, each version can present the output in a different way. The easiest versions are interface interactive.
The R implementation of TOPMODEL does not contain all these previous options. However, it can be coupled with GLUE which a statistical method for quantifying the uncertainty of the model predictions.

Figure 4-1. The relation between topography, topographic index and soil moisture deficit
CHAPTER 5
METHODOLOGY

Sensitivity Analysis

Limitations that related to model structures, data availability on parameter values, initial and boundary conditions will make hydrologic model application difficult. Uncertainties that have entered the model can substantially influence the output. There is always need to adjust model parameters for a better fit by calibration. However, the parameter calibration process would be more efficient if it was concentrated on the parameters that most influence the outputs of the model simulation. Also, measured dataset is required to perform the calibration process (Wallach et al., 2006; Beven 2008).

In this study, a Local sensitivity analysis (OAT Method) and two global sensitivity analyses (Morris Method and Fourier Amplitude Sensitivity Test Method) were performed to understand the parameters that most influence the output of the model.

Sensitivity Analysis Process

There is a four-step general procedure for performing global sensitivity analysis that are the determination of probability distribution functions (PDFs) of input parameters, the generation of input samples, the computation of the computation of the model output for each scenario and the analysis of the output distribution (Wallach et al., 2006)

Determination of Probability Distribution Functions (PDFs) of Input Parameters

TOPMODEL uses several parameters that reflect the hydrology, soils, and location of the catchment under investigation. Although TOPMODEL is a physically based model, only some parameters such as ln(α/tanβ) or ln (α/T₀tanβ) can be easily derived
from available information from the watershed characteristics. Even in the best experimental conditions, it is always difficult to determine precisely all the required data. Since natural systems such as soils are not homogeneous, and due to lack of measurement, it is difficult to assign specific values to some parameters which spatially vary in the catchment (Montesinos-Barrios and Beven, 2004; Wolock, 1993)

R-TOPMODEL is an implementation of TOPMODEL. It is based on the 1995 FORTRAN version by Keith Beven (Buytaert, 2011). Eleven parameters that are surface hydraulic conductivity ($k_s$), the areal average of transmissivity ($lnTe$), scaling parameter ($m$), capillary drive (CD), initial subsurface flow ($qs0$), initial root zone deficit ($Sr0$), maximum root zone storage deficit ($Sr_{Max}$), unsaturated zone time delay ($td$), channel flow inside the catchment ($vr$) and channel flow outside the catchment ($vch$) are used the R-TOPMODEL.

The selection of hydraulic conductivity technique is based on the level of information available on physical and hydraulic properties of the soil (Maidment, 1993). Using the soils parameters from the USDA classification, the saturated hydraulic conductivity was calculated by the generalized Kozeny-Carman equation expressed in the Equation (5-1).

$$k_s = B \theta_e^n$$  \hspace{1cm} (5-1)

Where $\phi_e$ is the effective porosity, $n$ is set equal to 4 and $B$ equals 1058; $k_s$ has units of cm/hr.

Calculated values obtained for the first layer (clay layer) using the Equation (5-1) were considered as the values of the surface hydraulic conductivity. It presents a uniform distribution between a minimum and a maximum values. The distribution of the
ks was expected to be lognormal. However there is no evidence that can support lognormal distribution in the Kozeny-Carman equation (Appendix D).

The parameter \( \ln \text{Te} \) \([L^2/T]\) is the log of the areal average of \( T_0 \). The transmissivity represents the integral over soil depth of hydraulic conductivity. The transmissivity is obtained by the Equation (5-2).

\[
T_0 = \frac{k_1}{f_1} e^{-f_1 z_1} + \frac{k_2}{f_2} e^{-f_2 z_2} + \frac{k_3}{f_3} e^{-f_3 z_3}
\]  \hspace{1cm} (5-2)

Where \( k \) is the hydraulic conductivity, \( f \) is the scaling parameter that controls the decrease of the hydraulic conductivity with depth and \( z \) is the thickness of each layer.

The parameter \( f \) is obtained by plotting the hydraulic conductivity of each layer. Three values of hydraulic conductivity were obtained for each layer of the soil: a lower value, an average value and an upper value. As indicated in Figure 5-1, three curves of variation of the hydraulic conductivity were plotted. From these plots result three values for the \( f \) parameter. The exponential factor governing the decrease of the hydraulic conductivity is the \( f \) parameter.

The parameter \( \ln \text{Te} \) is then obtained by taking the areal average of natural logarithm of \( T_0 \) which is the sum of the transmissivity of the layers. No particular trend of distribution was found for \( T_0 \). A maximum value and a minimum value were calculated for the parameter. A uniform distribution was also assumed for \( \ln \text{Te} \).

The parameter \( m \) \([L]\) is the model parameter that controls the rate of decline of transmissivity in the soil profile. It is usually derived from an analysis of the recession’s curves for the catchment when the assumption that the flow is derived from subsurface drainage is made. It is usually derived from a pure recession in which recharge is
considered negligible. Thus, discharge has an inverse or first order hyperbolic relationship to time. (Beven, 2001).

In this study, the scaling parameter could not be derived from recession curve. Long-term recession was not observed for the river discharge provided by the Early Warning Project dataset. Pure recession in which recharge can be considered being negligible shows that the flow presents an inverse or first-order hyperbolic relationship to time as expressed in the Equation (5-3) (Beven, 2001).

\[
\frac{1}{Q_b} = \frac{1}{Q_0} + \frac{t}{m}
\]  
(5-3)
The plot of $1/Q_b$ should be as a straight line with slope $1/m$ as shown in Figure 5-2.

For the Grise River basin, even weekly recessions were difficult to be found. Few recession curves resulting from the Early Warning Project dataset seem to provide unrealistic values for the parameter $m$. From previous study (Beven et al., 1997) $m$ cannot obviously be extremely high as determined in the Figure 5-3 and Figure 5-3.

According to David (1993) the parameter $m$ is calculated from the Equation (4-10). Likewise as a function of $\theta$ a normal distribution was found for the parameter $m$ indicating a mean and a standard of an average $\phi$ is obtained for the soil by the Equation (5-4).

\[
\phi = \frac{z_1\phi_1 + z_2\phi_2 + z_3\phi_3}{z_1 + z_2 + z_3}
\]  
(5-4)
where $z_i$ and $\phi_i$ are the thickness and the porosity of their respective layers.

$S_{r_{\text{Max}}}$ [L] is computed as:

\[
S_{r_{\text{Max}}} = z_{\text{root}}(\theta_{f_c} - \theta_{w})
\]  
(5-5)
Where \( z_{\text{root}} \) is the root-zone depth, \( \theta_{\text{fc}} \) is the field capacity and \( \theta_{\text{w}} \) is the wilting point of the soil. The Table 3-2 presents the field capacity and wilting point based on the ASCE classification (Rawls et al., 1983). \( S_{\text{rMAX}} \) for the entire soil was calculated by the Equation 5-6 based on the characteristics of the soil in the Table 3-3.

\[
S_{\text{rMAX}} = z_1 \theta_1 + z_2 \theta_2 + z_3 \theta_3
\]

(5-6)

\( \theta \) is the difference between \( \theta_{\text{fc}} \) and \( \theta_{\text{w}} \). \( S_{\text{rMAX}} \) presents a normal distribution as a function of \( \theta_\text{s} \) which present normal distributions (Maidment et al., 1993).

The parameter \( S_{r0} \) [L] is initial root zone storage deficit. When the gravity drainage layer is exhausted, soil moisture will still evaporate with the rate of \( E_p \) as indicated in the Equation 5-7. The rate of evapotranspiration loss \( E \) is assumed be proportional to a specified potential rate \( E_p \).

\[
E = E_p + (1 - \frac{S_{r0}}{S_{\text{rMAX}}})
\]

(5-7)

The initial root zone storage deficit varies in a certain range of \( S_{\text{rMAX}} \). In this study \( S_{r0} \) was kept constant. It has been demonstrated that likewise \( q_{s0} \), \( S_{r0} \) influences the flow process only in the beginning of model simulation. For a long simulation over 5 years of 3 hours' time step, its influence will be insignificant.

\( CD \) [L] is the capillary drive. It is a function of the capillary suction which is the combined adhesive forces that join the water molecules and the solid particles Morel-Seytoux and Khanji (1974), (Bedient et al., and 2008). The capillary drive is found in the Green Ampt infiltration method and is referred to as expressed in the Equation (5-8).

\[
CD = \Psi b \frac{2 + 3\lambda}{1 + 3\lambda}
\]

(5-8)
Where $\Psi_b$ is the bubbling pressure and $\lambda$ is the pore-size distribution index (Parlange et al., 1982).

According to Rawls et al. (1983), $\Psi_b$ and $\lambda$ are lognormally distributed. They provided the arithmetic and geometric mean values with the corresponding standard deviations for both parameters, for different texture class.

Based on the parameters’ statistics obtained from Rawls et al. (1983), Hantush and Khalin (2003) used the KINEROS2 which is event and physically based runoff and erosion model to calculate the arithmetic means and standard deviations of capillary drive for different soil textures by performing Monte Carlo (MC) simulations.

The Table 5-1 presents the arithmetic mean and standard deviations of the Capillary Drive for different soil textures obtained from the lognormal approximation and by performing 10000 Monte Carlo simulations, using the statistics of the lognormally distributed $\psi_b$ and $\lambda$ (Rawls et al., 1982).

Based on the Table 5-1 provided by Hantush and Khalin for different classes of soil, the combined capillary drive for the entire soil was calculated as stated in the Equation 5-9.

$$CD = \frac{z_1 CD_1 + z_2 CD_2 + z_3 CD_3}{z_1 + z_2 + z_3} \quad (5-9)$$

Where $z_i$ and $CD_i$ are the thickness and the capillary drive of their respective layers.

The channel velocity is also one of the most important parameter of R-TOPMODEL (Parsons et al., 2004). In this study, $vr$ [L/T] was calculated using the Manning equation. Water level data (Stage) generated by the Early Warming Project that has installed some instruments on the watershed was used.
Based on the information provided by Figure 5-5 and Figure 5-6, a rectangular shape was adopted for the channel (Figure 5-7), where \(b\) is the bed width and \(y\) is the stage at the measurement time. The water level gauge is installed on the bridge which has vertical abutments, made of masonry. The Manning coefficient for natural bed is estimated within the range 0.030- 0.035 by Chow (1959).

The location of the water level gauge was found within a range of slope of 0.8% to 1.08 % by processing the DEM in ARCGIS and the width of the bed \((b)\) is estimated using Google Earth at 45m. Calculated for different values of the ranges, the velocities were then obtained as indicated in the Manning Equation as stated in the Equation (5-10)

\[
vr = \frac{1}{n} \times R^{\frac{2}{3}} \times S^{\frac{1}{2}}
\]

(5-10)

Where \(n\) is the Manning coefficient, \(R [L]\) the hydraulic radius and \(S\) is the slope of the bed.

The velocities were plotted. A normal distribution was obtained for the velocity since the histogram has revealed a very normal distribution for the parameter with skewness null as showed in the Figure 5-8. The mean is 7651.56 m/h with a standard deviation of 719.44.

The parameter \(qs0 [L]\) is initial subsurface flow per unit area. It is usually assumed as the first measured flow. The minimum water level measured around the bridge of Croix des Missions from August 2011 to June 2012 was 0.27m and was considered as \(qs0\).

The parameter \(td\) is the unsaturated zone time delay per unit storage deficit. It controls the rate that recharge is added to the saturated zone per unit saturation deficit.
The parameter can be calculated as the quotient of the soil depth and the hydraulic conductivity (Ambikadevi, 2004) as expressed in the Equation (5-11).

\[ td = \frac{z_1}{k_1} + \frac{z_2}{k_2} + \frac{z_3}{k_3} \]  

(5-11)

where \( z_i \) and \( k_i \) are the thickness and the hydraulic conductivity of their respective layers, with \( i \) varying from 1 to 3.

The parameter \( dt \) is the time step. It corresponds to the increment in time of the data series. The time step is 3 hours since rainfall and potential evapotranspiration data were available at this time step.

**Generation of Input Factor Samples**

The local sensitivity analysis (OAT) was performed for ±10, ±20, ±50, ±100 ±150 of initial values of the parameters as presented in the Table 5-3. In some cases the range was infeasible or unrealistic.

In the GSA, based on PDFs and the choice of SA method, the number of samples plays an important role. R-TOPMODEL requires eleven parameters to perform. However, all of them are not equally important for the model output. In study, some parameters such as Initial subsurface flow per unit area (qs0), the channel flow outside the catchment (vch), the time step (dt), the unsaturated root-zone deficit (Sr0) were kept unchanged as indicated in the Table 5-1.

Simlab generated automatically the sampling of the parameters that were chosen for the sensitivity analysis. Two methods which are the Morris method and the extended FAST (Fourier Analysis Sensitivity Test) method were selected to conduct the sensitivity analysis (SA). Parameters were chosen to be uniformly, normally or lognormally distributed based on the literature or the calculation processes.
The Morris Method is well known as a screening method for environmental models. It is an easy method that requires few simulations with easily interpretable results (Saltelli et al., 2005). The number of simulations (N) to perform in the Morris analysis results as indicated in the Equation (5.12).

\[ N = r (k + 1) \]  

where \( r \) is the sampling size for search trajectory (\( r = 10 \) produces satisfactory results), and \( k \) is the number of factors.

The extended FAST method uses the replicated Latin hypercube sampling to randomly sample the \( k \)-dimensional space of the input parameters (r-LHS) design (McKay et al., 1979; McKay 1995). The number of simulations required in this analysis is expressed in the Equation (5.13).

\[ N = M \times k \]  

where \( m \) is a number between 500 and 1000. In this study \( M \) was chosen as 1000.

**Computation of the Model Output for Each Scenario**

Once the samples have been generated, the corresponding model output values were computed. Codes written in R presented in the Appendix A and appendix B were used to simulate the outputs.

Since TOPMODEL is quite simple, the running process is not really intensive. A few minutes were enough for the simulation. The output values generated from this process were formatted for the analysis in Simlab which was used for the global sensitivity analysis.
Analysis of the Output Distribution

For the OAT method, the analyses were carried out for specific values such as minimum, median, maximum and total streamflow. A slope was constructed between for the variation of the values. The bigger slope indicates the greater change.

For the Global Sensitivity analyses, outputs obtained from the model runs were stored in the desired SimLab post-processing format to run the statistical analysis that generates sensitivity indices and parameter rankings. SimLab analyzed the data and calculate sensitivity indexes of the Morris and the extended FAST methods.

In the Morris Method, the characterization the distribution of $F_i$ through its mean $\mu$ and standard deviation ($\sigma$) presents meaningful information about the $i$th factor on the output. A factor with a high mean presents a significant overall influence on the output; a high standard deviation indicates either a factor interacting with other factors or factor whose effect is nonlinear (Saltelli, et al., 2004).

In the FAST Method, the expected value and the variance of the output are estimated. The contribution of individual factor to the variance of the output is also estimated (Cukier et al., 1973). Two types of indices are generated: the first order indices (Classical FAST) which measure the main effect of factors. The second ones are the Total Sensitivity Indices (TSI) in the Extended FAST. The TSI of a parameter is the sum of all the sensitivity indices involving this parameter. They compute the total effect of the factors. The extended Fast analysis adds up the impacts of each factor and their interactions with other factors. Usually, When the TSI is greater than 0.8 the parameter is considered as very important; between 0.5 and 0.8 it is said to be important; when it is between 0.5 and 0.3 the parameter is not important; below 0.3 the parameter is said to be irrelevant (Sobol et al., 1990a, 1990b, 1993, Chan et al., 1997).
Excel was used to construct the output probability distributions such as Cumulative Distribution Frequency (CDF) and histograms.

**Data Elevation Model (DEM)**

The DEM is one of the most important data used by TOPMDEL. The DEM used in this study was obtained from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM). Land surfaces between 83°N and 83°S are encompassed by the ASTER GDEM. It is composed of 22,600 1°-by-1° tiles. Tiles that contain at least 0.01% land area are included. The ASTER GDEM is in GeoTIFF format with geographic latitude and longitude coordinates and a 1 arc-second (30 m) grid of elevation postings. It is referenced to the WGS84/EGM96 geoid. Estimated accuracies for this global product were 20 meters at 95 % confidence for vertical data and 30 meters at 95 % confidence for horizontal data before the production.

**Topographic Index**

The obtained DEM was processed using ArcGIS 10 (Arc Map 10) to delineate the Grise River watershed. After the extraction of the watershed using watershed delineation tools available in the (Arc Map 10), the output raster format is transformed into a text file format (ASCII) which can be used by the R-TOPMODEL version. Pixels outside the catchment area are given a distinct value that is set to NA in R. The -9999 value was set as the NA. The DEM was imported as a matrix which can then be processed by the topidx () function in R-TOPMODEL to obtain the Topographic index required by TOPMODEL.
Data

Data used to conduct the research was downloaded from the North American Regional Reanalysis (NARR) model. The NARR model is produced by the National Centers for Environmental Prediction (NCEP) and takes in, or assimilates a great amount of observational data to produce a long-term picture of weather over North America. A Matlab code (see Appendix A) was written to download 3-hrs precipitation and potential evapotranspiration over 1998 to 2002.

However, in comparison to monthly and annual totals available in the literature, NARR has overestimated the rainfall and potential evapotranspiration. To correct the data, monthly values are calculated for the NARR dataset. The dataset was compared to FAO monthly data. NARR data was also twice the average available in the literature. A factor of correction was calculated and applied to the NARR dataset. This factor was 0.55.

Soil information in this study is provided by Harmonized World Soil Database (HWSD) which is an initiative of Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA) to combine recently collected data of soil information with the information already contained within the FAO-UNESCO Digital Soil Map of the World.

Model Run

The version of TOPMODEL used to perform the hydrological simulation of the River Grise basin is the 97 version built in R. This implementation of TOPMODEL was performed by Buytaert et al., (2005). Codes written in R (see appendix A and B) provided in this package were modified to perform the processes encompassed in this
research. For the global sensitivity analysis, sampling are generated as stated before using SimLab

Table 5-1. Summary statistics of CD (cm) parameter for various soil types

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>Arithmetic</th>
<th>Geometric</th>
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<tr>
<td></td>
<td>Mean</td>
<td>Std</td>
</tr>
<tr>
<td></td>
<td>theo.</td>
<td>MC</td>
</tr>
<tr>
<td>Sand</td>
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<td>40</td>
</tr>
<tr>
<td>Loamy sand</td>
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<td>44</td>
</tr>
<tr>
<td>Sandy Loam</td>
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<td>62</td>
</tr>
<tr>
<td>Loam</td>
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<td>112</td>
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<tr>
<td>Silt loam</td>
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<td>156</td>
</tr>
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<td>Sandy clay loam</td>
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<td>180</td>
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<tr>
<td>Clay loam</td>
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<td>129</td>
</tr>
<tr>
<td>Silty clay loam</td>
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</tr>
<tr>
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<tr>
<td>Silty clay</td>
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<tr>
<td>Clay</td>
<td>242</td>
<td>232</td>
</tr>
</tbody>
</table>

From: Mohamed M. Hantush and Latif Kalin (2003)
Std: standard deviation   theo: theoretical    MC: Monte Carlo
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Parameters values for Simulation and Global sensitivity analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
</tr>
<tr>
<td>qs0 : Initial subsurface flow per unit area [m]</td>
<td>0.27</td>
</tr>
<tr>
<td>LnTe : log of the areal average of T0 [m2/h]</td>
<td>-1.85</td>
</tr>
<tr>
<td>m : Model parameter [m]</td>
<td>0.450</td>
</tr>
<tr>
<td>Sr0 : Initial root zone storage deficit [m]</td>
<td>0.01</td>
</tr>
<tr>
<td>SrMax : Maximum root zone storage deficit [m]</td>
<td>0.449</td>
</tr>
<tr>
<td>td : Unsaturated zone time delay per unit storage deficit [h/m]</td>
<td>0.43</td>
</tr>
<tr>
<td>vch* : channel flow outside the catchment [m/h]</td>
<td>4500</td>
</tr>
<tr>
<td>vr : channel flow inside catchment [m/h]</td>
<td>7651.56</td>
</tr>
<tr>
<td>k0 : Surface hydraulic conductivity [m/h]</td>
<td>0.055</td>
</tr>
<tr>
<td>CD : capillary drive, see Morel-Seytoux and Khanji (1974) [m]</td>
<td>0.48</td>
</tr>
<tr>
<td>dt : The time step [hours]</td>
<td>3</td>
</tr>
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</table>

Min: Minimum value
Max: Maximum value
Stdev: Standard deviation
*This parameter is not really used in TOPMODEL
Table 5-3. TOPMODEL parameters and their values for LSA

<table>
<thead>
<tr>
<th>Parameters</th>
<th>-300%</th>
<th>-200%</th>
<th>-100%</th>
<th>-50%</th>
<th>-20%</th>
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<th>10%</th>
<th>20%</th>
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<th>100%</th>
<th>200%</th>
<th>300%</th>
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<tr>
<td>qs0 [m]</td>
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<td>0.27</td>
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<tr>
<td>LnTe [m²/h]</td>
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<td>-0.305</td>
<td>-0.488</td>
<td>-0.549</td>
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<td>-0.915</td>
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<td>-1.83</td>
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<tr>
<td>m [m]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.225</td>
<td>0.36</td>
<td>0.405</td>
<td>0.45</td>
<td>0.495</td>
<td>0.54</td>
<td>0.675</td>
<td>0.9</td>
<td>1.35</td>
<td>1.8</td>
</tr>
<tr>
<td>Sr0 [m]</td>
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</tr>
<tr>
<td>SrMax [m]</td>
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<td>-</td>
<td>0</td>
<td>0.2245</td>
<td>0.3592</td>
<td>0.4041</td>
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<td>0.6735</td>
<td>0.898</td>
<td>1.347</td>
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<td>td [h/m]</td>
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<td>-</td>
<td>-</td>
<td>0</td>
<td>1.5</td>
<td>2.4</td>
<td>2.7</td>
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<td>4.5</td>
<td>6</td>
<td>9</td>
</tr>
<tr>
<td>vch [m/h]</td>
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<td>4500</td>
</tr>
<tr>
<td>vr [m/h]</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>6121.2</td>
<td>6886.4</td>
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<td>11477</td>
<td>15303</td>
<td>22955</td>
<td>30606</td>
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<tr>
<td>k0 [m/h]</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0</td>
<td>0.25</td>
<td>0.4</td>
<td>0.45</td>
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<td>-</td>
<td>-</td>
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<td>0.24</td>
<td>0.384</td>
<td>0.432</td>
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<td>0.576</td>
<td>0.72</td>
<td>0.96</td>
<td>1.44</td>
</tr>
<tr>
<td>dt [h]</td>
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<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
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</tbody>
</table>

Spaces mark “-” are unrealistic or unfeasible values
Variation of the hydraulic conductivity with depth

Figure 5-1. Decrease of the hydraulic conductivity with average depth
Figure 5-2. Derivation of an estimate of parameter m using recession curve analysis under exponential transmissivity profile assumption (Beven, 2001)

Figure 5-3. Recession curve for the third week of December, 2011
Figure 5-4. Recession curve for the first two weeks of January, 2012

Figure 5-5. Bridge of Croix des Missions in dry seasons
Figure 5-6. Bridge of Croix des Missions in rainy seasons

Figure 5-7. Shape of the channel at the stages gauge
Figure 5-8. Distribution of the channel velocity inside the catchment
CHAPTER 6
RESULTS AND DISCUSSIONS

Model Justification for the Watershed

The climate of the watershed where TOPMODEL is being applied varies whether it is the lowland or the mountain. In the lowland, the rainfall varies form 1300 mm to around 1000mm. while the climate is rather humid in the upstream with the annual rainfall varying from 1450 mm in Petionville to 2000 mm in Kenscoff. The depth to water is usually between 5 and 50 m. In the mountains, depth to water is usually higher than 100 m. Seasonal fluctuation in the water levels can be great (Knowles et al., 1999).

Also Haiti is a data-sparse region. Too demanding model in parameter cannot be applied there since it is difficult to find necessary data for parameters calculation.

As a result, the topographic and climate conditions of the watershed are not necessarily the best but are more or less suitable for the application of TOPMODEL. Also, since TOPMODEL does not require too many parameters compared to usual hydrological models, it was a convenient choice to use TOPMODEL.

DEM of the Catchment

The Figure 6.1 a represents the DEM of the River Grise catchment resulted from ArcGIS processing. This processed DEM was used in the R-TOPMODEL package to derive the Topographic Index. However, only the upstream part of this DEM contributes as drainage area.

The Figure 6-2 represents the hydrological cumulative area map. Located in the upper part of the watershed, only this area seems to contribute water based on the direction of the flow computed using the DEM. While the real watershed area is 393km², approximately only 290 km² was able to be processed by R-TOPMODEL using the
DEM. The determined outlet is different from the natural outlet observed on the real catchment.

However, it is important to notify that the flow computational process of this R-TOPMODEL version is based on multiple and single flow which is different from the algorithm used in ArcGIS. We also know that the lower part of this catchment is a flat area.

**Topographic Index Results**

The Figure 6-3 presents the areal distribution of the Topographic Index in the River Grise watershed. The areal average of the topographic index is 12.588 with the highest Topographic Index approximately 22. However, 93 percent of the surface of the catchment delineated by TOPMODEL has a topographic index lower than the average. As presented in the Figure 4-1, the soil moisture deficit index in inversely proportional to the topographic index. Since the soil moisture deficit indicates when runoff starts for each grid cell, locations with low topographic index are more likely to generate runoff.

The areal distribution of the topographic index reveals that the topographic index is lognormally distributed and skewed to the right in this catchment. More than 80 % of the watershed has a topographic index lower than 8. This catchment varies in altitude from approximately 50m to 2000m and presents steep slopes which indicate that this soil can easily become dry. However, due to steep slopes that prevail in this catchment surface runoff can be very important. Depressions can be almost inexistent to stock water while infiltration can be expected to be low.
Sensitivity Analysis

The following paragraphs present the sensitivity analysis results. The sensitivity analyses were realized for the 5 years of data. Both LSA (OAT) and GSA (Morris and FAST methods) results are presented below.

Local Sensitivity Analysis (OAT)

Model sensitivity was performed for ±10, ±20, ±25, ±50, ±75 ±100 ±150 of initial values of the parameters as presented in the Table 5-3. Model sensitivity is reported as the percent difference of model results as compared to the base simulation.

The Figure 6-4 presents the influence of the parameters on the minimum flows as depicted by the Local Sensitivity Analysis (LSA). The parameter m presents the most important influence. The parameters lnTe, SrMax and Ks are also showed important. The slope showed by the parameters indicates their level of influence on the output. The parameter m presents the largest slope within the range of variation, which is within the range obtained from the calculations. Also, the increase of the parameter m increases the minimum flows. However the increases of the SrMax and lnTe decrease the minimum flows.

Local Sensitivity Analysis (LSA) for the median flows is showed on the Figure 6-5. Within the range calculated from the watershed characteristics, the parameter SrMax is the most important since its slope is larger for the range of distribution of the parameters. When the parameters SrMax and m increase, the median flows decrease.

The Figure 6-6 presents the influence of the parameters on the average flows. The parameter SrMax presents the most important influence for the range of variation considered for the calculations of the parameters. Its slope is the steepest. Other parameters such as hydraulic conductivity (ks) and the decay factor the decrease of the
transmissivity with depth ($m$) are also important as showed on the Figure 6-6. Average runoff decreases also with the increase of the soil moisture deficit. The same trend is observed for the parameters $m$ and $ks$.

The Figure 6-7 presents the influence of the parameters on the maximum flows as depicted by the Local Sensitivity Analysis (LSA). The channel velocity is clearly the most important parameter influencing the runoff. It remains dominant in all range of variation. Maximum runoff increases with the increase of the channel velocity until it becomes stable.

The Figure 6-8 presents the influence of the parameters on the Total flows for the Local Sensitivity Analysis (LSA). Likewise for the average flows, $Sr_{Max}$ presents the most important influence for the common range of variation considered for the calculations of the parameters.

The LSA method reveal that the most important parameters are the transmissivity ($lnTe$), the scaling parameter of the decline of transmissivity ($m$), Maximum root zone storage deficit ($Sr_{Max}$) the hydraulic conductivity ($ks$) the channel velocity inside the catchment ($vr$). Their sensitivity varies with the type of flows.

The scaling parameter of the decline of transmissivity ($m$), Maximum root zone storage deficit ($Sr_{Max}$) the hydraulic conductivity ($ks$) seem to have a constant influence on almost all type of the flow output whether it is low or high flow.

**Global Sensitivity Analysis**

The following paragraphs present the Morris and the FAST sensitivity analyses. Due to the similarity between the results of the analyses for average flows and total flows, only the analyses for the total flows are presented.
Morris sensitivity analysis

The relative importance of the TOPMODEL parameters on the output based on the Morris Method is presented in the Table 6-1. Eighty (80) hydrographs were generated for the Sensitivity Analysis. Minimum, Maximum, Mean, Median and Total were calculated and were used for the sensitivity analysis.

The graphs 6-9 to 6-13 plot the indexes of sensitivity of each parameter on the minimum, maximum, mean, median, and the total flows. $\mu^*$ represents the total influence of the factor which the sum of the primary and the interactions while the standard deviation ($\sigma$) represents the interactions themselves. While presenting more information showing the impact of interactions within the parameters, the Morris method confirms the results revealed by the OAT analysis.

The Figure 6-9 plots the Global sensitivity analysis results or the minimum flows obtained from the Morris screening method. As indicated on the graph, the areal logarithm of transmissivity (lnTe), the decay factor ($m$), the moisture deficit ($Sr_{Max}$), and the hydraulic conductivity ($k_s$) are the most sensitive parameters for the minimum flows. However, the transmissivity decay seems to affect the most the minimum flows followed by the transmissivity. Not only are they important by their total influence but also they primarily impact since they are located below the angle 45 degree (Morris, 1991). Hydraulic conductivity and the moisture deficit seem to have a greater contribution through interactions. While the impact of the channel velocity and the unsaturated zone time delay being null on the minimum flows, the capillary drive seems to have a small impact with equal primary and interactions contributions.
The impact of the parameters on the median (Q0.50) flows is presented on the Figure 6-10. The parameters such as the areal logarithm of transmissivity (lnTe), the decay factor (m), the moisture deficit (SrMax), the hydraulic conductivity (ks) and the channel velocity are the ones that influence the output. However, the soil moisture deficit parameter has the greatest influence according to the results obtained from the Morris screening method. The hydraulic conductivity and areal logarithm of the transmissivity seem contribute equally by the primary and their interactions whereas the deficit moisture has a higher influence through his primary effect while the channel velocity presents higher influence by interactions. Parameters such as Capillary Drive and unsaturated zone time delay for per unit storage deficit don’t influence the output.

The Figure 6-11 presents the GSA results for the average flows obtained by the Morris method. Three (3) parameters that are the soil moisture deficit (SrMax), the decay factor of the transmissivity with depth (m) and the hydraulic conductivity (ks) show important effect on the flows. The moisture deficit presents the greatest influence. It also has the greatest primary effect. The scaling parameter for the decline of the transmissivity in the soil seems to contribute equally by interactions and by its primary impact. It seems to be located on the bisectrix of the origin angle. The hydraulic conductivity seems to contribute more by its interactions. The other parameters present no effect on the average flows.

The Figure 6-12 plots the Global sensitivity analysis results the maximum flows obtained from the Morris screening method. All the parameters but the unsaturated zone time delay per unit storage deficit seem to be detached from the origin, and consequently have an influence on the output. The channel velocity presents a more
important influence on the maximum flows whereas the other parameters seem to have small influence. It is also remarkable that all they parameters have a greater primary effect but the channel velocity that seems to contribute equally by its primary effect and by its interactions.

As indicated on the Figure 6-13 that presents the Global sensitivity analysis results or the Total flows obtained from the Morris screening method, only three parameters have an important effect on the total flows: the moisture deficit which presents the greater influence has also a greater primary effect, the scaling parameter for the decline of the transmissivity in the soil seems to contributes equally by interactions and by its primary impact, and the hydraulic conductivity that contributes more by its interactions.

The pattern showed by the Total flow is the same as the one observed for the average flows Parameters such as the logarithm of the areal transmissivity, the Capillary Drive, the channel velocity, and the unsaturated zone time delay for storage deficit present no effect on the total flows.

The plots of the Screening Method results of the sensitivity indexes of the parameters reveal the parameters are not all neither equally sensitive. Only five (5) of them such as the transmissivity (\(\ln Te\)), the scaling parameter of the decline of transmissivity \((m)\), Maximum root zone storage deficit \((S_{r\,Max})\) the hydraulic conductivity \((k_s)\) the channel velocity inside the catchment \((v_r)\) seem to influence the runoff simulation of R-TOPMODEL. Also their influence seems to vary whether the flows are low or high.

The Morris analysis reveals that the scaling parameter of the decline of transmissivity \((m)\), Maximum root zone storage deficit \((S_{r\,Max})\) the hydraulic conductivity
(ks) seem to constantly influence the flow output whether it is low or high flow. This is illustrated in the Figures 6-9 to 6-13.

However, the channel velocity inside the catchment (vr) seems to have significant influence on the median (Q0.50) and the maximum flows. Parameters such as unsaturated zone time delay per unit storage deficit (td) and capillary drive (CD) seem to have no influence on the output.

**FAST sensitivity analysis**

The process used for the Morris Method was duplicated for the FAST Method analysis. The relative importance of the TOPMODEL parameters on the output based on the FAST Method is presented in the Table 6-2 and Table 6-3. Seven thousands (7000) simulations were generated for the Sensitivity Analysis. Minimum, maximum, mean and median and total hydrographs were calculated and were used for the sensitivity analysis.

Two categories of plots are presented. First, the sensitivity indexes of the first order which indicate the impacts of the parameters without interactions; Second, the level of influence of the parameters through interactions. The interactions are obtained by subtracting the first order indices from the total order indices. The analyses were performed using the minimum, median, mean, maximum, and total flows.

The Figure 6-14, Figure 6-15 and Figure 6-16 plot the Global sensitivity Test results obtained from the Fourier Amplitude Sensitivity Test method. According to the plots the scaling parameter for the transmissivity (m) the areal logarithm of transmissivity (lnTe), the maximum storage deficit (SrMax), and the hydraulic conductivity (ks) are the most sensitive parameters for the minimum flows. However, the scaling parameter of the transmissivity affects the most the minimum flows and remains the
important one based on the Sobol’s classification (Sobol et al., 1993), since it is the only one to present a total index higher than 0.5 (Figure 6-14). As indicated by the Figure 6-15, the primary effects of the parameters such as channel velocity, the capillary drive and the unsaturated zone time delay of the storage deficit are null. It is also noticeable that interactions have low impacts on the minimum flows as confirmed by the Figure 6-16.

The impacts of the parameters on the median (Q0.50) flows are presented on the Figure 6-14 and Figure 6-15. According to the Figure 6-14 the maximum storage deficit ($S_{\text{rMax}}$) controls the median flows. While $S_{\text{rMax}}$ is responsible for approximately 65% all the remaining parameters show indexes lower than 5%. All the parameters seem to influence the median flows (Q0.50) laying within the range of 10% to 20%. However, according to the Sobol’s classification, only $S_{\text{rMax}}$ is very important while the others are irrelevant.

Based on the GSA results obtained from the FAST method depicted on the Figure 6-14 the maximum moisture deficit parameter is the most important factor influencing primarily the average flows. It is responsible for approximately 85% followed insignificantly by the scaling parameter for the decline of the transmissivity with depth ($m$), and the hydraulic conductivity ($k_s$) that are responsible for less than 10%. Also, the interaction effects are very low on the average flows; as a result some parameters such as the unsaturated zone time delay for moisture deficit ($t_d$), the channel velocity ($v_r$) and capillary drive ($C_D$) appear to be negligible. Likewise the OAT and the Morris analyses, The FAST analysis of the average flows presents the same pattern as the total flows.
The Global Sensitivity Analysis obtained from the FAST method for the first order indexes shows that only the channel velocity has a very significant impact on the maximum flows as presented that the Figure 6-15. It is responsible for 40%; all the other parameters appear to be negligible. However, the Figure 6-16 which presents the FAST results of the interactions seems to show that all the parameters have significant influence on the maximum flows in the River Grise watershed. They vary from 30% to 50%.

However based on the Sobol’s classification related in Chapter 5, only parameters with total sensitivity index (TSI) higher than 0.3 would be considered as important. In this case, only three (3) parameters would remain important that are the decay parameter for the transmissivity decrease with depth \((m)\), the soil moisture deficit \((Sr_{\text{Max}})\) and the channel velocity \((vr)\) would be important for this study.

The Fourier Amplitude Sensitivity Test method used for the sensitivity analysis strengthens and quantifies the results revealed by the Morris method. The sensitivity varies with the parameters and with low and high flows. The transmissivity \((\ln Te)\), the scaling parameter of the decline of transmissivity \((m)\), maximum root zone storage deficit \((Sr_{\text{Max}})\), the hydraulic conductivity \((k_s)\) and the channel velocity inside the catchment \((vr)\) are the parameters that have influenced the hydrologic response of the catchment. The scaling parameter of the decline of transmissivity \((m)\), maximum root zone storage deficit \((Sr_{\text{Max}})\), and the hydraulic conductivity \((k_s)\) seem to remain constantly the most sensitive. However, only important \(m\), \(vr\) and \(Sr_{\text{Max}}\) appear to be important or very important based on the type of flows while the other parameters are whether not important or irrelevant based on the type of flows.
Parameters such as the unsaturated zone time delay per unit storage deficit (td) and capillary drive (CD) seem to be present more through interactions.

**Discussions of the Parameters Impacts**

**The $m$ parameter**

The $m$ parameter is the model parameter that controls the rate of decline of transmissivity in the soil profile (Beven, 1984). The simulation of the River Grise basin by TOPMODEL reveals that the $m$ parameter is very sensitive for both Global and Local Sensitivity Analyses. It appears to be the most sensitive for the minimum flows with which it varies proportionally. According to the Figure 6-4, in the range of variation of the decay parameter of the transmissivity with soil depth ($m$) for the watershed as presented in the Table 5-2, when the parameter increases the minimum flows increases and vice versa. However the parameter $m$ is inversely to the other flows. When it decreases the average flows, the median flows, the maximum flows and the total increase and vice versa.

As a parameter related to recession flow in the watershed, it seems to be reasonable that $m$ be the most important parameter for minimum flows. It can be assumed that the methodology used for the calculation of the parameter is consistent with the nature of the parameters itself.

In term of management actions, the parameter $m$ can help in predicting the water lost by the aquifer or even expected in the downstream for others activities. In dry seasons, the river is alimented by the groundwater that consequently decreases. The recession curve can tell about the volume stored at any given time. Indeed, if $m$ is determined for a specific watershed, it is possible to evaluate its storage capacity by integration over the time interval. The determination of the water available in recession
time is important to evaluate the amount of water to provide in support to the low flow in dry seasons.

**The lnTe parameter**

The lnTe parameter is the natural logarithm of the effective transmissivity of the soil at saturation [m$^2$/h]. This parameter is also an important parameter as indicated by both sensitivity analysis methods. It appears to be more sensitive for the minimum flows likewise its scaling parameter m. It does not seem to be very sensitive for any other type of flows. It varies proportionally with the minimum flows. When it decreases the flows decrease and vice versa. However, likewise $m$, its variation is inversely proportional to the other flows. When the natural logarithm of the effective transmissivity of the soil at saturation decreases these flows increase and vice versa.

Likewise the parameter $m$, it is related to the recession (minimum flows) in the watershed. The transmissivity of the soil can tell about the ability of the soils in the watershed to stock water in rainy seasons and to release it during the dry seasons.

**The Sr$_{\text{Max}}$ parameter**

The Sr$_{\text{Max}}$ parameter is the maximum root zone storage deficit parameter in TOPMODEL. It controls the moisture deficit in the soil. It is the most sensitive parameter of TOPMODEL as revealed in this study. It appears to be important whether for minimum, average or high flows. As a continuous model, TOPMODEL accounts for the amount of moisture in the soil between rainfall events. According to the stage dataset, the watershed seems not to suffer from long term drought. Also, by nature, the moisture deficit is built to reflect any moisture situation in the watershed. It is more likely to be sensitive to any types of flows.
It is important to notice that the soil moisture deficit is inversely proportional with all types of flows. When the moisture deficit increases the flows decreases and vice versa. This is very important in term of management actions. By increasing the capacity of the soil to stock more water the amount of water to be released on rainfall event will necessarily decrease. The importance of vegetation in increasing the porosity of the soil is well known. Therefore a reforestation campaign can be a good action against flood occurrence in the watershed.

**The ks parameter**

The ks parameter is the surface hydraulic conductivity at saturation [m/h]. This parameter is also an important parameter as indicated by both sensitivity analysis methods. It is one the most widely sensitive parameters. It appears to be sensitive for all types of flows. It is well know that the hydraulic conductivity is very important parameter for the runoff generation in every hydrologic model since it describes the ease with which water moves through pore spaces.

The hydraulic conductivity presents a proportional relationship with the minimum flows for values between 0.25 and 1 m/h before starting to present no significant increase of the minimum flows. The relationship seems to level off after the hydraulic conductivity reaches 1m/h. It also seems to present a proportional relationship with the maximum flows but it is not significant. However the relationship seems to be inversely proportional to the other flows.

The hydraulic conductivity is Hydraulic conductivity is a property of the porous media. It depends on the pore size, its distribution, and its connectivity. Vegetation can help in fracturing the soil to create more pores. When the porosity of the soil increases the hydraulic conductivity will also increase.
The \( vr \) parameter

The \( vr \) parameter is the channel flow inside catchment [m/h]. The simulation of the River Grise basin by TOPMODEL reveals that the channel velocity is also sensitive for both Global and Local Sensitivity Analyses. It appears to be the most sensitive for the maximum flows. It does not seem to be too sensitive for other types of flows but maximum and median flows. This is the parameter of the effective surface routing velocity for the distance/area procedure. As linear routing is assumed in TOPMODEL, it is comprehensible that the parameter is more important for high flows.

The channel velocity presents proportional variation with the maximum flow. The other types of flows don’t show any significant variation with the variation of the channel velocity.

The parameters \( td \) and \( CD \)

The parameters \( td \) [h/m] and \( CD \) [m] that represent respectively the unsaturated zone time delay for root zone deficit and the capillary drive happen not to be really sensitive in the simulation of the River Grise catchment. They seem to have no primary effect on any flows. Their contributions appear only through interactions with other parameters. The situation of these parameters in this study happens not to be different from what that has been found in the literature.

These parameters did not show any significant variation with any type of flows. Indeed this was expeted because these parameters remain non important in these study and are usually revealed to be non important in the literature related to TOPMODEL application studies.
Discussions of the Sensitivity Analysis Results

The results obtained the three analysis methods seems not to be significantly different. They are even more similar for some specific output such as the minimum flows, the average flows and the total flows.

It seems that the interactions which are taken into account in the global sensitivity analysis (GSA) and neglected in the local sensitivity analysis (LSA) are really not important for almost all the outputs. When the interactions are important for the maximum flows for example, the parameters that have the most important primary effects are also the ones that have the most important interaction effects. As a result, their total sensitivity index remains the most important for both GSA and LSA methods.

FAST Uncertainties

Likewise the sensitivity analysis, simulation results provided by some selected outputs of the FAST analysis have been used to carry out uncertainty analyses. The uncertainty analysis determines the ranges of variation of the flows within the watershed. Analyses have been carried out for Minimum, Median, Mean, Maximum and Total and are presented on the Figures 6-17 to 6-21. Table 6-4 presents the uncertainty analysis statistics for the probability distributions of the selected results.

As indicated in the Table 6-4, the 95% confidence interval for the minimum flows lays within the 0.002 - 0.006 m³/3h. With an average flow of 0.004m³/3h, its cumulative distribution frequency, represented by the Figure 6-17, reveals that almost 95% of the flows are lower than 0.01m³/3h.

The median flows vary from 0.011 m³/3hto 0.253 m³/3h. The statistics are presented in the Table 6-4. The 95% confidence interval goes from 0.049 to 0.148
m³/3h with an average of 0.103 m³/3h. Approximately 85% of the flows are lower than 0.13 m³/3h as presented in the Figure 6-18.

The average flows vary from 0.333 m³/3h to 0.467 m³/3h with an average of 0.390 m³/3h. The 95% confidence interval lays within 0.357 m³/3h -0.427 m³/3h (Table 6-4). The distribution of frequency of the flows presents a normal distribution shape. However, the cumulative distribution frequency (CDF) reveals that more than 85 % of the flows is lower than 0.41 m³/3h. The average itself (0.389 m³/3h) is higher than more than 80 % of flows as indicated in the Figure 6-19.

The maximum flows represented by the Figure 6-20 present a very particular shape compare to rest of the flows. The 95% confidence interval varies within 6.403 m³/3h and 6.554 m³/3h. The range of variability is goes from 6.107 m³/3h to 6.569 m³/3h with an average of 6.538 m³/3h. The distribution of the frequency is very much skewed to the left. Most of the distribution of frequency represents approximately 10 % of the cumulative distribution function. The distribution seems to be lognormal as showed in the Figure 6-20.

The total for the 5 years under analysis presents a very normal distribution of the flows. The statistics are presented in the Table 6-4 and the Figure 6-21 presents the cumulative distribution of frequency and the density of the distribution. The flow range varies between 4866.803 m³/3h and 6810.111 m³/3h. The average flow is 5689.584 m³/3h which is not very different from the median flow. The 95 % confidence interval goes from 5208.013 m³/3h to 6817.795 m³/3h. Approximately 90% of the flow is cumulative distribution of the frequency curve (CDF) is lower than 5,966.44 m³/3h.
Table 6-1. Three (3) hours sensitivity Indexes for the Morris Analysis

<table>
<thead>
<tr>
<th>Morris Index</th>
<th>QMinimum Mu</th>
<th>Sigma</th>
<th>Q050 Mu</th>
<th>Sigma</th>
<th>QMean Mu</th>
<th>Sigma</th>
<th>QMaximum Mu</th>
<th>Sigma</th>
<th>QTotal Mu</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>lnTe</td>
<td>0.0023</td>
<td>0.0011</td>
<td>0.0032</td>
<td>0.0025</td>
<td>0.000559</td>
<td>0.0073</td>
<td>0.0055</td>
<td>8.0429</td>
<td>8.262</td>
<td></td>
</tr>
<tr>
<td>m</td>
<td>0.0026</td>
<td>0.000846</td>
<td>0.0151</td>
<td>0.006</td>
<td>0.0135</td>
<td>0.0037</td>
<td>0.0074</td>
<td>197.1407</td>
<td>54.4739</td>
<td></td>
</tr>
<tr>
<td>SrMax</td>
<td>0.0009</td>
<td>0.00093</td>
<td>0.0546</td>
<td>0.019</td>
<td>0.0507</td>
<td>0.0063</td>
<td>0.0044</td>
<td>0.0047</td>
<td>741.2635</td>
<td>91.6451</td>
</tr>
<tr>
<td>td</td>
<td>0</td>
<td>0</td>
<td>0.00008</td>
<td>0.00014</td>
<td>0.00002</td>
<td>6.32E-05</td>
<td>0.0004</td>
<td>0.000843</td>
<td>0.4047</td>
<td>0.9028</td>
</tr>
<tr>
<td>Vr</td>
<td>0</td>
<td>0</td>
<td>0.0228</td>
<td>0.0243</td>
<td>0</td>
<td>0.0202</td>
<td>0.0338</td>
<td>0.2154</td>
<td>0.0306</td>
<td></td>
</tr>
<tr>
<td>ks</td>
<td>0.0008</td>
<td>0.0009</td>
<td>0.0103</td>
<td>0.0088</td>
<td>0.0106</td>
<td>0.0082</td>
<td>0.0075</td>
<td>0.006</td>
<td>155.0077</td>
<td>119.45</td>
</tr>
<tr>
<td>CD</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0008</td>
<td>0.0007</td>
<td>0.0008</td>
<td>0.0004</td>
<td>0.0019</td>
<td>0.0027</td>
<td>11.575</td>
<td>6.5966</td>
</tr>
</tbody>
</table>

Mu: Mean    Sigma: Standard deviation    QMinimum: Minimum flows    QMean: Average flows    Q050: Median flows    QMaximum: Maximum flows    QTotal: Total flows
<table>
<thead>
<tr>
<th>Parameters</th>
<th>QMinimum</th>
<th>Q050</th>
<th>QMean</th>
<th>QMaximum</th>
<th>QTotal</th>
</tr>
</thead>
<tbody>
<tr>
<td>LnTe</td>
<td>0.2528</td>
<td>0.0022</td>
<td>7.61E-05</td>
<td>0.000363</td>
<td>7.45E-05</td>
</tr>
<tr>
<td>M</td>
<td>0.4748</td>
<td>0.0331</td>
<td>0.0587</td>
<td>0.000728</td>
<td>0.0587</td>
</tr>
<tr>
<td>SrMax</td>
<td>0.0833</td>
<td>0.6545</td>
<td>0.8474</td>
<td>0.0018</td>
<td>0.8474</td>
</tr>
<tr>
<td>Td</td>
<td>3.41E-05</td>
<td>5.98E-05</td>
<td>4.25E-05</td>
<td>0.000198</td>
<td>4.24E-05</td>
</tr>
<tr>
<td>Vr</td>
<td>9.66E-06</td>
<td>0.03</td>
<td>4.38E-05</td>
<td>0.4076</td>
<td>4.35E-05</td>
</tr>
<tr>
<td>K0</td>
<td>0.0578</td>
<td>0.0213</td>
<td>0.0311</td>
<td>0.0029</td>
<td>0.0311</td>
</tr>
<tr>
<td>CD</td>
<td>0.000317</td>
<td>0.000433</td>
<td>0.000445</td>
<td>0.000223</td>
<td>0.000444</td>
</tr>
</tbody>
</table>

QMinimum: Minimum flows  
QMean: Average flows  
Q050: Median flows  
QMaxinum: Maximum flows  
QTotal: Total flows

Table 6-2. Three (3) hours sensitivity Indexes for the FAST First-Order Analysis
Table 6-3. Three (3) hours sensitivity Indexes for the FAST Total-Order Analysis

<table>
<thead>
<tr>
<th>Parameters</th>
<th>QMinimum</th>
<th>Q050</th>
<th>QMean</th>
<th>QMaximum</th>
<th>QTotal</th>
</tr>
</thead>
<tbody>
<tr>
<td>LnTe</td>
<td>0.313557</td>
<td>0.116777</td>
<td>0.019069</td>
<td>0.311441</td>
<td>0.01905</td>
</tr>
<tr>
<td>m</td>
<td>0.53126</td>
<td>0.173188</td>
<td>0.078369</td>
<td>0.316737</td>
<td>0.078375</td>
</tr>
<tr>
<td>SrMax</td>
<td>0.12617</td>
<td>0.844516</td>
<td>0.911686</td>
<td>0.309478</td>
<td>0.911699</td>
</tr>
<tr>
<td>td</td>
<td>0.010351</td>
<td>0.120499</td>
<td>0.026736</td>
<td>0.299767</td>
<td>0.0267</td>
</tr>
<tr>
<td>vr</td>
<td>0.012245</td>
<td>0.221672</td>
<td>0.02812</td>
<td>0.920816</td>
<td>0.028131</td>
</tr>
<tr>
<td>K0</td>
<td>0.09388</td>
<td>0.179756</td>
<td>0.056358</td>
<td>0.43335</td>
<td>0.056325</td>
</tr>
<tr>
<td>CD</td>
<td>0.016355</td>
<td>0.16329</td>
<td>0.030488</td>
<td>0.424807</td>
<td>0.030478</td>
</tr>
</tbody>
</table>

| QMinimum: Minimum flows | QMean: Average flows | Q050: Median flows | QMaximum: Maximum flows | QTotal: Total flows |
Table 6-4. Uncertainty analysis statistics for probability distributions obtained from the FAST results

<table>
<thead>
<tr>
<th></th>
<th>Range</th>
<th>Mean</th>
<th>Min</th>
<th>Q2</th>
<th>95 %CI</th>
<th>Max</th>
<th>Kurtosis</th>
<th>Skew</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qminimum</td>
<td>0.008</td>
<td>0.004</td>
<td>0.000</td>
<td>0.004</td>
<td>0.002-0.006</td>
<td>0.008</td>
<td>0.236</td>
<td>0.280</td>
<td>0.001</td>
</tr>
<tr>
<td>Q0025</td>
<td>0.015</td>
<td>0.007</td>
<td>0.001</td>
<td>0.006</td>
<td>0.003-0.011</td>
<td>0.015</td>
<td>-0.194</td>
<td>0.532</td>
<td>0.002</td>
</tr>
<tr>
<td>Q025</td>
<td>0.024</td>
<td>0.011</td>
<td>0.003</td>
<td>0.010</td>
<td>0.005-0.020</td>
<td>0.027</td>
<td>-0.589</td>
<td>0.550</td>
<td>0.004</td>
</tr>
<tr>
<td>Q050</td>
<td>0.242</td>
<td>0.103</td>
<td>0.011</td>
<td>0.105</td>
<td>0.049-0.148</td>
<td>0.253</td>
<td>1.300</td>
<td>-0.064</td>
<td>0.025</td>
</tr>
<tr>
<td>Qmean</td>
<td>0.134</td>
<td>0.390</td>
<td>0.333</td>
<td>0.389</td>
<td>0.357-0.427</td>
<td>0.467</td>
<td>0.407</td>
<td>0.291</td>
<td>0.018</td>
</tr>
<tr>
<td>Q075</td>
<td>0.331</td>
<td>0.616</td>
<td>0.468</td>
<td>0.618</td>
<td>0.523-0.710</td>
<td>0.799</td>
<td>-0.236</td>
<td>-0.015</td>
<td>0.049</td>
</tr>
<tr>
<td>Q0975</td>
<td>0.353</td>
<td>1.836</td>
<td>1.650</td>
<td>1.832</td>
<td>1.754-1.932</td>
<td>2.003</td>
<td>0.133</td>
<td>0.201</td>
<td>0.046</td>
</tr>
<tr>
<td>Qmaximum</td>
<td>0.462</td>
<td>6.538</td>
<td>6.107</td>
<td>6.548</td>
<td>6.403-6.554</td>
<td>6.569</td>
<td>33.322</td>
<td>-5.401</td>
<td>0.041</td>
</tr>
<tr>
<td>Qtotal</td>
<td>1951</td>
<td>5690</td>
<td>4867</td>
<td>5678.6</td>
<td>5209.6-6236.5</td>
<td>6817.8</td>
<td>0.407</td>
<td>0.291</td>
<td>261.405</td>
</tr>
</tbody>
</table>

Range: Difference between Maximum flows and Minimum flows
Min: Minimum flows
Q2: Flows for 0.50 percentile
Mean: Average flows
Max: Maximum flows
Qtotal: Total flows
Figure 6-1. DEM of the River Grise catchment
Figure 6-2. Map of the area processed by R-TOPMODEL
Figure 6-3. Areal distribution of the Topographic Index
Figure 6-4. OAT sensitivity of the parameters for the minimum flows

Figure 6-5. OAT sensitivity of the parameters for the Median flows
Figure 6-6. OAT sensitivity of the parameters for the Average flows

Figure 6-7. OAT sensitivity of the parameters for the Maximum flows
One at a Time analysis of the total flows

Figure 6-8. OAT sensitivity of the parameters for the Total flows
Morris Analysis for minimum flows

Figure 6-9. Morris Sensitivity Index of the parameters for the minimum flows

Morris Analysis for median flows

Figure 6-10. Morris Sensitivity Index of the parameters for the Median flows
Morris analysis for average flows

Figure 6-11. Morris Sensitivity Index of the parameters for the Average flows

Morris analysis for maximum flows

Figure 6-12. Morris Sensitivity Index of the parameters for the maximum flows
Morris Analysis for total flows

Figure 6-13. Morris Sensitivity Index of the parameters for the Total flows
Figure 6-14. FAST Sensitivity for the Total order indexes of the parameters

Figure 6-15. FAST Sensitivity for the First order indexes of the parameters
Figure 6-16. FAST Sensitivity for the interactions of the parameters
Figure 6-17. Probability distribution of the minimum flows

Figure 6-18. Probability distribution of the median flows
Figure 6-19. Probability distribution of the average flows

Figure 6-20. Probability distribution of the maximum flows
Figure 6.21. Probability distribution of the total flows
CHAPTER 7
CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The implementation of TOPMODEL in R known as TOPMODEL package was applied to the flood-prone River Grise basin to simulate the hydrological response of the watershed and to determine the parameters of the model that can influence the most this response.

As TOPMODEL tends to compute the areas that have contributed water to the runoff process based on topographic index the downstream part of the catchment, which is a flat area, seems not to be considered as contributing area. As a result, while the total area of the watershed is about 393 km$^2$, only approximately 290 km$^2$ which constitutes the catchment delineated by TOPMODEL (outlet different from the natural outlet) was able to be processed in the hydrological simulation process. The topographic index from the natural outlet could not be determined.

In fact, the topographic index which determines the hydrological similarity of each part of the catchment is calculated as a function of the slope. Since estimating slopes in flat areas is a critical issue (Pan, et al., 2004), r.topidx seems to assign null values to the flat portion of the catchment.

In this study, the calculations and the Identification of parameters probability distributions based on field data were attempted. Some parameters were calculated as described in previous studies that have used TOPMODEL but, others such as the scaling parameter that controls the rate of decline of transmissivity in the soil profile was calculated by using soil data information from the literature.
Global and Local Sensitivity Analyses were performed in this study. The Local sensitivity Analysis (LSA) allows the quantification of the effect of each input on the overall output variance. It also indicates the range within the parameter can influence the output the most. The Global Sensitivity Analysis (GSA), mainly the FAST method, allows the separation of first-order versus total-order effects.

Both FAST and Morris methods that were used for the global sensitivity analysis showed that the sensitivity varies with flows type neither all the parameters are not sensitive. Only five (5) of them such as the transmissivity (lnTe), the scaling parameter of the decline of transmissivity (m), Maximum root zone storage deficit (SrMax) the hydraulic conductivity (ks) the channel velocity inside the catchment (vr) seem to influence the runoff simulation of R-TOPMODEL. Also their influence seems to vary whether the flows are low or high. Besides the hydraulic conductivity (ks), the moisture deficit parameter (SrMax), and the rate of decline of the transmissivity with depth (m) that seem to impact the hydrologic response of the catchment whether the flows are low average or high, the channel velocity (vr) seems to specially impact high flows with no impact on the total flows.

The sensitivity analyses results seem to confirm what other studies using TOPMODEL have already revealed. According to Montesinos-Barrios and Beven (2004), the model is very sensitive to the variations of the soil transmissivity decay parameter, the soil transmissivity at saturation, the root zone storage capacity and the channel routing velocity in large catchments. As demonstrated in this study, the transmissivity (lnTe), the scaling parameter of the decline of transmissivity (m), maximum root zone storage deficit (SrMax), the hydraulic conductivity (ks) are the most
sensitive parameters of TOPMODEL. The channel velocity inside the catchment \((vr)\), though less sensitive than the other previous parameters, is also sensitive for high flows. Parameters such as the unsaturated zone time delay per unit storage deficit \((td)\) and capillary drive \((CD)\) seem to have no influence on the output flow whatsoever. Is it also remarkable that not all versions of TOPMODEL use this parameter \((vr)\).

Morris is a qualitative screening method while FAST is a quantitative method that confirmed the results from Morris.

Besides the maximums flows, the uncertainty analysis is quite similar for the rest of the flows. They all present a relatively normal distribution sometimes skewed to the left.

According to the uncertainty analysis, minimum flows in the watershed is expected to be in the range of null to 0.008 \(m^3/3h\). This seems to relate the situation on the ground because the river has run out water in its lower part in some dry seasons and cannot reach the natural outlet.

The average flows vary from 0.333 \(m^3/3h\) to 0.467 \(m^3/3h\) with an average of 0.390 \(m^3/3h\). The 95 % confidence interval lays within 0.357 \(m^3/3h\) -0.427 \(m^3/3h\). However, the cumulative distribution frequency \((CDF)\) reveals that more than 85 % of the flows is lower than 0.41 \(m^3/3h\).

The maximum flows presented a very particular shape compare to rest of the flows. The 95% confidence interval varies within 6.403 \(m^3/3h\) and 6.554 \(m^3/3h\). The range of variability is goes from 6.107 \(m^3/3h\) to 6.569 \(m^3/3h\) with an average of 6.538 \(m^3/3h\). The distribution of the frequency is very much skewed to the left. Most of
the distribution of frequency represents approximately 10 % of the cumulative distribution function. The distribution seems to be lognormal.

It is important to notice that the hydraulic conductivity which is usually described as lognormally distributed was processed as uniformly distributed in this study. The equation of Kozeny-Carman has been used to determine the hydraulic conductivity. Unlike others parameters which calculations methods have clearly shown their distribution, no distribution pattern was observed for the hydraulic conductivity and was processed as uniformly distributed.

Also the importance of the parameters can tell about management actions needed to undertaken according to the management type that is pursuing. It was demonstrated that the soil moisture deficit is inversely proportional to the flows and should be increased in a perspective of flood control for example. The \( m \) parameter which is related to the recession curve is also very important in the watershed. The recession curve tells about the amount of water that can be released in dry seasons and consequently help in predicting the supporting amount of water to provide to satisfy the needs for downstream activities in dry seasons.

**Recommendations**

This study aimed at determining the hydrological behavior of the River Grise catchment using the implementation of the TOPMODEL in R. Attempts to define with precision parameters of the model using field data available in the literature have been made.

However, as presented in the results TOPMODEL seems to perform only for part of the catchment. The outlet processed by the model is different from the natural outlet; as a result a subcatchment representing the upstream of the watershed is delineated by
the model. This issue seems to be due to the flatness of the downstream of the watershed. In fact, the topographic index calculation using the DEM seems not to perform well in the flat area of the catchment. The quality of the DEM can also be considered.

The performance of the model cannot be measured because there is no measured flow data that is necessary to conduct the calibration and the validation which can confirm the effectiveness of the TOPMODEL application to model the River Grise basin. Besides the proper behavior of the parameters as revealed by their influence on the flows, it is important to collect field flow data to perform calibration. The calibration process will confirm the effectiveness of the TOPMODEL performance in the River Grise watershed.

It is also important to notice that in the perspective of flood occurrence, it would be important to analyze the stages in the watershed which this study did not consider.
APPENDIX A
MORRIS CODE IN R

setwd("C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel")
library(topmodel)
library(stinepack)
library(e1071)
library(Hmisc)
library(sensitivity)
library(zoo)
library(xlsReadWrite)
library(xts)
library(matrixStats)
DEM <- read.table("DEM2.txt")
DEM <- as.matrix(DEM)
DEM[DEM==9999] <- NA
library(lattice)
# levelplot(DEM)
# Fill sink0
DEM.filled <- sinkfill(DEM, res=30, degree=0.1)
DEM.filled <- sinkfill(DEM.filled, res=30, degree=0.1)
DEM.filled <- sinkfill(DEM.filled, res=30, degree=0.1)
DEM.filled <- sinkfill(DEM.filled, res=30, degree=0.1)
DEM.filled <- sinkfill(DEM.filled, res=30, degree=0.1)
DEM.filled <- sinkfill(DEM.filled, res=30, degree=0.1)
# View effect of filling sink0
difference <- DEM.filled - DEM
# Calculate Topographic Index
topindex <- topidx(DEM.filled, res=30)
# View atb
levelplot(topindex$atb)
# View area
levelplot(topindex$area)
topindex <- make.classes(topindex$atb, 16)
# Note in the area plot that the highest contributing area is approximately
# at row 381 and column 519 and not at 1,1. This is likely due to the lower
# portion of the basin being very flat with no "clear" flow direction to be
# found. In order to use the entire watershed, we may need to "burn" in the
# river.
# Calculate flow length and delay using the point with highest contributing
# area.
flowlength <- flowlength(DEM.filled, c(381,519)) * 30
flowlength <- hist(flowlength, 5)
delay <- data.frame(distance = flowlength$break0, area = c(0,flowlength$counts) / sum(flowlength$counts))
delay[,2] <- cumsum(delay[,2])

## DATA UPLOADING

### 3HRS DATA
hrsweather <- read.table("Data3hrs.txt", header=FALSE, sep="\t")
hrsrain <- hrsweather[,1]
hrsET0 <- hrsweather[,2]

### DAILY DATA
dailyweather <- read.table("Datadaily.txt", header=FALSE, sep="\t")
dailyrain <- dailyweather[,1]
dailyET0 <- dailyweather[,2]

### MONTHLY DATA
Monthweather <- read.table("Datamonth.txt", header=FALSE, sep="\t")
Monthrain <- Monthweather[,1]
MonthET0 <- Monthweather[,2]

### ANNUAL DATA
Anweather <- read.table("Datayear.txt", header=FALSE, sep="\t")
Anrain <- Anweather[,1]
AnET0 <- Anweather[,2]

## SIMULATION, MEAN, STANDARD DEVIATION AND CONFIDENCE INTERVAL CALCULATIONS

### MORRIS SIMULATION

#### Parameters declaration
param <- read.table("paramMorris.txt")
qs0 <- 0.27
LnTe <- param[,1]
m <- param[,2]
Sr0 <- 0.01
Srmax <- param[,3]
td <- param[,4]
vch <- 4500
vr <- param[,5]
k0 <- param[,6]
CD <- param[,7]
dt <- 3

Morrisparameters <- cbind(qs0, LnTe, m, Sr0, Srmax, td, vch, vr, k0, CD, dt)

#### Simulation
QsimhrsMorris <- topmodel(Morrisparameters, topindex, delay, hrsrain, hrsET0)
SumhrsMorris <- colSums(QsimhrsMorris)

#### Table of the outputs
write.table(SumhrsMorris, "C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ SumhrsMorris.xls", sep="\t")

#### Table Means, Standard Deviation and Confidence Interval
MeanhrsMorris <- colMeans(QsimhrsMorris)
write.table(MeanhrsMorris, "C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ MeanhrsMorris.xls", sep="\t")
StandarddevhrsMorris<-colSds(QsimhrsMorris)
write.table(StandarddevhrsMorris,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ StandarddevhrsMorris.xls", sep="\t")
QMhrs0.025<-colQuantiles(QsimhrsMorris, probs=0.025)
write.table(QMhrs0.025,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ QMhrs0.025.xls", sep="\t")
QMhrs0.50<-colQuantiles(QsimhrsMorris, probs=0.50)
write.table(QMhrs0.50,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ QMhrs0.50.xls", sep="\t")
QMhrs0.975<-colQuantiles(QsimhrsMorris, probs=0.975)
write.table(QMhrs0.975,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ QMhrs0.975.xls", sep="\t")
QMhrs1<-colQuantiles(QsimhrsMorris, probs=0.25)
write.table(QMhrs1,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ QMhrs1.xls", sep="\t")
QMhrs3<-colQuantiles(QsimhrsMorris, probs=0.75)
write.table(QMhrs3,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ QMhrs3.xls", sep="\t")
MinhrsMorris<-colMins(QsimhrsMorris)
write.table(MinhrsMorris,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ MinhrsMorris.xls", sep="\t")
MaxhrsMorris<-colMaxs(QsimhrsMorris)
write.table(MaxhrsMorris,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ MaxhrsMorris.xls", sep="\t")
SkewnesshrsMorris<-skewness(QsimhrsMorris)
write.table(SkewnesshrsMorris,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ SkewnesshrsMorris.xls", sep="\t")
KurtosishrsMorris<-kurtosis(QsimhrsMorris)
write.table(KurtosishrsMorris,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ KurtosishrsMorris.xls", sep="\t")
MeanhrsMorrismatrix<-mean(QsimhrsMorris)
StandarddevhrsMorrisMatrix<- apply(QsimhrsMorris, 2, sd)
QMhrs0.025Matrix<- quantile(QsimhrsMorris, probs=0.025)
QMhrs0.50Matrix<- quantile(QsimhrsMorris, probs=0.50)
QMhrs0.975Matrix<- quantile(QsimhrsMorris, probs=0.975)
QMhrs1Matrix<- quantile(QsimhrsMorris, probs=0.25)
QMhrs3Matrix<- quantile(QsimhrsMorris, probs=0.75)
MinhrsMorrisMatrix<- min(QsimhrsMorris)
MaxhrsMorrisMatrix<- max(QsimhrsMorris)
SkewnesshrsMorrisMatrix<- skewness(QsimhrsMorris)
KurtosishrsMorrisMatrix<- kurtosis(QsimhrsMorris)

## Uncertainty values
MeanhrsMorrismatrix
StandarddevhrsMorrisMatrix
QMhrs0.025Matrix
QMhrs0.50Matrix
QMhrs0.975Matrix
QMhrs1Matrix
QMhrs3Matrix
MinhrsMorrisMatrix
MaxhrsMorrisMatrix
SkewnesshrsMorrisMatrix
KurtosishrsMorrisMatrix
APPENDIX B
FAST CODE IN R

Setwd("C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel")
library(topmodel)
library(stinepack)
library(e1071)
library(Hmisc)
library(sensitivity)
library(zoo)
library(xlsReadWrite)
library(xts)
library(matrixStats)
DEM <- read.table("DEM2.txt")
DEM <- as.matrix(DEM)
DEM[DEM==9999] <- NA
library(lattice)
#levelplot(DEM)
# Fill sink0
DEM.filled <- sinkfill(DEM, res=30, degree=0.1)
DEM.filled <- sinkfill(DEM.filled, res=30, degree=0.1)
DEM.filled <- sinkfill(DEM.filled, res=30, degree=0.1)
DEM.filled <- sinkfill(DEM.filled, res=30, degree=0.1)
DEM.filled <- sinkfill(DEM.filled, res=30, degree=0.1)
DEM.filled <- sinkfill(DEM.filled, res=30, degree=0.1)
DEM.filled <- sinkfill(DEM.filled, res=30, degree=0.1)
DEM.filled <- sinkfill(DEM.filled, res=30, degree=0.1)
DEM.filled <- sinkfill(DEM.filled, res=30, degree=0.1)

# View effect of filling sink0
difference <- DEM.filled - DEM
# Calculate Topographic Index
topindex <- topidx(DEM.filled, res=30)
# View atb
levelplot(topindex$atb)
# View area
levelplot(topindex$area)
topindex <- make.classes(topindex$atb,16)
# Note in the area plot that the highest contributing area is approximately
# at row 381 and column 519 and not at 1,1. This is likely due to the lower
# portion of the basin being very flat with no "clear" flow direction to be
# found. In order to use the entire watershed, we may need to "burn" in the
# river.
# Calculate flow length and delay using the point with highest contributing
# area.
flowlength <- flowlength(DEM.filled, c(381,519)) * 30
flowlength <- hist(flowlength,5)
delay <- data.frame(distance = flowlength$break0, area = c(0, sum(flowlength$counts)))

delay[,2] <- cumsum(delay[,2])

## DATA UPLOADING

## 3 HRS DATA
hrsweather <- read.table("Data3hrs.txt", header=FALSE, sep="\t")
hrsrain <- hrsweather[,1]
hrsET0 <- hrsweather[,2]

## DAILY DATA
dailyweather <- read.table("Datadaily.txt", header=FALSE, sep="\t")
dailyrain <- dailyweather[,1]
dailyET0 <- dailyweather[,2]

## FAST SIMULATION

## Parameters declaration
param <- read.table("paramFAST.txt")
qs0 <- 0.27
LnTe <- param[,1]
m <- param[,2]
Sr0 <- 0.01
Srmax <- param[,3]
td <- param[,4]
vch <- 4500
vr <- param[,5]
k0 <- param[,6]
CD <- param[,7]
dt <- 3

Fastparameters <- cbind(qs0, LnTe, m, Sr0, Srmax, td, vch, vr, k0, CD, dt)

## Simulation of the outputs
Qsimhrsfast <- topmodel(Fastparameters, topindex, delay, hrsrain, hrsET0)
Sumhrsfast <- colSums(Qsimhrsfast)

## Tables of the outputs
write.table(Sumhrsfast, "C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ Sumhrsfast.xls", sep="\t")
Meanhrsfast <- colMeans(Qsimhrsfast)
write.table(Meanhrsfast, "C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ Meanhrsfast.xls", sep="\t")
Qhrs0.10fast <- colQuantiles(Qsimhrsfast, probs=0.10)
write.table(Qhrs0.10fast, "C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ Qhrs0.10fast.xls", sep="\t")
Qhrs0.025fast <- colQuantiles(Qsimhrsfast, probs=0.025)
write.table(Qhrs0.025fast, "C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ Qhrs0.025fast.xls", sep="\t")
Qhrs0.50fast <- colQuantiles(Qsimhrsfast, probs=0.50)
write.table(Qhrs0.50fast,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ Qhrs0.50fast.xls", sep="t")
Qhrs0.50fast<- colQuantiles(Qsimhrsfast, probs=0.50)
write.table(Qhrs0.50fast,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ Qhrs0.50fast.xls", sep="t")
write.table(Qhrs0.975fast,-colQuantiles(Qsimhrsfast, probs=0.975)
write.table(Qhrs0.975fast,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ Qhrs0.975fast.xls", sep="t")
write.table(Qhrs1fast,-colQuantiles(Qsimhrsfast, probs=0.25)
write.table(Qhrs1fast,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ Qhrs1fast.xls", sep="t")
write.table(Qhrs3fast,-colQuantiles(Qsimhrsfast, probs=0.75)
write.table(Qhrs3fast,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ Qhrs3fast.xls", sep="t")
write.table(Minhrsfast,-colMins(Qsimhrsfast)
write.table(Minhrsfast,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ Minhrsfast.xls", sep="t")
write.table(Maxhrsfast,-colMaxs(Qsimhrsfast)
write.table(Maxhrsfast,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ Maxhrsfast.xls", sep="t")
write.table(Skewnesshrsfast,-skewness(Qsimhrsfast)
write.table(Skewnesshrsfast,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ Skewnesshrsfast.xls", sep="t")
write.table(Kurtosishrsfast,-kurtosis(Qsimhrsfast)
write.table(Kurtosishrsfast,"C:/Users/Joseph/Desktop/r.topmodel_ex/r.topmodel_ex/r.topmodel/ Kurtosishrsfast.xls", sep="t")
write.table(Meanhrsfastmatrix,-mean(Qsimhrsfast)
write.table(StandarddevhrsfastMatrix,-apply(Qsimhrsfast, 2, sd)
write.table(Qhrs0.025fastMatrix,-quantile(Qsimhrsfast, probs=0.025)
write.table(Qhrs0.50fastMatrix,-quantile(Qsimhrsfast, probs=0.50)
write.table(Qhrs0.975fastMatrix,-quantile(Qsimhrsfast, probs=0.975)
write.table(Qhrs1fastMatrix,-quantile(Qsimhrsfast, probs=0.25)
write.table(Qhrs3fastMatrix,-quantile(Qsimhrsfast, probs=0.75)
write.table(MinhrsfastMatrix,-min(Qsimhrsfast)
write.table(MaxhrsfastMatrix,-max(Qsimhrsfast)
write.table(SkewnesshrsfastMatrix,-skewness(Qsimhrsfast)
write.table(KurtosishrsfastMatrix,-kurtosis(Qsimhrsfast)

## Uncertainty values
Meanhrsfastmatrix
StandarddevhrsfastMatrix
Qhrs0.025fastMatrix
Qhrs0.50fastMatrix
Qhrs0.975fastMatrix
Qhrs1fastMatrix
Qhrs3fastMatrix
MinhrsfastMatrix
MaxhrsfastMatrix
SkewnesshrsfastMatrix
KurtosishrsfastMatrix
%Program to write file in desired SIMLAB format for temporal output
clear all;
clc;
[data]=xlsread('Qhrsfast.xlsx');
[n,m]=size(data);
%data(1:n-1,1:m)=data(2:n,1:m)
fid=fopen('Qhrsfast.out','w');%Change output file name as required
fprintf(fid,'%d
',m);
fprintf(fid,'QMinimum
');
fprintf(fid,'Q0025
');
fprintf(fid,'Q010
');
fprintf(fid,'Q025
');
fprintf(fid,'Q050
');
fprintf(fid,'QMean
');
fprintf(fid,'Q075
');
fprintf(fid,'Q090
');
fprintf(fid,'Q0975
');
fprintf(fid,'QMaximum
');
fprintf(fid,'QTotal
');
fprintf(fid,'Q090010
');
fprintf(fid,'Q090050
');
fprintf(fid,'Q050040
');
fprintf(fid,'time = no
');
fprintf(fid,'%d
',n);
for j=1:n
  fprintf(fid,'%4.4f %4.4f %4.4f %4.4f %4.4f %4.4f %4.4f %4.4f %4.4f %4.4f
',data(j,1),data(j,2),data(j,3),
data(j,4),data(j,5),data(j,6),data(j,7),data(j,8),data(j,9),data(j,10),data(j,11),data(j,12),dat
a(j,13),data(j,14));
end
fclose(fid);
C2. MATLAB CODE B

% Read in 3 hours temperature files and abstract the daily maximum and minimum temperature
% and calculate the daily mean temperature, and then concatenate into three
% single files

clear;

directory = pwd; % Need to be changed if different path
newdir = [directory,'/processed'];

cd (newdir)

dayPosition = 1; % Day 1 is 1/1/1979

% Need to be changed if different grids; [y,x,days]
aPCP = NaN(3,2,97880);

for i=1979:2012

    year = int2str(i);
    fileName = ['apcp.HaitiBV.',year,'.nc'];

    % abstract data
    lat = nc_varget(fileName,'lat'); % 3 pts currently
    lon = nc_varget(fileName,'lon'); % 2 pts currently
    time = nc_varget(fileName,'time'); % 3 hours time-step
    T3hrs = nc_varget(fileName,'apcp'); % Has dimensions: (3,2,time)
    T3hrs(T3hrs<0)=0;

    maxTime = max(time);

    aPCP(:,:,dayPosition:dayPosition+maxTime-1) = T3hrs;

    dayPosition = dayPosition+maxTime;

end

days = 722816:0.125:735050; % Matlab serial dates, 1/1/1979 - 6/30/2012

days = days';

% Write to mean temperature file

cd (directory);
newFileName=('PCP_HaitiBV.nc');
% Add dimensions and sizes
nc_create_empty ( newFileName )
nc_add_dimension ( newFileName, 'lat', 3 )
nc_add_dimension ( newFileName, 'lon', 2 )
nc_add_dimension ( newFileName, 'days', 97880 )

varstruct.Name = 'aPCP';
varstruct.Nctype = nc_double;
varstruct.Dimension = {'lat','lon','days'};
nc_addvar ( newFileName, varstruct )

lon_varstruct.Name = 'lon';
lon_varstruct.Nctype = nc_float;
lon_varstruct.Dimension = {'lon'};
nc_addvar ( newFileName, lon_varstruct )

lat_varstruct.Name = 'lat';
lon_varstruct.Nctype = nc_float;
lon_varstruct.Dimension = {'lat'};
nc_addvar ( newFileName, lat_varstruct )

day_varstruct.Name = 'days';
day_varstruct.Nctype = nc_double;
day_varstruct.Dimension = {'days'};
nc_addvar ( newFileName, day_varstruct )

% Add the subset of data to the new netcdf file
nc_varput ( newFileName, 'lat', lat );
nv_varput ( newFileName, 'lon', lon );
nv_varput ( newFileName, 'aPCP', aPCP );
nv_varput ( newFileName, 'days', days );

% Add attributes
nc_attput ( newFileName, 'aPCP', 'units', 'kg/m^2');
nv_attput ( newFileName, 'aPCP', 'var_desc', '3 hourly precipitation');
nv_attput ( newFileName, 'days', 'units', 'matlab serial date');
nv_attput ( newFileName, 'lat', 'units', 'degrees_north');
nv_attput ( newFileName, 'lat', 'long_name', 'Latitude');
nv_attput ( newFileName, 'lat', 'actual_range', '18.83 18.33 f');
nv_attput ( newFileName, 'lon', 'units', 'degrees_east');
nv_attput ( newFileName, 'lon', 'long_name', 'Longitude');
nv_attput ( newFileName, 'lon', 'actual_range', '287.64 287.89 f');
C3. MATLAB CODE C

% Read in 3 hours temperature files and abstract the daily maximum and minimum temperature
% and calculate the daily mean temperature, and then concatenate into three single files

clear;

directory = pwd; % Need to be changed if different path
newdir = [directory, '/processed'];

    cd (newdir)

    dayPosition = 1; % Day 1 is 1/1/1979

    % Need to be changed if different grids; [y,x,days]
    apevap = NaN(3,2,97880);

    for i=1979:2012
        year = int2str(i);
        fileName = ['pevap.HaitiBV.',year,'.nc'];

        % abstract data
        lat = nc_varget(fileName,'lat'); % 3 pts currently
        lon = nc_varget(fileName,'lon'); % 2 pts currently
        time = nc_varget(fileName,'time'); % 3 hours time-step
        T3hrs = nc_varget(fileName,'pevap'); % Has dimensions: (3,2,time)
        T3hrs(T3hrs<0)=0;

        maxTime = max(time);
        apevap(:,:,dayPosition:dayPosition+maxTime-1) = T3hrs;

        dayPosition = dayPosition+maxTime;
    end

    days = 722816:735050; % Matlab serial dates, 1/1/1979 - 6/30/2012
days = days';

    %% Write to mean temperature file
    cd (directory);
    newFileName=('pevap_HaitiBV.nc');

    % Add dimensions and sizes
    nc_create_empty ( newFileName )
    nc_add_dimension ( newFileName, 'lat', 3 )

129
nc_add_dimension ( newFileName, 'lon', 2 )
nc_add_dimension ( newFileName, 'days', 97880 )

dimensions = {'lat', 'lon', 'days'};
varstruct.Name = 'pevap';
varstruct.Nctype = nc_double;
varstruct.Dimension = dimensions;
nc_addvar ( newFileName, varstruct )

lon_varstruct.Name = 'lon';
lon_varstruct.Nctype = nc_float;
lon_varstruct.Dimension = {'lon'};
nc_addvar ( newFileName, lon_varstruct )

lat_varstruct.Name = 'lat';
lat_varstruct.Nctype = nc_float;
lat_varstruct.Dimension = {'lat'};
nc_addvar ( newFileName, lat_varstruct )

day_varstruct.Name = 'days';
day_varstruct.Nctype = nc_double;
day_varstruct.Dimension = {'days'};
nc_addvar ( newFileName, day_varstruct )

% Add the subset of data to the new netcdf file
nc_varput ( newFileName, 'lat', lat );
nc_varput ( newFileName, 'lon', lon );
nc_varput ( newFileName, 'pevap', apevap );

% Add attributes
nc_attput ( newFileName, 'pevap', 'units', 'kg/m^2' );
nc_attput ( newFileName, 'pevap', 'var_desc', '3 hourly potential evaporation' );
nc_attput ( newFileName, 'days', 'units', 'matlab serial date' );
nc_attput ( newFileName, 'lat', 'units', 'degrees_north' );
nc_attput ( newFileName, 'lat', 'long_name', 'Latitude' );
nc_attput ( newFileName, 'lat', 'actual_range', '18.83 18.33 f' );
nc_attput ( newFileName, 'lon', 'units', 'degrees_east' );
nc_attput ( newFileName, 'lon', 'long_name', 'Longitude' );
nc_attput ( newFileName, 'lon', 'actual_range', '287.64 287.89 f' );
C4. MATLAB CODE D

% This code reads the NARR 3 hours time step precipitation data, access a subset of grid points, and then
% creates new netcdf files

%%% clear all, close all

dir = pwd;

datatype = 'apcp'; %extracting 3 hours precipitation data

for i=1979:2012

    if
            time = 2928;
        elseif (i==2012)
            time = 1456; % This is here since our ftp download only included data to 6/30/2012
        else
            time = 2920;
    end

    %% Access NARR data

directory = [dir,'/accumulated precipitation 3 hourly']; % Need to be changed if different

    cd (directory)

    % air = (y, x, time) [349,277,2920] for each nonlead year
    % time = hours since 1/1/1 0:00:00 in 3 hour increments
    % y = meters (0 to 8959788) at 32463m (mean) increments
    % x = meters (0 to 11297120) at 32463m (mean) increments
    % the projection coordinate is Lambert Conformal Format
    % the southwest corner is set as (0,0)
    % y is northward distance from southwest corner of domain in projection coordinates
    % x is eastward distance from southwest corner of domain in projection coordinates
    % each grid has its corresponding lon and lat. Corners of this grid are 12.2N; 133.5W, 54.5N; 152.9W, 57.3N; 49.4W, 14.3N; 65.1W.

    % degreesEast = (180 - degreesWest) + 180

    year = int2str(i);

    fileName = [datatype,'.',year,'.nc']; % Need to change for other variables
% Create a 0.25 degree lat-lon grids to do projection later
% Need to be changed for other grids
x = 287.64:0.25:287.89;
y = [18.83:-0.25:18.33]';

% Create a year precipitation array
maxX = length(x);
maxY = length(y);
T3hrs = NaN(maxY,maxX,time);

for dayi=0:8:time-8
    ncid = netcdf.open(fileName,'NC_NOWRITE');

    % For the temperautre data, the varid is 5 from year 1979 to 2002. The latitude
    % varid is 0 and the longitude varid is 1.
    if i>=1979 && i<=2002
        thisLat = netcdf.getVar(ncid,0);
        thisLon = netcdf.getVar(ncid,1);
        data = double(netcdf.getVar(ncid,5,[0 0 dayi],[349,277,8])); % Units of K
        missingValue = netcdf.getAtt(ncid, 5, 'missing_value');
        fillValue = netcdf.getAtt(ncid, 5, '_FillValue');
        data(iMissing)=nan;
        iFill = find(data == fillValue);
        data(iMissing)=nan;
    elseif i>=2003 && i<=2007
        thisLat = netcdf.getVar(ncid,0);
        thisLon = netcdf.getVar(ncid,1);
        data = double(netcdf.getVar(ncid,4,[0 0 dayi],[349,277,8])); % Units of K
        missingValue = netcdf.getAtt(ncid, 4, 'missing_value');
        fillValue = netcdf.getAtt(ncid, 4, '_FillValue');

    else
        % Apply scale and offset
        scaleFactor = netcdf.getAtt(ncid, 5, 'scale_factor');
        addOffset = netcdf.getAtt(ncid, 5, 'add_offset');
    end

    % Replace with NaN
    data(iMissing)=nan;
    data(iFill)=nan;
end
% Replace with NaN
iMissing = find(data == missingValue);
data(iMissing) = nan;

iFill = find(data == fillValue);
data(iMissing) = nan;

% Apply scale and offset
scaleFactor = netcdf.getAtt(ncid, 4, 'scale_factor');
addOffset = netcdf.getAtt(ncid, 4, 'add_offset');

elseif i>=2008

thisLat = netcdf.getVar(ncid, 1);
thisLon = netcdf.getVar(ncid, 2);

data = double(netcdf.getVar(ncid, 7, [0 0 dayi], [349, 277, 8])); % Units of K

missingValue = netcdf.getAtt(ncid, 7, 'missing_value');
fillValue = netcdf.getAtt(ncid, 7, '_FillValue');

% Replace with NaN
iMissing = find(data == missingValue);
data(iMissing) = nan;

iFill = find(data == fillValue);
data(iMissing) = nan;

% Apply scale and offset
scaleFactor = netcdf.getAtt(ncid, 7, 'scale_factor');
addOffset = netcdf.getAtt(ncid, 7, 'add_offset');

end

data = data*scaleFactor;
data = data+addOffset;

% change data to double
data = double(data);

%% Close File
netcdf.close(ncid);

% Convert all negative longitudes to positive
iNeg = find(thisLon < 0);
thisLon(iNeg) = thisLon(iNeg)*-1;
thisLon(iNeg) = (180-thisLon(iNeg)) + 180;
% Interpolate to a regular grid so it is easier to just access the points
% we want
thisLon = double(thisLon);
thisLat = double(thisLat);

maxTime = size(data,3);
data2 = nan(maxY,maxX,maxTime);
for j=1:8 % Could do this for all days
    data2(:,:,j) = griddata(thisLon,thisLat,data(:,:,j),x,y,'linear');
end

T3hrs(:,:,dayi+1:dayi+8) = data2;

end
timeNumber = [1:time];

%% Create 3 hours precipitation and give it dimensions, dimension sizes, and attributes
cd ('D:\Di\NARR data for Joseph\processed')
newfileName = ['apcp.HaitiBV.',year,'.nc'];

% Add dimensions and sizes
nc_create_empty ( newfileName )
nc_add_dimension ( newfileName, 'lat', maxY )
nc_add_dimension ( newfileName, 'lon', maxX )
nc_add_dimension ( newfileName, 'time', time )

%These attributes are the same as the GFS dataset
varstruct.Name = datatype;
varstruct.Nctype = nc_double;
varstruct.Dimension = { 'lat','lon','time'};
nc_addvar ( newfileName, varstruct )

lon_varstruct.Name = 'lat';
lon_varstruct.Nctype = nc_float;
lon_varstruct.Dimension = { 'lat' };
nc_addvar ( newfileName, lon_varstruct )

lat_varstruct.Name = 'lon';
l_lat_varstruct.Nctype = nc_float;
l_at_varstruct.Dimension = { 'lon' };
lnc_addvar (newfileName, lat_varstruct )

time_varstruct.Name = 'time';
time_varstruct.Nctype = nc_double;
time_varstruct.Dimension = { 'time' };
nc_addvar ( newfileName, time_varstruct )

% Add the subset of data to the new netcdf file
nc_varput ( newfileName, datatype, T3hrs );
nv_varput ( newfileName, 'lat', y );
nv_varput ( newfileName, 'lon', x );
nv_varput ( newfileName, 'time', timeNumber );

% Add attributes
nc_attput ( newfileName, datatype, 'units', 'kg/m^2' );
%nc_attput ( newfileName, datatype, '_FillValue', '-32767 s');
%nc_attput ( newfileName, datatype, 'scale_factor', '0.010000 f' );
nv_attput ( newfileName, datatype, 'var_desc', '3 hours accumulated potential evaporation' );
%nc_attput ( newfileName, datatype, 'add_offset', '327.649994 f' );
%nc_attput ( newfileName, datatype, 'missing_value', '32766 s' );

nc_attput ( newfileName, 'lat', 'units', 'degrees_north' );
nv_attput ( newfileName, 'lat', 'long_name', 'Latitude' );
nv_attput ( newfileName, 'lat', 'actual_range', '18.83 18.33 f' ); % Needs to be changed for different gridpoints

nc_attput ( newfileName, 'lon', 'units', 'degrees_east' );
nv_attput ( newfileName, 'lon', 'long_name', 'Longitude' );
nv_attput ( newfileName, 'lon', 'actual_range', '287.64 287.89 f' ); % Needs to be changed for different gridpoints

nc_attput ( newfileName, 'time', 'units', 'hours since 1-1-1 00:00:0.0' );
nv_attput ( newfileName, 'time', 'steps', '3 hours time step' );
en
C5. MATLAB CODE E

% This code reads the NARR 3 hours time step temperature data, access a subset of
% grid points, and then
% creates new netcdf files

%%
clear all, close all

dir = pwd;

datatype = 'pevap'; %extracting 3 hours temperature data

for i=1979:2004
  if
      time = 2928;
    elseif (i==2012)
      time = 1456; % This is here since our ftp download only included data to 6/30/2012
    else
      time = 2920;
  end

  %% Access NARR data

directory = [dir, '/accumulated potential evaporation 3 hourly']; % Need to be changed if different

  cd (directory)

  % air = (y, x, time) [349,277,2920] for each nonlead year
  % time = hours since 1/1/1 0:00:00 in 3 hour increments
  % y = meters (0 to 8959788) at 32463m (mean) increments
  % x = meters (0 to 11297120) at 32463m (mean) increments
  % the projection coodinate is Lambert Conformal Format
  % the southwest corner is set as (0,0)
  % y is northward distance from southwest corner of domain in projection coordinates
  % x is eastward distance from southwest corner of domain in projection coordinates
  % each grid has its corresponding lon and lat. Corners of this grid are 12.2N; 133.5W,
  % 54.5N; 152.9W, 57.3N; 49.4W, 14.3N; 65.1W.

  % degreesEast = (180 - degreesWest) + 180

  year = int2str(i);
  fileName = [datatype,'.',year,'.nc']; % Need to change for other variables
% Create a 0.25 degree lat-lon grids to do projection later
% Need to be changed for other grids
x = 287.64:0.25:287.89;
y = [18.83:-0.25:18.33]';

% Create a year temperature array
maxX = length(x);
maxY = length(y);
T3hrs = NaN(maxY,maxX,time);

for dayi=0:8:time-8

ncid = netcdf.open(fileName,'NC_NOWRITE');

% For the temperature data, the varid is 5 from year 1979 to 2002. The latitude varid is 0 and the longitude varid is 1.
if i>=1979 && i<=2007

thisLat = netcdf.getVar(ncid,0);
thisLon = netcdf.getVar(ncid,1);

data = double(netcdf.getVar(ncid,5,[0 0 dayi],[349,277,8])); % Units of K

missingValue = netcdf.getAtt(ncid, 5, 'missing_value');
fillValue = netcdf.getAtt(ncid, 5, '_FillValue');

% Replace with NaN
iMissing = find(data == missingValue);
data(iMissing)=nan;
iFill = find(data == fillValue);
data(iMissing)=nan;

% Apply scale and offset
scaleFactor = netcdf.getAtt(ncid, 5, 'scale_factor');
addOffset = netcdf.getAtt(ncid, 5, 'add_offset');

elseif i>=2008

thisLat = netcdf.getVar(ncid,1);
thisLon = netcdf.getVar(ncid,2);

data = double(netcdf.getVar(ncid,7,[0 0 dayi],[349,277,8])); % Units of K

missingValue = netcdf.getAtt(ncid, 7, 'missing_value');

fillValue = netcdf.getAtt(ncid, 7, '_FillValue');

% Replace with NaN
iMissing = find(data == missingValue);
data(iMissing)=nan;

iFill = find(data == fillValue);
data(iFill)=nan;

% Apply scale and offset
scaleFactor = netcdf.getAtt(ncid, 7, 'scale_factor');
addOffset = netcdf.getAtt(ncid, 7, 'add_offset');

end

data = data*scaleFactor;
data = data+addOffset;

% change data to double
data = double(data);

%% Close File
netcdf.close(ncid);

% Convert all negative longitudes to positive
iNeg = find(thisLon < 0);
thisLon(iNeg) = thisLon(iNeg)*-1;
thisLon(iNeg) = (180-thisLon(iNeg)) +180;

% Interpolate to a regular grid so it is easier to just access the points we want
thisLon = double(thisLon);
thisLat = double(thisLat);

maxTime = size(data,3);
data2 = nan(maxY,maxX,maxTime);
for j=1:8 % Could do this for all days
    data2(:,;j) = griddata(thisLon,thisLat,data(:,;j),x,y,'linear');
end

T3hrs(:,;dayi+1:dayi+8) = data2;

end

timeNumber = [1:time];
%% Create 3 hours temperature and give it dimensions, dimension sizes, and attributes

```matlab
% Create 3 hours temperature and give it dimensions, dimension sizes, and attributes
% Add dimensions and sizes
nc_create_empty ( newfileName )
nc_add_dimension ( newfileName, 'lat', maxY )
nc_add_dimension ( newfileName, 'lon', maxX )
nc_add_dimension ( newfileName, 'time', time )

% These attributes are the same as the GFS dataset
varstruct.Name = datatype;
varstruct.Nctype = nc_double;
varstruct.Dimension = { 'lat','lon','time' };
nc_addvar ( newfileName, varstruct )

lon_varstruct.Name = 'lat';
lon_varstruct.Nctype = nc_float;
lon_varstruct.Dimension = { 'lat' };
nc_addvar ( newfileName, lon_varstruct )

lat_varstruct.Name = 'lon';
l_at_varstruct.Nctype = nc_float;
l_at_varstruct.Dimension = { 'lon' };
nc_addvar ( newfileName, lat_varstruct )

time_varstruct.Name = 'time';
time_varstruct.Nctype = nc_double;
time_varstruct.Dimension = { 'time' };
nc_addvar ( newfileName, time_varstruct )

% Add the subset of data to the new netcdf file
nc_varput ( newfileName, datatype, T3hrs );
nnc_varput ( newfileName, 'lat', y );
nnc_varput ( newfileName, 'lon', x );
nnc_varput ( newfileName, 'time', timeNumber );

% Add attributes
nc_attput ( newfileName, datatype, 'units', 'kg/m^2' );
%nc_attput ( newfileName, datatype, '_FillValue', '-32767 s');
%nc_attput ( newfileName, datatype, 'scale_factor', '0.010000 f');
nnc_attput ( newfileName, datatype, 'var_desc', '3 hours accumulated potential evaporation' );
%nc_attput ( newfileName, datatype, 'add_offset', '327.649994 f');
%nc_attput ( newfileName, datatype, 'missing_value', '32766 s');
```
nc_attput ( newfileName, 'lat', 'units', 'degrees_north');
nc_attput ( newfileName, 'lat', 'long_name', 'Latitude' );
nc_attput ( newfileName, 'lat', 'actual_range', '18.83 18.33 f'); % Needs to be changed for different gridpoints
nc_attput ( newfileName, 'lon', 'units', 'degrees_east');
nc_attput ( newfileName, 'lon', 'long_name', 'Longitude' );
nc_attput ( newfileName, 'lon', 'actual_range', '287.64 287.89 f'); % Needs to be changed for different gridpoints
nc_attput ( newfileName, 'time', 'units', 'hours since 1-1-1 00:00:0.0');
nc_attput ( newfileName, 'time', 'steps', '3 hours time step');
end
# APPENDIX D
## PARAMETERS CALCULATIONS

<table>
<thead>
<tr>
<th></th>
<th>lower limit</th>
<th>upper limit</th>
<th>lower K₀</th>
<th>μ</th>
<th>upper K₀</th>
<th>μ</th>
<th>4e</th>
<th>B</th>
<th>Srmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>clay</td>
<td>0.28</td>
<td>0.14</td>
<td>0.269</td>
<td>0.385</td>
<td>0.501</td>
<td>0.055398</td>
<td>0.232449</td>
<td>0.666556</td>
<td>0.177051</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.385</td>
<td>1.28694</td>
<td>3.082204</td>
</tr>
<tr>
<td>clayloam</td>
<td>0.36</td>
<td>0.46</td>
<td>0.279</td>
<td>0.39</td>
<td>0.501</td>
<td>0.064107</td>
<td>0.244762</td>
<td>0.666556</td>
<td>0.177051</td>
</tr>
<tr>
<td>Sandy</td>
<td>0.61</td>
<td>0.945</td>
<td>0.235</td>
<td>0.33</td>
<td>0.425</td>
<td>0.032267</td>
<td>0.12547</td>
<td>0.345177</td>
<td></td>
</tr>
</tbody>
</table>

|          | 0.428821    | 3           | 4.797964 |
|          | 1.28694     | 3.082204    |          |

|          | 0.31911     | 0.4495      | 0.57989  |
|          | 0.13039     |             | 0.13039  |
LIST OF REFERENCES

Agroconsult-Haiti SA, 2009, Etude des systèmes de production agricole et des associations paysannes dans les bassins versants de la rivière la quinte et de la rivière grise, 251 pages


Alejandra S., Patrick D., Francisco R. & Hernan Al. 2008: Hydrological modelling with SWAT under conditions of limited data availability: evaluation of results from a Chilean case study, Hydrological Sciences Journal, 53:3, 588-601


Beven K., 1997 Topmodel: A Critique Hydrological Processes, Vol. 11, 1069±1085


Bois P., juin 2003, Hydraulique des écoulements en Rivière, notes de cours, Professor at the University of Grenoble.


Cappus, P. (1960) Etude des lois de l'écoulement, application au calcul et à la prévision des débits. La Houille Blanche 60,493-520


Durand, P, Robson, A, and Neal, C. 1992 Modelling the hydrology of submediterranean montain catchments (Mont Lozère, France), using TOPMODEL: initial results, J. Hydrol., 139, 1-14


Georges Y, 2008, Contribution à l'évaluation de l'érosion dans le bassin versant de la rivière Grise pour un meilleur plan d'aménagement. Faculte Universitaire des Sciences Agronomiques de Gembloux (FUSAGx). Mémoire de Master complementaire, 50p


Hantush M. and Khalin L., 2003, Modeling Uncertainty of Runoff and Sediment Yield Using a Distributed Hydrologic Model

Haygarth P. M., Beven K. J., Joynes A., Butlerb T., Keelera C., Freera J., Owensc P. Wood G. Sampling for Assessing Risk to Water Quality,


Horton, R.E., 1933. The role of infiltration in the hydrologic cycle, Transactions of the American Geophysical Union, 14: 446-460.


Joseph A., Mai 2004, Rapport de synthèse des études de vulnérabilité et d’adaptation aux conditions climatiques externes en Haïti, secteurs: zones côtières, ressources en eau, risques et désastres, agriculture et désertification, 73 pages


Montesinos-Barrios, P., Beven K. 2004, Evaluation of TOPMODEL
http://s1004.ok0tate.edu/S1004/Regional-Bulletins/Modeling Bulletin/
TOPMODEL.html

Moreda F. 1999 Conceptual rainfall - runoff models for different time steps with special consideration for semi-arid and arid catchments. Laboratory of Hydrology, Faculty of Applied Sciences, VUB, Pleinlaan 2, 1050 Brussels, Belgium. Dissertation 208pp

Morel-Seytoux H. J, 1999, Soil water retention and maximum capillary drive from saturation to oven dryness WATER RESOURCES RESEARCH, VOL. 35, NO. 7, PAGES 2031-2041


Pinol, J, Beven, K J and Freer, J, 1997, Modelling the hydrological response of Mediterranean catchments, Prades, Catalonia - the use of distributed models as aids to hypothesis formulation Hydrol. 11, 1287-1306

Projet Interuniversitaire Cible (PIC), 2008, Projet Pilote de support des zones habitables de Port-au-Prince. Feuille 1 - Pernier, 27 pages


Robson, A J, Whitehead, P G and Johnson, R C. 1993 An application of a physically based semi-distributed model to the Balquhidder catchments, J. Hydrol., 145, 357-370

Rodriguez-Iturbe, I., and J. B. Valdes (1979), the geomorphic structure of Hydrologic response, Water Resources., 15(6), 1409–1420


Sempere-Torres, D, 1990, Calcul de la lame ruisselée dans la modélisation pluie-débit: limitations des approches globales et introduction simplifiée de la topographie et de la variabilité spatiale des pluies. These de Doctorat., Institut de Mécanique de Grenoble, France


Swartley D. B., Toussaint J. R., May 06, Haiti Country Analysis of Tropical Forestry and Biodiversity, 80 pages
Timyan J. C. 2006, Criteria for selecting watershed priority in Haiti, 17 pp


BIOGRAPHICAL SKETCH

Joseph Beneche was born in Les Coteaux (Damassin) which is in the South of Haiti. He went to college St Jean des Cayes where he graduated from high school in July 2000. In October of 2000, he moved to Port au Prince and successfully passed the entrance exam at Faculté d’ Agronomie et de Médecine Vétérinaire (FAMV) of the State University (UEH) where he spent five years and received his bachelor’s degree in agricultural engineering. Over approximately the next five (5) years, Joseph worked among 2 private consulting firms and an NGO, holding position ranging from being site engineer to team leader. In July 2010, Joseph obtained a scholarship from USAID / WINNER project to come to University of Florida (USA) where he receives his master’s degree in agricultural and biological engineering with a concentration in hydrologic sciences in May 2013. His skills include water project management, hydrological modeling, computer programming. Joseph wants to be a long life learner in the field of hydrology, work in challenging environments, and give back to his country through the expertise he will have acquired.