# Hydrologic Modeling Analysis from Land Use Scenario Changes in Quebrada Seca and Bermudez Watershed

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**ABSTRACT**

During the last few years, the expansion of urban cover in the Quebrada Seca-Bermudez watershed has caused a series of floods that have damaged houses, bridges and other important infrastructure of the area. Hence local governments need a more precise description of these extreme rainfall events through reliable data and modeling. This study quantifies the discharge at several points in the Bermudez´s River watershed, based on 3 different storm durations and five different scenarios: three scenarios from previous years (2001, 2008 and 2012) and 2 forecasted scenarios for the year 2020 (one according to the projected urban growth and the other one based on local urban regulations). Land cover variations were determined using Lansat 7 ETM+ images. Both supervised and unsupervised classifications were applied to the satellite images and 6 common classes were obtained: forest, crops, pasture, urban, bare soil and industrial. The Curve Number was assigned based on this information and the soil data with a 1:20 000 scale resolution. A digital elevation model (DEM) with a 30 meters resolution was used to calculate the watershed parameters. Rainfall data over a period of almost 15 years from three meteorological stations were analyzed in order to obtain 2-, 5-, 10- and 25-year return periods. Discharge for all the scenarios was calculated with HEC-HMS program in order to evaluate the changes of urban growth. The results showed a rate of impervious cover of 27% for scenario 1 and 55% for scenario 2. The flow discharge increase for the year 2020 is expected to be between 1% to 14.9% for scenario 1.

**Key Words:** Hydrologic Modeling, urban expansion, land use change, Sensitivity Analysis, GIS, Remote Sensing, LandSat, Costa Rica

## 1. INTRODUCTION

Urban watershed management has to deal with the consequences of rapid internal urban dynamism in addition to flooding produced when water is not able to infiltrate the soil, which increases runoff. The main cause of this problem is attached to the impervious soil layers in the watershed due to uncontrolled urban growth (Zevenbergen, 2010). Hydrologic and hydraulic models are great tools for urban analysis as they provide helpful information to make designs and recommendations. In the last few years, Geographic Information Systems (GIS) and remote sensing along with hydrological models have been able to enhance the field of hydrological engineering and decision making. Hydrologic models allow engineering to recreate the physical characteristics of a watershed and to generate reliable flow data. Therefore local government can have a tool that evaluates future changes or future scenarios if something is changed or altered within their boundaries. The end results are better decisions for an adequate management of water resources. Several floods that have happened from 1999 to the present have made a great impact on infrastructure, houses and roads. Important reported events happened during the years 1999, 2006 and 2012 (Nación, 2013), in which the Quebrada Seca River suffered some disasters which had the characteristic of being very rapid. This study aims to calculate percentages of flow discharge increase both upstream and downstream due to land use changes in the period from the years 2000 to 2012, as well as two forecasted scenarios: one based on the development growth tendency and the other based on land use planning and regulations from the local governments. With this information the local government will be able to predict the impact to the most vulnerable areas of land use changes and its effect on the watershed`s characteristics and the water flow through some of the main rivers.

## 2. METHODOLOGY

The study area is located near the capital of Costa Rica at 9.96° – 10.09° North latitude and 84.05° – 84.21° West longitude, (Figure 1). It belongs to the northeast part of the greater metropolitan area and it has an approximate area of 72 $km^2$. The average annual precipitation is 2042.4 mm and the average temperature is 24.8 °C. The rivers that form this watershed are the Quebrada Seca and the Bermudez, covering different towns, such as San Rafael, Barva, Heredia, San Joaquín of Flores, Belén, San Pablo, San Isidro, Santo Domingo and San Rafael of Alajuela. Land use changes were estimated using three LanSat 7 images for January 2012, January 2008 and July 2001. These images fulfill the criteria of lower percentage of clouds and the optimal time range in order to analyze land changes over the years. The satellite images were projected to the country`s official projection code, CRTM05, a Transversal Mercator projection. An official ortho-rectified image of 2007 provided by a Costa Rican institution (Programa de Regularización y Catastro) was used to make the appropriate calibration.

### 2.1 Land Use

Remote sensing software was used to analyze the satellite images. A set of bands (3-2-1) and two classification methods were utilized (supervised and unsupervised classification). The 3-2-1 bands are better known as “natural color” and the 4-5-7 set were used to better identify between pixels and to established good training sites for soil use classification.
Both of these classification methods allow researchers to automatically identify the necessary groups of pixels in the area of study and develop the required soil classification. The 4-5-7 band set was selected because of the need to use thermal characteristics of plants

to better separate them from non-vegetation zones. (Velásquez M., 2011). To assure the accuracy of the classification, a confusion matrix was applied using 30 points of correlation with the ortho-rectified image of 2007 with the Lansat image of 2008 (Gutierrez, E., 2013) the correlation was about 90% between the images. Six different soil classes where assigned: forest, crops, pasture, bare soil, industrial and urban. Based on this soil use classification (Consultora Acón y Asociados, 1991), a curve number was assigned considering the soil characteristics taken from maps of soil taxonomy. Additionally, fieldtrips were held to assure proper use and classification.

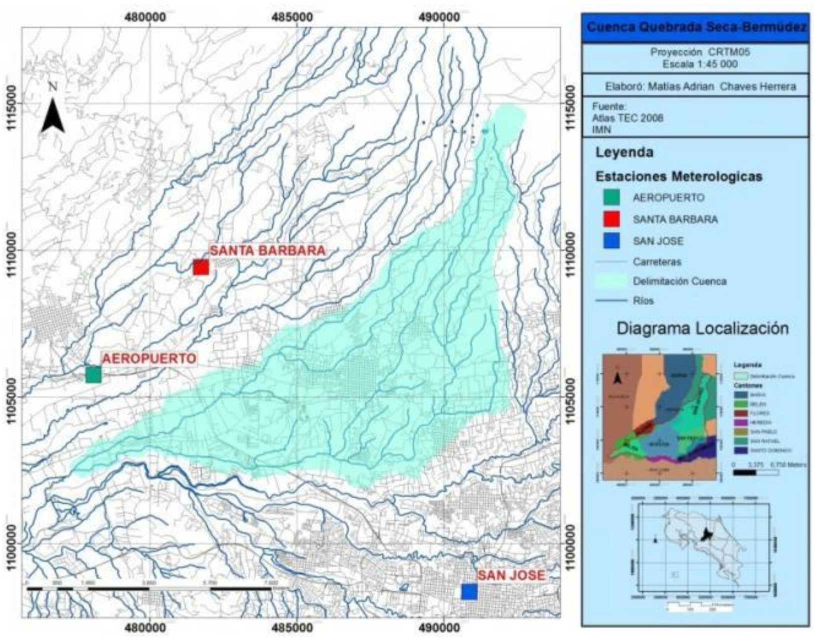


Figure 1. Quebrada Seca and Bermudez watershed location and Rainfall stations.

## 2.2 Design Storms

To estimate the change of the flow discharge as a consequence of land use changes, it was required to select a water depth from different storm durations and return periods. Therefore storm durations of 6, 12 and 24 hours were selected from approximately 15 years of hourly data from 3 meteorological stations (Figure 1). A Gumbel-type distribution was used to determine the return periods at 5, 10 and 25 years (Villón, M., 2012). Finally Intensity-Frequency-Duration curves (Figure 2) and synthetic hietograms were determinate in order to develop hydrologic model.

## 2.3 Modeling Method

The hydrologic model parameters were typed in HEC-HMS using the rainfall-runoff loss module of SCS-Curve number, a transformation method of SCS-Unit Hydrograph and a Channel routing base on Muskingum-Cunge method. For the SCS-Unit Hydrograph transformation method, a concentration time was calculated using different equations, such as Kirpich, SCS, cinematic wave, Isochrone and Federation Aviation Agency model (Chow, 1959) (Ministerio de Transportes y Comunicaciones) . Field trips were conducted to identify the *n* of Manning for cross sections. The alternate block method was selected to distribute the rainfall water depths for respective return periods and durations. Based on the tendency equation from the graph of the water depths, the amount of water for the synthetic storms of 30-minute duration was calculated. And these synthetic storms were then defined for the precipitation gauges of the time series data. To determine change of flow discharges, different rainfall events for the years 2001, 2008 and 2012 and 2 forecasted scenarios were simulated. These future scenarios were simulated according to the urban growth trend of the past years and the other one according to local territorial planning (PRUGAM, 2007) (ProDus, 2013). Due to the susceptibility of any hydrologic model, a sensitivity analysis was developed to the estimated changes in the flow due to changes in the parameter, adding or lowering by 10% its value. The parameters used were the concentration time, rainfall depth, curve number and combinations of the three parameters.

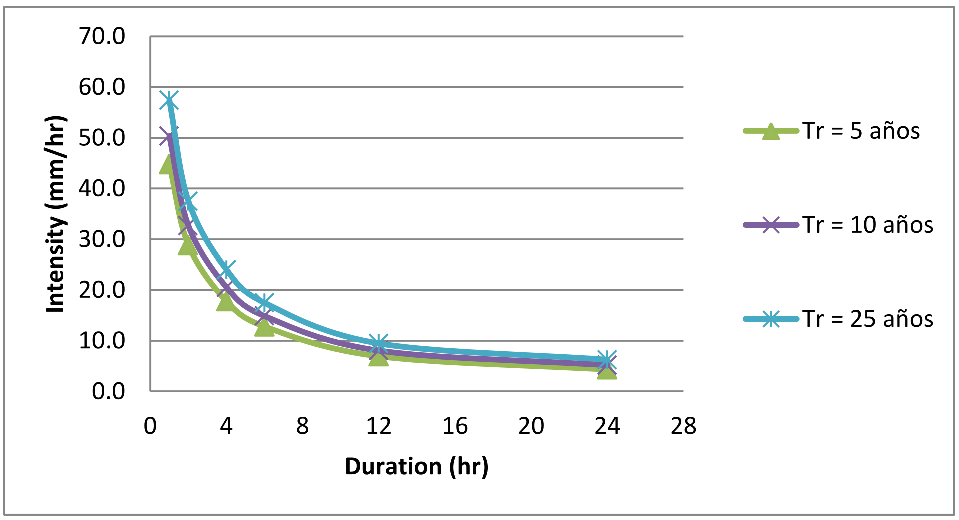


Figure 2. IDF curves for Airport Station

## 3. RESULTS

The land use maps for the different years show a high percentage of urbanization across the middle and lower part of the watershed. It was verified how the river boundaries are not urbanized as well as interrupting sometimes their flooding areas. Based on land use maps (Figure 3) of 2001 to 2012, a 35% increase is expected on the impervious land use areas, when compared to the year 2001. Most of the pasture or bare land use zones in 2001 became urban areas for the year 2012. Those were important areas where water was able to infiltrate and help to reduce runoff water. As stated before the first forecast scenario was calculated based on the growth trend of the selected years. Therefore a 21% increase is expected for the year 2020 on the impervious layers. In the upper part of the watershed there are noticeable permeable areas that should be kept. These areas are of great importance due to the presence of underground aquifers for human use.

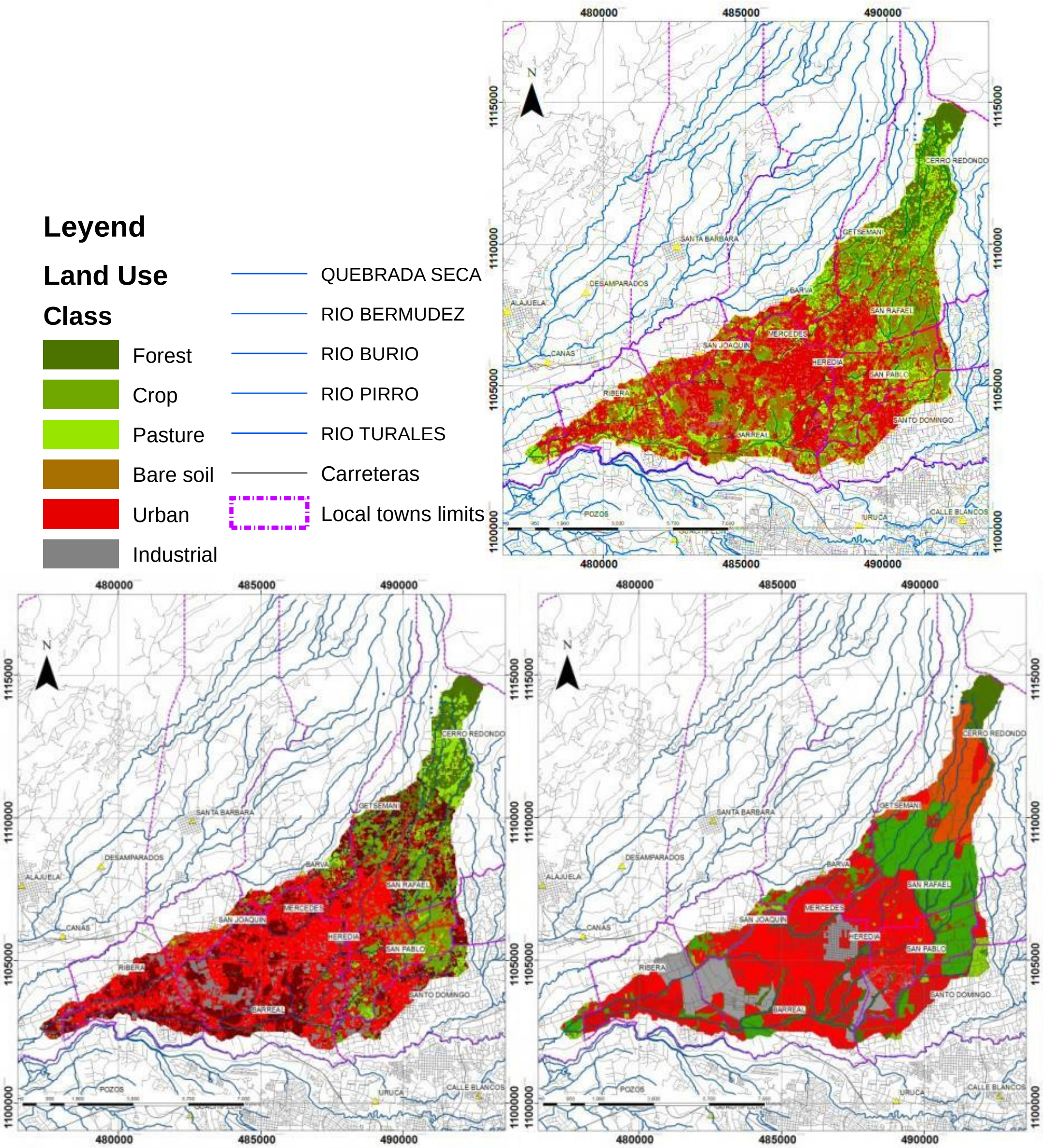


Figure 3. Land use map of 2012 (Up-Rigth), Scenario 1 (Up-Left) and of Scenario 2 (down)

The second scenario used local government-developed regulations. These studies have the goal to assure the correct urban dynamisms without compromising nature and natural waterways. For this reason, there is a protection buffer along the banks of the Quebrada Seca and the Bermudez rivers, as well as green recharge zones inside the cities. The second forecast scenario has the characteristic of having a lower average curve number for the entire watershed. The results of land use of the year 2012 (Figure 3) showed that most of the cities located in the watershed are impervious layers and cover more area than the permeable layers. This means only two cities have more percentage of permeable land use when compared to the entire watershed (Figure 4). For the hydrologic model, 7 different subwatersheds were established based on the main rivers and their influence. When the simulation was conducted, the expected flow increase was highlighted for each scenario. The selected concentration time equation was the Federation Aviation Agency method; it had a range of 50 to 100 minutes for the subwatersheds.

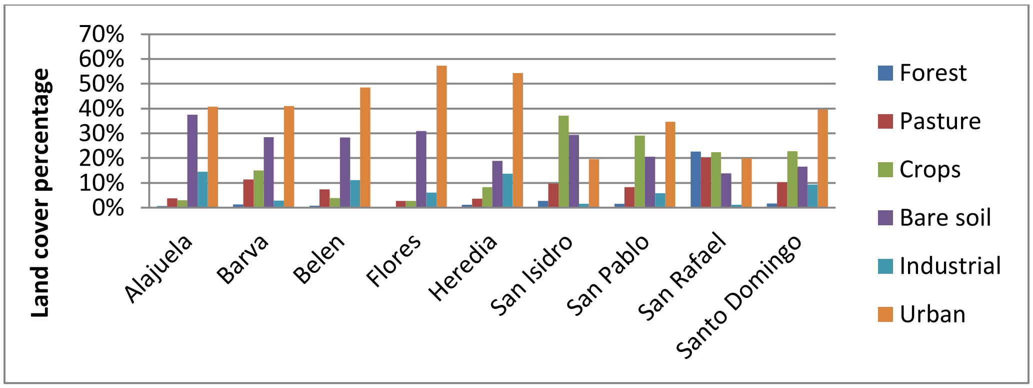

Figure 4. Percentage of land use sorted by local government in the watershed.

An increase in the flows is expected for the years 2001 to 2012 from 4.7% up to 10.6% for different storm durations and return periods. Likewise for the year 2012 and scenario 1 a 3.7% to 8.2% increase in the river flow is expected for Quebrada Seca (Table 1). It is important to mention that according to the current local territorial planning, no increase is expected on those places that have the proper territorial planning. Hence scenario 2 has lower average curve numbers compared to those of the year 2012. Therefore, it is an adequate scenario if the riverbank´s protection margins are protected for example for Quebrada Seca at outlet point a decrease of flow from 0 to -8% can be expected depends on duration and return period.

Table 1. Flow rates percentage increases for Quebrada Seca River

| Land Use | Return period (Years) | 6 hours | 12 hours | 24 hours |
|---|---|---|---|---|
| 2001-2012 | 2 | 10.6 | 9.4 | 9.2 |
| | 5 | 7.9 | 7 | 6.6 |
| | 10 | 6.4 | 6.3 | 5.4 |
| | 25 | 5.9 | 5.1 | 4.7 |
| 2012 - Scenario 1 | 2 | 8.2 | 7.8 | 7.2 |
| | 5 | 5.9 | 5.7 | 5.3 |
| | 10 | 5.0 | 5.0 | 4.3 |
| | 25 | 4.6 | 4.3 | 3.7 |

The sensitivity analysis was developed using one duration time (24hr) and one return year (25 years). It showed that changing the curve number (+10%) produces an increase from 21.2% and 24.4 % in the water flow depending on the river chosen (Table 2). Likewise changing the rainfall depth by +10% can create increases in the flow from 14.7% to 9.4% (Table 2).This demonstrates the importance of having dependable meteorological data in order to achieve an accurate hydrological model.

Table 2. Sensitive analysis results

| **Land use 2001** | **25 year Return Period and 24-hour duration** | |
|---|---|---|
| | **Quebrada Seca River** | **Bermúdez River** |
| CN (+10%) | 21.2 | 24.4 |
| CN (-10%) | -22.0 | -24.3 |
| Tc (+10%) | -5.0 | -6.3 |
| Tc (-10%) | 5.5 | 7.3 |
| Rainfall Depth (+10%) | 14.7 | 9.4 |
| Rainfall Depth (-10%) | -15.4 | -9.8 |

## 4. CONCLUSIONS

In this study the unsupervised classification showed a higher accuracy when generating land use maps and analyzing changes over time. This is probably due to the size of the watershed and the number of pixel elements assigned to every group. Similar to this, the equation provided by the Federation Aviation Agency gave a better estimate of the concentration times (Tc). For the land use change between the years 2001 to 2012, a flow increase of 4.7% to 10.6% is expected, depending on the time period and the duration of storm. Each of the towns inside the watershed can contribute between 1% to 5% to the total flow, again depending on the time period and the duration of storm. Based on the soil change of the last 10 years in scenario 1, a flow increase of 3.7% and 8.2% is expected depending on return periods and storm durations. Likewise, no flow growth is expected for the soil change based on territorial planning setups because the conditions presented in the territorial planning layout promote water infiltration.

## 5. REFERENCES

Chow, V. T. (1959). *Open Channel Hydraulics.* New York: MacGraw-Hill.

Consultora Acón y Asociados. (1991). Manual Descriptivo de la leyenda del Mapa de Capacidad de Uso de la Tierra de Costa Ric. San José, San José, Costa Rica.

Gutierrez, E. (2013). Apuntes de clase *Sig: Sistemas De Información Geográfica.*.

Ministerio de Transportes y Comunicaciones, Perú, (2011) (s.f.). Manual De Hidrología, Hidráulica Y Drenaje. Perú.

Nación (2013). Recuperado el 5 de Enero de 2013. http://wvw.nacion.com/ln_ee/2007/junio/14/ultima-sr1132785.html

ProDus. (2013). Plan Regulador del Cantón de San Joaquin de Flores. Heredia: ProDus.

PRUGAM. (17 de Junio de 2007). Recuperado el 2 de Noviembre de 2012, de Http://201.194.102.38/PRUGAM/Documentos/Propuesta.pdf.

Villón, M. (2012). *Hidroesta 2.* Cartago, Costa Rica, Costa Rica: MaxSoft

Velásquez M., S. (Noviembre de 2011). Apuntes curso Gestión de Recursos Hidrológicos. Cartago, Costa Rica: CATIE.

Zevenbergen, C. (2010). *Urban Flood Management.* CRC Press.