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Distributed River Basin Modeling for Analyzing Flood Mitigation Measures under Non-stationary Conditions

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Interim Report IR-09-054

Distributed river basin modeling for analyzing flood mitigation measures under non-stationary conditions

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Approved by

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October, 2009

Foreword

This report describes the research that the author advanced during her participation in the 2009 Young Scientists Summer Program (YSSP) with the Integrated Modeling Environment Project. The focus of this research is on the application of a new methodology for hydrological modeling, and flood risk quantification. Although many methods exist for flood frequency analysis, they usually require long series of hydrological data. This methodology was developed giving emphasis to areas for which stream flow data is not available or, if available, their use are limited due to nonstationary systems and processes.

The hydrological model used attempts to provide a spatially realistic description of the basin, offering an important tool for a more pragmatic simulation of the physical processes that generate flood. Remote sensing information is the main source of data for the model, making its application viable in any part of the world. During the YSSP the author improved the model to include a more realistic representation of rainfall-runoff processes. The truthfully spatial representation of the basin landscape provides an important instrument to assess the effects of spatial modifications on the basin landscape, like land cover changes or implementation of spatial flood mitigation measures, on flood risk intensity and frequency.

Using the capabilities of the developed model, the author proposed a new framework for the evaluation of land cover changes on flood risk intensity and the assessment of effectiveness of flood mitigation measures. A case study was developed to exemplify the methodology. A simple flood damage estimation model was used as criteria to link changes on flood peak intensity to economic consequences of floods.

The summer-period of the YSSP is only three months short, and this type of research requires substantially more time for completing. Some specifics points of the proposed framework should be review and improved, especially in terms of implementation of more robust probabilistic flood risk analysis. At that time the results presented by the author delineate the framework and the methodology, but future activities will endeavor improvements to each component of the framework.

Abstract

Flood frequency analysis is in the main component of flood risk management projects, influencing pre and post-flood activities. Apart from its importance and the intense research in the area, the available hydrological methods are not adequate, especially under non-stationary conditions caused by land cover or climate change. In this work a new hydrological model is proposed, with the goal of overcome the main weakness of the traditional methodologies.

This research is composed by three main goals. First, the authors attend to add functionalities to an existing calibration-free hydrological model based on the scaling theory of floods. The goal is to provide a better representation of the rainfall-runoff processes that occur in a hillslope scale through the use of empirical models. This model constitutes an important tool for the evaluation of effects of land characteristic changes on flood intensity and frequency.

The second goal is the development of a flood risk framework, with the aim of link hydrological criteria of flood intensity estimation (peak discharge) to criteria that measures flood impact (damages). This activity requires the development of flood maps and the quantification of flood damage. This research presents a simplified methodology for flood risk mapping that can be used for areas with very limited information about the river network. Annual expected damage was used as criteria to evaluate different land characteristics scenarios, being damage estimated by a simple model based on the city parcels structure value and water level-damage curves proposed by FEMA.

The last goal is to develop a simplified case study to demonstrate the model applicability on flood risk management. A case study for Charlotte City, North Carolina was developed. The city has experienced an extensive urban growth since 1960 which has led to significant changes in city's risk and vulnerability to floods. The impacts of urbanization were evaluated using current land cover conditions and two extreme scenarios: pre-development and built-out. The effectiveness of non-punctual flood mitigation measures that are easily harmonized in the urban environment was also evaluated.

The innovative aspect of this study is to present a new methodology for flood frequency analysis that does not require calibration and has the potential to be applied to any region in the world. By this framework a multiple scale analysis of flood peak and flood damage is obtained, providing essential information for the implementation of an optimal flood risk management policy over different levels of governmental policies (local, regional and global).

Acknowledgments

This report and all the research described here were done during my participation in the Young Scientists Summer Program (YSSP) 2009 at the International Institute of applied Systems Analysis in Laxenburg, Austria. The research was done in Integrated Modeling Environment (IME) Project.

I would like to thank my YSSP supervisors Marek Makowski, and his colleagues Yuri Ermoliev, and Tatiana Ermolieva, for their help and guidance in diverse aspects of my research and professional life.

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Finally I would like to thank my IIHR research team, including Witold Krajewski, my PhD adviser, and Ricardo Mantilla, my PhD co-adviser, for their priceless help and to share with me their contagion enthusiasm for science.

About the Author

Luciana Cunha is currently a third year Ph.D. student in the Civil and Environmental Department of The University of Iowa. She earned her Bachelor's Degree in Civil Engineering (2002) and her M.S. in Water Resources and Environmental Engineering (2004) from Universidade Federal do Parana, Brazil. Her main fields of scientific interest include measuring and modelling of hydrological variables, remote sensing and flood forecasting. Her current research focuses on probabilistic flood forecasting based on the scaling properties of hydrometeorological and geomorphological variables.

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1. Introduction:

1.1. Background

In United States approximately 90 percent of presidential declared disasters resulted from floods. According to the National Weather Service, in US floods caused more than 10,000 deaths and approximately more than 470.00 billions of dollars in losses since 1900. The vulnerability to floods is especially high in urban areas, due to high population density and uncertainty on the estimation of floods risk.

Urbanization usually amplifies the intensity and frequency of floods, as well as the vulnerability and exposure of the population. Over the next 30-35 years the total urban population is expected to double from 2 to 4 billion (United Nations, 2006). If not well planned, design and implemented, this rapid and intense urbanization processes can intensify even more the losses caused by urban floods.

Flood management is a difficult task since it involves the quantification of rare events that are usually non-stationary due to climate or land surface changes. According to Dalinsky (1970), conventional statistical approach to flood-frequency analysis attempts to create “something out of nothing”, since the data is neither sufficient, nor descriptive of the physical processes under current and future situations.

Physical models that attempt to promote a better understanding of the physics of flood generation provide an alternative approach to the traditional statistical methods. Since the 60’s the hydrological community has put unquantifiable efforts in developing hydrological models that are able to reproduce this phenomena. Unfortunately the majority of the models apply equation derived for punctual physical processes, such as infiltration or interception rates, and these values are extrapolated to bigger areas without scale considerations. Several studies have demonstrated that this bottom-up incremental approach has been largely unsuccessful (Savenije, H. H. G., 2008; Fenicia, F et al, 2008; Mantilla et al, 2008; Sivapalan, M et al, 2003). In this case, calibration based on streamflow in the outlet of the basin is used to achieve a good match among observed and simulated data. This method also relies in insufficient and non explanatory data.

With the goal of reducing uncertainties in hydrological science and practice the Prediction for Ungauged Basins (PUB) initiative was established by the International Association of Hydrologic Sciences in 2003 (Sivapalan, et al, 2003). One of the main goals of PUB is to promote the development of more understanding-based methods instead of calibration-based ones. This knowledge of process control over flood frequency would allow the estimation of flood frequency under non-stationary and heterogeneous processes (Struthers, et al., 2007).

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In this context, the nonlinear geophysical theory of floods emerges as an alternative approach for hydrological model, linking the "physics of runoff generating processes with spatial power-law statistical relationships between floods and drainage areas across scales of space and time" (Gupta, 1996, Gupta et al 2007). Kidson and Richards (2005) discuss the use of Power-law based on self-similarity as a more plausible framework for flood frequency analysis, compared to the traditional statistical approaches. More details about this theory will be presented in the following section.

Since hydro-meteorological gauge data is lacking around the world, remote sensing information appears as an important tool to achieve the goal of hydrological modeling in these areas. Topography, land cover, and soil moisture are some of the information that are available in a near global based, and that play an important role on hydrological modelling. Topography, for example, is essential since it presents the signature of the river network, determining the existence of power law in floods (Menabde, M eta al, 2001; Furey, P. R. et al. 2005, Mantilla et al, 2008). This information can be extracted from Digital Elevation Models (DEM) that are available for almost every region in the world (with different spatial resolution).

In this work, I present an application of the theory of flood for flood risk estimation under non-stationary hydrological conditions for which historic data does not represent actual and future conditions. As the main data required for model application is available through space born satellite remote sensing technologies, this methodology has the potential to be applied to any location in the world.

In this report a case study developed for Charlotte City and metropolitan area is presented. The reasons for this basin choice are twofold. First, this basin has experienced fast and intense urbanization, what resulted in changes in the hydrological processes that generate flood. Second, this is a very unique area, since a lot of hydrological and hydraulic data are available to validate the results of this study.

1.2. Research Goal

This research is composed by three main goals. First, the author attended to add functionalities to an existing calibration-free hydrological model based on the scaling theory of floods. The goal is to provide a better representation of the rainfall-runoff processes that occur in a hillslope scale through the use of empirical models. This model constitutes an important tool for the evaluation of effects of land characteristic changes on flood intensity and frequency.

The second goal is the development of a flood risk framework, with the aim of link hydrological criteria of flood intensity estimation (peak discharge) to criteria that measures flood impact (damages). This activity requires the development of flood maps and the quantification of flood damage. This research presents a simplified methodology for flood risk mapping that can be used for areas with very limited information about the river network. Annual expected damage was used as criteria to evaluate different land characteristics scenarios, being damage estimated by a simple model based on the city parcels structure value and water level-damage curves proposed by FEMA.

The last goal is to develop a simplified case study to demonstrate the model applicability on flood risk management. A case study for Charlotte City, North Carolina was developed. The city has experienced an extensive urban growth since 1960 which has led to significant changes in city's risk and vulnerability to floods. The impacts of urbanization were evaluated using current land cover conditions and two extreme scenarios: pre-development and built-out. The effectiveness of non-punctual flood mitigation measures that are easily harmonized in the urban environment was also evaluated.

1.3. Research Scope

The scope of this research is to develop a methodology for flood risk estimation that takes advantage of remote sensing information and has the potential of being applied globally. To achieve this goal, a parsimonious hydrological model called CUENCAS is used. This model uses topographic data to extract the network geometry, hydro-meteorological data as its main input and land surface data (e.g. land cover and soil data) to estimate hydrologic partitioning at the hillslope scale. The model was improved to provide a better description of the rainfall-runoff transformation processes that occurred in a hillslope scale.

The methodology was tested in a flood intensity study for Charlotte City and metropolitan area. The hydrological model presents an estimation of the impacts of land cover changes on flood peak and consequently flood intensity. Though a spatial representation of the basin landscape it is also possible to assess the effectiveness of spatial distributed flood mitigation measures. A simple methodology for the generation of flood inundation maps and a flood damage estimation model were used to estimate flood losses. This provided a link between hydrological intensity of the flood and flood losses.

2. Methodology

In this section I present a review of the main subjects involved in this work. The main goal of this research is to uphold the understanding of the physics of flood generation, and the factors that affect flood intensity and frequency. To exemplify how this knowledge can be used for flood management activities, a case study for Charlotte city was developed.

In the first section I provide the definition and an overview of flood risk management activities, giving emphasis to the difficulties involved in the quantification of hydrological variables. The intention is to demonstrate the importance of precise hydrological information for flood mitigation studies. In the second and third part a review of the main hydrological concepts and methodologies applied in this work is presented. It is important to emphasize that a better understand of the hydrology of floods is the key to reduce uncertainties on hydrological modeling. This is the main focus of the author's research. The next sub-sections briefly describe the tools used to estimate the benefits of flood mitigation projects, including generation of inundation map and quantification of flood damage.

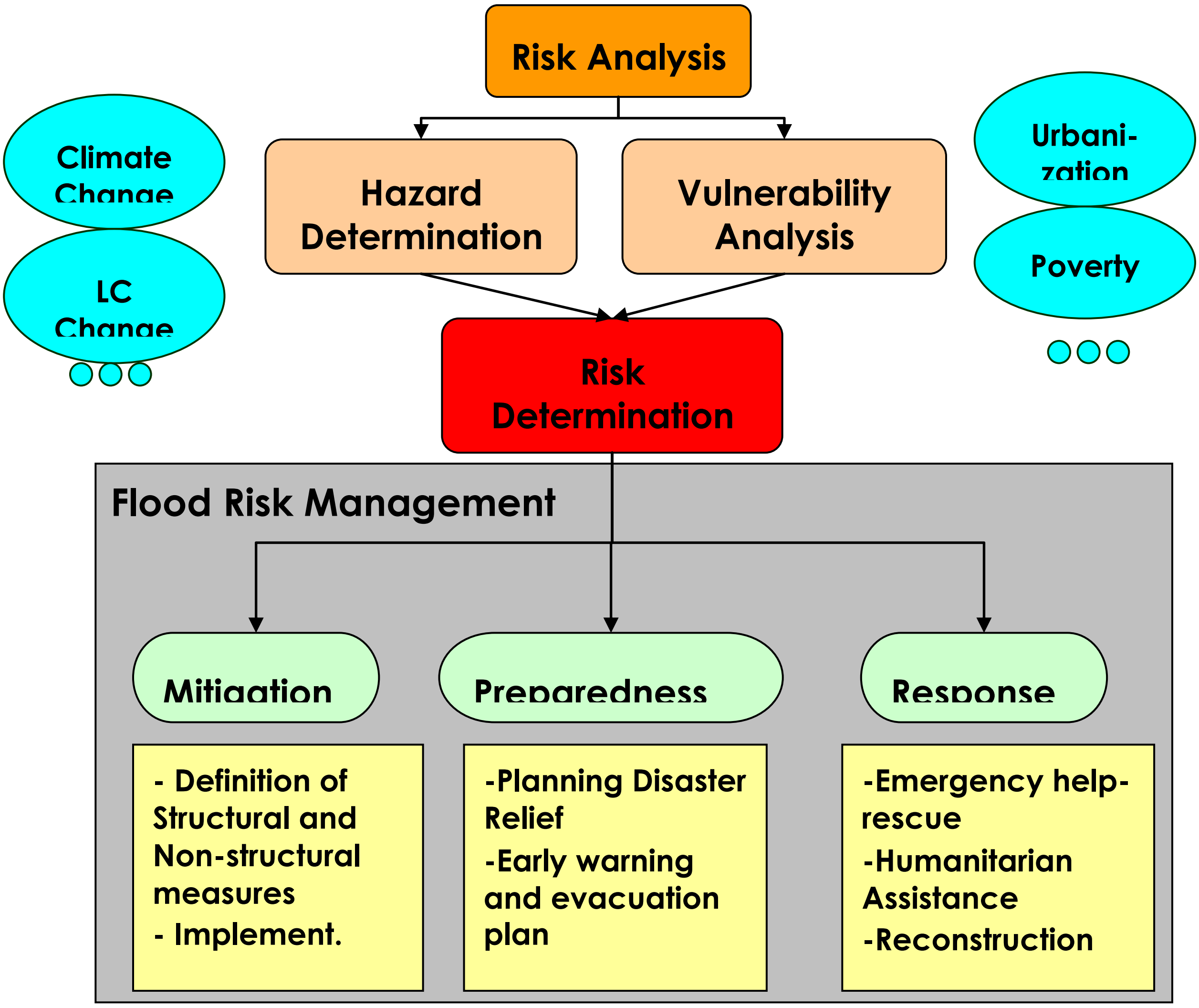
2.1. Flood risk Management

Risk management involves the identification, assessment, and prioritization of risks followed by coordinated and economical application of resources to minimize, monitor, and control the probability or impact of unfortunate events (Douglas Hubbard, 2009).

An effective flood risk management involves activities related to the prevention, protection, preparedness, emergency response, and recovery from floods. As pointed out by Plate, E. J, (2002) risk quantification forms the basis for all these activities, including decisions on maintaining and improving the flood mitigation system (Figure 1). In despite of its relevance on disaster management, sometimes not enough importance is given to this phase of the project. Very often inappropriate methods are used, and the consequences are completely ignored. For example, historical records of streamflow are used in the estimation of floods with different time recurrence, under the assumption of stationarity of physical processes, ignoring the fact that this assumption is not valid under scenarios of climate and land cover change.

In this context, one of the main challenges in urban flood management is the precise consideration of risk hazard with and without the implementation of flood mitigation measures, and across different spatial and temporal scales. The effects of urbanization, and flood control measures, cannot be considered in isolation at the local (city) scale, or just on points where streamflow data is available. Watersheds are complex dynamics systems that have to be analyzed as a whole, rather than focusing on isolated components or areas.

Figure 1: Flood mitigation management - activities and the role of risk analysis



2.2. Scaling theory of floods (present an example for the Charlotte basin)

One of the key challenges in hydrology today is to understand the scaling of hydrological process, and to determine at which scale hillslope scale heterogeneities average out, and an average hydrological response can be found (Didszun et al, 2006).

Diverse studies have supported the evidence that extreme natural events can be described by power law distributions (Turcotte, 1994; Scheidegger, 1997; Birkeland and Landry, 2002, and Gupta and Waymire, 1990; Hubert, 2001, Scanlon, T. M., 2007). In the case of floods, diverse authors demonstrate that peak flows quintiles are related to drainage areas through a power law relationship, and the study of this relationship is called "Scaling theory of floods" (Gupta and Dawdy, 1995; Robinson and Sivapalan, 1997, Michele et al., 2002, D. L. Turcotte and L. Greene, 1993, Molnar, 2006). The current research effort aims to provide a physical basis for this theory, linking the parameters of the power–law statistical relations to physical processes involved on runoff generation (Gupta, 2007).

According to this theory, peak flow scaling structure is expressed by the power law equation that relates peak flow to basin contribution area:

$$Q_p(s) = \alpha A(s)^{\theta}$$

This relationship is characterized by the scatter of the points around the fitted line, the scale break characterized by a critical area Ac at which the scaling exponent changes, and the regression parameters: (1) exponent α , and (2) intercept θ. As described by Gupta (2003), the slope α is nearly the same for floods of different return periods when the processes present statistical simple scaling.

According to the scaling theory of floods, these parameters are a function of the river network, rainfall and rainfall – runoff processes characteristics and variability in space and time. These hypotheses have been demonstrated in a series of theoretical (Furey et al. ,2005; Menabde et al., 2001a,b; Veitzer et al, 2001; Troutman et al, 2001; Morrison et al, 2001; Gupta et al., 1998; Gupta et al., 1996) and data-based (Furey et al. 2005; Ogden FL, 2003; Goodrich et al, 1997; Lee et al, 2009; Fu et al, 2008, Furey et al, 2007) studies that demonstrate that the rainfall and the channel network topology play an important role on the peak flow power law parameters.

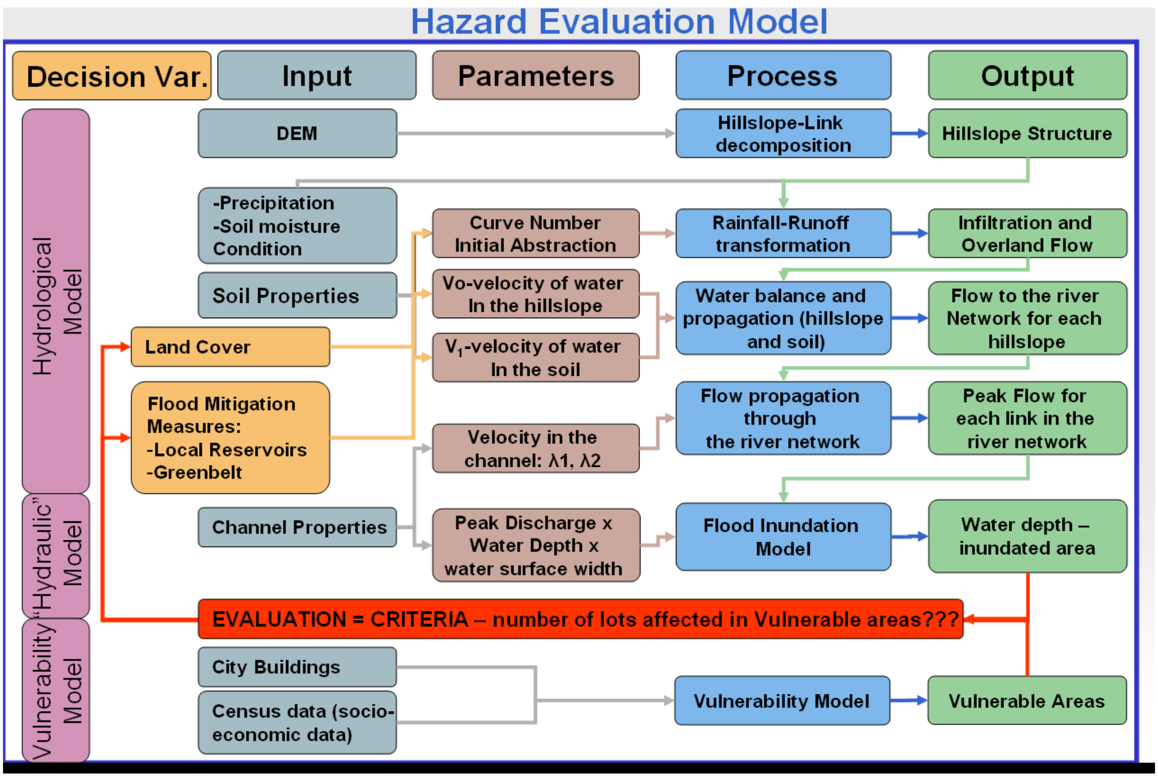
Many of the studies mentioned in this report relate physics of the river channel, or rainfall characteristics, to the scaling parameters of the peak flow. The relationships between rainfall-runoff transformation processes and their parameters is still not well studied and constitute one of the goals of this work.

2.1. Hydrological Model

A hillslope-linked based spatially distributed hydrologic model, called CUENCAS (Mantilla et al. 2006), was used in this study. One of the goals of this work was the improvement of this model to include a more realistic representation of physical processes that occurred in the hillslope scale. The model was used to calculate hydrographs for all the links in the river network, providing information to investigate the effects of land cover changes on runoff generation and on the scaling properties of floods.

The following sections present a brief description of the model components. The model is composed by four main components and the schematic overview of the processes, input, output and parameters is presented in Figure 2. A more detailed description of the model and its equation is presented in Appendix 1.

Figure 2: CUENCAS – Diagram of input, parameters, processes and outputs



2.1.1. Hillslope-link decomposition of the landscape

The drainage basin can be treated as a collection of hillslopes and channel links, and CUENCAS reproduce this spatial distribution of natural hydrological systems. High resolution digital elevation model is used to extract the drainage structure using algorithms based on the maximum gradient method and pruning algorithms to determine the initial location of the river network.

Hillslope is the fundamental element where the partition of rainfall into interception, infiltration, and runoff occurs. Runoff generated in each hillslope drains to the river network. Appendix presents the hillslope discretization for the study area. The main stream corresponds to a 7th order Horton stream with total area equal to 714 km2. This area was discretized in more than 15000 hydrological units with an average hillslope area equal to 0.05km2.

2.1.2. Rainfall-Runoff transformation

For this study, the Soil Conservation Service Curve Number Method (SCS, 1972) was chosen to compute direct runoff and infiltration rate. The main advantage of this method is the reliance on only one parameter, the Curve Number that depends on soil properties, land cover, and antecedent soil moisture. This model has been extensively studied and used in the hydrological community to solve a large diversity of problems (USDA, 1986, Sharpley and Williams, 1990, Williams et al., 1985; Arnold et al., 1990, Young et al., 1989, Ponce and Hawkins, 1996; Bhuyan et al., 2003). The relationship between basin physical properties and Curve Number is based on a large number of empirical experiments realized in watersheds with areas similar in size to the unit area defined by CUENCAS.

The original method formulation combines the water balance equation and two basic hypotheses. The main one considers that the ratio of actual amount of direct surface runoff to the total rainfall is equal to the actual infiltration to the amount of potential maximum retention. The second one is related to the initial abstraction that considered that runoff starts after an initial abstraction due to interception, infiltration, and depression is satisfied. The final model equation estimates accumulated runoff based on accumulated precipitation for a rainfall event. For this application the previous equation was modified to account for infiltration rates that vary in time as a function of the deficit of water in the soil. A differential form of this equation is used to estimate runoff and infiltration rate for each time step. The basic model equations are presented in Appendix 1.

This model formulation allows an analysis of how hydrologic heterogeneities on the hillslope scale give rise to aggregated answer in a basin scale, responsible for the scaling properties of floods.

2.1.3. Hillslope water balance and routing

A conceptual model compound by two reservoirs is used to represent the surface and the soil water balance. The outflow for each reservoir is calculated using a linear reservoir model. The response factor (or reservoir storage constant) is calculated by each hillslope as a function of its physical properties (area, length, slope, soil type and land cover) using the NRCS Velocity Method [4]. The velocity of the subsurface depends on soil type and properties, hydraulic gradient and presence or not of different soil structures. These variables represent the heterogeneities of hydrological processes for the hillslope. The water balance and routing equations are presented in Appendix 1.

2.1.4. Flow propagation through the river network

Using a mass conservation equation and the hillslope-link structure defined in the decomposition of the basin, the channel discharge for each link in the river network can be calculated using a numerical method. In this application we use the Runge-Kutta-Felberg algorithm for solving non-linear ordinary differential equations. This method uses a time step control algorithm to avoid numerical errors.

The velocity of the flow in each channel is calculated using a nonlinear equation that relates velocity in channel to the discharge in each link and the corresponding upstream area. The parameters of this equation were estimated using observed velocity and discharge data by diverse points in the basin.

2.2. Inundation map

A simplified methodology to estimate inundation maps is used in this work. The hillslope-link structure of the hydrological model provides peak information for each link in the river network. Water depth for each river section is estimated using a hydraulic relationship that relates water depth with peak discharge and basin contributing area:

$$D_p(s) = \alpha Q_p(s)^{\lambda d1} A(s)^{\lambda d2}$$

The parameters of this equation are estimated using hydraulic measures provided by USGS containing water depth and discharge measures for different locations under different hydraulic conditions. The altitude of water is calculated considering the river bed altitude of each link and the inundated area is estimated in a hillslope base.

Flood inundation maps are an important instrument on flood management, affecting all the agents involved in flood management. Such maps serve to identify vulnerable areas, providing the basic information used by local government to develop regulations and zoning taking in consideration the risk of floods. Local Planners are geared in terms of the location they should consider for their new developments. General public are oriented about the risk of floods for the property they intend to buy. Especially in US, flood inundation maps forms the basis for the definition of flood insurance premiums in the floodplain (FEMA, 2009).

Hydraulic models for estimation of inundation maps are highly data demanding. While some cities already collect the necessary information to accurately model their flood area, the majority of the cities around the world, especially in developing countries, still do not have such database available. In this work we present a simplified methodology for the execution of inundation map with very low data requirements.

We recognize that errors are expected, being the main source the low resolution of digital elevation model being used. But this is an alternative methodology developed to be applied for the cases for which just DEM information is available.

2.3. Risk Analysis

Risk Analysis is based on the determination of flood hazard, flood vulnerability and flood risk. In this work a simplified risk-analysis method is used for the assessment of flood risk with and without the implementation of different flood mitigation measures. Estimating flood risk is a multidisciplinary task that involves statistics, climatology, meteorology, hydrology, hydraulic engineer, sociology, and geography.

Flood risk is the product of flood occurrence probability and expected damage potential. The expected annual damage is calculated by the integral of the risk density curve. Measures to reduce flood risk can act in the reduction of the probability of risk (structural) or the potential damage (non-structural).

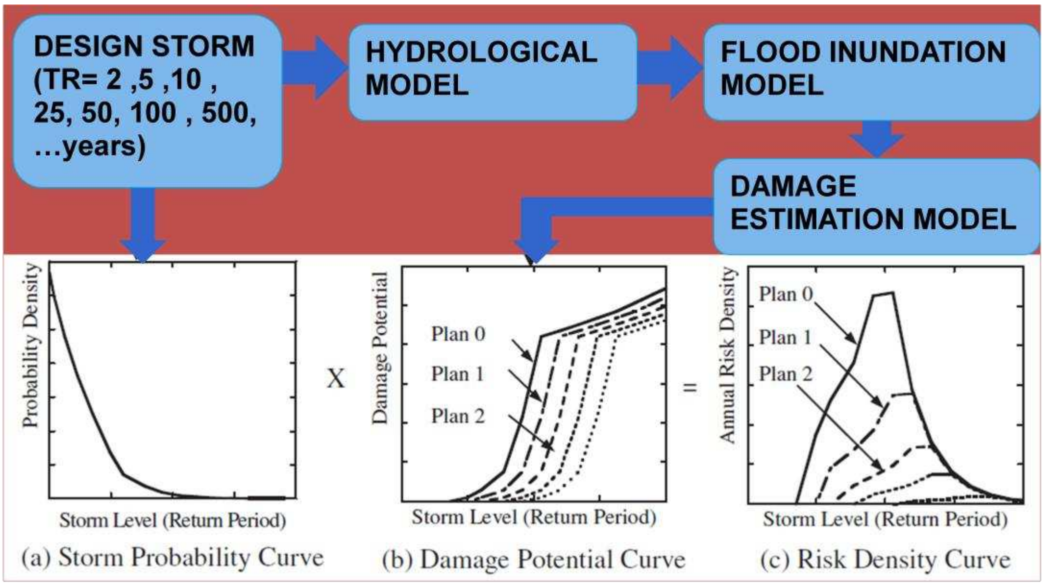
In another conceptualization of risk, reinsurance companies estimate risk though the multiplication of three factors: hazard, exposure and vulnerability. The first one represents the flood probability, the second the capital and population in flood risk areas and the third the acceptance of floods and capacity to recover.

In this work we considered the first formulation, since the vulnerability of the population to floods is not altered with the implementation of structural flood measures. Sarewitz (2003) defines vulnerability as an inherent characteristic of a system that creates the potential for harm independent of the probabilistic risk of the occurrence. To decrease the vulnerability of the populations to floods instruments as early warnings and emergency response, or adjustments to individual houses and infrastructures making there more resistant to floods, are necessary. We acknowledge that a complete flood risk management project should contemplate vulnerability reduction, but this subject is out of the scope of this study, that focuses in the hydrological part of flood.

It is important to point out the importance of consideration of uncertainty on flood risk analysis. Two types of uncertainties should be considered: (1) Eleatory, that is related to natural variability of the processes over time; and (2) Epistemic, that is related to the limited knowledge of elements and processes that generate flood. In the study, expected annual damage does not contain considerations about knowledge uncertainty, since it is calculated by averaging natural variations among floods. Future improvement of this methodology will incorporate knowledge uncertainty through the specification of a probability distribution for expected annual damage.

As represented in Figure 3, the risk density curve (curve c) is the product of flood occurrence probability (curve a - Storm Probability Curve) and expected damage potential (curve b- Damage Potential Curve). The expected annual damage is calculated by the integral of the risk density curve. Measures to reduce flood risk can act in the reduction of the probability of risk (structural) or the potential damage (non-structural). In this figure the different plans (0, 1, 2) represent the reduction of the potential damage to the implementation of flood mitigation measures (Morita, 2008).

Figure 3: Risk analysis assessment



Adapted from: Morita, M. Flood risk analysis for determining optimal flood protection levels in urban river management. Journal of Flood Risk Management, v1,n3, 2008.

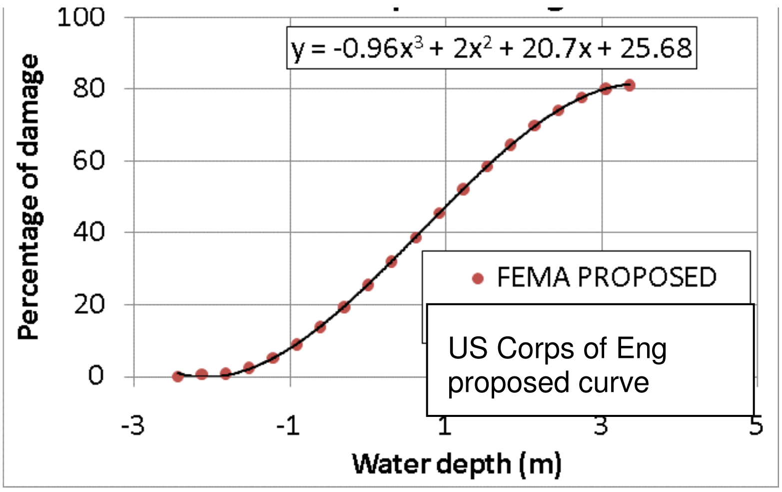
2.4. Potential Damage Estimation

In this work direct tangible damages are estimated as a function of water depth using structure water depth – damage curves. There is a great variety of depth-damage relationships in around the world. The curve used here was presented by The US Corps of Engineer (Figure 4).

Other factors should be included in the estimation of potential damage, considering that the consequences of a flood encompass multiple types of damage, such as environmental losses, economic damage, and loss of life. As an example, in the last case Jonkman, S.N. (2007) presented a methodology to estimate the number of fatalities caused by a flood event where loss of life is a function of flood characteristics (depth, velocity), the possibilities for warning, evacuation and shelter and the loss of shelter due to the collapse of buildings. Other social and behavior aspects can also be included.

Even though the methodologies to quantify different types of losses are available, on this research just tangible damage were considered. Since the goal of this research is to present an application of the proposed model, we considered that a not subjective loss measure would be more appropriate. The inclusion of social and environmental factors would require a broad analyze of available methods, what is not the scope of this research.

Figure 4: Depth – percentage of damage - structural loss.



2.5. Flood mitigation measures (non-structural)

In this work a risk approach is used to quantify the effectiveness of flood mitigation measures, where flood risk is equal to the flood probability time the potential damage. This is a simple method that is being used in this research to exemplify the application of the new framework proposed, that involves new hydrological model for flood risk analyze. Probabilistic flood risk analyzes would be a more appropriate methodology, but due to the long time required this method is not suitable for a short term research project.

In this research flood mitigation measures that seek to control the rainfall water (rainfall and snowmelt) at the point it is generated are considered. These type of mitigation systems attempt to simulate the natural flow of water before the area was developed. Among the measures study are on-site reservoirs, parks and greenways and green roof.

Reduction of expected annual damage is the criteria used to evaluate the effectiveness of flood mitigation measures. The decrease of expected annual damage is caused by reduction of peal discharge for different return period floods, and consequently water depth.

2.5.1. On-site reservoirs

The idea of on-site reservoirs is to define areas where the storm water can be retained during the flood event, without causing relevant losses. The reservoirs are usually designed and implemented in recreational areas that are flooded during extreme events. Depending on the intensity of the storm and the reservoir size, water is released out at a rate that the river can better support without causing major floods locally or downstream.

In this study we first calculated the amount of reservation necessary to guarantee peak discharges not higher than the pre-development values for each hillslope. The relevance of this analysis is due to the fact that many local governs use the pre-development runoff as urban performance standards for new construction sites. To establish a new development the maintenance of pre-development peak discharge rates for the 2-year, 24 hour design storm is usually required. The pre-development versus post-development runoff volume analysis is usually in this report to estimate the minimum reservation required for each hillslope.

In a second approach, a specific constant volume of reservation was defined for each unit area and its effects throughout the basin are investigated.

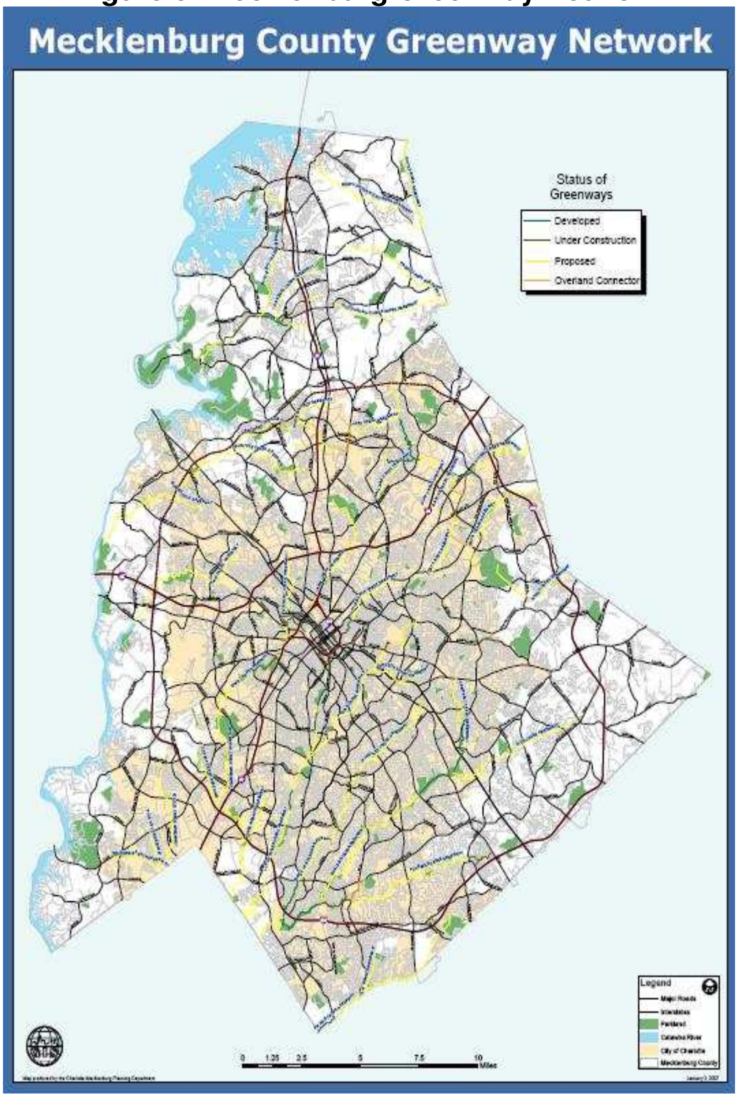
It is important to emphasize that the goal of this work is to present the framework and methodology to evaluate the effectiveness of flood mitigation measures. At this point, this study does not aim on optimizing the reservoirs spatial location and volume in order to achieve the best flood mitigation with the resources available. This will be the subject of future research.

2.5.2. Parks and Greenways

The Meckeland County developed the “Greenway Action Plan” that aims the implementation of more than 42 miles of new greenways in the next five years, in addition to the 24 miles that already exist. The main function of the Greenways is recreational, but it is also known that this green buffer filter out pollutants from storm water, increase the infiltration capacity of the hillslope, and decrease the velocity of the flow to the river, reducing peak flows. It also presents the big advantage of avoid occupation of the floodplain areas.

In this study the effect of the implementation of these structures on peak flow is investigated. The 2001 land cover map was modified to include Parks and Greenways as flood mitigation measures, and estimation of peak flow and flood damage were performance.

Figure 5: Mecklenburg Greenway Network



Source: http://www.charmeck.org/Departments/Park+and+Rec/Greenways/Home.htm

2.5.3. Green Roof

A green roof is a building covering that incorporates vegetation with the goal of essentially replace the natural vegetation that was in the area before the building was constructed. Green roofs present diverse environmental benefits, including stormwater management, energy conservation, mitigation of the urban heat island effect, increased longevity of roofing membranes, as well as providing a more aesthetically pleasing environment to work and live (Oberndorfer, E. 2007). In terms of stormwater management, some studies have demonstrated that green roofs work as a water retention system that reduces the amount of runoff from the roof and the velocity of the flow to the river (Getter, K.L.2007).

In this study we quantify the effects of green roofs using different scenarios of public policy. We considered that Green Roof will be required for different types of edification according to it use, or for all the building located in a specific region of the basin. These scenarios are used to exemplify how green roofs could be established in an already urbanized area.

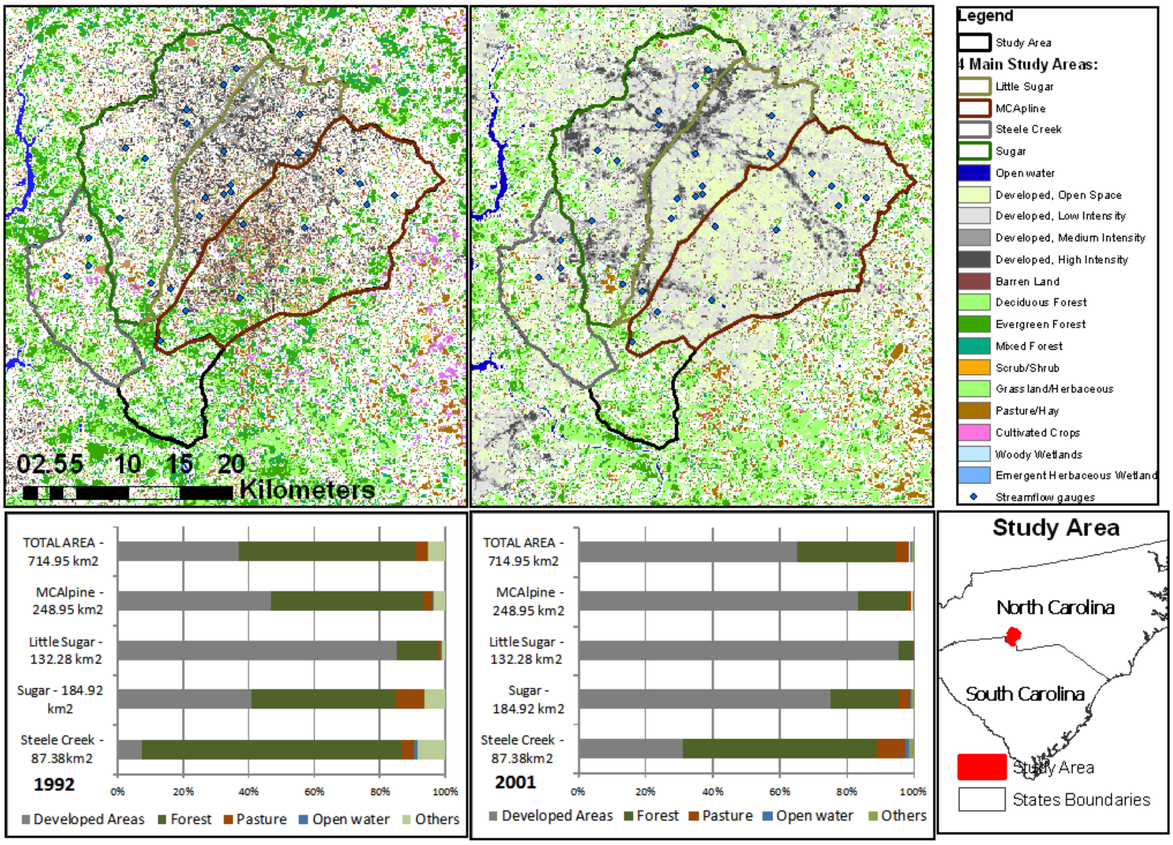
3. Case Study: Charlotte City

3.1. Area Description

The study will be developed for Charlotte City and metropolitan area. It is the largest city in the state of North Carolina and has experienced fast and intense urbanization, with population growth rate of 82% in last two decades. The urbanization process has accentuated the changes in city's land cover, which originally constituted Forests mostly. Land cover being one of the main factors that shapes the hydrological response of a basin to rainfall, it is believed that these changes caused intense modifications in the hydrological processes of this area.

Figure 6 presents a map for the Study Area with Land Cover for 1992 and 2001. The total 714 km2 will be discretized in four main regions that experienced different land cover changes during this period. The spatial location as well as land cover information about each one of them is also presented in Appendix 1. In the map we can see that changes in land cover are not just due to the increased percentage of urban area, but also in the intensity of development of each region. For example, in 1992 almost all of the Little Sugar Basin area was already urbanized. The biggest change in this case was due to the intensity of development that altered from Low to Medium or high.

Figure 6: Land Cover 1992 and 2001



3.2. Data requirement

3.2.1. DEM

In this study 2-arc-second (also known as 30-minute) USGS Digital Elevation Model (DEM) data were used. DEMs files are digital representations of cartographic information in a raster form. DEMs consist of a sampled array of elevations for a number of ground positions at regularly spaced intervals. These digital cartographic/geographic data files are produced by the U.S. Geological Survey (USGS) as part of the National Mapping Program (USGS, 1997).

3.2.2. Land Surface Data

Land cover data with generated by The Multi-Resolution Land Characteristics (MRLC) Consortium for years 1992 (NLCD-1992) and 2001 (NLCD-2001) were used in this study (Vogelmann, et al, 2001and Huang, C, 2002). The spatial resolution of the data is 30 meters, what is adequate to study urbanized areas.

NLCD 1992 (National Land Cover Dataset) was derived from the early to mid-1990s Landsat Thematic Mapper satellite data and presents 21-class land cover classification scheme mapped consistently over the United States using unsupervised clustering and GIS modeling. NLCD 2001 is also a Landsat based land cover database with 21 classes of land-cover data.

3.2.3. Hydraulic Relationships

U.S Geological Survey (USGS) performs periodic measurements of stream flow, gage height, and flow properties in diverse locations around US river network. These measurements are often used to supplement and (or) verify the accuracy of the time-series measurements.

These measures are also very important for the study of at-a-station hydraulic geometry. These relationships promote the link between cross-sectional hydraulic characteristics and instantaneous discharge (Rhoads, 1991) and are fundamentally important to physical and biological studies of streams and in the development of the basis of the scaling theory of floods.

USGS maintain 44 sites in the study area, for which a total of more than 5400 measures where made since 1960. These measures were used in a multivariate regression model to estimate the following variables:

1) Velocity in the channel that is calculated in function of channel discharge and drainage area. The validity of this relationship was studied by Mantilla (2007). Figure 7 presents the estimated values versus the observed values of velocity for all observations in the area.
2) Water depth is calculated in function of peak flow and drainage area. Figure 8 presents the estimated values versus the observed values of water depth for all observations in the area.

Figure 7: Predicted Velocity x Observed Velocity

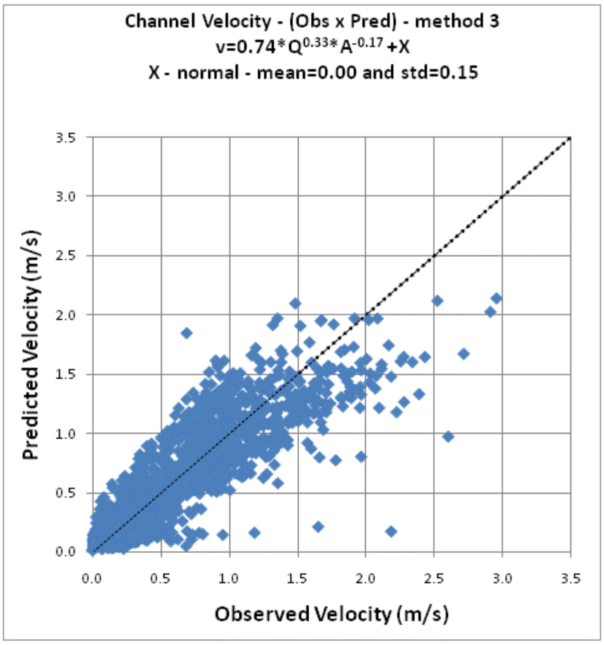
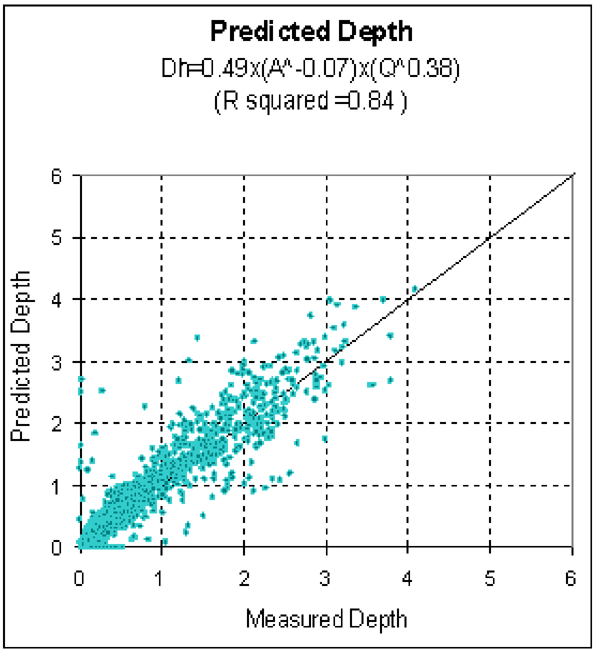


Figure 8: Predicted Depth x Observed Depth



3.3. Simulation Framework

3.3.1. Probable maximum precipitation for different recurrence interval

A design storm expressed in terms of return period is derived from an intensity-duration-frequency relationship presented by USGS for Mecklenburg County (Weaver, J. C., 2004). The study provides information about the occurrence of precipitation amounts for given durations (1 min to 24 hours) that can be expected to occur within a specified recurrence interval (2, 5, 10, 25, 50, 100, and 500 years). In total, 27 sites having more than 10 years of precipitation record were considered in the derivation of the relationships.

The alternating block method (Vent e Chow et al. 1988) was used to generate hyetographs using the IDF relationships for different return periods. Precipitation varies in time with the peak of the storm being in the middle of the event. This precipitation is applied uniformly over the entire basin.

As demonstrated by Mandapaka et al. (2009) the effect of rainfall spatial variability on the basin response is scale-dependent. The intensity, duration and spatial distribution of rainfall are just relevant for small scale, while for bigger scales the variability in rainfall is dampened by the aggregate behavior of the river network. In this case the important factor is the precise quantification of the total storm volume.

The aggregated behavior of the stream flow generation is the result of the hillslope and river network action. The first one filters and attenuates the rainfall signal producing runoff that is routed to the river network. The river network connects the different part of the basin, organizing the volume of water received and averaging out heterogeneities in the hillslope scale.

3.3.2. Land Cover Scenarios

Different scenarios of land cover were considered with the main goal of providing a broad view of the effects of land cover changes on flood intensity across multiple scales and different spatial heterogeneity conditions. The scenarios included extreme and homogeneous situations (from pre-development and built-out conditions), past and existing condition, and situations for which flood mitigation measures are implemented. A brief explanation of each one of these scenarios is presented below and a description of the flood mitigation measures is presented in the next section.

3.3.2.a) Pre-development (considering that series are stationary and basin properties do not change)

This scenario considered the pre-development situation, when just native vegetation where in place. The land cover condition is almost homogeneous in time, with just 4 types of land cover: Open water, Woody Wetlands, Emergent Herbaceous Wetlands, and forest. The spatial variability is still present due to the soil properties that vary from low to high runoff potential. The land cover and soil properties for this scenario are presented in Figure XXX.

3.3.2.b) 1992 and 2001 Land Cover

Land cover information for 1992 and 2001 were used in this work to evaluate the effects of land cover change on flood intensity. These two years were chosen since high resolution land cover (30 meters) information is provided by The Multi-Resolution Land Characteristics (MRLC) Consortium.

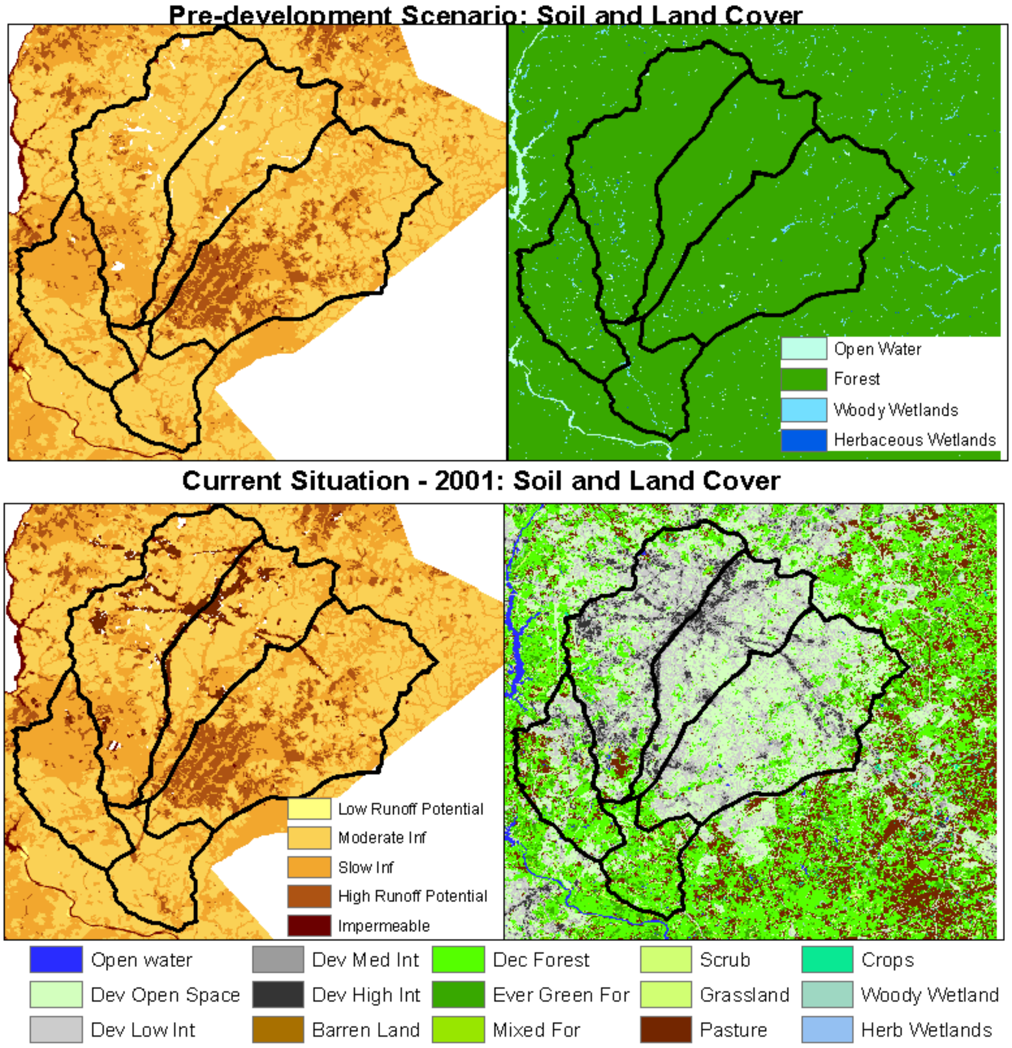
The land cover characteristics from 2001 is considered similar to the current situation (2009) since a big part of the basin was already developed. The land cover for 2009 could be obtained through the use of remote sensing data (LANDSAT) but this option would provide land cover maps with much lower resolution. We opt to work with information not update on time, but with high accuracy and resolution in space. Future work will considered more recent land cover information.

Figure 9 also present the division of the study area for 4 main basins, with different degrees of urbanization. Little Sugar Basin is located in the core of Charlotte City and present the highest percentage of developed areas for 1992 and 2001. The changes in the basin during this period were from low to high intensity development area. The other extreme case is the basin located in the west part of the study area. The percentage of developed area increased from 6% in 1992 to 34% in 2001.

3.3.2.c) Full-built-out (in a similar approach presented by Michael A. Spencer (2007) – Using risk-based analysis and geographic information system…..

This "full build-out" scenario represents the case for which the whole basin is impermeable. A similar approach was used by Hardmeyer et al (2007) in an study for an urban watershed in the state of Rhode Island, USA. This scenario was established as the worst case scenario, where all the rainfall is directed converted in runoff. The interesting aspect of this scenario is the homogeneity of land properties (soil and land cover properties) in space. The comparison of the power law relationships and variability from this scenario with the ones described before provides information about how much heterogeneity on peak discharge is caused by heterogeneity in land surface properties and how much is caused by heterogeneities on hillslope geometry.

Figure 9: Soil and Land Cover maps for Pre-development scenario and current (2001) situation



4. Results

4.1. Effects of land cover on flood

4.1.1. Runoff Coefficient

Land surface characteristic has a strong effect on the hydrological response of river basins, and its change can dramatically modify the risks of floods. These effects can be mitigated by the use of structural measures that attempt to hold the water where it is generated.

Runoff coefficient is defined as the percentage of the precipitation that is converted in runoff. During an extreme event the major part of the precipitation either infiltrates in the soil, or flows to the river. Part of the water is also retained in small terrain depression. The urbanization processes usually increases the runoff coefficient due to the impermeabilization of the soil, caused by concrete surfaces or soil compactation.

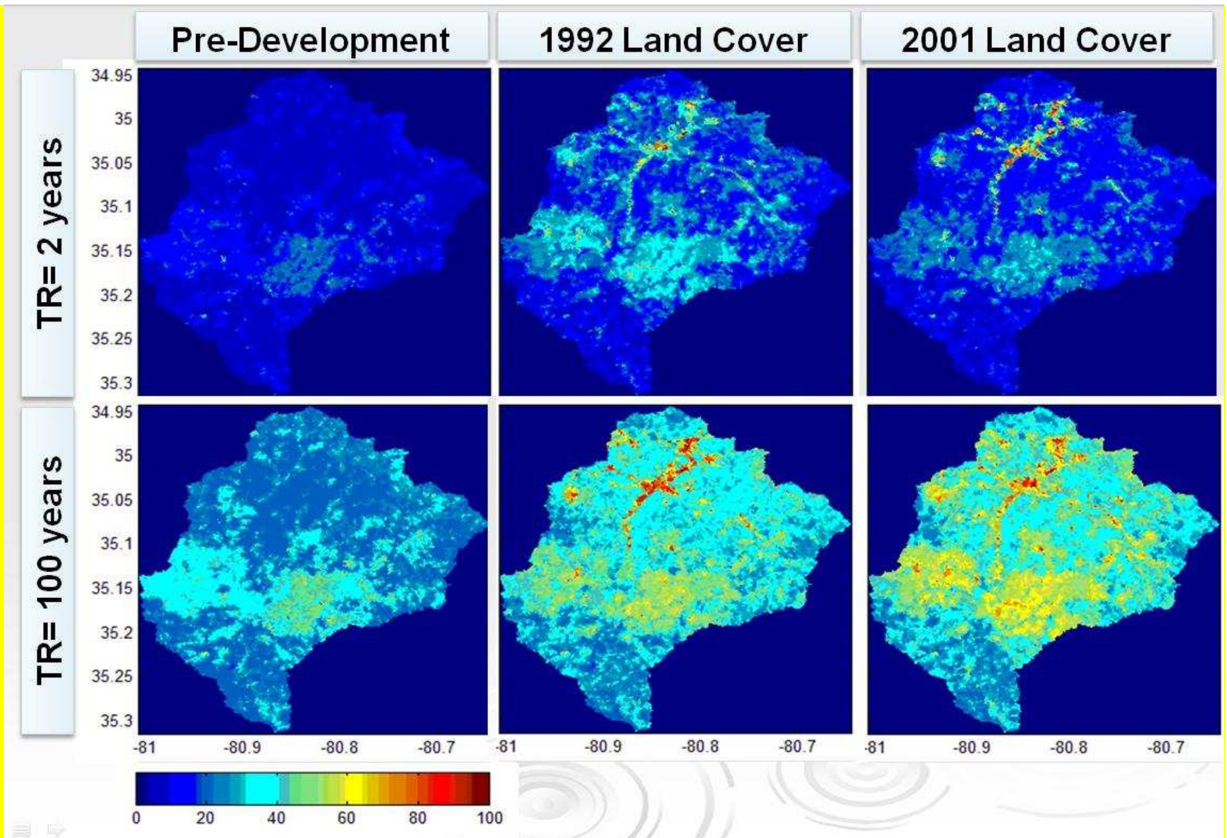
Figure 10 presents the runoff coefficient for different land cover scenarios and Return periods (2,100). We can see that for 2 years return period, there is a significant increase in the runoff coefficient for different land cover configurations. In this case for the pre-development scenario almost 90% of the water infiltrates in the soil.

On the other hand, for 100 years return period the values for the pre-development land cover were already high. The reason for that is that after certain volume of water reaches the basin, the basin soil is already saturated, and water will be converted in runoff independently of the type of land cover. The difference on runoff coefficient in this case is due to the fact that the saturation of the soil occurs faster for urbanized areas, since the soil is compacted and not a lot of space is available to retain the water.

With that we can conclude that the effects of urbanization on runoff coefficient are higher for lower return periods. For higher return periods the volume of water is so high, that even in forest condition a lot of water will be converted in runoff.

Another important factor is the soil hydrologic group, a classification of the soil according to their water infiltration characteristics and their runoff potential. The south part of the basin is constituted by soil of the Group B, that are characterized by moderate infiltration rate when thoroughly wet. These consist chiefly of moderately deep or deep, moderately well drained or well drained soils that have moderately fine texture to moderately coarse texture. These soils have a moderate rate of water transmission, independent of the land cover type. In this case the effects of land cover are less significant.

Figure 10: Runoff coefficient for different land cover scenarios (Pre-Developed, 1992 and 2001) and Return Period



4.1.2. Scaling properties of floods

As discussed on item 2.2, according to the scaling theory of floods peak flow scaling structure is expressed by the power law equation that relates peak flow to basin contribution area. This relationship is characterized by the scatter of the points around the fitted line, the scale break characterized by a critical area Ac at which the scaling exponent changes, and the regression parameters: (1) exponent α , and (2) intercept θ. In the case of statistical simple scaling the slope α is nearly the same for floods of different return periods.

Figure 11 shows an example of power law relationships between peak flow and basin area for different land cover scenarios (pre-development, 2001, and build-out) and return periods (2 and 100 years). The red and green lines represent the fitted regression lines for small and large scales basins.

In this figure we can observe a high variability on peak discharge for small basin area. This variability is caused by land surface heterogeneities and different basin geometries. For example, the precipitation that falls in a longer shape basin will reach the channel faster than the one that falls over a more rounded shape basin, even if both basins present the same surface characteristics. On the other hand, the variability is much smaller for the higher scale basins, due to the aggregated behavior of the peak flow, that smooth out small basins heterogeneities.

The build-out scenario presents much lower variability, since the land cover characteristics are homogeneous in the entire basin area (impermeable). In this case the small variability observed is due to hillslope geometry. The pre-development scenario is almost homogeneous in terms of land cover changes, but includes spatial variability in terms of soil properties (soil hydrologic group) and hillslope geometry. The 2001 includes variability in terms of land surface characteristics (land cover and soil properties) and hillslope geometry.

In Figure 11 we can also see that the slope of curves for small (α =0.85) and large (α =0.70) basins do not change for different return periods (2 and 100). This fact characterizes a simple scaling process. The intercept parameter changes for different return periods flood for both small and bigger scales basin, as can be seen on Figure 12. Figure 12 also show how the intercept, or the peak flow, is affected by different land cover scenarios. Considering the 500 years return period, we can see that for big scales basins the intercept changes from around 24 for the pre-development scenario to 85 for the build out scenario, being land cover 2001 (45) and 1992 (41). This means that the peak flow for worst scenario, for which the whole basin is urbanized, is 3.5 times bigger than the peak flow for the pre-development scenario, and 1.88 times bigger than the peak flow for the current situation. This graphic provides an idea about how land cover changes affects flood risk intensity.

Figure 13 presents the scaling relationships for different land cover types (pre-development, 1992, 2001, and build-out) and return periods (2, 10, 25, 50, 100 and 500 years). In this Figure we can see that in relative terms the effects of land cover changes are higher for lower return period floods.

Figure 11: Example of power law relationships between peak flow and basin areas for different land cover scenarios and return periods. The picture also shows the fitted regression lines

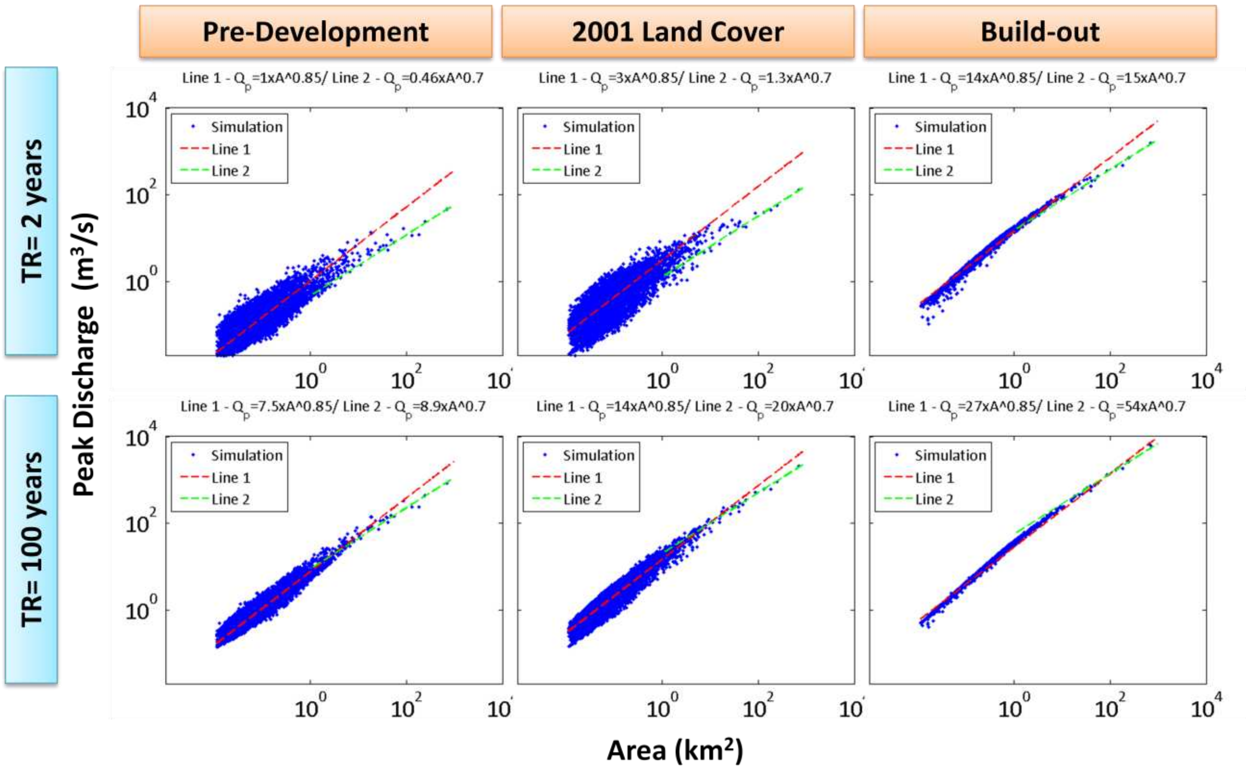
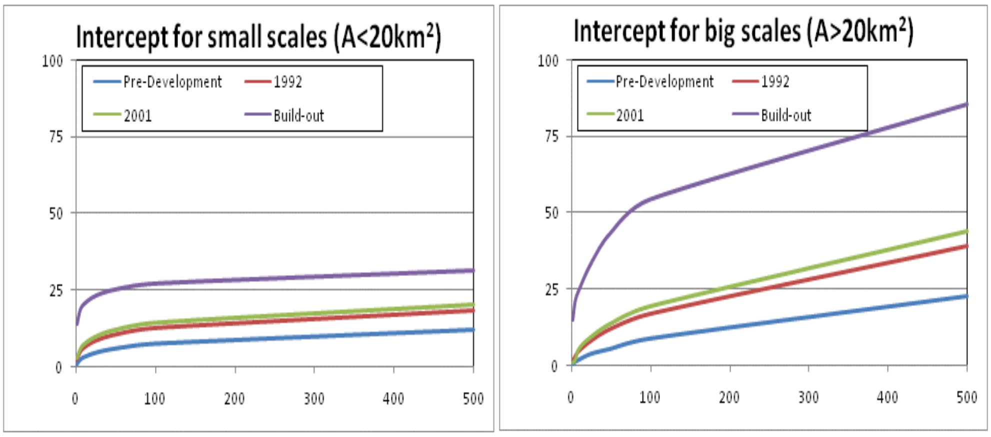
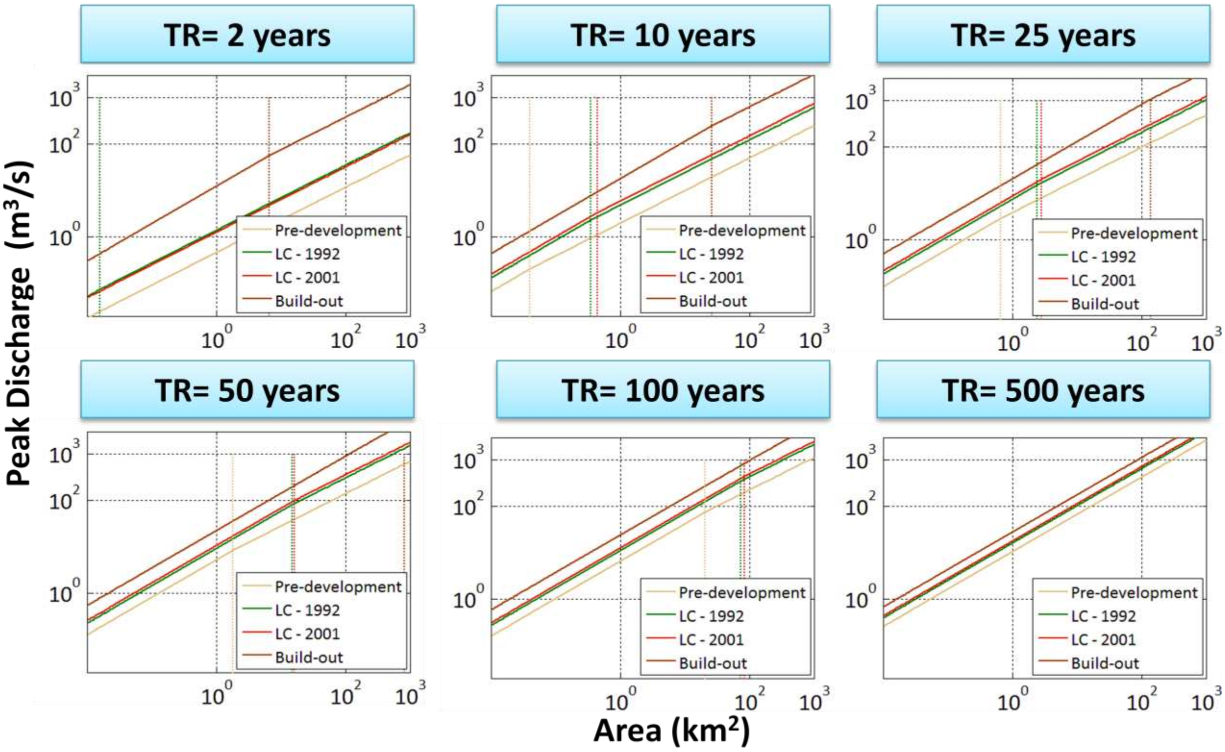


Figure 12: Intercept for small scales basins and big scales basins versus return period



Return Period (from 2 to 500 years)

Figure 13: Scaling relationship for different land cover types (pre-development, 1992, 2001, and build-out) and return periods (2, 10, 25, 50, 100 and 500 years)



4.2. Inundation map and flood damage estimation

Inundation map for all different return periods and land cover scenarios are generated according to the processes described previously. Once the depth of water is estimated for each pixel in the basin, damage is calculated using the water depth – percentage of structural damage curves described before. The expected damage is the sum of all damage that occurs in the basin area. An example of inundation map, and the parcel structural values for the basin area are presented in Figure 14.

In the future, the inundation map generated by this methodology using 30 meters resolution DEM will be compared with the FEMA inundation map generated with 3m resolution DEM obtained though LIDAR data. This is not a direct task since the inundation map generate by FEMA includes just the main river.

Figure 15 presents the expected damage for different land cover and return periods. This figure also includes information for the flood mitigation scenarios that will be described in the following sections. Figure 16 presents the expected annual damage for different land cover scenarios.

Figure 14: Example of inundation maps and parcel structure value

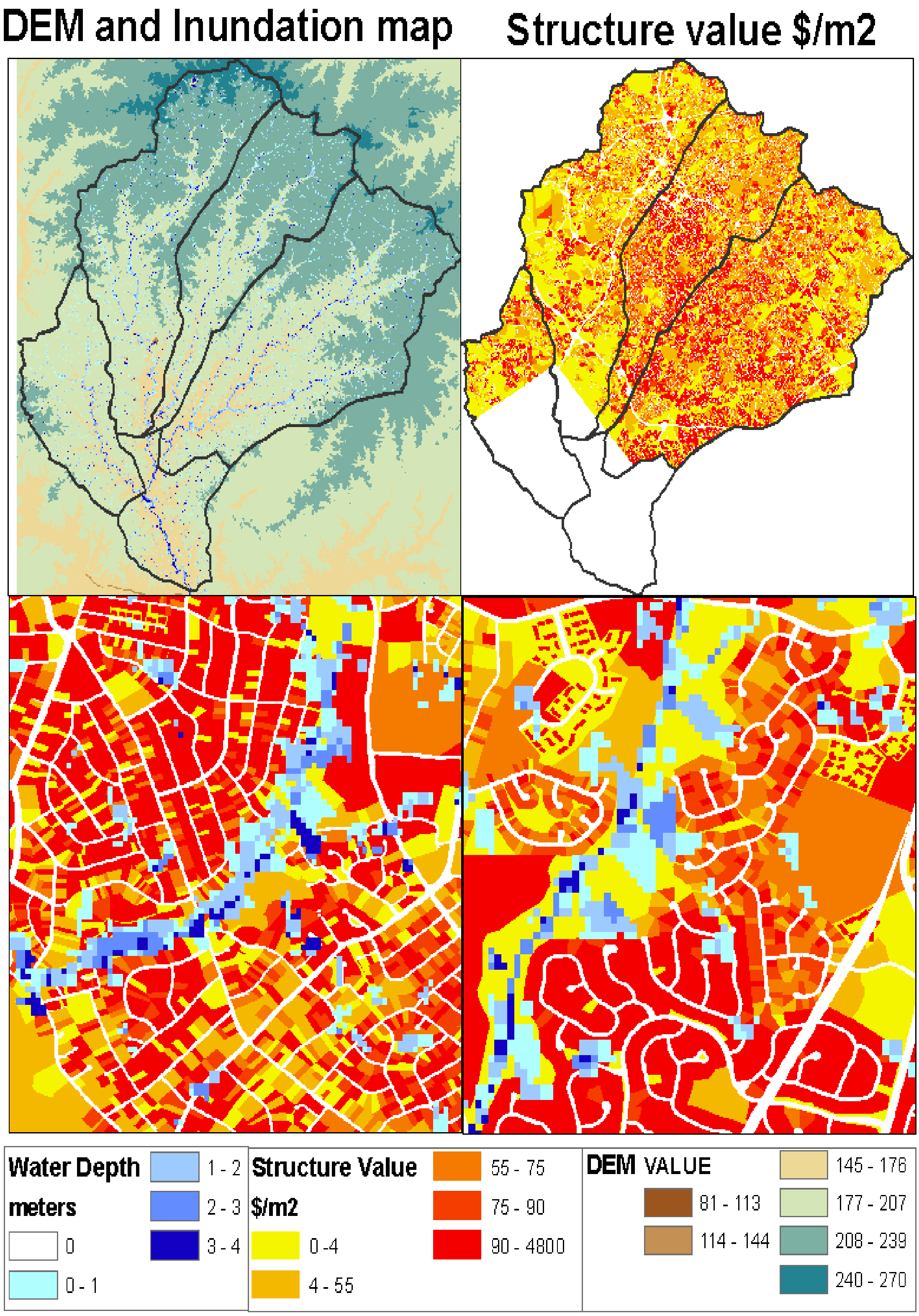


Figure 15: expected damage for different land cover and return periods

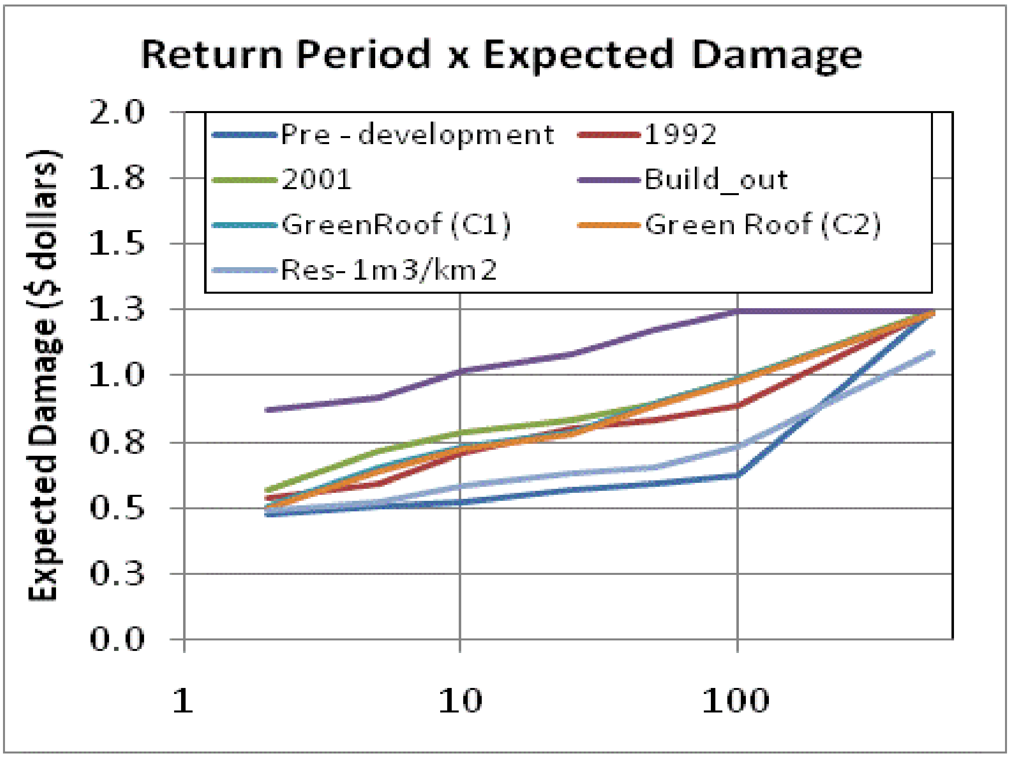
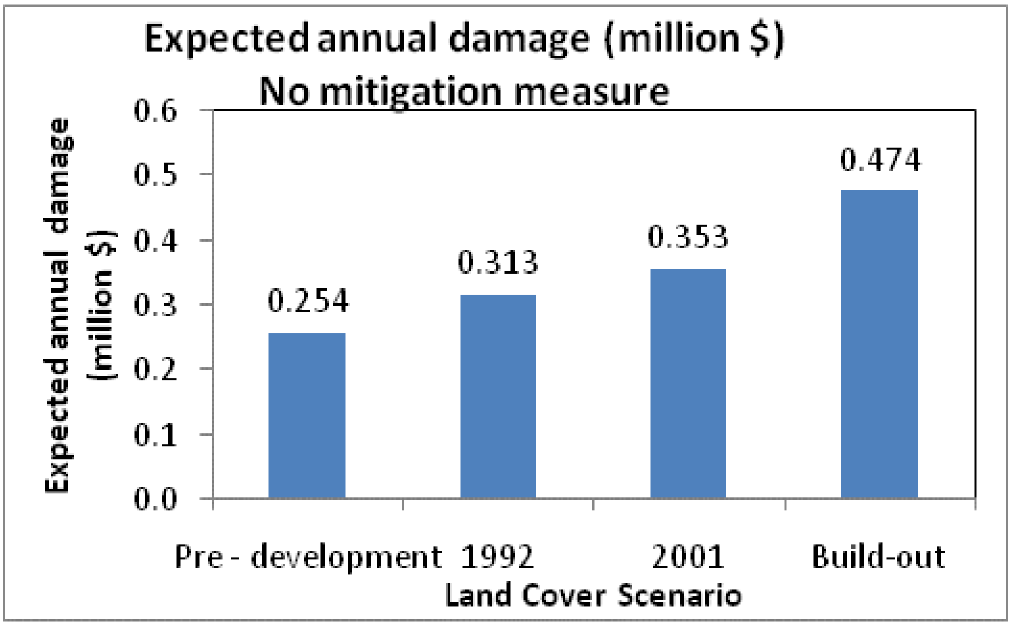


Figure 16: Expected annual damage for different land cover scenarios without flood mitigation measures



4.3. Effects of flood mitigation measures

Land surface characteristic has a strong effect on the hydrological response of river basins, and its change can dramatically modify the risks of floods. These effects can be mitigated by the use of structural measures that attempt to hold the water where it is generated. In this study we considered non-punctual reservoirs, greenways and parks and green roof, defining the following scenarios:

1) Non-Punctual reservoirs scenario 1: calculate the necessary reservation to maintain a pre-development runoff for a specific return period. This criteria is usually adopted for the implementation of new edifications;
2) Non-Punctual reservoirs scenario 2: define a constant volume of reservation for unit are of the basin, and use CUENCAS to quantify the effectiveness of this measure;
3) Greenways and Parks: according to the Meckeland County "Greenway Action Plan", described previously;
4) Green Roof Scenario 1: Considered that 80% of the roof areas for buildings localized in business, commercial and industrial areas will be transformed in green roofs (Figure 17);
5) Green Roof Scenario 2: Considered that 80% of the roof areas for buildings localized in medium to intense developed areas will be transformed in green roofs (Figure 17);

The expected annual damages considering different mitigation measures and 2001 land cover are presented in Figure 18. We can see that Greenways and parks are not very efficient measures in terms of reducing the expected damage, but it is important to observe that more than reduce the volume of flow, these structures have the goal of avoiding flood plain occupation. This can reduce the losses of life for example, that is not considered in this work.

Green roofs presented a relative efficiency in reducing the expected annual flood damage. In this case more research will be conduct to analyze different types of green roofs. The simulations performed here considered that green roofs cannot reserve the water over it, but just decrease the velocity of flow and increase the infiltration. Most of green roofs designed today have also the potential to reserve part of the precipitated water, what would improve considerable the efficiency of these structures for flood mitigation. Besides the reduction of peak flow, these structures have many other functions as specified before.

Non-Punctual reservoirs are very efficient in amortizing the peak of the flood. These structures hold the storm water in the place that it is generated, and usually decrease the velocity of the flow to the rivers. Figure 19 presents the necessary reservation to maintain a pre-development runoff for different return periods and land cover scenarios. This figure shows that these structures can mitigate floods with low return periods, but in order to mitigate high return period floods a very high volume of mitigation is necessary, what is not viable. Figure 20 shows how this volume is distributed in the basin for different return periods. We can see that they concentrate in the urban areas.

Figure 17: Green Roof Scenarios

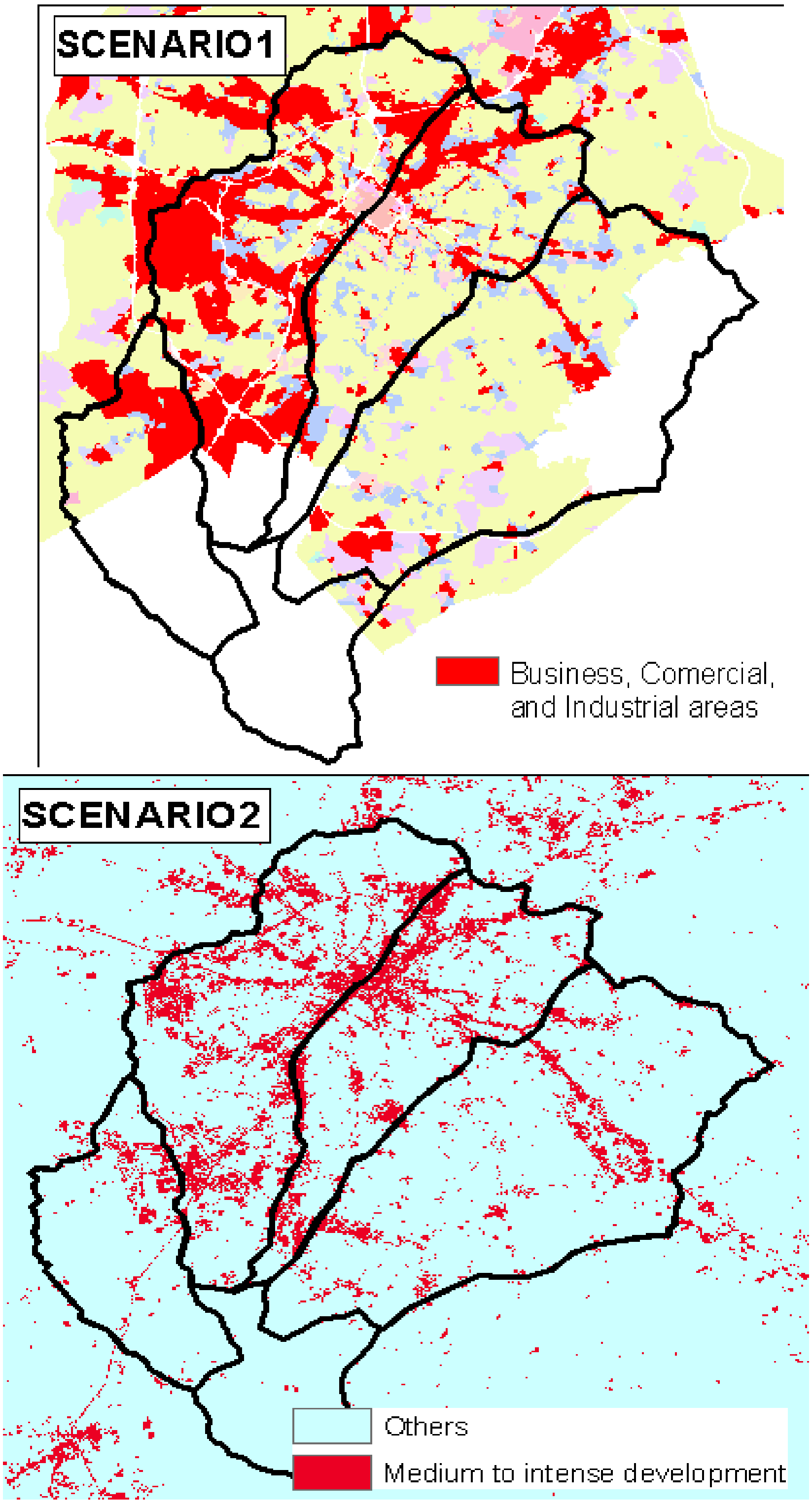


Figure 18: Expected annual damage for 2001 land cover with flood mitigation measures

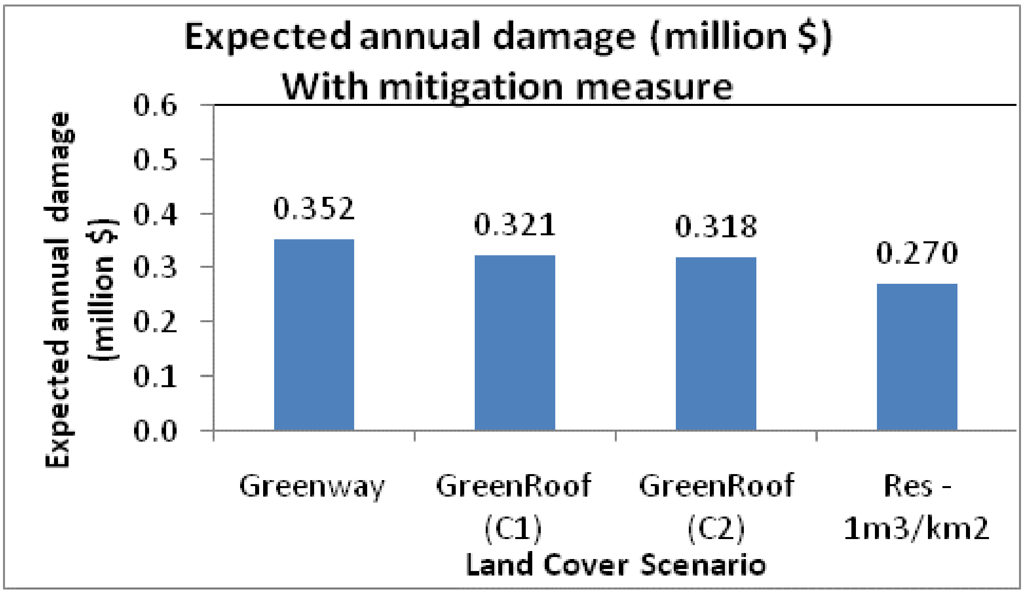


Figure 19: Total Volume of reservation necessary to maintain the pre-development runoff for different return periods

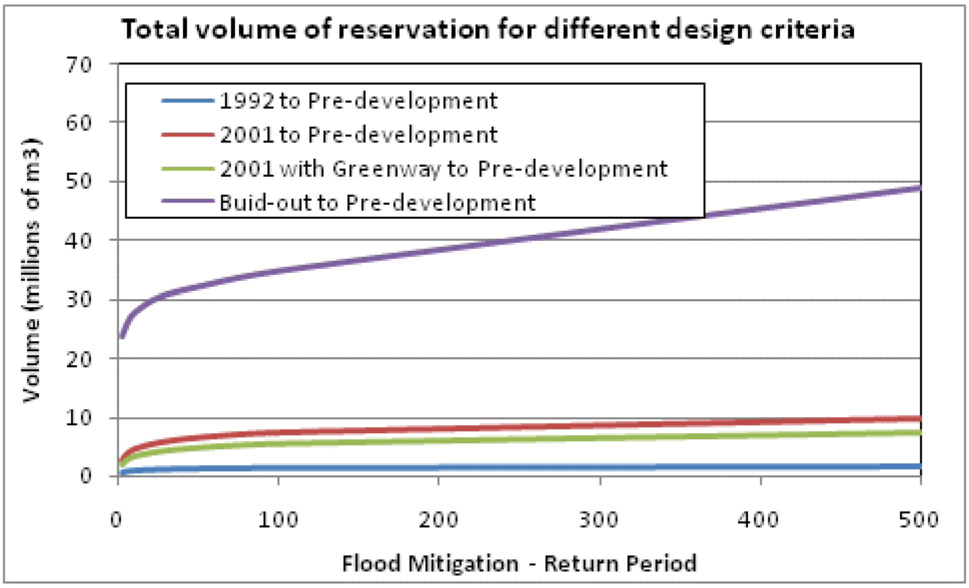


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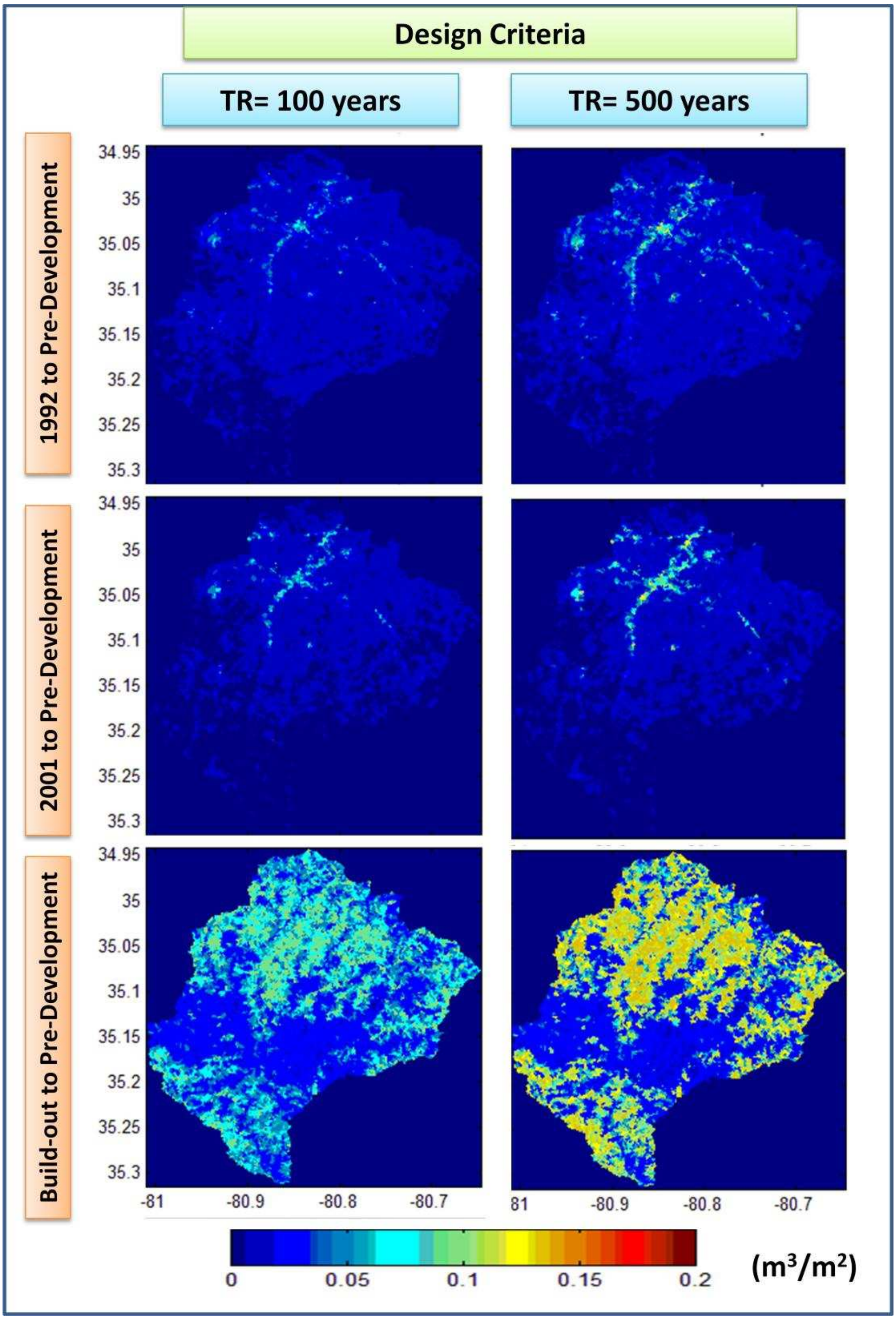
Figure 20: Spatial distribution of total volume of reservation necessary to maintain the pre-development runoff for different return periods (100 and 500 and land cover scenarios)



5. Conclusion

A calibration free hydrological model based on the scaling theory of floods was modified to provide a better representation of the rainfall-runoff processes that occur in a hillslope scale through the use of empirical models. This model constitutes an important instrument for flood risk analysis, especially for area for which hydrological data is not available or where the physical processes that generated floods are not stationary.

This model was used as the basis for the development of a flood risk analysis framework, with the aim of link hydrological criteria of flood intensity estimation (peak discharge) to criteria that measures flood impact (damages). This activity requires the development of flood maps and the quantification of flood damage.

Both the model and the framework were tested in a case study for the city of Charlotte, North Carolina. The city has experienced an extensive urban growth since 1960 which has led to significant changes in city's risk and vulnerability to floods. The impacts of urbanization were evaluated using current land cover conditions and two extreme scenarios: pre-development and built-out. The effectiveness of non-punctual flood mitigation measures that are easily harmonized in the urban environment was also evaluated. Some of the main conclusions of this work are:

- The simulation of the physical processes that generate floods was possible through the use of the hydrological model modified/improved by the author. The main advantage of this model is the use of concepts from the scaling theory of floods and the use of remote sensing. Calibration of parameters is avoided trough the use of concepts from the scaling theory of floods, and trough the use of remote sensing information to describe the basin system;

- This model represents an important tool to deal with climate and land cover change scenarios, since it is not based in stream flow statistic analysis;

- The model successfully represents the effects of urbanization on runoff coefficient and peal flow across multiple basin scales;

- The impacts of urbanization on runoff coefficient are more accentuated for floods with low return periods. For high return periods the high amount of precipitated water quickly saturates the soil, and the water is converted in runoff independently of the land cover configuration;

- Greenways, parks and green roofs are not very efficient in reducing peak flow, but are important structures to avoid flood plain occupation;

- Green roofs can considerably reduce peak flow if located in very impermeable parts of the basin. Besides that these structures present many other important functions in an urban environment;

- Non-punctual reservoirs are very efficient in mitigate floods. Nevertheless, they present limited efficient for high return periods, due to the very high volume of reservation necessary to really mitigate floods with high magnitude.

6. Reference

Arnold JG, Williams JR, Nicks AD, Sammons NB. SWRRB—A Basin Scale Simulation Model for Soil and Water Resources Management. Texas A&M University Press: College Station, TX. 1990.

Bhuyan SJ, Mankin KR, Koelliker JK.. Watershed-scale AMC selection for hydrologic modeling. Transactions of the ASAE 46 (2003), pp. 237–244.

Birkeland, K.W. and Landry, C.C., Power laws and snow avalanches. Geophysical Research Letters **29**, (49) (2002), pp. 41–49.

Committee on FEMA Flood Maps; Board on Earth Sciences and Resources/Mapping Science Committee; National Research Council. Mapping the Zone: Improving Flood Map Accuracy. The National Academies Press, 2009.

D.C. Goodrich, L.J. Lane, R.M. Shillito and S.N. Miller, Linearity of basin-response as a function of scale in a semiarid watershed, Wat Resour Res **33** (12) (1997), pp. 2951–2965.

Dalinsky, Joseph S., An Unconventional Approach to Flood-Frequency Analysis," Bull Internat. Assoe. of Scientific Hydrology, **IS** (3) (09-1970).

De Michele, C. and Rosso, R.: A multi-level approach to flood frequency regionalisation, Hydrol. Earth Syst. Sci., **6** (2002), pp. 185-194,

Douglas H., The Failure of Risk Management: Why It's Broken and How to Fix It, John Wiley & Sons, 2009

Erich J. Plate, Flood risk and flood management, Journal of Hydrology **267**, (1-2) (2002), pp. 2-11.

F. Fenicia, H.H.G. Savenije, P. Matgen and L. Pfister, Understanding catchment behavior through stepwise model concept improvement, Water Resour. Res. **44** (2008), p. W01402

F.L. Ogden and D.R. Dawdy, Peak discharge scaling in small Hortonian watershed, J Hydrol Eng **8** (2003), pp. 64–73.

Getter, K.L., D.B. Rowe, and J.A. Andresen. Quantifying the effect of slope on extensive green roof stormwater retention. Ecological Engineering 31 (2007), pp. 225-231.

Gupta VK, Dawdy DR.. Physical interpretations of regional variations in the scaling exponents of flood quantiles. Hydrological Processes **9** (1995),pp. 347–361.

Gupta VK, Troutman TM, Dawdy DR. Towards a nonlinear geophysical theory of floods in river networks: an overview of 20 years of progress. In: Tsonis AA, Elsner J, editors. Nonlinear dynamics in geosciences (2007), pp. 1–31.

Gupta VK, Waymire E. Spatial variability and scale invariance in hydrologic regionalization. In: Sposito G, editor. Scale dependence and scale invariance in hydrology; 1998. p. 88–135.

Gupta, V. K., Castro, S. and Over, T.M. On scaling exponents of spatial peak flows from rainfall and river network geometry. J. Hydrol. **187** (1996), pp. 81-104.

Gupta, V.K. andWaymire, E., Multiscaling properties of spatial rainfall and river flow distributions.

Huang, C., Zhang, Z., Yang, L., Wylie, B., and Homer, C. MRLC 2001 Image Preprocessing Procedure, USGS White Paper (2002).

Hubert, P., Multifractals as a tool to overcome scale problems in hydrology. Hydrological Sciences **46** (2001), pp. 897–905.

Jonkman, S.N. Loss of Life Estimation in Flood Risk Assessment Theory and Applications. PhD Thesis. Delft University (2007), Delft, The Netherlands.

Journal of Geophysical Research **95(D3)** (1990) 1999–2009.

K. Hardmeyer and M. A. Spencer, Using Risk-Based Analysis and Geographic Information Systems to Assess Flooding Problems in an Urban Watershed in Rhode Island, Environmental Management 39 (4) (2007), pp. 563 – 574.

Kidson R., Richards K.S. Flood frequency analysis: Assumptions and alternatives, Progress in Physical Geography, **29** (3) (2005), pp. 392-410.

Kidson, R., Richards, K.S. and Carling, P.A. Cello, G. and Malamud, B.D. (eds.) Power-law extreme flood frequency. Geological Society, **261** (2006), 141-153.

M. Menabde, S. Veitzer, V. Gupta and M. Sivapalan, Tests on peak flow scaling in simulated self-similar river networks, Adv Water Resour **24** (2001), pp. 991–999.

M. Menabde, S. Veitzer, V.K. Gupta and M. Sivapalan, Tests of peak flow scaling in simulated self-similar river networks, Adv. Water Resour. **24** (2001), pp. 991–999.

M. Morita, Flood risk analysis for determining optimal flood protection levels in urban river management, Journal of Flood Risk Management **1** (3) (2008), pp. 142-149.

Mantilla R. Physical basis of statistical self-similarity in peak flows on random self-similar networks. PhD dissertation, University of Colorado, Boulder; 2007.

Mantilla R., V. K. Gupta and O. Mesa. Role of coupled flow dynamics and real network structures on Hortonian scaling of peak flows. J. Hydrology (special issue on Hydrofractals), **322** (2006), pp. 155-167.

Mantilla, R. and Gupta, V.K. and Troutman, B.M. and Krajewski, W., Self-similarity in Channel Network Topology as a Necessary Condition for the existence of Power Laws in Flood Magnitudes, AGU Fall Meeting Abstracts, (12-2008).

Mantilla, R.; Cunha, L.; Krajewski, W. F.; Kruger, A.; Gupta, V. K. A Top-Down Guided Hydrologic Instrumentation in Kansas to Test Scaling of Peak Flows in Real Basins American Geophysical Union, Spring Meeting 2008, abstract #H31C-03

Mantilla, R.; Gupta, V. K.; Troutman, B. M.; Krajewski, W., Self-similarity in Channel Network Topology as a Necessary Condition for the existence of Power Laws in Flood Magnitudes, American Geophysical Union, Fall Meeting 2008, abstract #H31G-0975.

Masaru Morita, Flood risk analysis for determining optimal flood protection levels in urban river management, Journal of Flood Risk Management **1** (3) (2008),, pp. 142-149.

Menabde, M.2001 - and Sivapalan, M. (2001a) Linking space-time variability of river runoff and rainfall fields: a dynamic approach. Adv. Water Resour. 24, 1001-1014.

Molnar, P., Anderson, R.S., Kier, G., and Rose, J. , Relationships among probability distributions of stream discharges in floods, climate, bed load transport, and river erosion: Journal of Geophysical Research, **111 (**2006).

Morrison and J.A. Smith, Scaling properties of flood peaks, Extremes **4** (2001), pp. 5–22.

Oberndorfer, E., J. Lundholm, B. Bass, M. Connelly, R. Coffman, H. Doshi, N. Dunnett, S. Gaffin, M. Köhler, K. Lui, and B. Rowe. Green roofs as urban ecosystems: ecological structures, functions, and services. BioScience 57(10) (2007), pp. 823-833.

P. V. Mandapaka, W. F. Krajewski, R. Mantilla, V. K. Gupta, Dissecting the effect of rainfall variability on the statistical structure of peak flows, Advances in Water Resources **32**(10) (10-2009), pp. 1508-1525.

P.R. Furey and V.K. Gupta, Diagnosing peak-discharge power laws observed in rainfall–runoff events in Goodwin Creek experimental watershed, Adv Water Resour **30** (2007), pp. 2387–2399.

P.R. Furey and V.K. Gupta, Effects of excess rainfall on the temporal variability of observed peak-discharge power laws, Adv Water Resour **28** (2005), pp. 1240–1253.

P.R. Furey and V.K. Gupta, Effects of excess rainfall on the temporal variability of observed peak-discharge power laws, Adv Water Resour **28** (2005), pp. 1240–1253.

P.R. Furey and V.K. Gupta, Effects of excess-rainfall on the temporal variability of observed peak discharge power laws, Adv Wat Resour **28** (2005), pp. 1240–1253.

Ponce VM, Hawkins RH. Runoff curve number: has it reached maturity? Journal of Hydraulic Engineering, ASCE **121** (1996), pp. 11–18.

Rhoads, 1991 B.L. Rhoads, A continuously varying parameter model of downstream hydraulic geometry, Water Resources Research **2**7 (1991) (8), pp. 1865–1872.

Robinson JS, Sivapalan M., Temporal scales and hydrological regimes: Implications for flood frequency scaling. Water Resources Research **33 (**1997), pp. 2981–2999

S.A. Veitzer and V.K. Gupta, Statistical self-similarity of width function maxima with implications to floods, Adv Water Resour **24** (2001), pp. 955–965.

Sarewitz, Daniel, Roger Pielke, Jr. , and Mojdeh Keykhah. Vulnerability and risk: some thoughts from a political and policy perspective. Risk Analysis **23** (4) (2003), pp.805-810.

Savenije, H. H. G.: HESS Opinions "The art of hydrology"*, Hydrol. Earth Syst. Sci. **13** (2009), 157-161.

Scanlon, Todd M., Caylor, Kelly K., Levin, Simon A., Rodriguez-Iturbe, Ignacio, Positive feedbacks promote power-law clustering of Kalahari vegetation, Nature **449** (7159) (2007), pp. 209-212.

Scheidegger, A.E., Complexity theory of natural disasters; boundaries of self-structured domains. Natural Hazards **16** (1997), pp. 103–12

Sharpley AN, Williams JR. EPIC—Erosion/Productivity Impact Calculator: 1. Model Documentation. US Department of Agriculture Technical Bulletin No. 1768. (1990) US Government Printing Office: Washington, DC.

Sivapalan, M., Bloschl, G., Zhang, L., and Vertessy, R.: Downward approach to hydrological prediction, Hydrol. Process., **17**(11), 2101–2111, 2003.

Sivapalan, M., Takeuchi, K., Franks, S., Gupta, V., Karambiri, H., Lakshmi, V., Liang, X., McDonnell, J., Mendiondo, E., O'Connell, P., Oki, T., Pomeroy, J., Schertzer, D., Uhlenbrook, S. and Zehe, E. (2003) IAHS decade on predictions in ungauged basins (PUB), 2003-2012: Shaping an exciting future for the hydrologic sciences. Hydro. Sci. J. **48**, 857-880.

Struthers, I. and Sivapalan, M., A conceptual investigation of process controls upon flood frequency: role of thresholds, Hydrology and Earth System Sciences, **11** (2007), pp.1405-1416

T. Skaugen and T. Varingstad, A methodology for regional flood frequency estimation based on scaling properties, Hydrol Process **19** (7) (2004), pp. 1481–1495.

Technical Instructions. 1997.

Troutman, B. M. and Over, T.M. River flow mass exponents with fractal channel networks and rainfall. Adv. Water Resour. **24** (2001), 967-989.

Turcotte, D.L., and Greene, L., A scale-invariant approach to flood frequency analysis: Stochastic Hydrology and Hydraulics, **7** (1993), pp. 33–40.

Turcotte, D.L., Fractals and chaos in geology and geophysics. Cambridge: Cambridge University Press, **221 (**1994).

U.S. Geological Survey. Standards for Digital Elevation Models. National Mapping Program

USDA Soil Conservation Service, Urban Hydrology for Small Watersheds. Technical Release 55, 2nd ed., NTIS PB87-101580 (1986), Springfield, VA.

V.K. Gupta, S.L. Castro and T.M. Over, On scaling exponents of spatial peak flows from rainfall and river network geometry, J Hydrol **187** (1996), pp. 81–104.

V.K. Gupta, S.L. Castro and T.M. Over, On Scaling exponents of spatial peak flows from rainfall and river network geometry, J Hydrol **187** (1996), pp. 81–104.

Vogelmann, J.E., S.M. Howard, L. Yang, C. R. Larson, B. K. Wylie, and J. N. Van Driel, Completion of the 1990's National Land Cover Data Set for the conterminous United States, Photogrammetric Engineering and Remote Sensing **67** (2001), pp. 650-662.

Weaver, J. C. Frequency of Annual Maximum Precipitation in the City of Charlotte and Mecklenburg County, North Carolina, through 2004. Prepared in cooperation with the City of Charlotte and Mecklenburg County. USGS Scientific Investigations - Report 2006-5017.

Williams JR, Nicks AD, Arnold JG. Simulator for water resources in rural basins. Journal of Hydraulic Engineering, ASCE **111** (1985), pp. 970–986,.

Young RA, Onstad CA, Bosch DD, Anderson WP. AGNPS: a nonpoint-source model for evaluating agricultural watersheds. Journal Soil and Water Conservation **44** (1989), pp. 168–173.

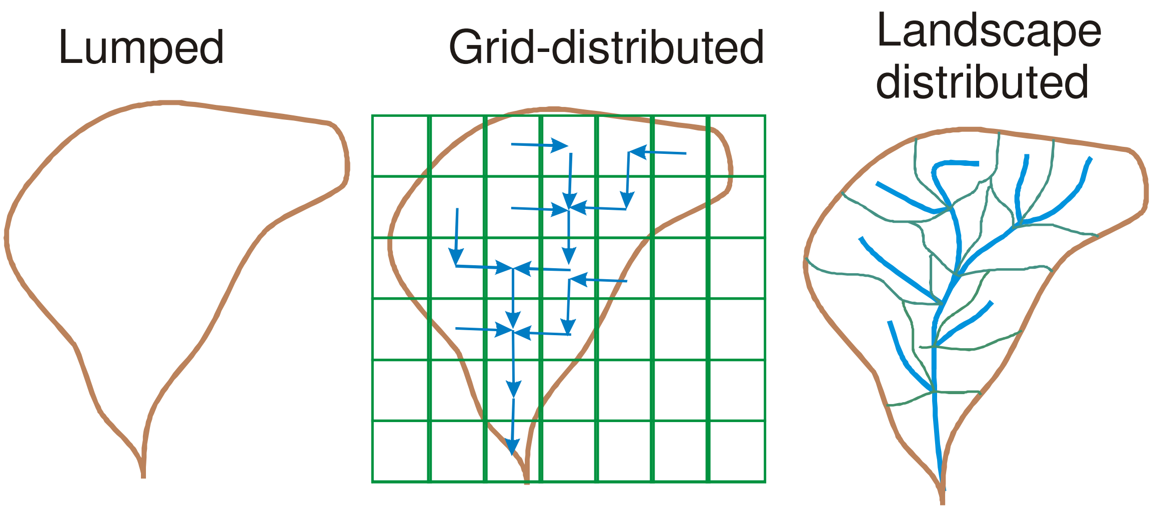
Appendix 1

Two main methods are used for flood estimation nowadays. Statistical methods require long series of historical data for the estimation of the flood frequency distribution. Sometimes inferences about 100,500 or 1000 years return period floods are made based on less than 20 years of record. In the case that data is not available for the study areas, data is transferred from a nearby basin using scaling relationships, without considerations about the hydrological similarities of the areas.

The second method uses hydrological models in a Bottom-Up approach, seeking to quantify characteristics of point processes such as infiltration or interception rates. These physical equations are inserted in basin models without consideration about the scale for which they were derived, and because of that they usually have to be calibrated in order to provide predictions that agree with observations.

Another big issue related to traditional lumped and grid-distributed hydrological models is the pour representation of the river network. It is known that the river network plays an important role in the distribution of water in the watershed and in generation of floods, so this factor cannot be neglected or not well represented in the models. Figure Ap. 1 presents a schematic representation of lumped, distributed and hillslope base models, and how each model takes the river network in consideration on its formulation.

Figure Ap. 1: Different hydrological models representation of the river network



In this context CUENCAS model was chosen for flood risk quantification due to the following main advantages in the reproduction of peak discharge:

- Full preservation of the river network through the hillslope-base decomposition of the landscape. This realistic representation of the river network maintains the self-similar structure of peak flows;
- No-need for calibration, since it uses mass conservation equation and momentum equation to represent the flow of water thought the river network links, and hydraulic geometry properties to estimate velocity of the flow in the channel;
- Possibility of being applied worldwide if land surface data is available;
- Explicitly consideration of soil and land surface properties;
- Runoff generation and propagation of the flow in the hillslope are represented by an empirical model that does not required calibration and have been extensively applied, studied and improved since 1960;
- Quantification of flood risk across multiples spatial scales, according to physical characteristics of the basin;
- Explicit consideration of non-stationarity of physical processes due to land surface or climate changes.

Hillslope-link decomposition of the landscape

Model Component Description:

CUENCAS extracts the drainage structure from a high resolution digital elevation model using algorithms based on the maximum gradient method and pruning algorithms to determine the initial location of the river network [2]. The hillslope is the fundamental element in this model where the partition of rainfall into infiltration and overland flow occurs. Figure Ap. 2 presents the hillslope decomposition for the study area. The main stream corresponds to an 8th order Horton stream with total area equal to 714 km2. This area is composed by 15.122 hydrological units with an average area equal to 0.047km2. In the model equations each link is represented by the letter “s” and the adjacent upstream links by the “s1” and “s2”.

Variables description:

$A_h(s)$ = hillslope area (mm2);

$A_U(s)$ = basin area (upstream area) (mm2);

$I_h(s) =$ hillslope slope (m/m);

$I_c(s) =$ channel slope (m/m);

$L_c(s)$ = channel length (m);

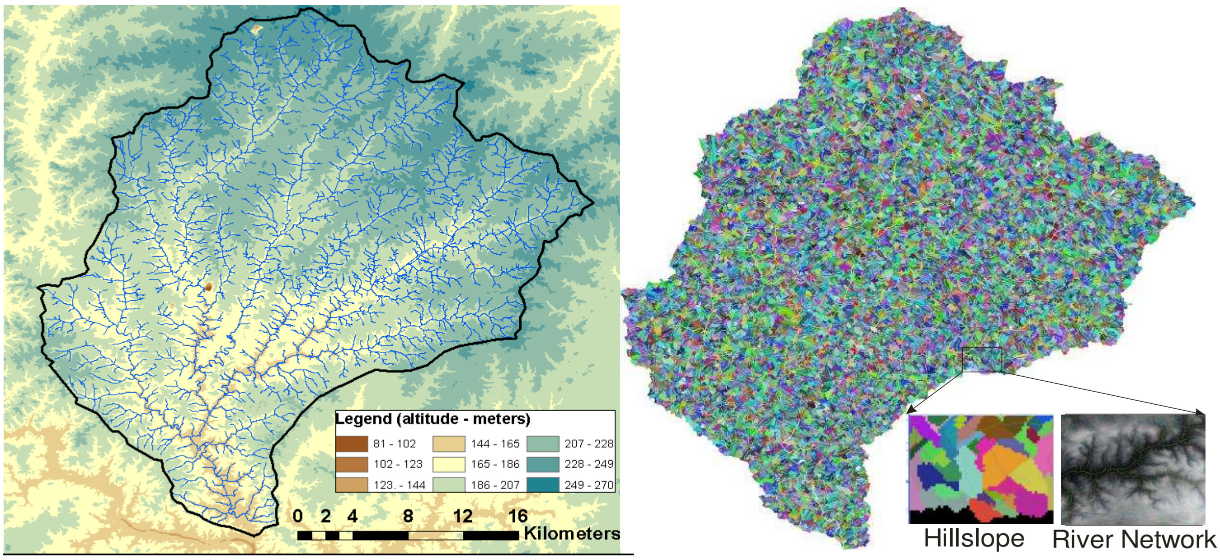
$s1(s), s2(s) =$ Upstream links – use in the solution of the differential equation that describes flow propagation in the river network

Parameters: No parameters;

Input: Digital Elevation model (10 or 30 meters resolution);

Output: $s1(s), s2(s)\ A(s)\ , I(s)\ , L(s)$;

Figure Ap 2: Hillslope decomposition for the study area



Rainfall-Runoff transformation

Model Component Description:

For this study, the Soil Conservation Service Curve Number Method was chosen to compute infiltration and overland flow rate during a storm. The relationship between basin physical properties and Curve Number is based on a large number of empirical experiments with watersheds areas similar in size to the unit area defined by CUENCAS.

The original method formulation combines the water balance equation and two basic hypotheses [1, 3, 5, 6, 7, 8]. For this application the original model equation was modified to account for infiltration rates that vary in time as a function of the deficit of water in the soil, being more appropriate for continuous simulation. The accumulated runoff based on accumulated precipitation for a rainfall event is calculated by:

$$Q(s,t) = \frac{Pe(s,t)^2}{Pe(s,t) + D(s,t)} \qquad Pe(s,t) > 0$$

$$D(s,t) = S(s)_1 - S(s,t)$$

$$Pe(s,t) = P(s,t) - Ia \quad (2)$$

$$S(s)_{sm} = 254 - \frac{25400}{CN(s)_{sm}} \quad \text{(sm=1, 2, 3)}$$

$$Ia(s) = \alpha S(s)_2$$

sm = 1 $CN(s)_1 = CN(s)_2 - 20 \times \frac{(20 \times (100 - CN(s)_2))}{(100 - CN(s)_2 + \exp(2.533 - 0.0636 \times (100 - CN(s)_2)))}$

$$S(s)_{sm} = 254 - \frac{25400}{CN(s)_{sm}}$$

In CUENCAS a differential form of SCS modified equations is used to calculate runoff and infiltration rates:

$$\frac{dQ(s,t)}{dt} = \frac{Pe(s,t)(Pe(s,t) + 2 \times D(s,t))}{(Pe(s,t) + D(s,t))^2} \frac{dPe(s,t)}{dt} \qquad Pe(s,t) > 0$$

$$\frac{dI(s,t)}{dt} = \frac{dPe(s,t)}{dt} - \frac{dQ(s,t)}{dt}$$

Variables description:

$Q(s,t) =$ Accumulated runoff for hillslope s and time t (mm);

$I(s,t) =$ Accumulated infiltration for hillslope s and time t (mm);

$P(s,t)$ = Accumulated rainfall for hillslope s and time t (mm);

$Pe(s,t)$ = Accumulated effective rainfall for hillslope s and time t (mm);

$Ia(s)$= Initial abstraction for hillslope s (mm);

$S(s)_{sn}$= Potential maximum water retention by the soil for antecedent soil moisture condition for hillslope s and time t. Sm varies from 1 to 3, 1 corresponding to the driest condition and 3 to the wettest one;

$CN(s)_{sn}$ – Curve number for hillslope s. It is a function of land cover, hydrological group and antecedent soil moisture condition. See table in Append 1;

$S(s,t) =$ Soil water content for hillslope s and time t (mm);
$D(s,t) =$ Deficit of water in the soil for hillslope s and time t (mm);

Parameters: $CN(s)_{sn}$, $S(s)_{sn}$, $Ia(s)$

Input: $P(s,t)$, $S(s,t)$

Output: $Q(s,t)$, $I(s,t)$

Water Balance (Soil and Surface)

Model Component Description:

A conceptual model compound by two reservoirs is used to represent the water balance in the hillslope surface and soil. The outflow for each reservoir is calculated using a linear reservoir model. The response factor (or reservoir storage constant) is calculated by each hillslope as a function of its physical properties (area, length, slope, soil type and land cover).

The travel time of the surface flow is calculated using the NRCS Velocity Method [4]. The velocity of the subsurface depends on soil type and properties, hydraulic gradient and presence or not of different soil structures. In this case the velocity is estimated by calibration. The flow in the surface is usually one order of magnitude faster than the flow in the subsurface, so both processes are modeled independently.

$$\frac{dQ_{o\_channel}(s,t)}{dt} = K_0(s,t-1) \times S_0(s,t-1)$$

$$\frac{dQ_{1\_channel}(s,t)}{dt} = K_1(s,t-1) \times S_1(s,t-1)$$

$$v_0(s,t) = K_{NRCS}(s) \times A_U(s) \times I(s)^{0.5} \times S_0(s,t-1)^{2/3}$$

$$K_0(s,t) = \frac{\bar{d}(s)}{v_0(s,t)} = \frac{0.6 \times A_h(s)}{v_0(s,t) \times L(s)}$$

$v_1(s,t) = \text{calibrated}$ or $v_1(s,t) = f(Kx(s))$

$$K_1(s,t) = \frac{\bar{d}(s)}{v_1(s,t)} = \frac{0.6 \times A_h(s)}{v_1(s,t) \times L(s)}$$

$$\frac{dS_o(s,t)}{dt} = \frac{dQ(s,t)}{dt} - \frac{dQ_{o\_channel}(s,t)}{dt}$$

$$\frac{dS_1(s,t)}{dt} = \frac{dPe(s,t)}{dt} - \frac{dQ(s,t)}{dt} - \frac{dQ_{1\_channel}(s,t)}{dt}$$

Variables description:

$S_0(s,t)$ = surface reservoir for hillslope s and time t (mm);

$S_1(s,t)$ = soil reservoir for hillslope s and time t (mm);

$Q_{o\_channel}(s,t)$ = superficial flow –superficial flow from hilllslope s to the channel at time t (mm/h);

$Q_{1\_channel}(s,t)$= sub-superficial flow – soil flow from the hilllslope s to the channel at time t (mm/h);

$v_0(s,t) =$ velocity of the superficial for hilllslope s and time t (mm/h);

$K_{NRCS}(s) =$ NRCS method coefficient, presented in Table 2 for different land covers;

$A(s)$ = hillslope area (mm2);

$I_h(s) =$ hillslope slope (m/m);

$v_0(s,t) = K_{NRCS}(s) \times A(s) \times I(s)^{0.5} \times S_0(s,t)^{2/3}$

$K_o(s,t)$= surface reservoir storage constant for hillslope s and time t (1/h);

$K_1(s,t)$= soil reservoir storage constant for hillslope s and time t (1/h);

$K_s(s,t)$= Hydraulic conductivity for hillslope s and time t (1/h);

Parameters: $K_{NRCS}(s)$, $K_1(s,t)$

Input: $S_0(s,t-1)$, $S_1(s,t-1)$,

Output: $Q_{o\_channel}(s,t)$ $Q_{1\_channel}(s,t)$

Flow propagation through the river network

Model Component Description:

Using a mass conservation equation and the hillslope-link structure defined in the decomposition of the basin, the channel discharge for each link is calculated using a numerical method. In this application we use the Runge-Kutta-Felberg algorithm for solving non-linear ordinary differential equations. This method uses a time step control algorithm to avoid numerical errors. $v_c(s,t) = v_o \times q_c(s,t-1)^{\lambda 1} \times A(s)^{\lambda 2}$

The velocity of the flow in each channel is calculated using a nonlinear equation that relates velocity in channel to the discharge in each link and the corresponding upstream area.

$$v_c(s,t) = v_o \times A(s)^{\lambda 1} \times q_c(s,t-1)^{\lambda 2}$$

$$\frac{dq_c(s,t)}{dt} = \frac{v_c(s,t)}{L(s)}\left[\frac{A_h(s)}{10^6} \times \left(Q_{o\_channel}(s,t) + Q_{1\_channel}(s,t)\right) - q_c(s,t-1) + q_c(s1(s),t-1) + q_c(s2(s),t-1)\right]$$

Variables description:

$v_o, \lambda 1, \lambda 2 =$ Parameters estimated using observed velocity and discharge data;

$q_c(s,t) =$ Discharge in the channel (m3/h);

$q_c(s1(s),t-1), q_c(s2(s),t-1)$ = contribution from the upstream links (m^3/h);

Parameters: $v_o, \lambda 1, \lambda 2$

Input: $Q_{o\_channel}(s,t), Q_{1\_channel}(s,t), q_c(s,t-1), q_c(s1(s),t-1), q_c(s2(s),t-1)$

Output: $q_c(s,t)$