3.15 VULNERABILITY TO DISASTERS IN PUERTO RICO: INCORPORATING THE SOCIAL, PHYSICAL AND BUILT ENVIRONMENT TO RADAR SCANNING STRATEGIES*

Jenniffer M. Santos*, Jackie Miller, Alejandra Gonzalez***, Meredith Beaton**, Xiomara Ortiz*****

*** University of Delaware, ** Oklahoma University, *** University of Puerto Rico-Mayagüez**

OVERVIEW*

For the past three years the Center for Collaborative Adaptive Sensing of the Atmosphere (CASA), a National Science Foundation Engineering Research Center, has conducted research to develop a new weather observing system that will enhance our ability to sense, predict, and respond to severe storms, tornadoes, floods, and other atmospheric phenomena. The main objective of CASA is the development of a dense network of small, low-power, low-cost radars with the ability to sample the lower troposphere where many atmospheric events develop. CASA is currently conducting interdisciplinary research through the implementation of three proof-of-concept test beds in Oklahoma, Texas and Puerto Rico. This paper describes a research project being conducted as part of the Puerto Rico test bed that links different disciplines involved in CASA's research. Research in the social aspects of disasters asserts that technology is not socially neutral and that it should be implemented upon consideration of the characteristics of the population and the different impacts it may have on different sectors of the population. Therefore, an assessment of the interaction between the social, physical, and built environment is necessary to understand the contexts in which this new technology will be implemented and develop ways to reduce vulnerability to natural disasters.

Given its climatology and geography, Puerto Rico, is susceptible to weather events including tropical storms, hurricanes, and floods. When such events affect a socially vulnerable population, a disaster can occur. Puerto Rico has a long-standing history of natural disasters. As a result of changing social and demographic patterns, there has been a significant increase in population density, in the proportion of the elderly and physically disabled population, and an increasing concentration of residents in flood and/or landslide prone areas. Therefore an assessment of the interaction between weather phenomena, the built environment and the social characteristics of Puerto Rico is imperative to determine where to allocate resources and how to use Collaborative Adaptive Sensing techniques. The primary objective of this research effort within CASA is to develop and implement a quantitative model that takes into account the context of Puerto Rico to understand how social, political, economic, geographic, climatological, physical, infrastructural and demographic factors that may influence the capacity of the population living within these areas to plan, anticipate, withstand, respond and recover in an extreme weather event. This holistic approach affords an opportunity to implement scanning strategies that provide better coverage of at-risk geographies with higher vulnerability indexes. Therefore, the proposed model will be an integral part of determining the location of the dense radar network and how the radar should scan the atmosphere. The technology that CASA is developing could potentially be more valuable if it adapts to the specific context and characteristics of Puerto Rico and its residents.

VULNERABILITY TO DISASTERS: AN ECOLOGICAL APPROACH

Individuals live in a complex system composed of many related subsystems with which they constantly interact. Using an

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* *Corresponding author address:* Jenniffer M. Santos, Disaster Research Center (DRC), 87 E Main St, Newark, DE, 19716; e-mail: jsantos@udel.edu

ecological approach is germane to understanding vulnerability to natural disasters as it allows us to study the social relations of power that manifest in disasters. Vulnerability is defined as “an internal risk factor of the subject or system that is exposed to a hazard and corresponds to its intrinsic predisposition to be affected, or to be susceptible to damage” (Cardona, 2004). An ecological approach allows us to understand the actions, reactions and adaptation of human populations from a more holistic perspective because it offers an opportunity to analyze the constant immersion of the individual in a social system.

Natural disasters are not novel or surprising events, but events that should be expected when extreme weather events interact with vulnerable social, political, geographic, economic, climatological, and built environments. Oliver Smith (2002) claims, that in natural and technological disasters, all dimensions of the physical, biological and social systems are involved. Furthermore, he contends that anthropologists can contribute to the study of disasters through the analysis of the processes, multiple dimensions and relationships that those events reveal. Likewise, he argues that the analysis of disasters can contribute to anthropology because it can assist in the conception of socio-cultural theory because of the opportunity to examine their multiple linkages. We argue that since disasters occur when a weather event intersects with multiple interacting environments they constitute an inter-disciplinary issue that we should address by analyzing each part of the system. Moreover, analyzing the multiple dimensions of vulnerability in Puerto Rico can not only make significant contributions to an array of disciplines, but also to develop an empowering technology that attends more effectively the specific needs of Puerto Rican end users.

For the past three years, the Center for Collaborative Adaptive Sensing of the Atmosphere (CASA) has worked on the conceptualization and design of networks of low power radar systems that could potentially revolutionize human ability to observe, predict, and respond to severe storms, floods, and other atmospheric events. In order to develop a technology that meets the needs of the end-user community, which includes the National Weather Service, the emergency management personnel, the media, researchers and the general public, CASA has taken the challenge of understanding the needs of the end-user community and incorporating them into the radar system design and implementation. Currently, interdisciplinary research efforts are devoted to the implementation of three proof-of-concept test beds in Oklahoma, Texas and Puerto Rico. As part of the Puerto Rico test bed we are involved in the development of a holistic model to generate a better understanding of vulnerability to disasters in Puerto Rico.

Parallel to CASA’s ultimate goal, this research project has set as its goal the reduction of disaster-related deaths, injuries and damage to property in Puerto Rico. Canon (1994) asserts that technology is not socially neutral and that we must have an understanding of the context in which it is implemented. Acknowledging that technology can have different implications and generate different results in different contexts is vital to the success of CASA. An inadequate or incomplete understanding of the environment in which a technology is to be implemented translates into a potential for adverse societal impacts. Therefore, we are concentrating our efforts on generating a better understanding of the social, climatological and physical dimensions of vulnerability. Our goal is to bring together these dimensions of vulnerability to disasters to develop a measurement that will allow us to identify which areas are more vulnerable and determine the location of the CASA radars so that they can provide a better coverage of the areas that need it the most. This paper explains how this research project emerges, the challenges this research effort confronts, and how we are planning to address those challenges.

PUERTO RICO’S SOCIAL CHARACTERISTICS

Puerto Rico’s distinct social and economic inequalities contribute to increasing social vulnerability among some sectors of the population and explain the differential impact of disasters. Rodriguez (2001) claims that the island’s geographic location, large number of households located in high-risk zones, its high population density; the age distribution of the population, high poverty rates; low educational attainment in the population ; and lack of disaster mitigation initiatives contribute to the island’s vulnerability to disasters. Understanding the characteristics of the population and their exposure to weather events is vital to the development of any technology and its associated system configuration. Furthermore, understanding the vulnerability of the population exposed to flooding in Puerto Rico's West Coast offer an opportunity for the development of short and long-term mitigation policies. Since disasters highlight everyday inequalities, the analysis of social vulnerability to disasters in Puerto Rico focuses on understanding the distribution of the population and their ascribed and achieved characteristics, which can hamper their capacity to prepare, interact and resist an unexpected weather event.

As part of her graduate work and as a research assistant for CASA and other research projects, Santos' master thesis looks at the development of social vulnerability to disasters in Puerto Rico. This ongoing analysis looks at the social and economic development of Puerto Rico in order to provide a better understanding of social vulnerability in that particular context. The analysis uses data, at the block group level, from the Summary File 3 of the 1990 and 2000 of the U.S. Census of Population and Housing. The assessment conceptualizes vulnerability as a fluid phenomenon that varies according to the capacity of individuals from different social groups to accumulate social, political, economic and cultural capital that can enhance their capacity to prepare, adapt and respond to weather events. Therefore, her measurement of Social vulnerability focuses on the population characteristics that can adversely impact their capacity to experience weather hazards (Wisner, et al. 2004) and explain the consequences of disasters and consequently reinforce the social status. For instance, Delica-Willison and Willison (2004) argue that while it is erroneous to infer that poverty and vulnerability are the same, they do reinforce each other. In other words, a disaster resulting from the intersection between a weather event and a particular social context is a depiction of its inequalities, moreover, disasters can perpetuate and/or intensify these inequalities.

Using Geographic Information System technology, geographic areas were classified according to their levels of social vulnerability (see Figure 1). The GIS analysis generated as part of her thesis includes data on the sociodemographic characteristics of the Island's residents, critical emergency management infrastructure in high risk areas, and a layer including the social vulnerability 'score' of each block group in Puerto Rico, among others. The model developed borrows from existing vulnerability indexes (Cutter, 2003; Peacock, unpublished) and measures social vulnerability as follows:

Social Vulnerability = f(population density + proportion of children + proportion of elderly + proportion of female headed households with children + proportion of vehicle tenure + proportion of phone tenure + proportion of renters + proportion of the labor force unemployed + proportion of population with physical or mental disabilities + proportion of the population with low education)

measurement and conceptualization of social vulnerability to disasters and existing ones is that vulnerability is conceptualized as part of a negotiated historical process. While Cutter (2003) conceptualizes vulnerability as a 'potential for loss', Santos moves beyond to argue, that the 'potential for loss' emerges as part of a multidimensional historical process that has facilitated or hindered the power of some individuals and groups to accumulate the capacity and resources to take the desired protective measures and management decisions. This research will expand Santos' analysis of social vulnerability to incorporate the climatological and physical dimensions of vulnerability.

PUERTO RICO'S CLIMATOLOGY

Puerto Rico has two distinct seasons. The dry season is from December to March, and the wet season lasts from May to November. However, precipitation averages vary across Puerto Rico. For instance, according to the National Oceanic and Atmospheric (NOAA) and the National Weather Service (NWS), annual precipitation totals for the Western region of Puerto Rico range from 30 inches (76.2 cm) across the narrow southern coastal plain, to nearly 100 inches (254 cm) for the central mountain range of the island (Figure 3). The highly varied topography influences the rainfall distribution. The 'Cordillera Central' and 'Sierra de Luquillo' mountain ranges, located in central and northeast Puerto Rico, respectively, affect rainfall distribution in Puerto Rico (see Picó, 1969). Puerto Rico's mountain ranges create an orographic lift that makes the ascending air cooler in elevated areas and produces more rainfall in some areas. The patterns of Puerto Rico's rainfall combined with the topography and the urbanization patterns that have transformed the landforms make the island susceptible to flash floods and mudslides. Therefore, accurate Quantitative Precipitation Estimates (QPE) and flood forecasts are vital.

Currently, there is one NEXRAD radar in Puerto Rico, located in Cayey in Eastern Puerto Rico. The elevation of the radar site is 850m. In western Puerto Rico, the ability of the NEXRAD radar to sample the troposphere, the lower portion of the atmosphere, is compromised. The distance from Cayey to Mayaguez is approximately 112km (Figure 4). Because of the earth's curvature, the beam's elevation increases 600m making the total beam elevation above Mayaguez approximately 1.4km. The incapacity to scan the troposphere alters the precipitation estimates given that the precipitation detected at 1.4km may drift with the ambient airflow or may evaporate before reaching the ground (Figure 5). In May 2001, a flooding event in western, southwestern and the western interior of Puerto Rico caused over $150 million in damage and killed two people (Mojica et al. 2001, Preliminary Report). The Storm Total Precipitation Estimates from Doppler Radar data underestimated the rainfall by up to 66% in some areas (NOAA, 2006). Therefore the magnitude of the event was not anticipated by forecasters or the public.

The CASA radar strategy in Puerto Rico aims to improve QPE by sampling lower in the atmosphere. The radars developed by CASA are low-powered "off-the-grid" (OTG) network radars that communicate with the other radars via wireless connections. Therefore, if implemented appropriately, the CASA technology affords an opportunity to have better coverage and more accurate precipitation estimates. Furthermore, the CASA radars in Puerto Rico will receive power from on-site solar panels eliminating the constraints that power could have presented in the placement of the radars. This allows us to place radars in regions that allow a better coverage of flood-prone areas and the accurate quantification of precipitation. As a consequence, the rainfall climatology will be incorporated into the proposed vulnerability model. Combining the hourly precipitation maximums with the physical characteristics will allow us to identify which areas have the highest probability of flash floods.

Previous work has been done to determine the peak rainfall amounts received across Puerto Rico. Figure 3 (NOAA, 2006) shows isopluvials of hourly precipitation with an average recurrence interval of 1 year. The recurrence interval tells the expected length of time between hourly precipitation totals that exceed the given amount. This product is produced by NOAA and is based on quality-controlled rain gauge information. Therefore, potential error in the plot is related to the accuracy of the gauge information and the density of the stations. In Mayaguez, for example, hourly rainfall totals will exceed 2.1" once every year on average. This plot will serve as the climatological "layer" for the proposed Vulnerability Model.

PUERTO RICO'S PHYSICAL CHARACTERISTICS

To incorporate the physical and built environment dimension of vulnerability we are currently developing a hydrologic flash flood simulation tool. The main challenge we encounter is incorporating the infrastructure in the region. Nevertheless, incorporating the infrastructure is imperative because it defines and changes the flow path in the flood plain. Remote sensing images of the area, soil characteristic measures, digital infrastructure elevation models (data provided by the *Centro de Recaudación de Ingresos Municipales*-PR Office of Municipal Tax and Revenues or Laser Imaging Detection and Ranging-LIDAR survey), adjusted NEXRAD data, and revised river and stream flow data will be used to develop a flash flood simulation tool. The NEXRAD data needs to be adjusted to address sampling issues previously discussed. In addition, the river and stream flow data also needs to be revised because some stations are far from the outlet basin and some are uncalibrated. After pre-processing and revising the existing data, new cross sections will be taken in the principal rivers and new relationships will be developed to assume the river width where no cross sections exist. The hydrologic model (Vflo) seems appropriate as it is capable of integrating the information derived from remote sensing and the available GIS data to recreate the physical characteristics of the region. This distributed model presents an opportunity for an enhanced model that better represents the characteristics and spatial variability of the basin because it calculates high resolution runoff.

In addition, Vflo, can read rainfall information derived from radar in real time or post-analysis. Initially, a hydrologic model configuration was developed for the Añasco, Guanajibo and Yagüez rivers using the USGS 30m x 30m Digital Elevation Model (DEM), and resized to 200m X 200m to calculate overland slope, flow direction, and stream locations. Their basins had approximately 800 km^2. Preliminary findings reveal that about 75% of the flood plain is flooded with high rainfall events. This initial analysis will be extended to incorporate the area of Aguadilla and Cabo Rojo, which are also part of the test bed region (see Figure 4 & 5).

DEVELOPING AN EMPOWERING SCANNING STRATEGY

The achieve CASA's ultimate goal, the design and development of an empowering adaptive scanning strategy for the CASA radars to be placed in Puerto Rico is faced with many challenges as discussed throughout this paper. By 'empowering' we mean, a scanning strategy that in the end will lead to a more accurate forecast by incorporating the social, climatological and physical environments of Puerto Rico. If CASA radars deliver a better data product this can translate into a potentially enhanced capability for meteorologist to understand Puerto Rico's climate patters and make more informed warning decisions. Improvements to severe weather detection and prediction will contribute to more accurate forecasts and to more truthful expectations of the magnitude of a weather event. Furthermore, understanding the context in which this technology will be implemented can allow policy makers to craft effective policies to increase the resilience of the population in exposed geographies. While we cannot change the existing distribution of the population across Puerto Rico, we can measure the likelihood of different flood plains to inundate, how long it will take for them to saturate, and the social vulnerability of the population in the exposed vicinity. Finding an optimal location to place the CASA radars and designing a scanning strategy that allows us to better predict weather events can facilitate more informed and reliable warning decisions as it can allow us to understand the social context in which this events occurs, the needs of the population in those areas, and develop ways to reduce the prevalence of population with a limited capacity to confront and withstand this weather events.

To incorporate the social, climatological and physical dimensions of the environment we will create a numerical equation following the Meteorological Command and Control (MC&C) equation used (see Diagram 1) in the IP1 testbed in Oklahoma (Zink, M., et.al, 2005:37-42) We propose to use this equation to develop an adaptive scanning strategy for the IP3 radars using reinforcement learning. The latter is a type of machine learning designed to learn through interaction. Instead of providing a set of correct answers, the external teacher provides evaluative feedback in the form of scalar rewards, and the agent learns to maximize the reward received over time. Currently, the radars are only capable of performing 360° spins at one angle to scan the environment. The goal of this research is to demonstrate that by using previous knowledge of the hydrological, climatological, and sociological factors, we can determine the optimal scanning strategy (e.g. angle of scan, speed of scan) to improve our ability to predict flash flooding in Western Puerto Rico. Two advantages of machine learning are the ability to scale and adapt to larger radar configurations and to consider the high level tasks, such as tracking a mesocyclone through the system or focusing on a particular storm system over a socially vulnerable area.

An important challenge we face in developing and implementing our scanning strategy is quantifying the previous knowledge of the environment and testing the strategy. It is vital to understand the ecology of Puerto Rico so that we can adapt our systems to its needs. Therefore, an interdisciplinary analysis of the ecology of the island and generating a holistic understanding of the island's vulnerability to flash floods is crucial to the well-being of the residents.

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FIGURES & DIAGRAMS

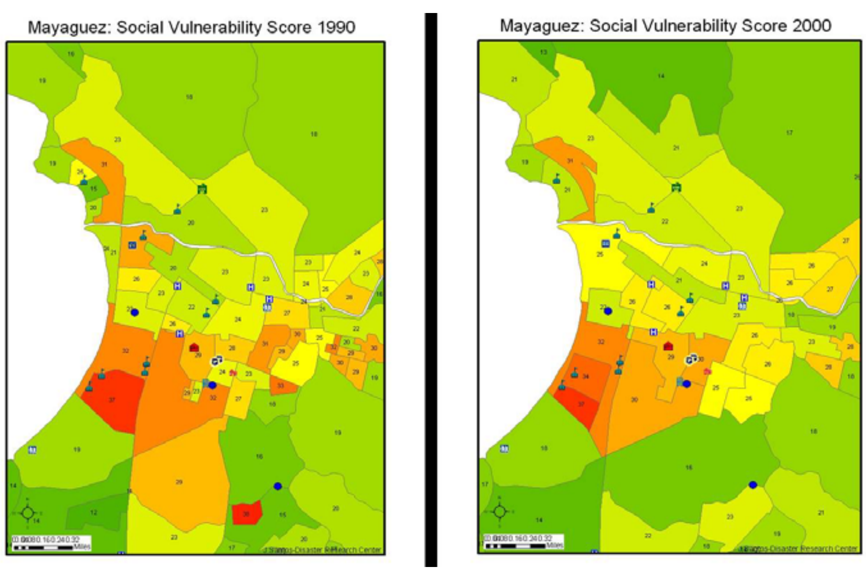

Figure 1. 1990 and 2000 Social Vulnerability of Mayagüez Puerto Rico. Social Vulnerability is measured as a function of population density, proportion of children, proportion of elderly, proportion of female headed households with children, proportion of vehicle tenure, proportion of phone tenure, proportion of

renters, proportion of the labor force unemployed, proportion of population with physical or mental disabilities, proportion and proportion of the population with low education.

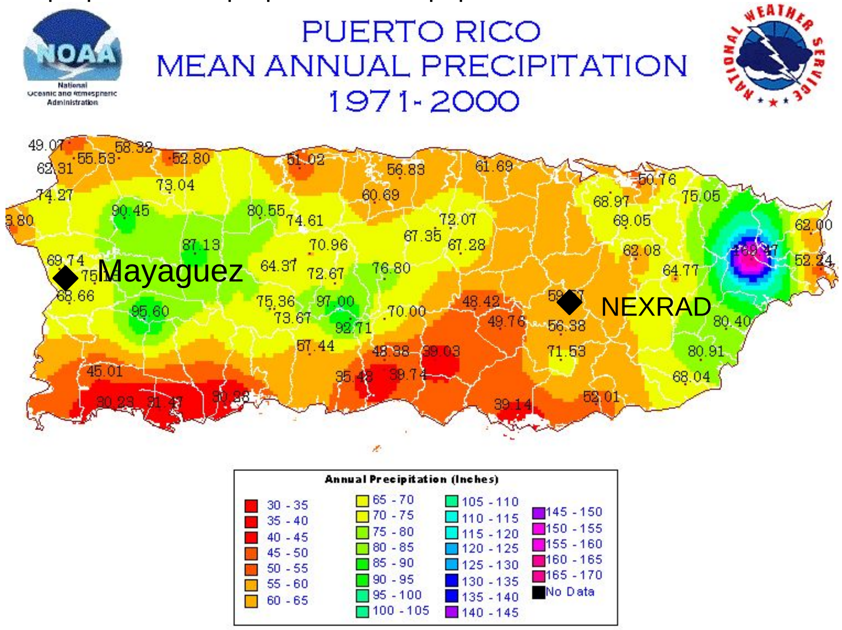

Figure 2. Mean annual precipitation in Puerto Rico according to the National Oceanic and Atmospheric Administration (NOAA). In addition, the approximate relative locations of Mayaguez, on the west coast of Puerto Rico, and the NEXRAD radar in Cayey, Puerto Rico are shown. The radar is approximately 112 km east of Mayaguez. (NEXRAD lat= 18.12N; lon= 66.08W; Mayaguez lat=18.21N; lon=67.14W)

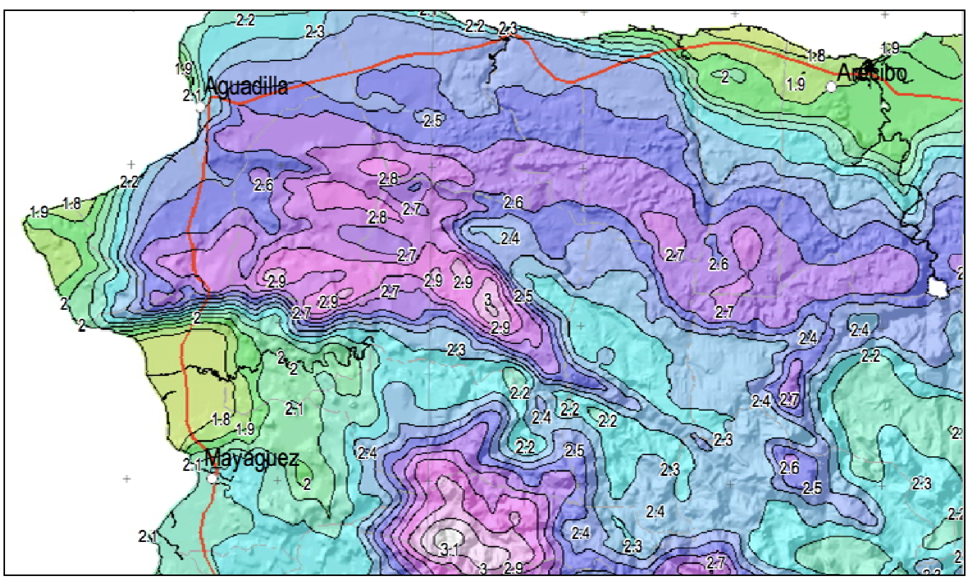

Figure 3. A regional shot of isopluvials of 60-minute precipitation (in inches) with an Average Recurrence Interval of 1 year. Precipitation values are shown. The area shown is part of the CASA radar domain. (NOAA)

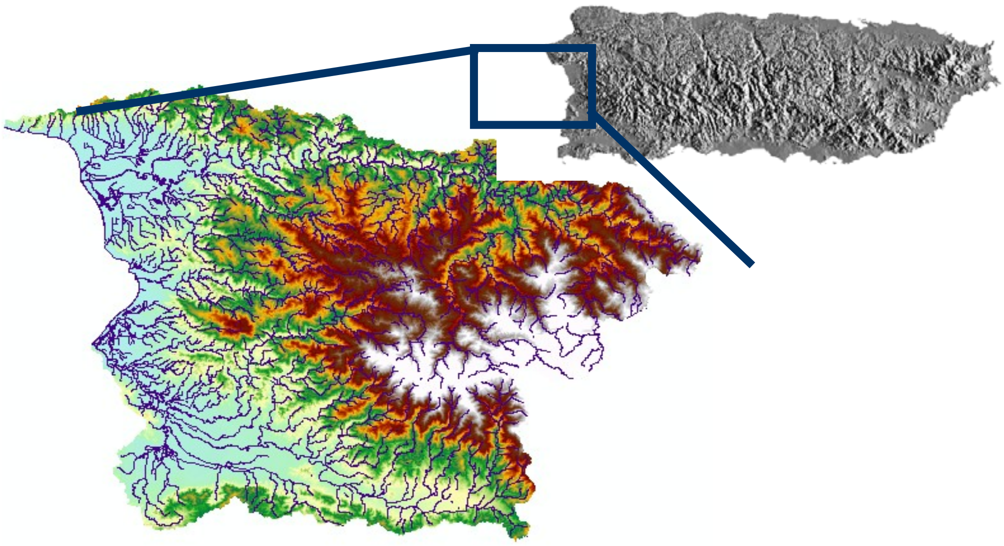

Figure 4. Puerto Rico Digital Elevation Model and basins that drain to Mayaguez Bay

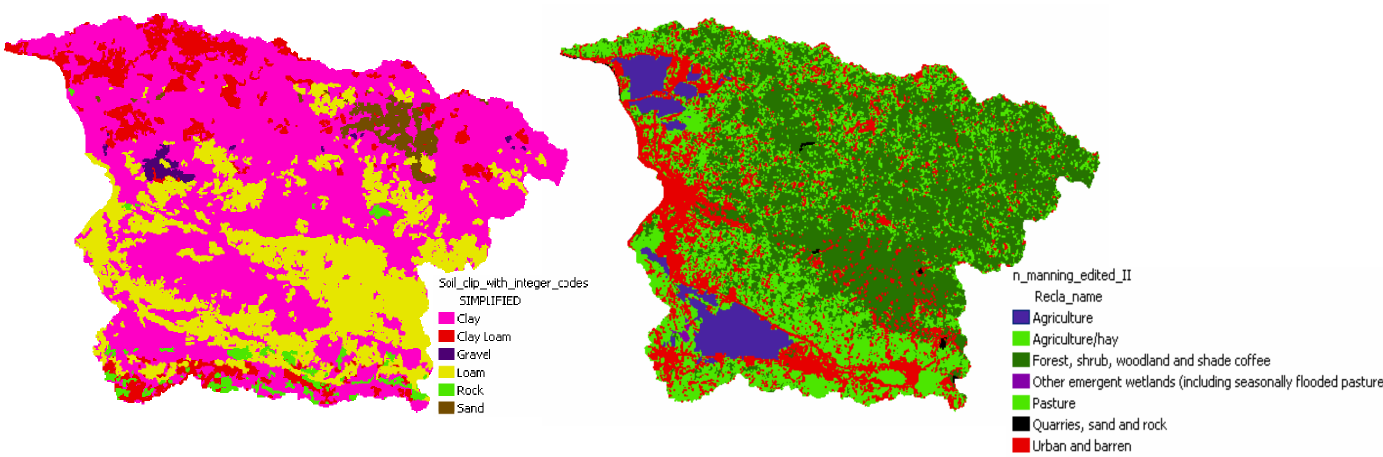

Figure 5. Soil texture (left) and land use (right) map for Añasco, Yagüez and Guanajibo basin. Data Source: SSURGO(Soil Survey Geographic Database)

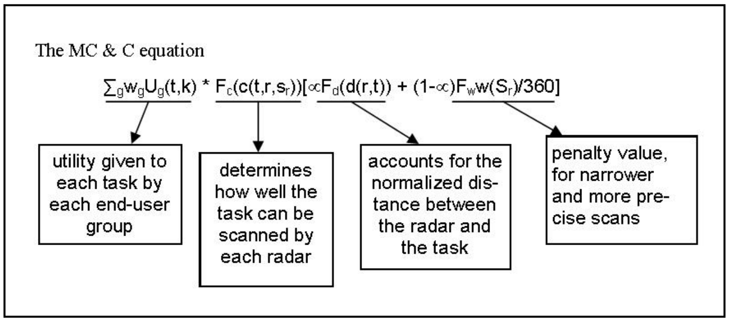

Diagram 1. The MC & C Equation (Zink, M., et.al, 2005:37-42)