Impacts of future climate and landuse on water resources in Espírito Santo, Brazil

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Abstract

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Increasing temperature and precipitation changes are expected to bring fundamental changes to the country of Brazil as predicted by Global Climate Models (GCMs) (IPCC, 2007). Potential effects of climate change in Brazil suggest changes of 4-4.5°C in surface temperature as a result of increased CO_2 concentrations. In plantation states such as Minas Gerais and Espírito Santo, a much drier climate is predicted to be a result of global warming and/or reduced water vapor transport from Amazonia. However, the responses of regional and local streamflow to these changes are still not well quantified, particularly in data-sparse regions and where hydrologic studies have not been thoroughly explored, making it difficult for water managers to plan for uncertainties associated with a changing climate. The overarching goal of this dissertation is to address a set of management issues related to local climatology and land use

change and to present the results on a platform that helps improve understanding and communication between water managers, stakeholders and decision makers. The specific science questions that this dissertation will answer are: how does the long-term climate affect water availability in the region, how do changes in weather and landuse alter water flow and affect the mobilization of sediments, and how can these results be described in a way that helps water managers make decisions? More specifically, this dissertation will study the linkages between streamflow, precipitation and temperature through the use of a macroscale land surface hydrology model for the entire State of Espírito Santo. I also use a sensitivity-based approach to estimate future streamflow in the region. At a finer resolution, I apply a hydrology-soil-vegetation model to simulate effects of increased eucalyptus and agriculture on the Jucu and Santa Maria watersheds and investigate how changes in land use and water management issues will impact sediment flow. I also describe the integration of the results into a decision support system or dynamic information framework (DIF) that can be easily transferable to tropical regions and other areas with similar climatology to Espírito Santo. This study will be particularly useful in helping water managers assess changes in land surface water availability due to climate and land cover change and to plan for ensuing uncertainties.

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I. INTRODUCTION

Climate projections and scientific analyses have provided ample evidence that freshwater resources are vulnerable to changes in precipitation and temperature change, imposing societal and ecosystem pressure in various regions of the world (e.g. Arnell, 1999; Vorosmarty et al., 2000 and 2010; Foley, 2005; Oki & Kanae, 2006; IPCC, 2013 and many others). In the developing regions of the world, many countries still lack an understanding on the full impact of potential climate hazards on climate-sensitive sectors such as agriculture and water resources (Mirza, 2003).

In addition to the climate, population expansion and land use change also stress water availability. Large scale conversion of tropical forests in regions like Brazil not only influences the climate feedback of the region through rain interception and evapotranspiration, but also changes stream geomorphology, promote soil erosion and increase sedimentation (Nobre et al., 1991). This could potentially lead to issues such as siltation in dams, pollution of surface water and flooding (Foley et al., 2005).

Temperatures across Brazil are predicted to increase on average by about 4ºC over the next decade and in northeast Brazil, semi-arid and arid areas will suffer a decrease of water resources due to climate change (Nobrega et al., 2011; IPCC, 2013). This region of the world is particularly important due to the presence of several different ecosystems that sustains some of the world's largest biodiversity (da Silva & Casteleti, 2003). Field observations and numerical studies revealed that large-scale deforestation in Amazonia could alter regional and global climate significantly, projecting a warmer and somewhat drier post-deforestation climate. For example, studies by Lean et al., 1989, Shukla et al., 1990 and Sampaio et al., 2007 showed that deforestation of the eastern Amazon rainforest would increase in near-surface air temperature, and decrease in evapotranspiration and precipitation, which occurs mainly during the dry season. Globally, Werth et al., 2002 showed that deforestation in the Amazon would reduce rainy-season precipitation in many parts of the world.

The state of Espírito Santo is located in the Atlantic Forest biome, which, due to its exceptional level of species diversity and its vulnerability to continuing threats, is one of the five hottest biodiversity hotspots among the world‘s top priority conservation areas and is known as the Central Ecological Corridor of the Atlantic Forest (Myers et al., 2000). Noting the potential effects of long-term climate and land use hazards on water resources in this significant area, the World Bank in conjunction with the state of Espírito Santo in Brazil launched the Espírito Santo Biodiversity and Watershed Conservation and Restoration Project (Floresta para Vida, FpV) in 2013.

The FpV project focuses on two critical, high-biodiversity watersheds in south-central Espírito Santo (ES): the watersheds of the Jucú and the Santa Maria da Vitória (SMV) Rivers, comprising 401,000 ha, or 9 percent of the State‘s territory (Fig. 1.1). The selected watersheds are of critical importance to the state because they provide approximately 95 percent of the water supply to the Greater Vitoria Metropolitan Area (GVMA) while also generating hydroelectricity. The GVMA in turn is of great importance to the economy of the state because it houses close to half the state's population of 3.1 million and generates 62 percent of state GDP.

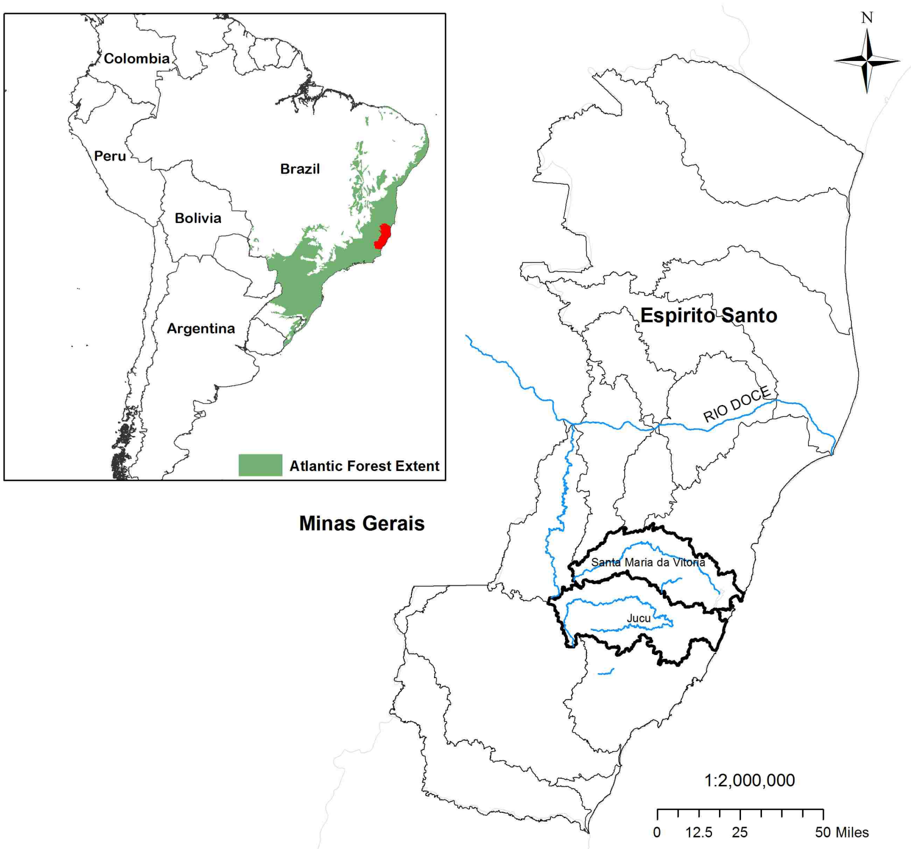

Figure 1.1 Map of Espírito Santo state and location of the Jucu and Santa Maria da Vitoria river basins

The watersheds of Jucú and Santa Maria have forest cover ranging up to 50% of its area—significantly more than state and national averages for any area inside the Atlantic Forest biome and account for more than half the total area of Atlantic Forest in the ES, about 1,900 km^2. Despite being quite fragmented, the existing forest cover in the headwater regions of these watersheds provides extremely important environmental services, such as the regulation of hydrological flows, groundwater recharge, soil conservation, and water quality preservation, including the reduction of sedimentation in water bodies, in addition to contributing to the local climate.

The municipalities in the upper watershed (Domingos Martins, Marechal Floriano, Santa Maria, and Santa Leopoldina Jetibá) have predominantly been used by traditional small family farmers, with an average farm size of 20 to 30 ha and an average of about two families for property. The main agricultural activities are the cultivation of maize, beans, root crops, coffee, bananas, horticulture, orchards, plantations, livestock, and poultry. Other economic activities found in the area include mining, eucalyptus plantations, and small hydropower plants. These traditional agricultural practices in the headwater regions of these watersheds have contributed to the reduction and fragmentation of forest cover. In turn, this reduction, coupled with the rugged local relief, has resulted in soil erosion, which has harmed water quality, leading to higher treatment costs and reducing the storage capacity of reservoirs.

Espírito Santo, therefore, is facing serious medium and long-term threats to the water supply for the GVMA, power generation, and industrial use. On a watershed level, land use change has resulted in problems such as soil erosion and siltation of rivers while changes in precipitation and temperatures will lead to extreme hydrological events (floods and reduction on low flows) that can exacerbate landscape changes and reduce biodiversity. Managing land use, particularly on slopes and other areas of permanent preservation can address some of these changes. Increasing forest cover by restoring denuded and degraded lands can also benefit biodiversity. On a regional level, changes in precipitation and temperature can contributed climate-related hazards such as flooding (e.g. the 2013 flooding of the state) and water availability.

However, efforts to conserve and restore habitat and natural ecosystem services have also been hampered by the lack of institutional and individual capacity to implement sustainable land management and water resource management, at both the national, regional, and watershed levels. Technical assistance and services that could spread knowledge and skills of new land use practices among landholders and producers is limited relative to demand. Previous approaches to inducing land use change in the region have not been able to produce an effective conservation of the remnants of this biome, with its globally significant biodiversity, in the face of continuing threats of human occupation, and restore or enhance connectivity between forest fragments.

In order to optimize resolutions towards building communicable and effective conservation policies, a decision support system that houses the relevant geospatial components and datasets need to be made readily available at all times to stakeholders and policy makers. My research focuses on using modern "landscape/hydrology" models of river basins as a powerful tool for the analysis of coupled landscape properties, water resources, and future change scenarios (due to climate, or land use practices). The results or outputs from the models are used to address questions on areas for conservation, effects of land use and climate on water availability and to develop suitable results to inform stakeholder and decision makers. Incorporating spatial datasets into geophysical models help expedite understanding of the systems through the development of various hypothetical scenarios about how these systems might evolve under different conditions. To this end, this dissertation seeks to address the following overarching questions:

1. How does the climate influence the hydrologic regime across the landscape of Espírito Santo across different spatial and temporal scales? Can hydrologic models be used to construct future scenarios of the impact of climate change on the water resources in the

region? Is it possible to identify the impacts of climate change on the management of water in urban areas?

2. What are the impacts of changes in the practices agricultural activities on local and regional water balances and water availability in the short, medium, and long terms? More specifically, could cultivation of eucalyptus and other monocultures on high land plantations impact the hydrologic flows and water availability in the coastal zone? Can suitable recommendations be developed based on hypothetical scenario analyses?
3. How do changes in landuse and water movement effect the mobilization of sediments? More specifically, what are the impacts of changes in the practices of agricultural activities on local and regional water quality and can I predict the effect of the increase in forest cover on the reduction in erosion potential? For example, what is the effect of the increase in forest cover on the discharge (flow) of water bodies (streams, rivers), and the reduction in erosion potential? Likewise, how does agriculture impact sediment yield?

The questions will be answer in three main chapters. Chapter I evaluates how variations in precipitation and temperature sensitivities and understanding their interactions with the hydrologic regime of the state can be used in water management planning and decision making. This approach helps to approximate effects of future climate change scenarios on the cumulative distribution functions of long-term annual streamflow change (Question 1). Chapter II looks at how different landcover changes for past, present and hypothetical future scenarios can help provide an insight into the potential effects of the cultivation and increase of eucalyptus buffers and other agricultural crops on hydrologic flow and what areas are most likely to be of concern for conservation (Question 2). Finally, Chapter III will address the issue of erosion and sedimentation caused by landuse change (Question 3). The climate, hydrological, sediment and water quality data available for this region has been extremely sparse thus far, and I show in this dissertation that hydrologic models and scenario analyses are effective tools in replicating the regional water balance while providing an insight into interactions between the atmosphere-biosphere dynamic. This dissertation also stresses the need for drastic expansion on data collection and observation points in order to provide stakeholders and policy makers with sufficient information to make effective decisions, particularly as global water resources become stressed under climate and population growth in developing regions such as Espírito Santo.

References

Arnell, N. W. (1999). Climate change and global water resources. *Global environmental change*, *9*, S31-S49.

Broad, K., Pfaff, A., Taddei, R., Sankarasubramanian, A., Lall, U., & de Souza Filho, F. D. A. (2007). Climate, stream flow prediction and water management in northeast Brazil: societal trends and forecast value. *Climatic Change*, *84*(2), 217-239.

da Silva, J. M. C., & Casteleti, C. H. M. (2003). Status of the biodiversity of the Atlantic Forest of Brazil. *The Atlantic Forest of South America: Biodiversity Status, Threats, and Outlook. CABS and Island Press, Washington*, 43-59.

Foley, Jonathan A., et al. "Global consequences of land use." *science* 309.5734 (2005): 570-574.

IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324.

Lean, J., & Warrilow, D. A. (1989). Simulation of the regional climatic impact of Amazon deforestation. *Nature*, *342*(6248), 411-413.

Milly, P. C., Dunne, K. A., & Vecchia, A. V. (2005). Global pattern of trends in streamflow and water availability in a changing climate. *Nature*, *438*(7066), 347-350.

Nobre, C. A., Sellers, P. J., & Shukla, J. (1991). Amazonian deforestation and regional climate change. *Journal of Climate*, *4*(10), 957-988.

Nóbrega, M. T., Collischonn, W., Tucci, C. E. M., & Paz, A. R. (2011). Uncertainty in climate change impacts on water resources in the Rio Grande Basin, Brazil. *Hydrology and Earth System Sciences*, *15*(2), 585-595.

Oki, T., & Kanae, S. (2006). Global hydrological cycles and world water resources. *Science*, *313*(5790), 1068-1072.

Shukla, J., & Sellers, N. P. (1990). Amazon Deforestation and Climate Change. *Science*, *247*(4948), 1322.

Vörösmarty, C. J., Green, P., Salisbury, J., & Lammers, R. B. (2000). Global water resources: vulnerability from climate change and population growth. *Science*, *289*(5477), 284-288.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., & Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature*, *467*(7315), 555-561.

Werth, D., & Avissar, R. (2002). The local and global effects of Amazon deforestation. *Journal of Geophysical Research: Atmospheres (1984–2012)*, *107*(D20), LBA-55.

II. HYDROLOGIC SENSITIVITY OF STREAMFLOW RUNOFF TO CLIMATE CHANGE IN ESPIRITO SANTO, BRAZIL

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Abstract

Increasing temperature and precipitation changes, as predicted by Global Climate Models (GCMs), are expected to bring fundamental changes to the hydrological cycle in Brazil. Water resources managers are tasked with planning for the potential consequences of these changes, despite the lack of quantification of the sensitivity of streamflows to these changes. These difficulties are particularly acute in data-sparse, developing regions such as the plantation states of Espírito Santo and Minas Gerais in Brazil where hydrologic studies are sparse. Long term, difficult policy decisions, will likely falter where managers cannot confidently quantify and explain future impacts. The need is critical for computationally efficient and easily adaptable methodologies of analysis that make use of available data. This paper summarizes the results of our analyses of the sensitivity of streamflow to changes in temperature and precipitation in the Brazilian plantation states of Espírito Santo and Minas Gerais. Using a land surface hydrology model forced with gridded data from 1950 – 2007, I estimated the precipitation elasticity and temperature sensitivity of the regional streamflows, in order to understand the interactions between climate and hydrology in the region. I then applied a sensitivity-based approach coupled with future climate scenarios (RCP 4.5 and RCP 8.5) from the Coupled Modeled Intercomparison Project (CMIP5) to estimate the long-term annual streamflow feedback to impending changes in precipitation and temperature. Spatial maps of precipitation elasticity (denoted e) showed that the areas most sensitive to changes in precipitation are the upper ES and

coastal regions. Findings of low temperature sensitivities suggested that streamflow regime for Espírito Santo is largely sensitive to precipitation alone. The estimates of future streamflow using the sensitivity-based approach developed here suggested an average increase of 20% to 45% across the region for all emissions scenarios, with the highest change in streamflow predicted for the Cachoeira basin.

2.1 Introduction

Global Climate Models (GCMs) scenarios suggest changes of 4-4.5°C in surface temperature in Brazil as a result of increased CO_2 concentrations (IPCC, 2010). Rainfall patterns could change drastically, increasing by up to 30% in the south and southeast of the country, while diminishing by up to 40% in the north and northeast (PBMC, 2015). Recent studies based on future climate projections (e.g. Yin et al, 2013; Koirala et al., 2014; Torres et al., 2014) have pointed to an increase in high-season streamflow and a decrease in low-season flows over eastern Brazil. Fu et al. (2013) indicated uncertainty of climate models in estimating the dry-season time scale in southern Amazonia, due to stronger convective inhibition energy (CIN) and/or a poleward displacement of the subtropical jet over South America. Under such conditions, water quality and availability will become increasingly stressed due to extreme and uncertain rainfall events.

The Atlantic Forest biome is considered one of the five most important hotspots in the world for conservation due to its exceptional level of species diversity and its vulnerability to continuing threats (Myers et al., 2000; Galindo-Leal et al., 2003; Ribeiro et al., 2009). Within this biome lies the southeastern regions of Brazil that form the most important center of economic and social development of the country -- 61% of the economic wealth and 44% of the population are concentrated here (IBGE, 1990). Agriculture is a key component of the economy, while sudden floods often cause significant damage.

As a result of the Brazilian National Water Resources Policy enacted in 1997, states are given a major role in administering water management, and determining the policy arena in which river basins will operate. But unprecedented economic development and deficiencies in national governance are already straining the capacity of local water managers, who must plan for the ensuing insecurities (UNDP, 2006; Kundzewicz et al., 2008). These difficulties are compounded by that fact that there are many areas in Brazil where few hydrologic studies have been conducted and data remains sparse. Scant information and ambiguities in data collection make it difficult for water managers to analyze climate and streamflow trends with confidence and to convey the necessary long-term solutions to decision makers and stakeholders. Narrowing and bounding the uncertainties of streamflow sensitivity to hydrologic forcings as well as understanding the potential impacts of a near-term future are critical in this region for flood predictions, water resources management, agricultural planning and biodiversity conservation.

Recognizing the importance of the Atlantic Forest biome and the effects of climate on the state's water supply, the State of Espírito Santo, working with The World Bank, developed a program for biodiversity and watershed conservation, the *Florestas para a Vida* (FpV) project (Boni et al., 2012). To help resolve the emerging dichotomy between conservation and economic development, exacerbated by looming water resources issues, a goal of FpV was to develop the capability to enable scenario analyses for decisions on the resources of Espírito Santo. As in most of the world, monitoring in the region is hampered by the scarcity of in situ measurements and barriers to data access. As highlighted by the floods in 2013 and the major drought of 2014-

2015, the economic and conservation viability of the region has been compromised by climate change. Hence the project objective was to centralize a resource database, primarily from remote sensing and regional data, and develop predictive scenarios from it by using numerical modeling, with climatic and ecosystem changes in mind and to plan for future climate hazards.

In this paper I explore the practicalities of how land surface modeling driven by remote sensing can address how changes in climate will affect streamflow runoff in river basins of Minas Gerais (MG) and Espírito Santo (ES) and quantify and specify which regions would be most impacted by changes in the climate. Given that the major economic drivers of these plantation states depend upon water availability, understanding how regional streamflow will respond to future changes in precipitation and temperature is extremely important. More specifically, the science questions addressed are (1) What are the long-term impacts of climate change on the water resources of the region and how will discharge from major rivers, particularly the Rio Doce, be impacted? (2) How sensitive are streamflows in this region to future changes in precipitation and temperature? (3) How do the sensitivities vary across the region spatially? (4) Can a sensitivity-based approach be used to quantify the changes in the future streamflow regime and to provide water managers with a practical and efficient method to measure future regional and local streamflow?

The sensitivity-based approach utilized measures of precipitation elasticity and temperature sensitivities (whether streamflow change is more sensitive to precipitation (P) or temperature (T) change in a particular river basin) as described in previous studies (e.g., Schaake, 1990; Dooge, 1992; Dooge et al., 1999; Sankarasubramanian, 2001; Vano et al., 2012, 2014). Precipitation elasticity, (ε) is defined as the proportional change in mean annual streamflow divided by proportional change in mean annual precipitation. Similarly, temperature sensitivity, (S) is the percent change in annual runoff per degree change in temperature. Estimates of ε and S can be completely model independent provided that there exists consistent and reliable data for precipitation, temperature and streamflow.

However, in many developing nations, including our study domain, quality observed data remains sparse. In order to quantify ε and S spatially to understand how streamflow in different parts of the domain responds to changes in P and T, I used a land surface hydrology model to simulate streamflow on a pixel-by-pixel basis. The sensitivity-based approach to estimating future changes in streamflow was successfully applied to the Colorado river basin at Lees Ferry as described in Vano et al., 2012. The authors concluded that sensitivity-based approximations of streamflow change were comparable to estimations from coupled GCM outputs and land surface hydrology modeling runs.

In addition to providing an effective and less data intensive method for estimating future flows and as a complement to downscaling methods, the sensitivity-based approach also allows the influence of temperature and precipitation changes to be isolated, and in so doing encourages better understanding of the factors that will drive changes in the hydrologic system. Further, maps of ε and S can be used as a preliminary guide to determine the targeted areas for further studies and future management plans. This is particularly important in areas where hydrologic expertise and resources are limited.

To address overarching science questions, I used a land surface hydrology model to estimate the water balance of the basins across the region. The hydrological model was forced using two sets of meteorological data to quantify the sensitivity of the hydrologic regime to changes in precipitation and temperature. The first set of meteorological data, gridded from a combination of station and reanalysis data, was used to validate and calibrate the model and to estimate the sensitivities of streamflow to changes in precipitation and temperature based on historically observed data. The second set of data is based on future projections of climate from the Coupled Model Intercomparison Project (CMIP5). The CMIP5 data provided the boundaries for future precipitation and temperature changes from 2010 – 2099. I then extended the sensitivity-based approach to gain a better understanding of future land-atmosphere scenarios and to investigate the underlying mechanisms governing local hydrology.

2.2 Study Area

Espírito Santo state occupies an area of 45,597 km², equivalent to 0.53% of the area of Brazil. The state's watershed is divided into twelve sub-basins. Its largest river, the Rio Doce, extends for 853 km, originating at the confluence of the Piranga and Carmo near the foothills of the Mantiqueira and Espinhaco mountain ranges in the neighboring state of Minas Gerais. A significant amount of the region's agricultural (coffee and sugar cane in particular), industrial, and mining production occurs within the Rio Doce basin, which contains a population of roughly 3.1 million people. The relief map is characterized by the low mountain ranges of the Aimorés Mountains on the western border and by isolated groups of hills on the eastern coastal plains (Fig. 2.1).

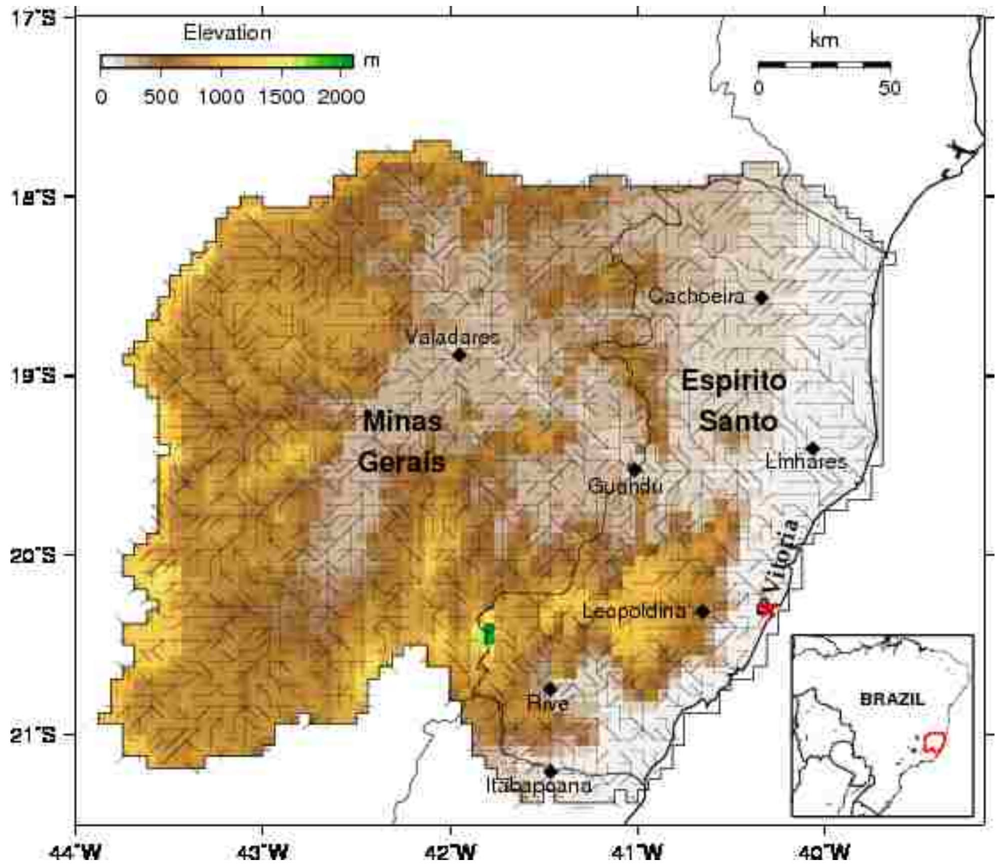

Figure 2.1: DEM and domain of Espírito Santo and Minas Gerais with station locations and flow directions.

The state is today sparsely forested, as most of the forests, that formerly supplied Brazil with a substantial proportion of its exports of rosewood and other tropical hardwoods, have now been destroyed (Morton et al., 2005; personal correspondence). The soil in the state is generally fertile, with the exception of the sandy plains and swamps of the coastal strip. Repeated plantings of the same crops have, however, exhausted some soils, and many fields have been converted to pasture land. The region holds two main climatic types: tropical rainy and humid mesothermal. The first one dominates the lowlands and is characterized by high temperatures throughout the year and average temperature above 22°C. The humid mesothermal climate is found in mountainous areas in the south of the region and is characterized by low temperatures in the winter and an average temperature below 18°C. The climate of the coastal zone and the valleys is hot and humid. In the highlands the temperature is lower, and the climate more comfortable. Rainfall, which averages about 50 inches (1,270 mm) a year, is heavier from October to March.

2.3 Methods

2.3.1 Hydrological Model

I used the Variable Infiltration Capacity Model (VIC) macroscale hydrology model (Liang et al. 1994) to simulate the relationship between climate, landscape structure, and water distribution (hydrology) across the domain. VIC is a semi-distributed grid-based land surface hydrologic model that parameterizes the dominant hydrometeorological processes taking place at the land surface-atmosphere interface. The model consists of two major components – vertical and horizontal. The vertical component calculates the water and energy balance components for each individual grid cell. The horizontal component is a convolution integral, which routes the runoff generated at each grid cell to basin outlet (tributary or main stem) channels. VIC has been used extensively at regional and global scales in numerous studies, mostly in off-line simulations where gridded surface precipitation, temperature, wind speed, downward solar and longwave radiation, and vapor pressure (humidity) are prescribed (e.g., Nijssen et al., 2001; Elsner et al., 2010; and many others). VIC has also been used for hydrologic prediction in tropical regions (e.g. Zhu and Lettenmaier, 2007; Collischonn et al., 2008; Su et al., 2008).

A mosaic representation of land cover, and sub-grid parameterizations for infiltration and the spatial variability of precipitation and temperature, account for sub-grid scale heterogeneities in key hydrological processes. The model uses three soil layers and a single vegetation layer with energy and moisture fluxes exchanged between the layers. The application of VIC requires the development of a set of input data files, including meteorological forcing (land surface climatology of daily precipitation, minimum and maximum temperature, and winds), vegetation attributes by vegetation class, a river network derived from a digital elevation model, and river discharge history at select stations.

2.3.2 Historical Meteorological Forcings

I used a global half-degree gridded meteorological forcing dataset to generate daily historical gridded forcings of temperature minima and maxima, precipitation, and wind speed at one-sixteenth degree latitude-longitude resolution from observed station data using methods described in Maurer et al., (2002). This dataset is hereafter referred to as the UW dataset. This dataset was then downscaled to a 1/16º grid using an inverse-distance interpolation algorithm.

Daily values of precipitation and temperature were then disaggregated into 3-hourly time steps according to methods outlined in Nijssen et al., (2001) and Wang et al., (2009). Similar to Maurer (2002), other meteorological and radiation variables were calculated from established relationships, for example downward solar and longwave radiation and dew point were derived from the daily temperature and temperature range using methods described in Nijssen et al., (2001). The UW global gridded dataset is available for 1948 – 2011, however I selected 1950 to 2006 as our period of analysis with the first twenty years used to spin-up the model and specify the initial conditions. I then calibrated the model from 1970 – 1979 and validated the model from 1980 – 2006 since this time period corresponds with long-term, continuous observed streamflow records available from the Brazilian national water agency (data available from the Brazilian

National Water Agency, ANA, Brazil at http://hidroweb.ana.gov.br/). The streamflow observation stations are shown in Figure 2.1, and their attributes are shown in Table 2.1.

2.3.3 Topographic and Derived Data

The 90-m Shuttle Radar Topography Mission (SRTM) digital elevation model was conditioned with basin masks from HydroSHEDS (Lehner et al., 2006) to identify inundation zones and flow paths. Since the local Brazilian topographic information was available only for Espírito Santo and did not include the upper Rio Doce basin, the SRTM data helped fill in the missing data. The VIC domain, as derived from the topographic data, was set at a basin scale 1/16º (~ 6km) to capture the finer nuances in land cover and topography. Soil texture files were obtained from the Brazilian Corporation of Agricultural Research (EMBRAPA) product of soil maps (EMBRAPA, 2011). Soil percentages and profiles were obtained from the RADAM-BRASIL Project (Cooper, 2005). Where soil data were unavailable for the parameterization of VIC, the corresponding parameters for each soil type were obtained from the United States Department of Agriculture (USDA) soil database. Landcover for the entire simulated region was obtained from the 2010 MODIS (Moderate Resolution Imaging Spectroradiometer) data.

Table 2.1: Summary of the seven basin gauges used to analyze streamflow sensitivities; averages are from observed data for 1970 – 2006.

Basin/Gauge Name	Area (km2)	Data availability	Annual Precipitation (mm)	Annual Streamflow (m3/s)
Linhares	86210	1970 - 1994	1600	991
Valadares	39828	1970 - 2006	1883	571
Cachoeira	6732	1970 - 2006	1752	45
Itabapoana	2854	1970 - 2006	1849	44
Rive	2217	1970 - 2006	2527	44
Guandu	2135	1970 - 2006	1863	22
Leopoldina	1950	1970 - 2006	1817	14

2.3.4 Precipitation Elasticity and Temperature Sensitivity formulation

Both daily temperature and precipitation for the Wood and Lettenmaier dataset were perturbed by the same amount throughout the record period (1970 – 2006). With the actual gridded precipitation data as a baseline, additional reference climates were created at 101%, 110%, 120% and 130% of the current precipitation. Thus, there were 4 different forcings from the precipitation perturbation only. Similarly, the actual gridded temperature (both t_{max} and t_{min}) was used as a reference, with additional climates created by adding 1ºC, 2ºC, 3 ºC and 6ºC to daily average minimum and maximum temperatures.

I used precipitation elasticity (ε) and temperature sensitivity (S) to represent the land-surface response to precipitation (P) and temperature (T) change and then applied these concepts to provide first-order estimates of future hydrological changes from GCM output. This approach creates a tool that can be used to bound future runoff change across the states of Espírito Santo and Minas Gerais and is summarized in equations 2.1 and 2.2. In Equation 2.1, ε represents a measure of how an incremental change in precipitation (ΔP) results in a percentage change in streamflow (Q). Similarly, S (Equation 2.2) represents a measure of how an incremental temperature perturbation (ΔT) results in a percentage change in Q.

$$\varepsilon = \frac{\frac{Q_{hist+\Delta P} - Q_{hist}}{Q_{hist}}}{\Delta P} \qquad (2.1)$$

$$S = \frac{\frac{Q_{hist+\Delta T} - Q_{hist}}{Q_{hist}}}{\Delta T} \qquad (2.2)$$

2.3.5 Future Climate Scenarios

The downscaled and biased-corrected monthly global precipitation and temperature from atmosphere-ocean general circulation models (AOGCMs) participating in CMIP5 were obtained from the "Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections" archive at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/. Since the sensitivity-based streamflow estimation has been shown to be robust only to calculate for the long-term annual average discharge (Vano et al., 2012), the monthly product was sufficient. Six AOGCMs (GFDL-CM3, GISS-E2R, HadGEM2-CC, HadGEM2-ES, INM-CM4 and MPI-ESM) that performed best in terms of precipitation simulations and related processes over the tropics and for southeastern Brazil were selected (Lei, 2013). The Representative Concentration Pathways (RCP) 4.5 and 8.5 scenarios were chosen since these scenarios take into account modest and extreme emission scenarios. The GCM output was regridded to a 1/16º resolution for consistency with the VIC analyses and associated soil and landcover data.

$$\Delta Q_{est} = \Delta P_{GCM} * \varepsilon + \Delta T_{GCM} * S + d(P,T)_{int} \qquad (2.3)$$

where:

$\Delta P_{GCM} = (P_{GCMfut} - P_{GCMhis}) / P_{GCMhis}$

$\Delta T_{GCM} = T_{GCMfut} - T_{GCMhis}$

To estimate future streamflow changes with the sensitivity-based approach, I multiplied P and T changes from GCM output by their related hydrologic sensitivity measures (e, S) to estimate the long-term average percent change in streamflow (dQ) at a specific location and time period according to Eq. 2.3, where dP is the long-term average percent change in P and dT is the difference in long-term average T between the future and historical GCM simulation. The factor d(P,T)int is the interaction between P and T changes which was neglected, due to the additive nature of S and ε reported by Vano et al., (2014). The future streamflows for three 30-year average time periods (2010 – 2039, 2040 – 2069 and 2070 - 2099) relative to the 1980 - 2006 historical period were then calculated. In Vano et al., 2014, seasonal adjustments were applied to account for seasonal variations in ε and S and to improve the performance of the sensitivity-based approach. Based on our analysis for Espírito Santo, seasonal temperature had no effect on the variability of ε and S, and precipitation had a very small effect on the estimated streamflow.

2.4 Results and Discussion

2.4.1 VIC Model Calibration and Validation

VIC was spun up for 20 years (1950 – 1969) to achieve stable moisture conditions, and subsequently calibrated from 1970 – 1979 and validated from 1980 – 2006, which is the extent overlap between the available dataset and observed data. Model performance was evaluated using both the Nash-Sutcliffe Efficiency (E) and the linear correlation coefficient, R^2. The E value (Eq. 2.4) gives a view of how well the model is able to predict the flows while the correlation coefficient quantifies how well the model matches the observed data.

$$E = 1 - \frac{\sum_{t=1}^{N}[q_{obs}(t) - q_{sim}(t)]^2}{\sum_{t=1}^{N}[q_{obs}(t) - \bar{q}_{obs}]^2} \qquad \text{(Eq. 2.4)}$$

In both cases of statistical analyses measures, a value of '1' would indicate an exact match between simulated and observed data.

VIC captures streamflow seasonality for all the basins (R^2 is between 0.7 to 0.95; E is between 0.553 – 0.872) but underestimates the magnitude of low-flows; the largest basins produce the highest correlation coefficients due to heterogeneity (Fig. 2.2). The gauges with the lowest E and R^2 values were Leopoldina (E=0.553) and Guandu (E=0.642). The lower E and R^2 values are partially attributable to the chains of individual dams and reservoirs preceding the gauges and the difficulty in modeling un-naturalized streamflow (Malveira, 2011). This is particularly the case for the Leopoldina gauge located at the mouth of the Rio Doce. The low E-value for Itabapoana on the other hand, may be explained by it location in the foothills of a steep terrain towards the southern edge of the Espírito Santo. Streamflow from mountainous regions is particularly difficult to model since the steep topography makes the basin highly sensitive to distribution of precipitation and complexity in runoff events (Alford D., 1992). While the UW dataset used in this study accounts for orographic effects and is bias-corrected against gauge data, many variables such as the accuracy of streamflow records, temperature lapse rate and anthropogenic influence can also affect the values of gridded precipitation.

2.4.2 Sensitivity Analysis for historical VIC simulations

Spatial maps for precipitation elasticity, e and temperature sensitivity, S were produced and ε values ranged from 1.5 to 8 (Fig. 2.3) depending on station location. Maps of sensitivities provide an overview of the interactions between precipitation, temperature and streamflow. For example, if ε is 3, a 10% increase in precipitation would result in a 30% increase in streamflow. Our analysis shows that the areas in northern Espírito Santo showed the highest sensitivity to changes in precipitation. Sensitivities are highest in lower precipitation regimes such as Cachoeira and Linhares (Fig. 2.4, Table 2.1).

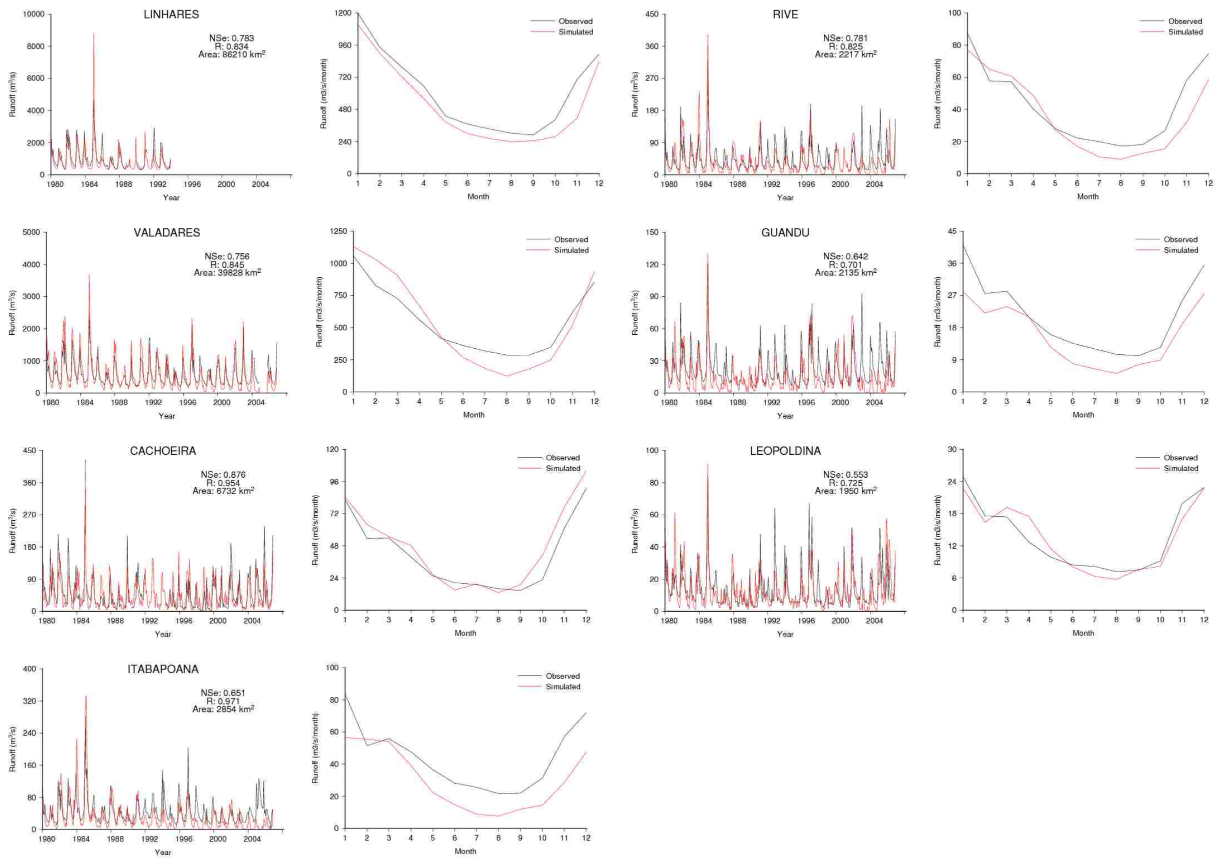

Figure 2.2: Calibration and validation for seven gauges in Espírito Santo

When precipitation is perturbed up to 30%, a streamflow increase of about 150% is predicted using the sensitivity analysis (ε = 5.5). This is plausible if the upper soil layer is relatively thin, and the water holding capacity of the upper soil is likewise limited as denoted by reduced soil moisture (Fig. 2.5). Very wet, tropical areas that receive large annual amount of precipitation are likely to see huge increases in streamflow as precipitation increases, since runoff and baseflow are limited by soil saturation and evaporation. The rank of the models from the most to the least elastic closely aligns with the magnitude of their historical flows. This indicates that more in-depth studies and full regional climate change studies in the drier precipitation regimes in northern Espírito Santo might be important to understand how the long-term mean annual streamflow will change due to increasing or decreasing precipitation.

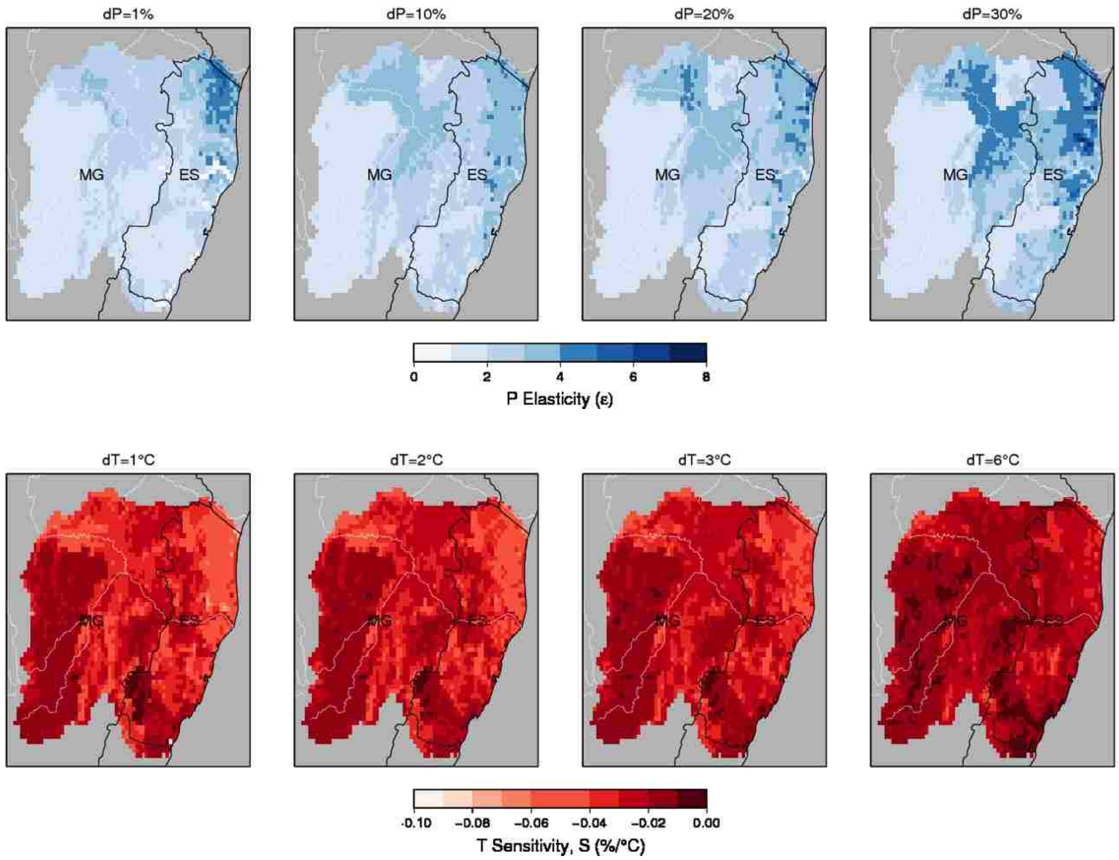

Figure 2.3: Spatial map of precipitation elasticity, ε and temperature sensitivity, S

For temperature sensitivity, S remains relatively unchanged with respect to the reference T for all the gauges, i.e., sensitivities < -0.1%. Sensitivity increases slightly after a 3°C perturbation (Fig. 2.3). The negative direction of S is generally due to runoff decreases caused by increases in ET and T. S therefore demonstrates the linkages between land surface hydrology and climate change. The low S values however, suggest that the streamflow regime in Espírito Santo is influenced largely by precipitation.

2.4.3 Future streamflow estimations

The projected changes in precipitation and temperature for all seven basins were calculated from the AOGCM data for three 30-year average time periods (2010-2039, 2040-2069 and 2070-2099) relative to the 1980 - 2006 historical period (Fig. 2.6). Each of these scenarios are hereafter noted as Scenario I for RCP4.5 (2010 – 2039), Scenario II for RCP4.5 (2040 – 2069), Scenario III for RCP4.5 (2090 – 2099), Scenario IV for RCP8.5 (2010 – 2039), Scenario V for RCP4.5 (2040 – 2069) and Scenario VI for RCP8.5 (2090 – 2099).

RCP 4.5 is taken to be the middle emissions scenario, while RCP 8.5 is the extreme scenario. For the middle emissions scenario, temperature changes (dT_{GCM}) is projected to increase on average about 2ºC every 30-year interval while precipitation changes (dP_{GCM}) increases slightly for each 30-year interval. The mechanisms governing precipitation changes are still not well understood in literature but changes in trade winds and meridional gradient of SST in the tropical Atlantic may influence precipitation in the dry season by changing the pattern of moisture convergence and vertical motion (Good et al., 2008; Xie and Carton, 2004). While I have selected GCMs that work best for the study domain, it should be noted that there exists a large variability between P_{GCM} from each model particularly for the northern most basin of Cachoeira.

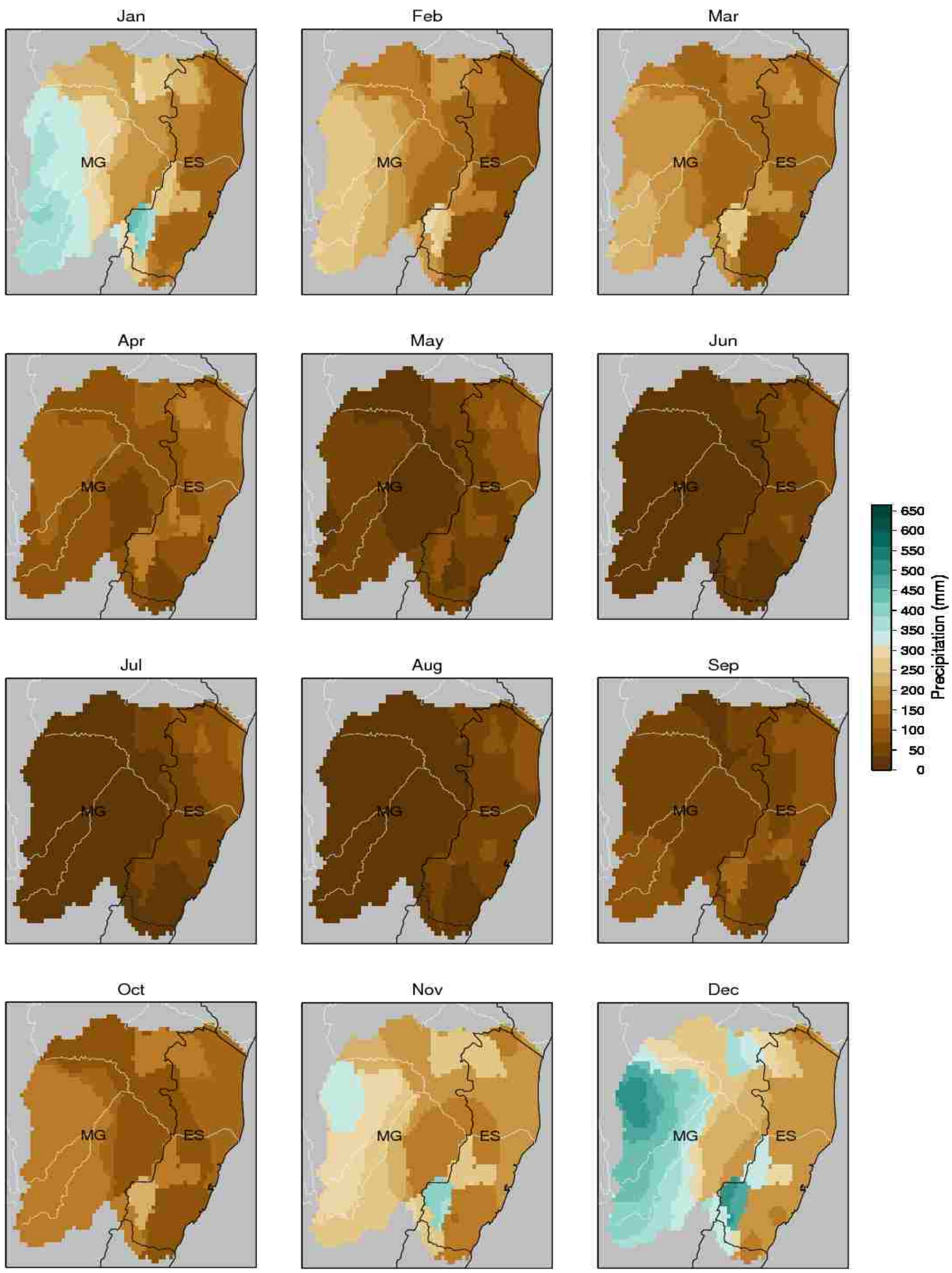

Figure 2.4: Average monthly precipitation (1950 – 2006) from VIC model output for the study domain

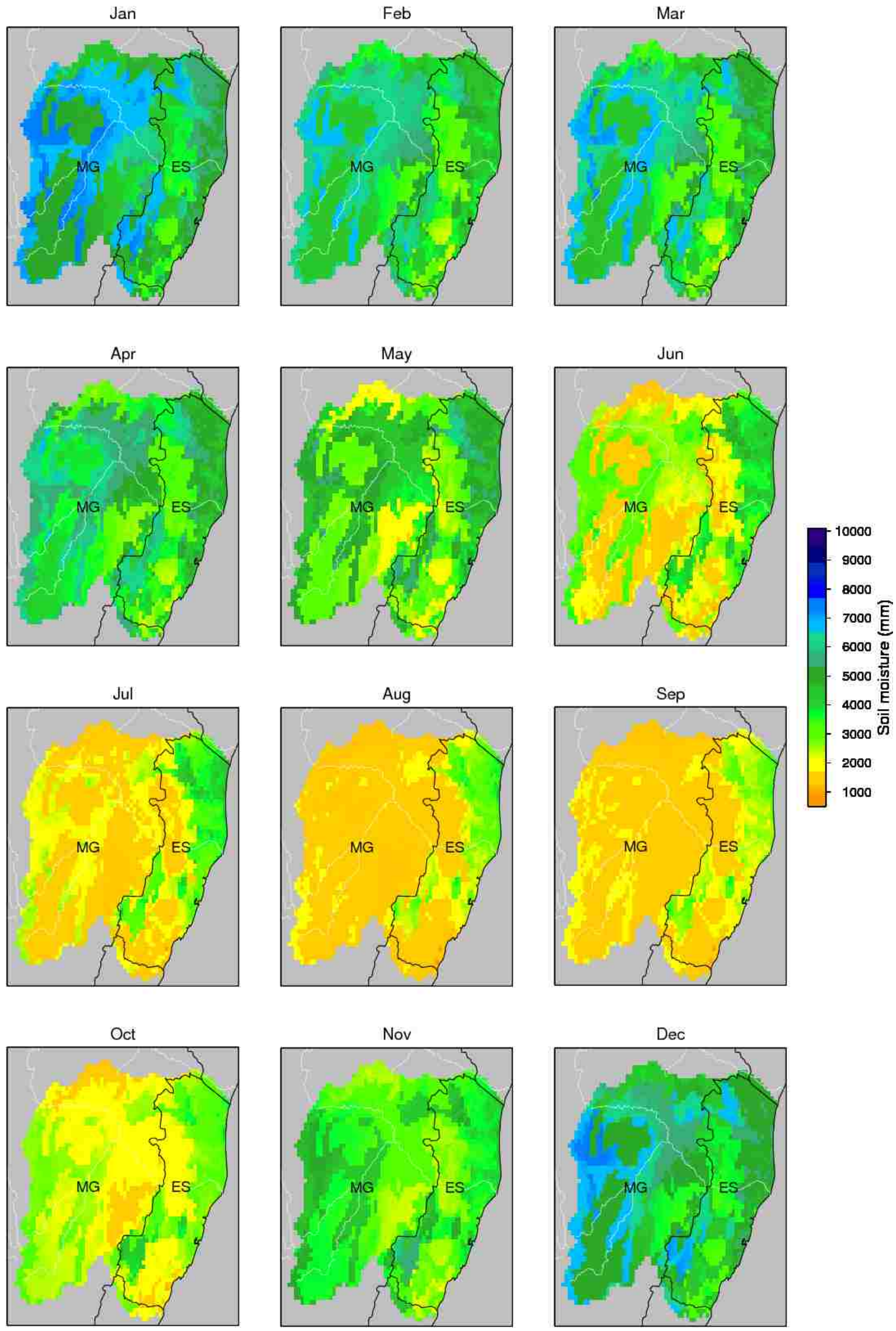

Figure 2.5: Average monthly top layer soil moisture (1950 – 2006) from VIC model output for the study domain

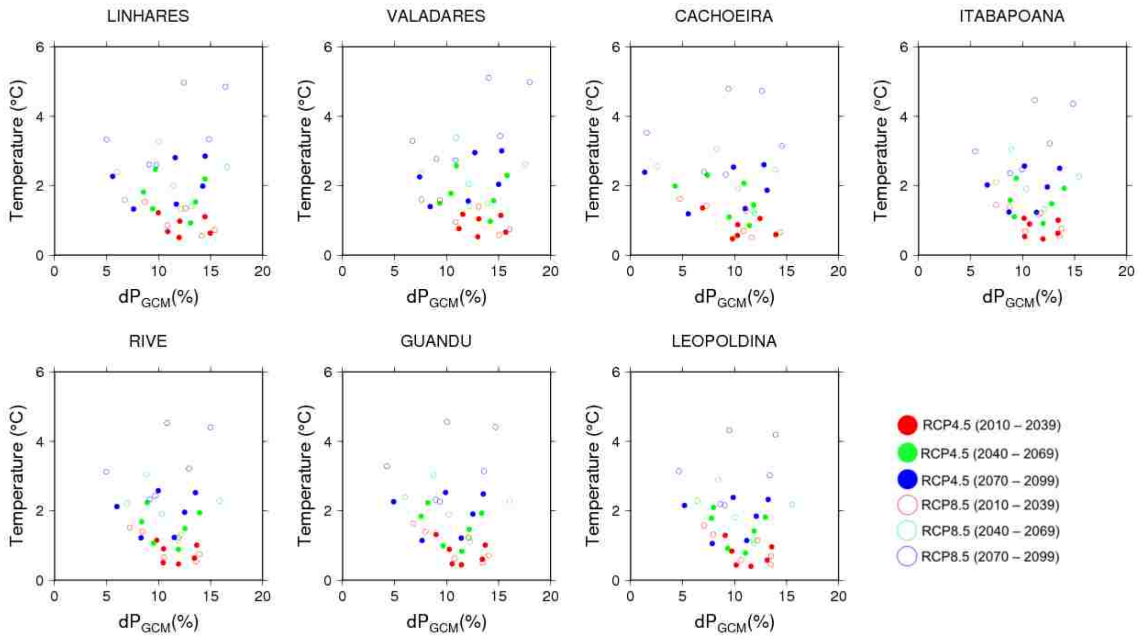

Figure 2.6. Projected changes in precipitation and temperature for all seven basins were calculated for three 30-year average time periods (2010-2039, 2040-2069 and 2070-2099) relative to the 1980 - 2006 historical period. The data are from the CMIP5 AOGCM output. Scenario I: RCP4.5 (2010 – 2039), Scenario II: RCP4.5 (2040 – 2069), Scenario III: RCP4.5 (2090 – 2099), Scenario IV: RCP8.5 (2010 – 2039), Scenario V: RCP4.5 (2040 – 2069), Scenario VII: RCP8.5 (2090 – 2099)

The overall changes in P_{GCM} and T_{GCM} were used to bound the limits for sensitivity calculations by developing plots for ε and S based on perturbing P up to 30% and T up to 6ºC from the historical reference (1980 – 2006). This resulted in values that can be approximated by a linear function thus providing the relationship between changes in ΔP, ΔT and their sensitivities (Fig. 2.7 and Fig. 2.8). The sensitivity-based approach indicated that Cachoeira is particularly sensitive to both precipitation and temperature changes (higher slope values). This is consistent with the fact that the climatology in Cachoeira is closer to the climate of Northeast Brazil where it is much hotter than the rest of ES and the rainfall is influenced primarily by ocean circulation patterns and variability (Moura and Shukla, 1981).

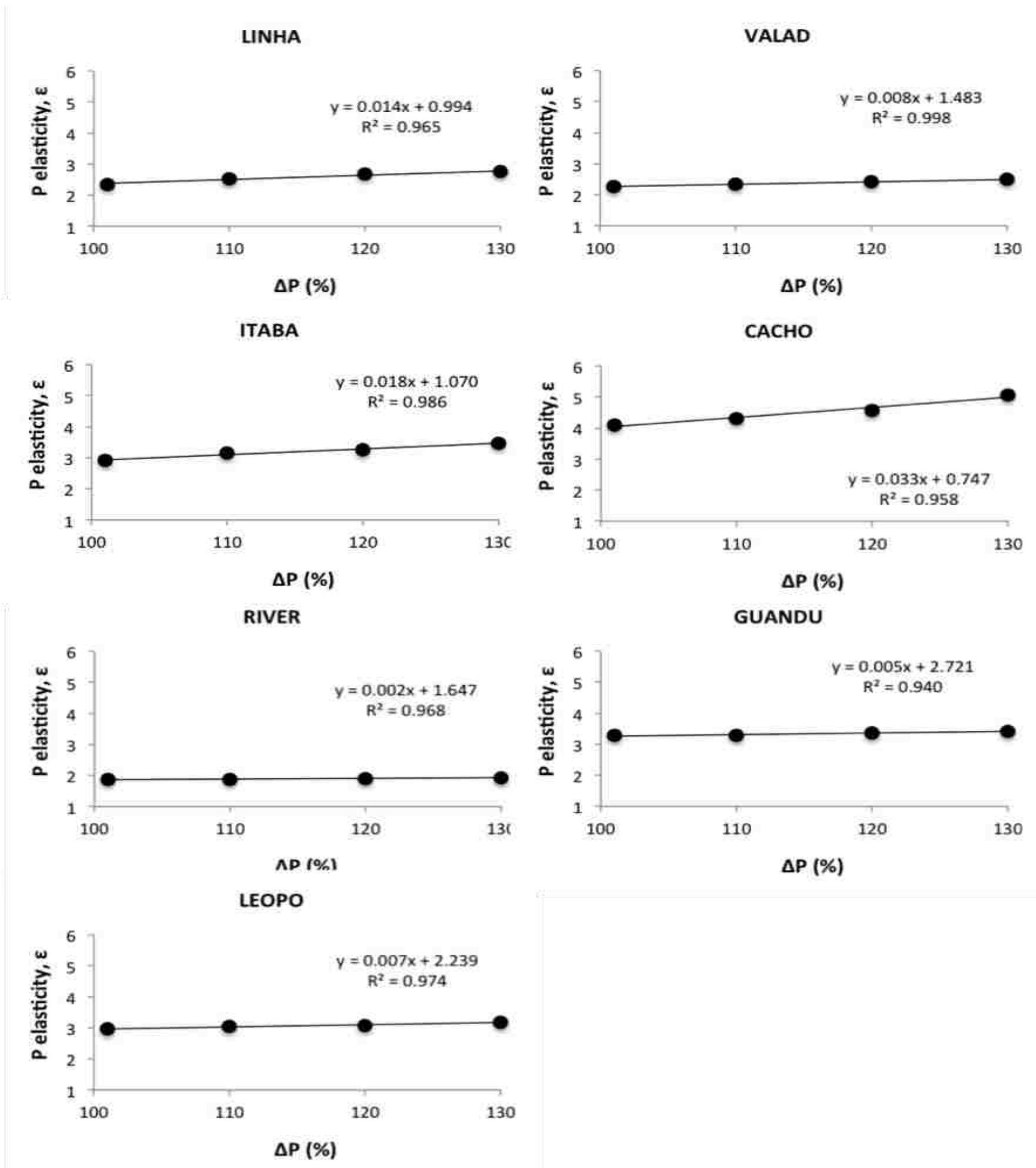

Figure 2.7. Precipitation elasticity (e) for the seven gauging stations from VIC simulations.

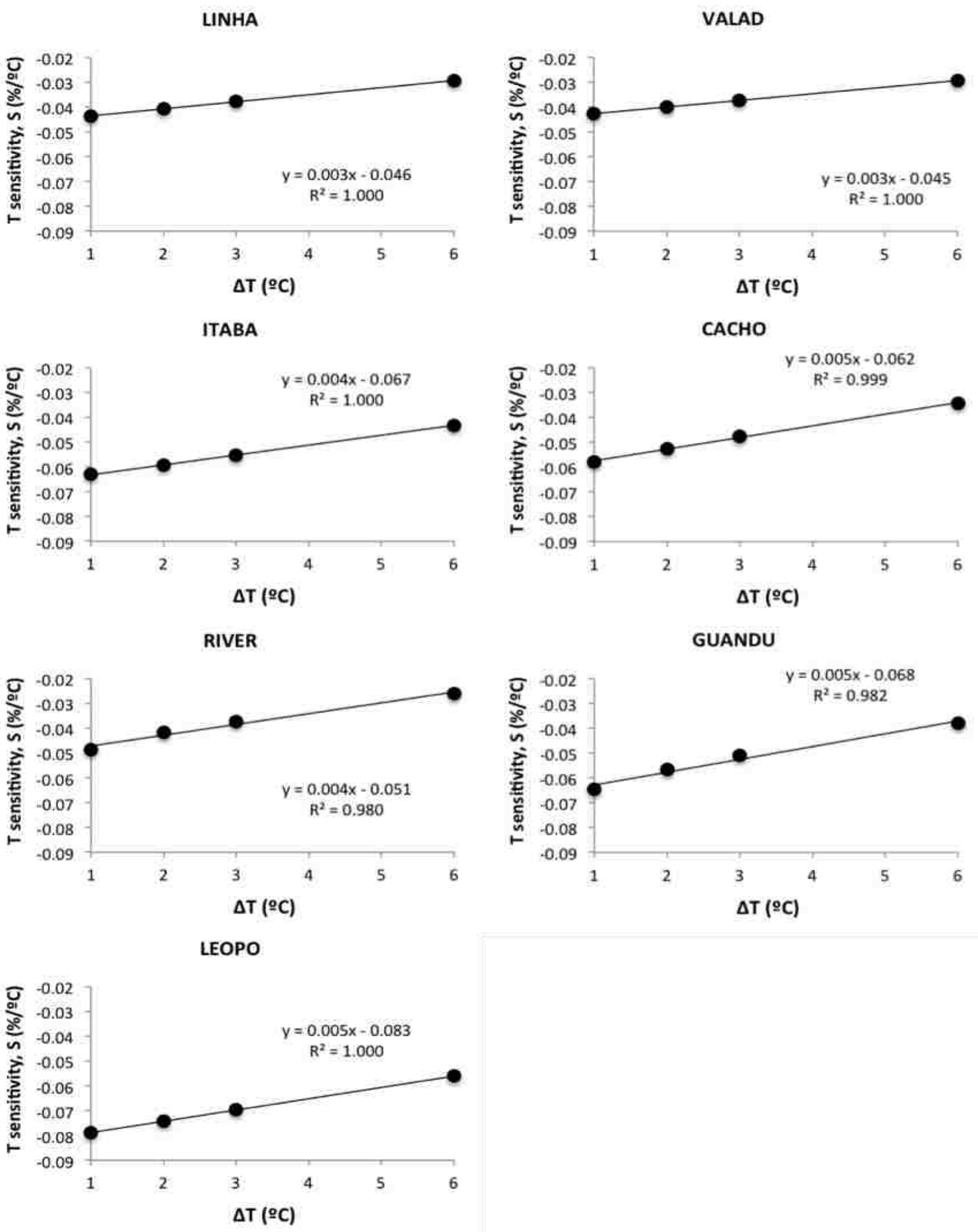

Figure 2.8. Temperature sensitivities (S) for the seven gauging stations from VIC simulations.

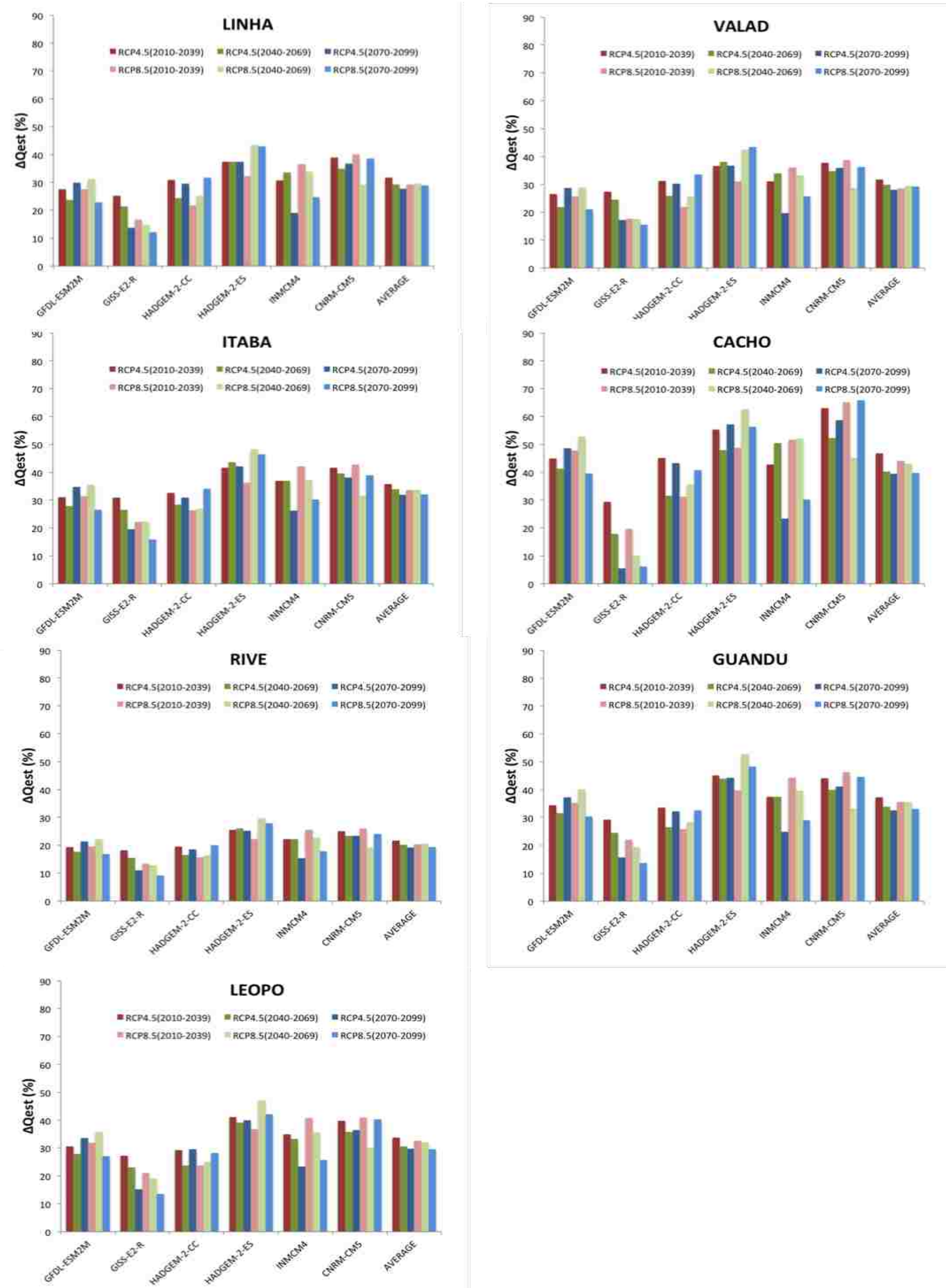

Figure 2.9. Predicted rate of change of streamflow, ΔQ_{est} for the seven basins by the different selected AOGCMs for RCP4.5 and RCP8.5 for each corresponding 30-year interval (2010 – 2039, 2040 – 2069 and 2070 – 2099)

The estimates of future streamflow (ΔQ_{est}) using the sensitivity-based approach, produced an average increase of 20% to 45% across the region (Fig. 2.9). The results vary depending on the AOGCM chosen, but the differences between each scenario for each basin (e.g. Scenario I vs. Scenario II) were usually small (<10%) except for Cachoeira. For example, in the Rive (a medium sized basin with a consistent precipitation elasticity of 2), the average projected increase in streamflow is 20% for Scenario I and 18% for Scenario IV. This indicates that the largest increases in streamflow would already be felt within the first 30-year time period (2010 – 2039).

The average ΔQ_{est} decreases for each subsequent time period except for the two largest basins. In Valadares and Linhares, Scenario V and Scenario VI produced higher flows than Scenario IV although the differences were extremely small (<1.5%). Past studies on climate change and its impact on hydrology at global scale however, do not show any robust agreement about future runoff trends in the tropical basins of Brazil. The discrepancies between runoff trends are largely associated with differences in precipitation prediction from climate models (Giumbetreau et al., 2013). For example, in the Amazon river, some studies find an increase in discharge at the end of the 21st century (e.g. Nohara et al., 2006; Salati et al., 2009) while decreases of up to 30% are shown in studies by Milly et al., 2005 and Tomasella et al., 2009 using ensembles of regional climate models. Our results however, show that for the basins in Espírito Santo, precipitation and streamflow are predicted to increase. This may be skewed that increased precipitation calculated by the HadGEM models; the ΔQ_{est} values for HadGEM-2CC and Hadgem-245 far exceed the values calculated from the other models (Fig. 2.9).

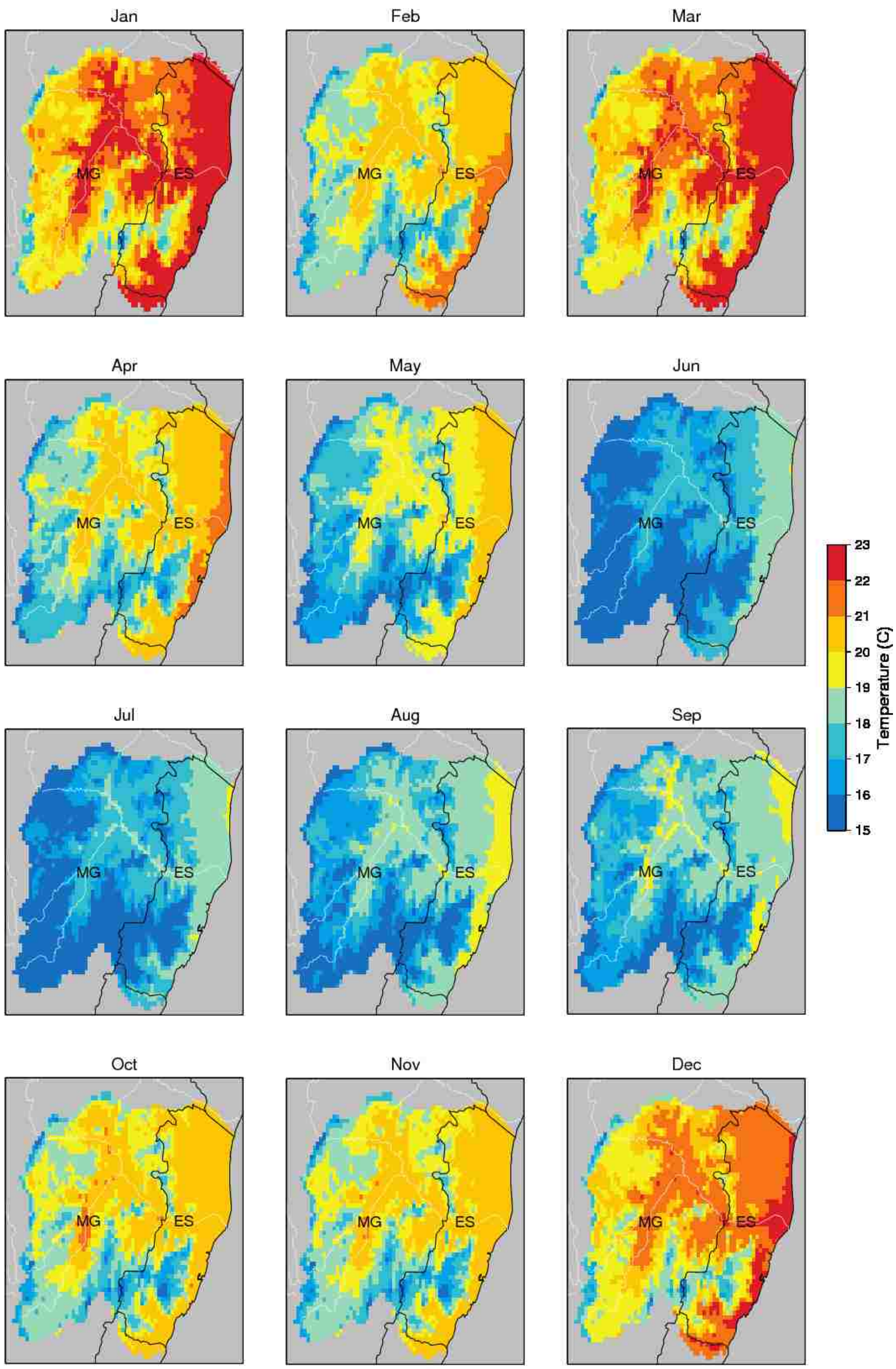

Figure 2.10: Average monthly surface temperature (1950 – 2006) from VIC model output for the study domain

In the Cachoeira, located in the Northern part of the state where it is the hottest (Fig. 2.10), the AOGCMs had the largest variation in precipitation predictions (Fig. 2.6), resulting in a larger variation of ΔQ_{est}. As discussed in the preceding section, Cachoeira was determined to have the highest sensitivity to changes in precipitation, resulting in a higher ΔQ_{est} . Streamflow in the Cachoeira basin is predicted to increase by 45% for Scenario I, the highest of all the basins. Results from the sensitivity-based analysis are consistent with more robust studies of estimated global streamflow studies estimated from full GCM analyses (e.g. Koirala, 2014).

2.5 Conclusion

I investigated the sensitivity of streamflow in the states of Espírito Santo and Minas Gerais to changes in temperature and precipitation in order to understand the processes that modulate streamflow in that region. I also estimated future streamflow based on six IPCC AR5 future scenarios by using a sensitivity-based approach that minimizes the need for a full-scale land-surface-atmosphere modeling. The results from the sensitivity-based approach are consistent with recent studies looking at predicted streamflow from full GCM simulations. Our analysis suggests that a sensitivity-based approach to estimating long-term changes in future streamflow may be a useful tool to meet the requirement by water managers to quantify response of streamflow to changes to P and T and isolate areas of higher sensitivity to changes without the need for computationally exhaustive evaluations of data. The sensitivity-based approach can also help water managers understand the underlying complexities of the hydrologic system and to measure the uncertainties related to differing GCM outputs that is, whether and to what extent dry or wet biases in precipitation data influence the streamflow predictions.

Estimated future streamflow from the sensitivity-based approach indicates an increase of 20% - 45% for all future scenarios, with the Cachoeira basin having the highest estimated increase in streamflow (45%) for period of 2010 – 2039 and southern-most basin of Rive having the lowest (20%). In 2013, the biggest flood in 35 years was recorded in Espírito Santo and Minas Gerais, claiming 46 lives, displacing 54, 000 people and causing millions of dollars in damages (Defesa Civil do Espírito Santo, 2013; Government of Espírito Santo, 2014). Our analysis suggests that the likelihood of flooding events will only increase given the magnitude of the calculated increase in streamflow due to a changing precipitation regime. This study shows that water managers can plan for long-term uncertainties by using computationally efficient methods to determine areas or regions of concern and to channel resources towards building a more detailed understanding of future climate impacts in these areas.

References

Alford, D. (1992). Streamflow and sediment transport from mountain watersheds of the Chao Phraya Basin, northern Thailand: a reconnaissance study. *Mountain Research and Development*, 257-268.

Boni, R.; Costa, J.S. Raphael, F.Z. Novelli, Z. Fabiano, Sossai, F. Marcos, S.R.A. Souza, And R.A. Sandr. 2012. *The Florestas para a Vida Project in Espírito Santo, Brazil*. Payments for Environmental Services (PES) learning paper; no. 2012-1. Washington DC, World Bank Group, http://documents.worldbank.org/curated/en/2012/10/19456314/florestas-para-vida-project-espírito-santo-brazil

Collischonn, B., Collischonn, W., & Tucci, C. E. M. (2008). Daily hydrological modeling in the Amazon basin using TRMM rainfall estimates. *Journal of Hydrology*, *360*(1), 207-216.

Cooper, M., Mendes, L. M. S., Silva, W. L. C., & Sparovek, G. (2005). A national soil profile database for Brazil available to international scientists. *Soil Science Society of America Journal*, *69*(3), 649-652.

Defesa Civil do Espírito Santo (2013, 31 December) Boletim de Chuvas da Defesa Civil. Available here: www.defesacivil.es.gov.br/conteudo/noticias/detalhe/default.aspx?id=13587f26-04b0-4086-8208-0db14287f2e7

Dooge, J. C. (1992). Sensitivity of runoff to climate change: A Hortonian approach. *Bulletin of the American Meteorological Society*, *73*(12), 2013-2024.

Dooge, J. C. I., Bruen, M., & Parmentier, B. (1999). A simple model for estimating the sensitivity of runoff to long-term changes in precipitation without a change in vegetation. *Advances in Water Resources*, *23*(2), 153-163.

Elsner, M. M., Cuo, L., Voisin, N., Deems, J. S., Hamlet, A. F., Vano, J. A., ... & Lettenmaier, D. P. (2010). Implications of 21st century climate change for the hydrology of Washington State. *Climatic Change*, *102*(1-2), 225-260.

Fu, R., Yin, L., Li, W., Arias, P. A., Dickinson, R. E., Huang, L., ... & Myneni, R. B. (2013). Increased dry-season length over southern Amazonia in recent decades and its implication for future climate projection. *Proceedings of the National Academy of Sciences*, *110*(45), 18110-18115.

Galindo-Leal, C., & Câmara, I. D. G. (2003). Atlantic Forest hotspot status: an overview. *The Atlantic Forest of South America: biodiversity status, threats, and outlook*, *1*, 3-11.

Government of the State of Espírito Santo (2014, January 2) Governo do ES estima reconstrução am R$ 540 milhões. (Portuguese) Available here: http://www.es.gov.br/Noticias/167148/governo-do-es-estima-reconstrucao-em-r-540-milhoes.htm

Guimberteau, M., Ronchail, J., Espinoza, J. C., Lengaigne, M., Sultan, B., Polcher, J., ... & Ciais, P. (2013). Future changes in precipitation and impacts on extreme streamflow over Amazonian sub-basins. *Environmental Research Letters*, *8*(1), 014035.

Good, P., Lowe, J. A., Collins, M., & Moufouma-Okia, W. (2008). An objective tropical Atlantic sea surface temperature gradient index for studies of south Amazon dry-season climate variability and change. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1498), 1761-1766.

Intergovernmental Panel on Climate Change (IPCC) (2007) In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) Climate change 2007: The physical science basis. contribution of working group I to the fourth assessment report of the IPCC. Cambridge University Press, Cambridge, http://www.ipcc.ch/ipccreports/ar4-wg1.htm

Koirala, S., Hirabayashi, Y., Mahendran, R., & Kanae, S. (2014). Global assessment of agreement among streamflow projections using CMIP5 model outputs. *Environmental Research Letters*, *9*(6), 064017.

Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Jimenez, B., Miller, K., ... & Shiklomanov, I. (2008). The implications of projected climate change for freshwater resources and their management.

Lehner, B., Verdin, K., & Jarvis, A. (2006). HydroSHEDS technical documentation, version 1.0. *World Wildlife Fund, Washington, DC. Available from: www. worldwildlife. org/hydrosheds*.

Liang X, Lettenmaier DP, Wood EF, Burges SJ (1994) A simple hydrologically based model of land surface water and energy fluxes for general circulation models. J Geophys Res 99:14 415–14 428

Malveira, V. T. C., Araújo, J. C. D., & Güntner, A. (2011). Hydrological impact of a high-density reservoir network in semiarid Northeastern Brazil. *Journal of Hydrologic*

Engineering, *17*(1), 109-117.

Maurer EP, Wood AW, Adam JC, Lettenmaier DP, Nijssen B (2002) A long-term hydrologically-based data set of land surface fluxes and states for the conterminous United States. J Clim 15:3237–3251

Maurer, E. P., L. Brekke, T. Pruitt, and P. B. Duffy (2007), 'Fine-resolution climate projections enhance regional climate change impact studies', Eos Trans. AGU, 88(47), 504.

Milly, P. C., Dunne, K. A., & Vecchia, A. V. (2005). Global pattern of trends in streamflow and water availability in a changing climate. *Nature*, *438*(7066), 347-350.

Moura, A. D., & Shukla, J. (1981). On the dynamics of droughts in northeast Brazil: Observations, theory and numerical experiments with a general circulation model. *Journal of the Atmospheric Sciences*, *38*(12), 2653-2675.

Morton, D. C., DeFries, R. S., Shimabukuro, Y. E., Anderson, L. O., Del Bon Espírito-Santo, F., Hansen, M., & Carroll, M. (2005). Rapid assessment of annual deforestation in the Brazilian Amazon using MODIS data. *Earth Interactions*, *9*(8), 1-22.

Myers, N., Mittermeier, R. A., Mittermeier, C. G., Da Fonseca, G. A., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, *403*(6772), 853-858.

Nijssen, B., O'Donnell, G. M., Hamlet, A. F., & Lettenmaier, D. P. (2001). Hydrologic sensitivity of global rivers to climate change. *Climatic change*, *50*(1-2), 143-175.

Painel Brasileiro de Mundaças Climacitas, P.B.M.C. (2015) Base Científica das Mudanças Climáticas. *Sumário executivo do*, *1*.

Ribeiro, M. C., Metzger, J. P., Martensen, A. C., Ponzoni, F. J., & Hirota, M. M. (2009). The Brazilian Atlantic Forest: How much is left, and how is the remaining forest distributed? Implications for conservation. *Biological conservation*, *142*(6), 1141-1153.

Sankarasubramanian, A., Vogel, R. M., & Limbrunner, J. F. (2001). Climate elasticity of streamflow in the United States. *Water Resources Research*, *37*(6), 1771-1781.

Schaake, J. C., & Waggoner, P. E. (1990). From climate to flow. *Climate change and US water resources.*, 177-206.

Su, F., Hong, Y., & Lettenmaier, D. P. (2008). Evaluation of TRMM Multisatellite Precipitation Analysis (TMPA) and its utility in hydrologic prediction in the La Plata Basin. *Journal of Hydrometeorology*, *9*(4), 622-640.

Tomasella, J., Rodriguez, D. A., Cuartas, L. A., Ferreira, M., Ferreira, J. C., & Marengo, J. (2009). Estudo de impacto das mudanças climáticas sobre os recursos hídricos superficiais e sobre os níveis dos aqüíferos na bacia do rio Tocantins. *Convênio de Cooperação Técnico-Científica INPE-VALE*.

Torres, R. R., & Marengo, J. A. (2014). Climate change hotspots over South America: from CMIP3 to CMIP5 multi-model datasets. *Theoretical and Applied Climatology*, *117*(3-4), 579-587.

Wang, A., Bohn, T. J., Mahanama, S. P., Koster, R. D., & Lettenmaier, D. P. (2009). Multimodel ensemble reconstruction of drought over the continental United States. *Journal of Climate*, *22*(10), 2694-2712.

Vano J.A., Das T, Lettenmaier DP (2012) Hydrologic sensitivities of Colorado River runoff to changes in precipitation and temperature. J Hydrometeorol 13:932–949. doi:10.1175/JHM-D-11-069.1

Vano, J. A., & Lettenmaier, D. P. (2014). A sensitivity-based approach to evaluating future changes in Colorado River discharge. *Climatic change*, *122*(4), 621-634.

Xie, S. P., & Carton, J. A. (2004). Tropical Atlantic variability: Patterns, mechanisms, and impacts. *Earth's Climate*, 121-142.

Yin, L., Fu, R., Shevliakova, E., & Dickinson, R. E. (2013). How well can CMIP5 simulate precipitation and its controlling processes over tropical South America?. *Climate Dynamics*, *41*(11-12), 3127-3143.

Zhu, C., & Lettenmaier, D. P. (2007). Long-term climate and derived surface hydrology and energy flux data for Mexico: 1925-2004. *Journal of climate*, *20*(9), 1936-1946.

III. Effects of land use change on the hydrologic regime in the Jucu and Santa Maria Da Vitória river basins in Espírito Santo, Brazil

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Abstract

The Santa Maria da Vitória River (SMV) and the Jucu River are two of the primary river basins that supply water to Vitória, the capital of Espírito Santo. Land use alterations such as the conversion of natural forests to agricultural plots and/or plantation forests are thought to be the main causes of siltation in these rivers, which exerts a large strain on regional water resources. Deforestation of riparian vegetation further increases sediment loads during the rainy season and especially during strong flood events. Likewise, land use alterations can have a profound effect on river discharge. However, unraveling the basin-scale hydrologic responses to land use alterations in this region is complicated by the lack of observed field data within the basins themselves. This study describes the application of a distributed hydrology-soil-vegetation model (DHSVM) to assess the hydrologic characteristics of the two basins and to analyze the effects of six different land use scenarios on streamflow (2007 landcover, 1996 landcover, reverting agriculture and eucalyptus to native forests, 25% increase in eucalyptus, 50% increase in eucalyptus and 25% increase in agriculture). In the SMV, an increase in eucalyptus buffers decreased flows by 30% while in the Jucu, flows were decreased by 26%. There were no discernible differences between increasing eucalyptus buffers from 25% to 50%. Agricultural land uses in the highlands caused the most an increase in streamflow (about 30%), particularly in Jucu basin where there is currently more natural forests compared to the SMV. Results from this study can be used to inform regional agricultural policies and to target areas of potential concern,

particularly zones where eucalyptus are projected to be grown. Likewise, the framework developed here can be applied to systems worldwide to address questions of regional/global concern with regards to freshwater availability.

3.1 Introduction

Water and land resource management decisions have a direct effect on the environmental and economic sustainability of a watershed. Major concerns focus on consequences of land use change for water supply and demand, for local and downstream hydrological hazards, and for biodiversity conservation (e.g. Sala et al., 2000; Lambin et al., 2001). Over the past 30 years, fast-growing species of eucalyptus have become an important option for high-productivity forests in Brazil. Eucalyptus plantations occupy more than 5.1 million hectares, with approximately 67% of these plantations concentrated in the southeastern region that includes the states of Sao Paulo, Rio de Janeiro, Espírito Santo and Minas Gerais. Siqueira et al., (1989) reported that eucalyptus plantations account for over 79% of pulp and paper, 29% of lumber, plywood and boards, 25% of charcoal for iron and steel production, 38% of industrial energy from wood, and 8% of rural energy from wood in Brazil. Forest productivity ranges from 30-40 m^3/ha/y in the coastal forests of Espírito Santo to less than 20 m^3/ha/y in the drier interior forests of Minas Gerais. The plantation expansion has largely occurred on the plateau part of the landscape away from streams.

Concerns have been raised about the potential for future expansion of land used for eucalyptus plantations in Brazil (Soares et al., 2001). Many studies have point out that this type of land use conversion causes severe losses in terms of biodiversity and dries out the soil (e.g. Barrocas et al., 1998; Marsden et al., 2001; Dupouey et al., 2002; Barbosa et al., 2004). Deeprooted trees like eucalyptus are important drivers of water cycling in dry ecosystems that can have a significant effect on landscape hydrology (Bernardo et al., 1998; Jackson et al., 2005; Pfautsch et al., 2010; Brown et al., 2012). On a global scale, modeling studies have shown that the current Amazonian climate is dependent on considerable amounts of water being extracted by trees from very deep soil layers and transpired back into the atmosphere during dry periods (Kleidon and Heimann, 2000; Saleska et al., 2007). The drying of the soil and recession of water tables is also of concern to local populations. These large-scale changes in vegetation may have already affected streamflows, but these effects have not been widely quantified (Aragao et al., 2008).

The state of Espírito Santo is located in the Atlantic forest biome, an area that has been designated as one of the five most important biodiversity hotspots in the world owing to its exceptional level of species diversity. Due to the vulnerability of the area to continuing threats such as deforestation and mining, this ecosystem has become a top conservation priority in Brazil (Myers, 2000; ABRAF, 2012). Efforts to conserve and restore habitat and natural ecosystem services have been hampered by the lack of institutional and individual capacity to implement sustainable land management and water resource management, at both the national and watershed levels. Understanding how agricultural crops (e.g. banana and coffee) and plantation forests (particularly eucalyptus) influences changes in the hydrologic regime of the watersheds is of particular interest to policymakers.

With support from the World Bank, the State of Espírito Santo launched the Espírito Santo Biodiversity and Watershed Conservation and Restoration Project (Floresta para Vida, FpV). A focus was on understanding the impacts of changing land use patterns on two critical, high-biodiversity watersheds in south-central ES: the watersheds of the Jucú and the SMV rivers that comprise 9% of the area of ES. Streamflow has been reportedly reduced after afforestation in grasslands and the construction of the dams and reservoirs along these rivers. Sedimentation and a decrease in water quality is also a concern due to erosion from cropland expansion.

The challenge is, how to evaluate the impacts of such landuse change, with sufficient resolution and confidence to influence decision makers? The problem is exacerbated by few hydrologic studies in the region, and data remains sparse. As in most of the world, monitoring is hampered by the scarcity of in situ measurements and barriers to data access. Scant information and ambiguities in data collection make it difficult for water managers. There is a growing need for a comprehensive set of tools, capable of accurately predicting the impact of land use changes on small to large spatial scales, as global development continues to steadily increase (Pahl-Wostl, 2007). The ability to evaluate basin hydrology beyond simple stream flow characteristics is crucial for determining spatially-explicit relationships between landscape structure, configuration of land use change, and the hydrology across the landscape.

In this study, I examine the influence of land use on the hydrology of two major river basins in the state of Espírito Santo, the Jucu and Santa Maria da Vitoria (SMV) basins. I (1) evaluate seasonal patterns and the composition of hydrologic components of the Jucu and the SMV river basins, (2) assess the impacts of changes in cropland expansion on local and regional water balances and (3) assess the impact of eucalyptus plantations on streamflow in the Jucu and SMV basins. More specifically, I seek to understand how conversion between forest cover and crops or plantations would affect water availability in this specific region and the potential policy implications for the Jucu and SMV basins. These objectives are pursued through application of the Distributed Soil Hydrology Vegetation Model (DHSVM) and scenario analyses of past, present and hypothetical future land use changes.

Various hydrologic modeling environments have been developed to address the hydrologic dynamics of systems at varying resolution. For example, the Variable Infiltration Capacity (VIC) model has been widely used for meso-scale studies in relatively large basins (Liang et al., 1994; Lohmann et al., 1996;Wood et al., 1997). However, DHSVM is particularly useful for higher resolution applications (Wigmosta et al., 1994). It is a fully-distributed model that recognizes the spatial heterogeneity of the watershed, thus, the spatial variation of hydrologic attributes inside the basin can be evaluated, and calculations based on the availability of data and level of complexity can be adjusted accordingly (e.g. Beckers & Alila, 2004; Cuo et al., 2006).

3.2 Methods

3.2.1 Study Area

The Santa Maria da Vitória (SMV) and Jucu rivers provide approximately 95% of the water supply to the Greater Vitória Metropolitan Area (GVMA) while also generating hydroelectricity (Fig. 3.1). The GVMA houses close to half of the state's population of 3.1 million people and generates 62% of the state's GDP. Upstream of the GVMA, land use alterations have resulted in severe erosion, substantially increasing silt loads and reducing the quality and timing of water supply.

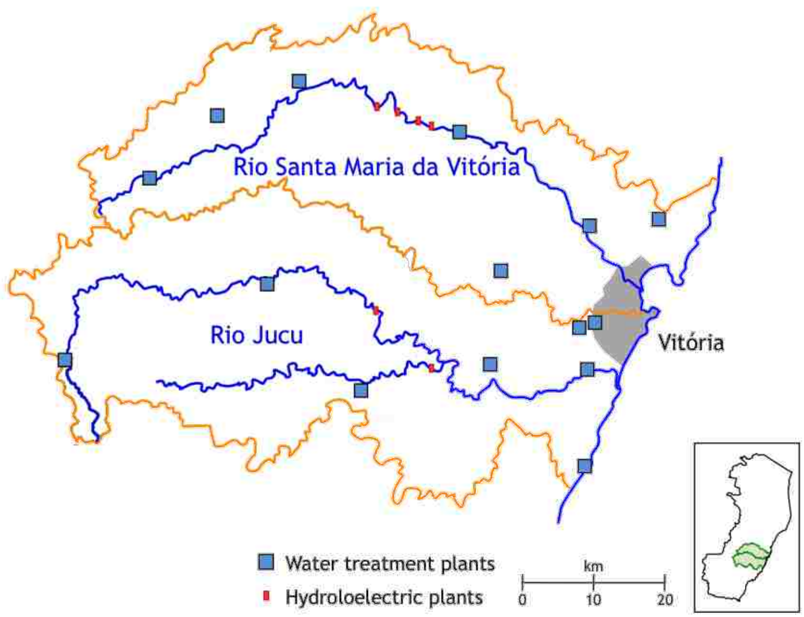

Figure 3.1: The Jucu and Santa Maria da Vitoria river basins, in the state of Espírito Santo, showing hydroelectric dams and water treatment plants (Figure courtesy of Marcos Sossai, IEMA, 2013).

The SMV watershed covers a region of 1,660 km^2, with a river length of 122 km, passing through five municipalities of varying sizes (Santa Maria de Jetiba, Santa Leopoldina, Cariacica, Serra, and Vitória). The SMV river mouth empties into the Bay of Vitória, an important commercial port for the region, and forms the island of Vitória, the capital city of Espírito Santo. There are two dams on the SMV upstream of Vitoria, the Rio Bonito (ten megawatts) and the Suico (thirty megawatts). These dams significantly alter the sediment transport and storage dynamics of the basin, storing large amounts of sediments in their reservoirs. A significant amount of sediments from the riparian zone and tributaries enters the river downstream of these dams. The central SMV basin is primarily influenced by rural development, pasture land, and agricultural uses such as banana, coffee, eucalyptus and sugar cane. There is little or no treatment of wastewater in the upper and central regions of the basin. The SMV provides water for roughly

35% of the greater Vitória population. The upper region of the SMV basin is characterized by mountainous landscapes and is composed of roughly 40% natural forested landcover.

The Jucu river is fed by two tributaries from the municipalities of Domingo Martins - one from the north and one from the south. The Jucu river supplies water to 60% of the population of GVMA, including Vila Velha, Viana, most of Cariacica and the entire island of Vitória (the mainland capital is supplied primarily by the SMV). Thewatershed is primarily forested and not nearly as developed as the SMV although eucalyptus plantations are found in higher elevations.

3.2.2 Model Description

DHSVM was used to examine hydrological change in the Jucu and SMV rivers. The model was designed specifically for computing regional-scale water balance and takes into account the spatial heterogeneity of a watershed. DHSVM has been applied in both tropical (e.g. Mae Cham and Pang Khum river basins in Northern Thailand: Cuo et al., 2006, 2008; Thanapakpawin et al., 2007) and temperate catchments (e.g. Pacific NW in North America: Storck et al., 1998; Bowling et al., 2000; La Marche and Lettenmaier, 2001; VanShaar et al., 2002; Thyer et al., 2004; Cuo et al., 2011). The results from the small basin hydrology modeling studies showed that DHSVM captured seasonal streamflow trends and evaporation in tropical regions well.

The effects of topography and land cover in DHSVM are accounted for by explicitly representing the spatial distribution of stream and road networks, stream and road morphology, soil properties, soil depth, vegetation properties, and elevation. Digital elevation data are used in the model for flow routing, estimation of soil depth distribution, and meteorological data extrapolation (Cuo et al., 2006). Each cell can have up to two vegetation layers, and a user-specified number of soil layers. DHSVM also incorporates canopy precipitation interception, evapotranspiration, energy and radiation balance, runoff generation through saturation excess and infiltration excess mechanisms, unsaturated soil moisture movement, saturated subsurface flow, and ground water recharge and discharge. A detailed description of DHSVM can be found in Wigmosta et al. (1994, 2002), Storck et al. (1998), and Nijssen and Lettenmaier (1999).

3.2.3 Topography and flow network

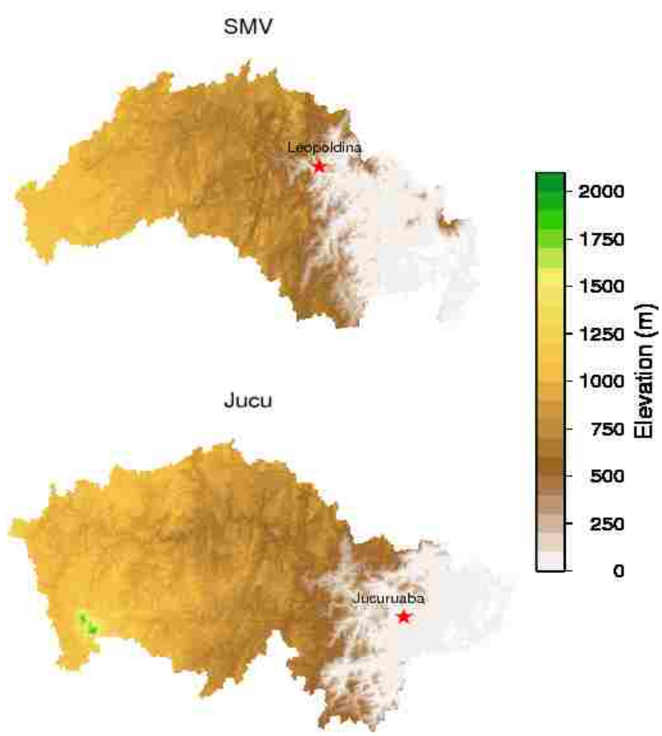

Figure 3.2. Topography of Jucu and SMV.

A user-defined resolution of digital elevation model (DEM) was used to set the spatial framework (Figure 3.2.). The topography for the Jucu and SMV basins was first obtained by scaling the CGIAR SRTM ver4.1 DEM (Jarvis et al., 2008) to a 150m resolution. Rivers for the basins were clipped out of Brazilian mapping database "Base de Dados Vetorial" (IBGE, 2007) and rasterized at 30-meter resolution. The DEM was then re-projected to the Universal Transverse Mercator (UTM) grid at 30-meter resolution, and the rivers from the Brazilian mapping database were overlaid on top of the 30-m DEM. Flow directions were subsequently calculated from the 30-m resolution combined map and upscaled back to 150 meters. The resulting flow directions were displayed over aerial imagery and a few small adjustments were made for precision (e.g., closing small gaps and redirecting flows down hill slopes).

3.2.4 Soil map and vegetation cover

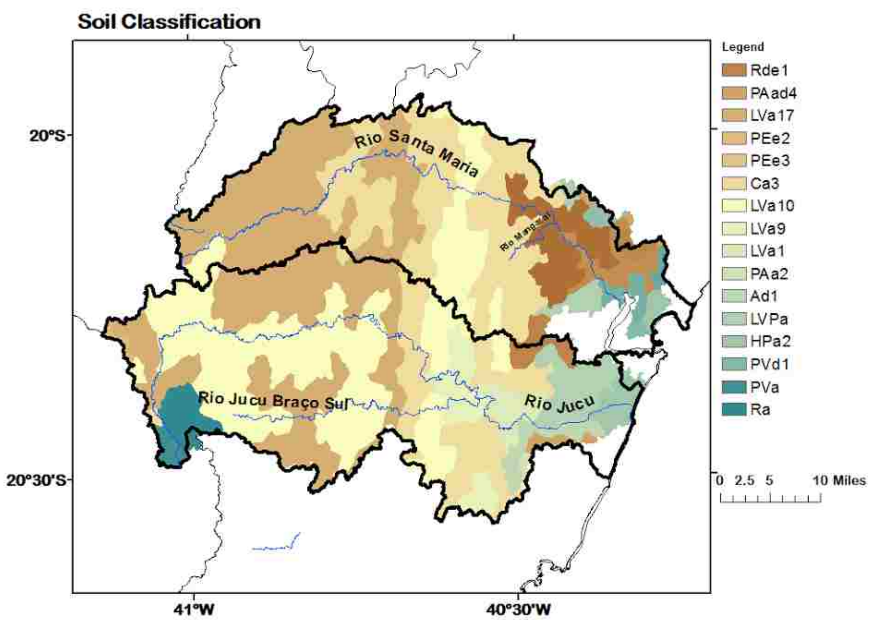

Figure 3.3. Soil distribution for Jucu and SMV; latosols (LVa10, LVa17) and cambisols (Ca3)

Soil data exists in Brazil but the exact period or source of data is usually difficult to obtain. For this investigation, the Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão

Rural (INCAPER) provided a 1:1,000,000 soil map of Espírito Santo, cut to the Jucu and SMV (Figure 3.3.). The data were derived originally from the Radar Amazon Project (Azevedo, 1971). Soil texture was assigned based on clay and sand percentages. The corresponding soil parameters were then obtained from literature e.g. Giambelluca et al., 1996, Meyer et al., 1997 and Cuo et al., 2011.

The map of vegetation cover and land use was provided by the State Institute for the Environment (IEMA) and was derived from the national 1m^2 aerial survey that occurred in 2007 and 2008. This map contained 25 different classes, including agricultural crops, forestry, water bodies, mineral exploration, rocky outcrops, vegetation, urban area and exposed soil. This landcover scheme will hereafter be referred to as IEMA2007, and is the base reference scheme (Figure 3.4(a) for the SMV and Figure 3.5(a) for the Jucu).

For the historic vegetation scenario, I used the 1996 national landcover data (GEOBASE96), which was the national land cover product prior to IEMA2007 (Figure 3.4(b) and Figure 3.5(b)). In the 10 years between GEOBASE96 and IEMA2007, fragmented forests were reduced, eucalyptus plantations increased and urban areas became more prominent. Since the classification schemes differed between these two land cover datasets, I converted both the GEOBASE96 and IEMA2007 to a generalized 11 classes. I used a spatial overlay analysis that took into account the frequency of all unique landcover combinations and correlated the different vegetation class from both datasets into a common classification scheme.

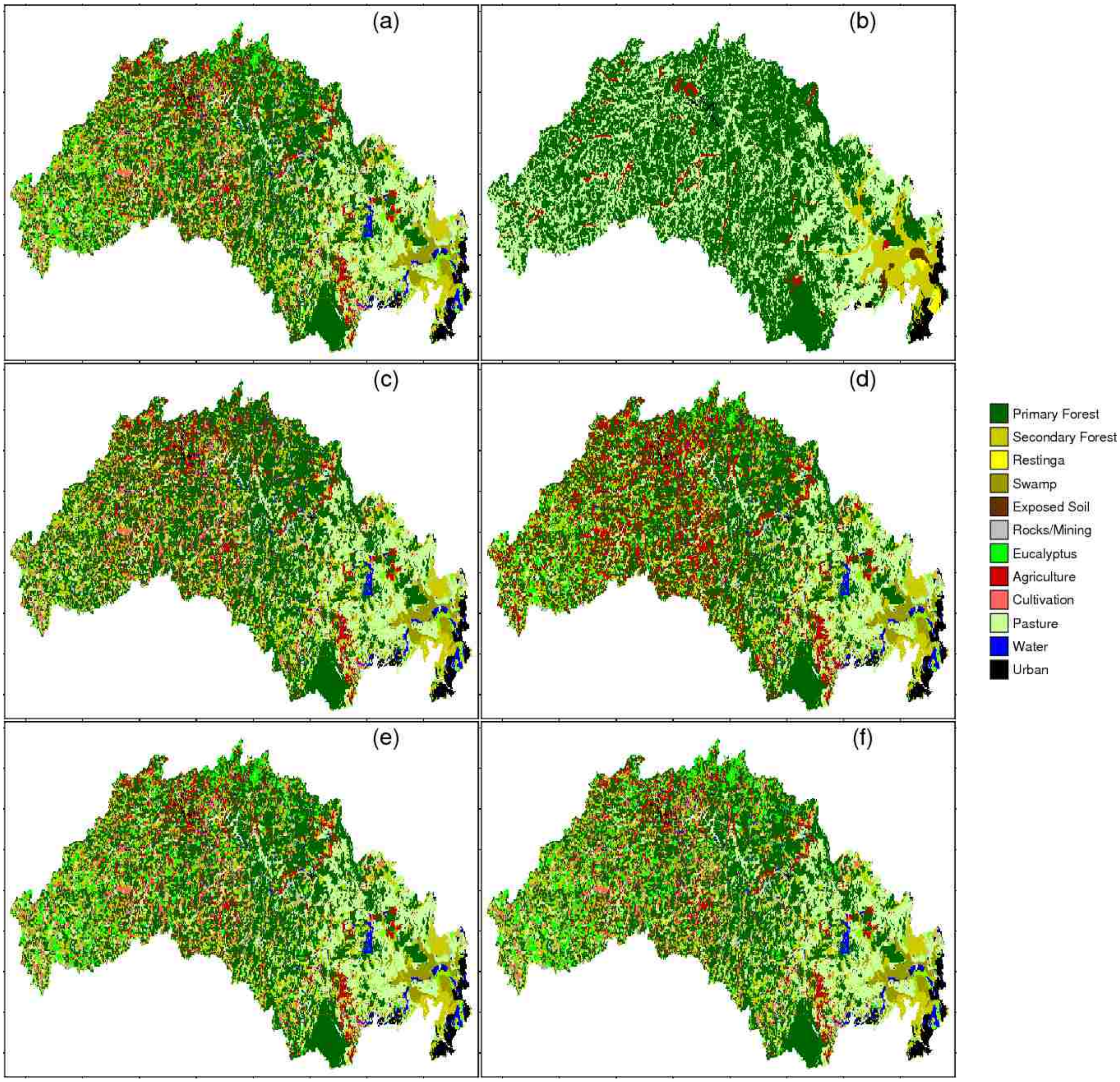

Figure 3.4: Vegetation scenarios used to test for land use effects in the Santa Maria da Vitória river basin: (a) reference IEMA2007, (b) historical GEOBASE1997, (c) Prim+, (d) Agriculture+25%, (e) Euc+25%, and (f) Euc+50%.

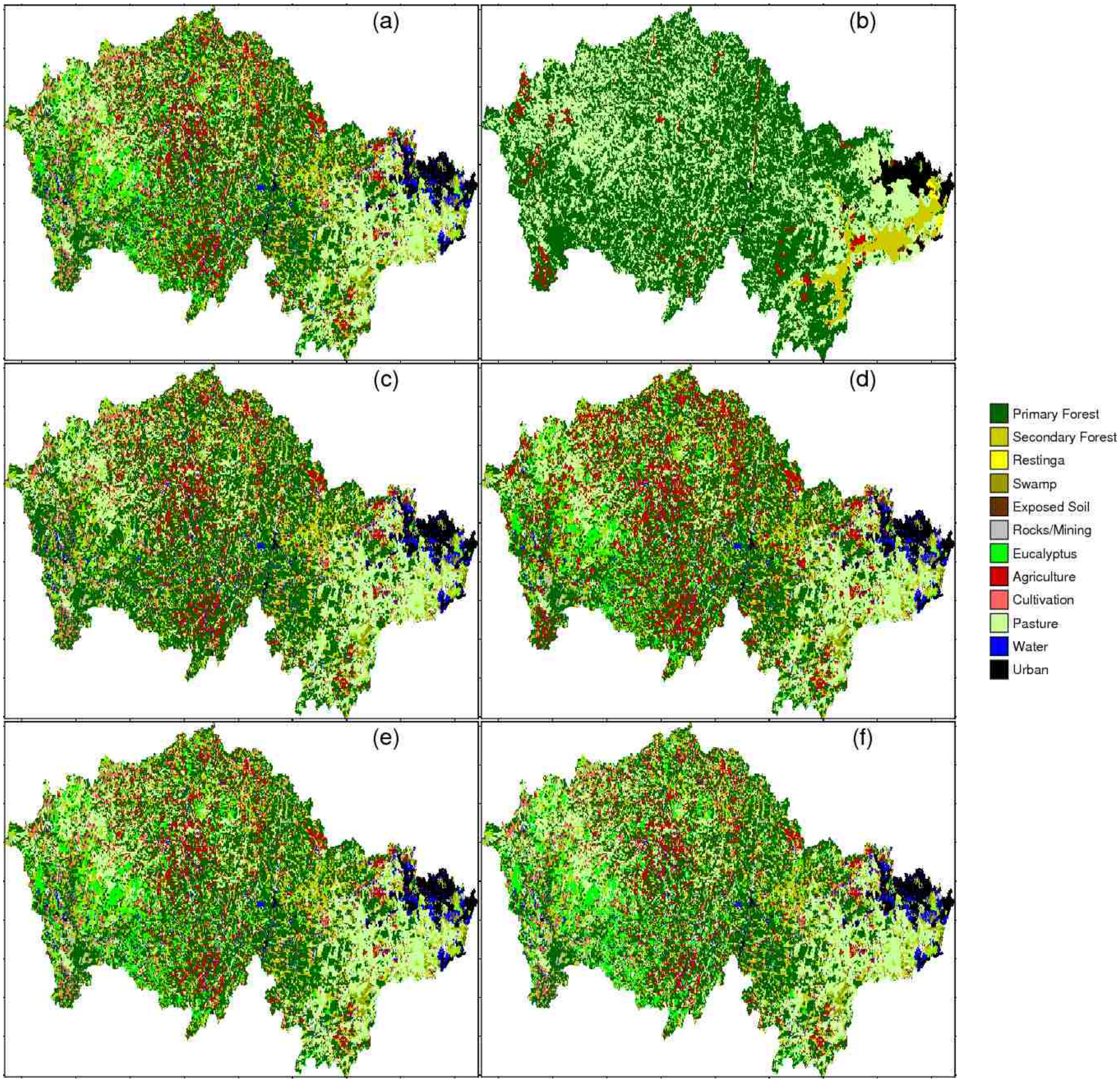

Figure 3.5: Vegetation scenarios used to test for land use effects in the Jucu river basin: (a) reference IEMA2007, (b) historical GEOBASE1996, (c) Prim+, (d) Agriculture+25%, (e) Euc+25%, and (f) Euc+50%.

IEMA2007 formed the baseline vegetation for the four hypothetical future scenarios and I created to test changes in the hydrologic regime due to decreased forest cover and increased eucalyptus plantation and agriculture (crops and pasture) land uses. The first scenario (Scenario I) reverted upland croplands, lowland agriculture, regenerated forests and eucalyptus back to the native forest of tropical moist broadleaf (Prim+, Figure 3.4(c) and Figure 3.5(c)). The second to fourth scenarios (Scenario II, Scenario III and Scenario IV) were based on projected land use changes as outlined in the state's urban planning handbook (personal correspondence). (Figures 3.4 (d),(e),(f) and Figures 3.5 (d),(e),(f), Scenario II forecasted a 25% increase in agricultural crops (Ag.+25%, Figure). I generated this land cover dataset by growing a 25% buffer of new agriculture patches around existing cells into surrounding natural or secondary forests. This increased the overall agricultural area to 16.6% for the Jucu (from 13.1%) and 18.2% for SMV (from 15.3%). Scenario III and Scenario IV expanded the eucalyptus plantation buffer by 25% (Euc.+25%)and 50% (Euc.+50%) respectively into forested areas. This increased the overall eucalyptus plantation areas to 5.1% and 10.2% for the Jucu and 7.8% and 15.3% for the SMV.

3.2.5 Climate forcings and hydrology

The region receives most of its rain in October through January and receives an average rainfall of roughly 1200 mm annually. For the basin climatology, I used daily rainfall, minimum and maximum air temperature, relative humidity and wind measurements obtained from 11 stations (6 in Jucu and 5 in SMV) within the National Water Agency (ANA) network (Figure 3.6). The most complete and widest ranging observational station data available is for the period of 2009 – 2011, therefore, I limited our model simulations to coincide with this period. I then applied the Variable Infiltration Capacity model (VIC) to disaggregate the daily data into sub-daily meteorological data for all the aforementioned parameters as well as shortwave and longwave parameters (from Chapter 2). The method of disaggregation using diurnal interpolation is described in Maurer et al., 2002.

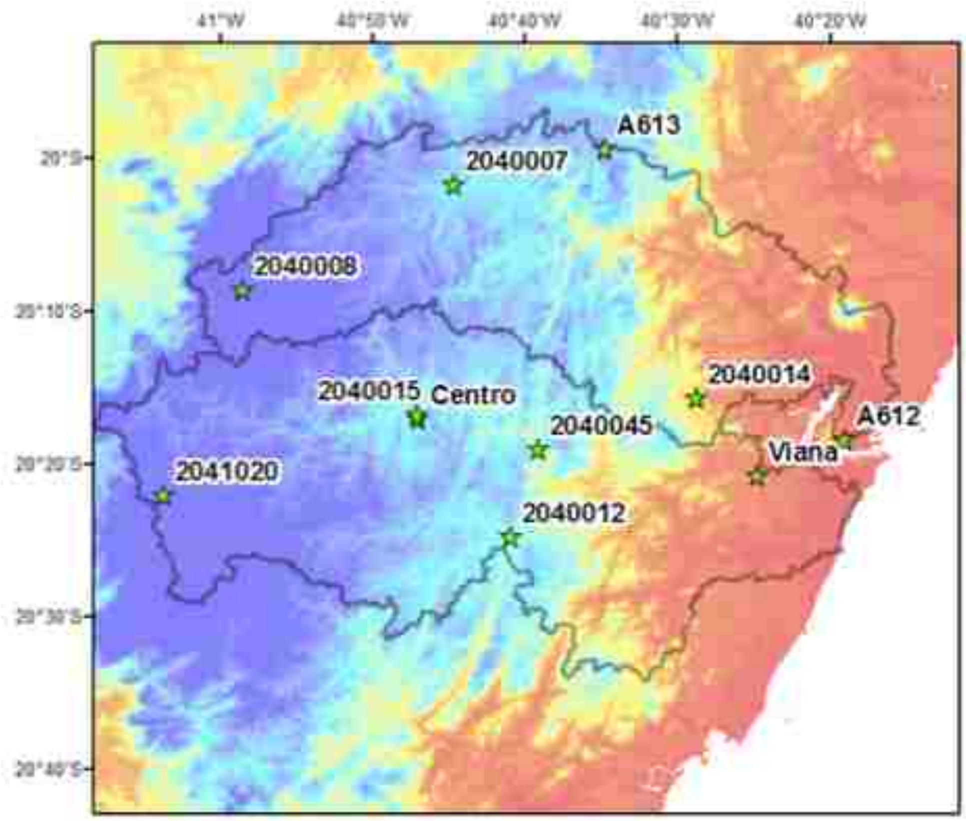

Figure 3.6. Meteorological station locations and basin extents for the Santa Maria da Vitoria (SMV) and Jucu river basins, plotted against the DEM. There are 6 stations in the Jucu, and 5 in the SMV.

3.2.6 Calibration and validation

The basins were set up at a 150-m resolution and simulations were run on a 3-hourly timestep using the current landcover (IEMA2007). The model was initialized by running the entire simulation period ten times and saving the last date of the simulation. I then calibrated the model from 2009 – 2010 and validated the model for 2011 – 2012. In a study by Cuo et al., 2011, the authors found that DHSVM results for tropical regions were more influenced by soil parameters than by vegetation parameters and the most sensitive soil parameters were soil porosity, lateral saturated hydraulic conductivity. The same study also found an exponential decrease rate of lateral saturated hydraulic conductivity with soil depth. Calibration parameters in our analysis were total soil depth, soil lateral and vertical hydraulic conductivities, and vegetation parameters. Values of vegetation parameters were initially set to correspond with Global Land Data Assimilation System (GLDAS) vegetation parameters mapped to the University of Maryland (UMD) classification scheme, and were then tuned to Southeastern Brazil based on descriptions by Allen et al. (2002), Galvincio, Correa and Araujo (2006) and de Castro Teixeira et al. (2008). Simulated hydrographs from January 2009 – December 2012 using the IEMA2007 landcover (baseline) were compared to observed stream flows at Leopoldina for SMV and Fazenda Jucuruaba for the Jucu river. Final calibration parameters are listed in Table 3.1. I found that the model was the most sensitive to precipitation inputs, lateral soil hydraulic conductivity and soil depth.

Table 3.1: Final values for DHSVM parameters after calibration and validation

Parameter	**Values**	
	Jucu	**SMV**
Ground roughness, m	0.02	
Reference height, m	40	
Rain LAI multiplier	0.000375	0.00025
Temperature lapse rate, ºC/m	-0.0065	
Precipitation lapse rate, m/m	0.002	
Lateral saturated hydraulic conductivity (ms^{-1})	0.0003 – 0.0017	
Exponential decrease rate	0.02 – 0.32	
Maximum infiltration capacity (ms^{-1})	3.24e6 – 5e3	
Vertical saturated conductivity (ms^{-1})	3.24e6 – 5e3	
Overstory vegetation height (m)	20 – 30	
Understory vegetation height (m)	0.3 – 3.3	
Maximum stomatal resistance (sm-1)	4000 - 5000	
Overstory leaf area index	2.55 – 8	
Overstory vapor pressure deficit threshold, kPa	2000 - 3650	

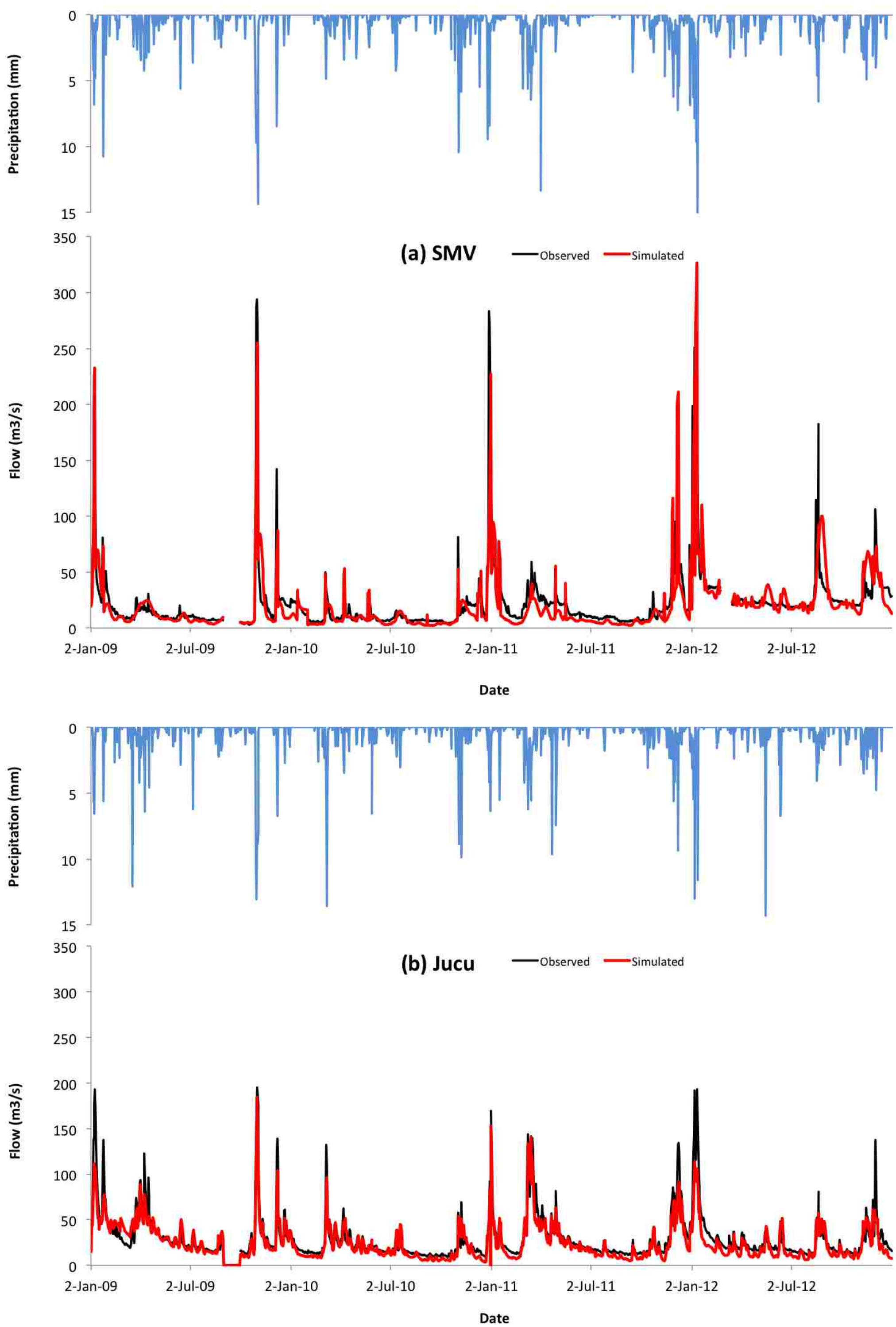

Figure 3.7. Observed precipitation (blue) and simulated (red) and observed (black) river flow for the (a) SMV and (b) Jucu.

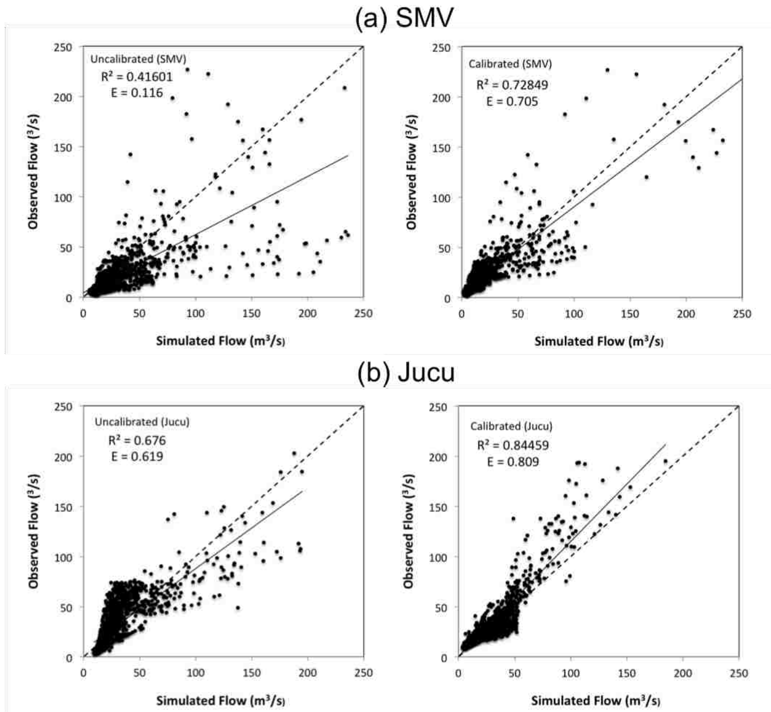

Figure 3.8. Linear regression of observed river discharge with uncalibrated and calibrated simulated river flow.

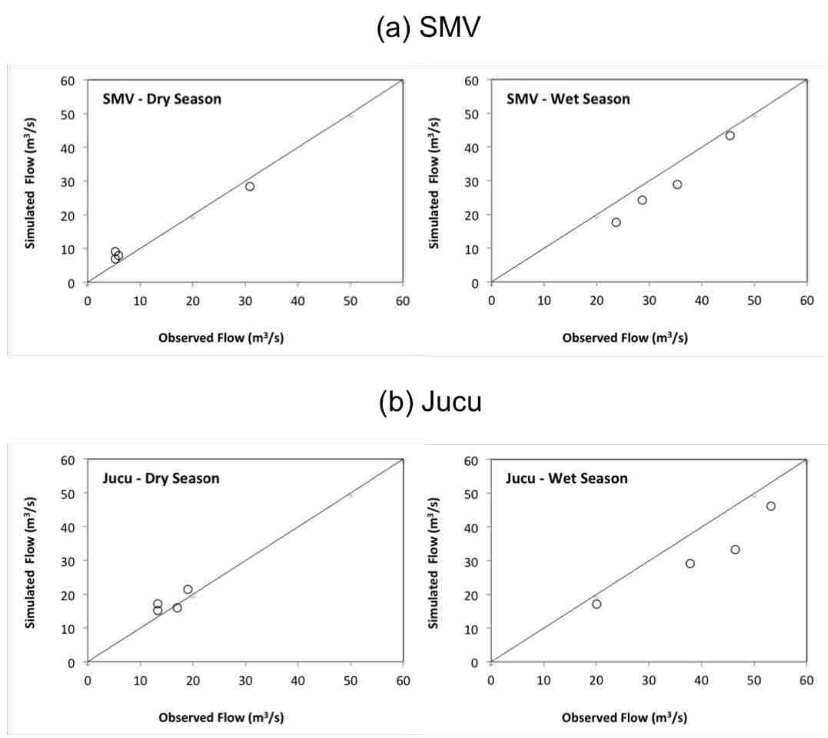

Figure 3.9: Comparison of simulated and observed river discharge for (a) the SMV and (b) Jucu rivers during periods of low (left) and high (right) discharge

Figure 3.7 and Figure 3.8 shows the pre-calibration and calibrated flows for both the SMV and Jucu. The model captures the onset of the storm season, and estimated flows were relatively close to recorded values as denoted by the Nash-Sutcliffe efficiency measuring model performance (E=0.81 for Jucu and E=0.70 for SMV). The average natural base flow was underestimated; this can be explained by the fact that the model does not include deep groundwater components. The other explanation may be that the soil parameters used did not accurately capture soil dynamics in the basins. However, the model is consistent in estimating dry season flows (Figure 3.9) but has a wider-scatter of wet season flows. This indicates that the wet season flows are highly dependent on climate inputs (precipitation) during the storm period.

3.3 Results and Discussion

For both the Jucu and SMV basins, I demonstrated that increased highland agriculture caused higher unregulated annual water yields especially during the low flow season (November - January) for both the Jucu and SMV river basins (Figure 3.10 and Table 3.2). Dry season flows increased by 29% in the SMV and 31% in the Jucu while wet season flows increased by 16% in the SMV and 14% in the Jucu. Overall, crop expansion increased annual flows by 22% in the SMV and by 30% in the Jucu. Forest to crop conversion reduces the transfer of precipitation to the ground due to lower evapotranspiration rates, thus increasing discharge. Agriculture in this region of Brazil has also caused soil compaction, lowering infiltration rates and hydraulic conductivity, and causing excess in overland flow (Hamza & Anderson, 2005). Furthermore, since the Jucu has less croplands than the SMV, an higher increase in runoff is to be expected.

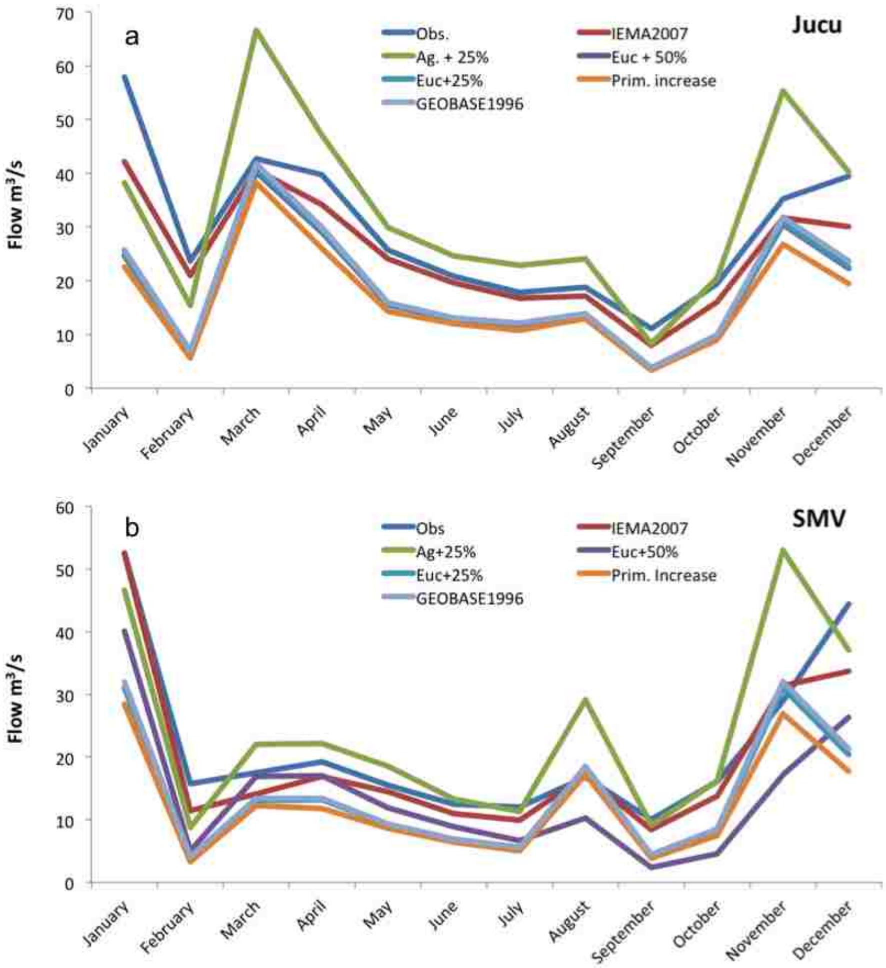

Figure 3.10. Average monthly discharge comparisons from the different landcover scenarios for the (a) Jucu River and (b) Santa Maria da Vitória River.

When existing agriculture was converted to forests (baseline to Scenario I), annual water yield decreased but evapotranspiration increased (Jucu - Figure 3.11, SMV – Figure 3.12). In the Jucu, average flows were decreased by 30% and in the SMV, annual flows were decreased by 36%. Based on future scenario analyses, effects of land use change on seasonal and annual water yields are a net balance of change in basin moisture storage size, vegetation-soil interaction, and flow regulation. Tropical forests have higher evaporation from rainfall interception and transpiration than other landcover types as evidenced in our study and corroborated by Worden et al. (2007). The basin hydrology is particularly sensitive to changes in landcover attributes, with a general pattern of increasing runoff with migration from trees to crops due to decreasing evapotranspiration. Upland crop expansion may lead to higher peak flow and higher seasonal and annual yields. This is due to increased water yields resulting from reduced evapotranspiration (Table 3.3). Since the increased water percolates through well-drained soils, primary implications are for downstream main channel flooding rather than increased overland flow. Extractions for irrigation may also reduce downstream impacts and will need to be investigated further.

Table 3.2. Comparison of observed and simulated annual (January to December) hydrologic compositions for Jucu and SMV

Average annual values (2009 – 2011)					
	Annual yield m^3/s	High flow m^3/s	Low flow m^3/s	Annual ET [a] mm	Runoff ratio
Jucu					
Observed	30.1	17.4	39.4	1120[a]	0.36
DHSVM	28.2	15.7	31.4	1410	0.28
SMV					
Observed	22.6	33.2	13.1	1070[a]	0.35
DHSVM	20.3	28.6	11.8	1325	0.32

[a] Value from Satellite-derived Global Record of Monthly Land Surface Evapotranspiration (1983-2006)

Increasing eucalyptus areas decreased discharge (from the IEMA2007 baseline) by an average of 26% in the Jucu and 30% in the SMV (Figure 3.10). The results from increased agriculture and increased eucalyptus scenarios are consistent with studies by Viola et al., 2014 that showed that an increase in eucalyptus areas in Southeastern Brazil would decrease discharge while an increase in agriculture would cause the opposite effect. However, the difference in discharge between Euc.+25% and Euc.+50% was indiscernible in both basins. Smethurst et al., 2014 suggested that eucalyptus plantations would not have any significant impacts on streamflow especially if natural forests buffer the eucalyptus plantations. The effect of eucalyptus and natural forests are similar in some respects, and this may help explain why the difference between the two different eucalyptus buffer values was minimal; both study basins have a high concentration of native forests interspersed with and surrounding eucalyptus plantation.

Table 3.3. Simulated basin hydrology from different landcover scenarios

Landcover Scenarios	Annual yield m^3/s	High flow m^3/s	Low flow m^3/s	Annual ET mm
		Jucu		
GEOBASE1996	19.3	51.7	29.8	1120
Prim+	16.7	45.1	27.1	982
Euc. + 25%	18.5	50.0	29.5	897
Euc. + 50%	18.4	49.5	29.3	915
Ag. + 25%	32.7	86.3	55.2	785
		SMV		
GEOBASE1996	14.5	19.1	9.5	975
Prim+	12.4	16.5	8.7	795
Euc. + 25%	13.7	18.5	9.4	825
Euc. + 50%	13.1	20.6	6.4	892
Ag. + 25%	23.9	30.8	16.5	692

Longer-term observations of streamflow would be needed in order to fully understand the mechanisms that govern eucalyptus effects on the water uptake and evapotranspiration in these particular basins. Effects of land use on streamflow in the SMV also seem to be governed by underlying soils. Higher soil moisture (Figure 3.11) corresponds to areas containing latosols, a very old type of clay found mostly in the tropics that have a high moisture holding capacity. The effects of this soil type may also account for the differences in the amount of streamflow decrease between the SMV and Jucu. As the soil retains more moisture, an increase in evaporation due to increase eucalyptus areas would reduce the water available for overland runoff.

The results of this study further show that runoff increased substantially from 1997 to 2007. It is surmised that this could be due to increased lowland agriculture. This implies that there needs to be a radical rethinking or development of incentives to change current agricultural practices in this region. The type of monoculture used and the types of landcover replaced differentially impacts delivery of water to the coastal zone. For example, if eucalyptus were to replace primary forest, differences would likely be small. If low-lying vegetation were replaced with eucalyptus, discharge would be reduced and ET increased. Alternatively, if the existing landcover were replaced with crops, discharge would increase. Results from the modeling efforts show that forest cover decreases downstream streamflow. Increasing forest cover also reduces the amount of exposed soil susceptible to erosion since forest covers have deeper roots that stabilize soil and that reduce the rainfall through the canopy layer. Further studies would be useful in investigating contributions of agricultural irrigation to changes in streamflow.

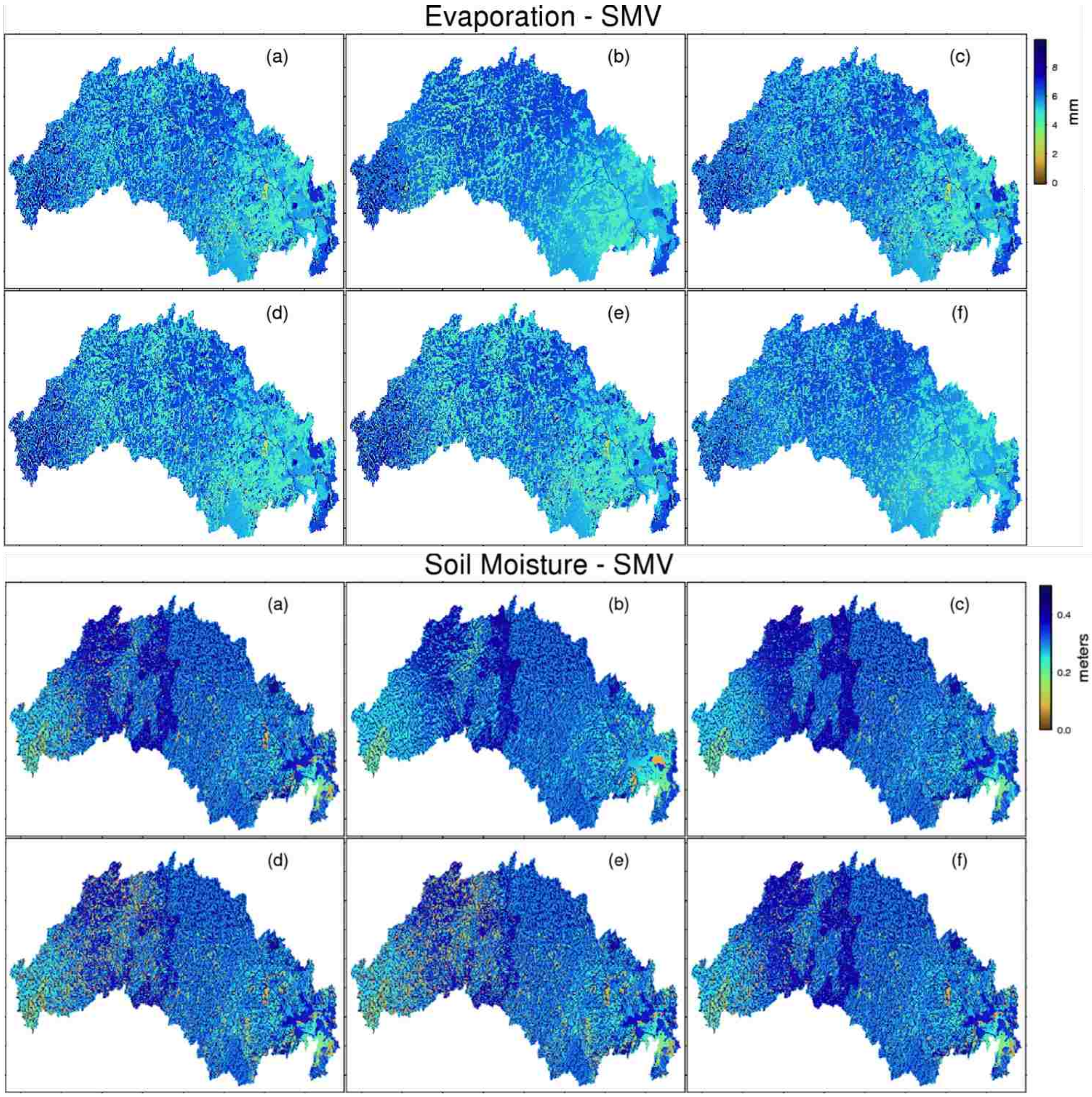

Figure 3.11. Comparisons of soil moisture (top) and ET (bottom) for the different landcover scenarios in the SMV basin: a) IEMA2007 b) GEOBASE1996 c) Increase in Primary Forests d) Euc. + 25% e) Euc. + 50% and f) Ag. + 25%

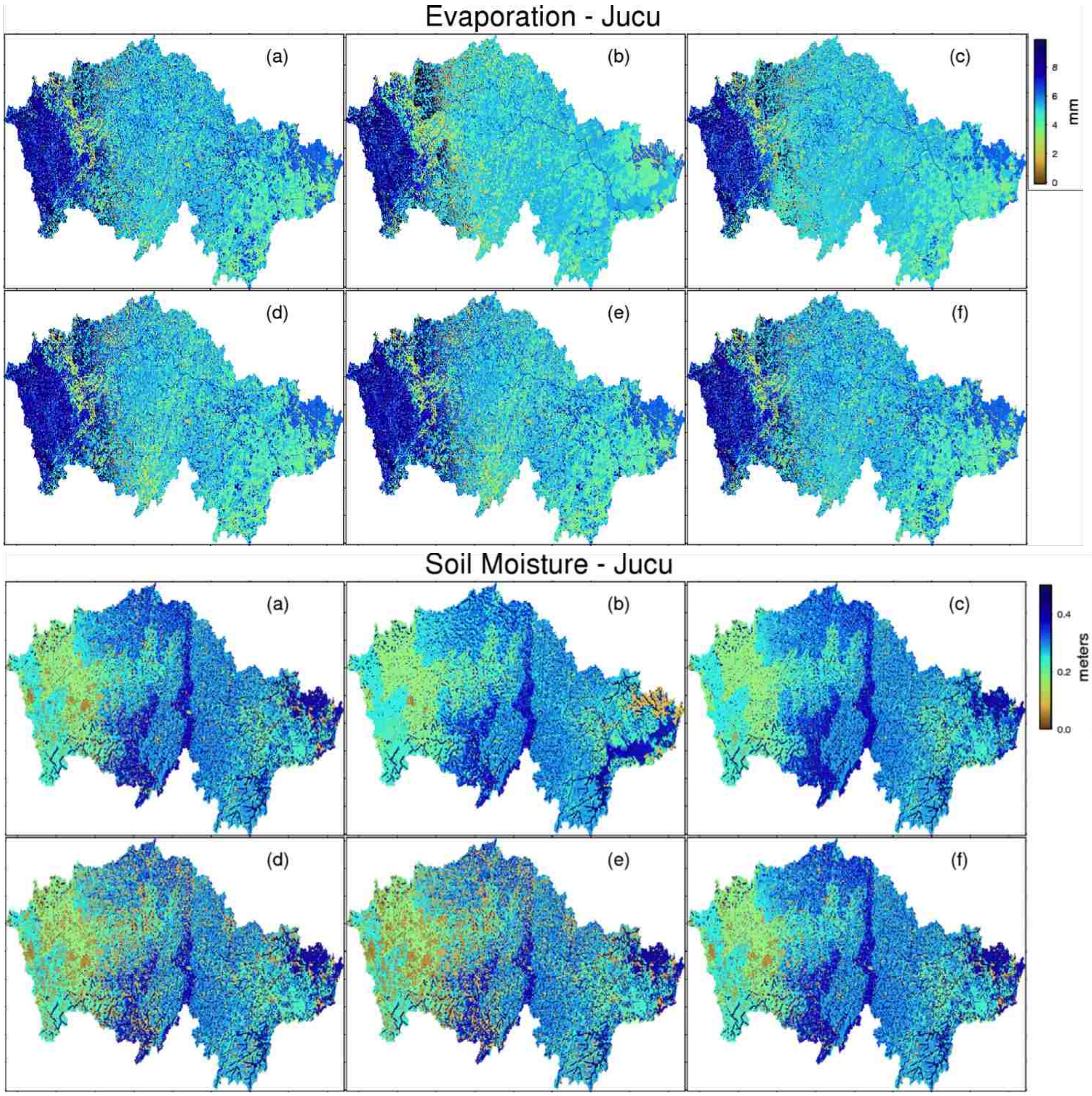

Figure 3.12. Comparisons of soil moisture (top) and ET (bottom) for the different landcover scenarios in the Jucu River basin: a) IEMA2007 b) GEOBASE1996 c) Increase in Primary Forests d) Euc. + 25% e) Euc. + 50% and f) Ag. + 25%

3.4 Conclusions

I have shown that land cover scenario analysis using a hydrological model is useful analytical tool in helping stakeholders and water managers understand the basin dynamics and the interactions between crops and forest cover and the effects on evapotranspiration and soil moisture. The model was able to replicate hydrographs for both basins with a high Nash-Sutcliffe efficiency even though data was particularly sparse. This modeling approach can be useful in assessing the influence of spatial configuration or fragmentation of land covers.

Land use changes in the Jucu and SMV river basins are largely due to increases in farming and expansion in eucalyptus plantations. I have shown here, using hypothetical landcover scenarios, that agricultural crops change the hydrologic regime of the river basins far more than eucalyptus growth, particularly in the SMV basin where there exist many manmade private irrigation dams and the forest cover is slightly more fragmented. In the SMV, soil types also play an important role in modulating the hydrologic regime.

The primary take away from this study however, is a more practical one – helping the local Espírito Santo state government form effective policies to address land use change issues that would ultimately impact biodiversity and water resources of the region. On a global scale, the results of this study and the methods discussed herein would be easily transferable to tropical regions and other areas with similar climatology and governance needs as Espírito Santo.

References

ABRAF (Brazilian Association of Producers of Planted Forests). (2012). Statistical Yearbook.

Allen, R. G., Tasumi, M., Trezza, R., Waters, R., & Bastiaanssen, W. (2002). SEBAL (Surface Energy Balance Algorithms for Land). *Advance Training and Users Manual–Idaho Implementation, version*, *1*, 97.

Aragao, L. E. O., Malhi, Y., Barbier, N., Lima, A., Shimabukuro, Y., Anderson, L., & Saatchi, S. (2008). Interactions between rainfall, deforestation and fires during recent years in the Brazilian Amazonia. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1498), 1779-1785.

Azevedo, D. (1971). Radar in the Amazon(RADAM/Radar Amazon/ side-looking radar imagery and multiband aerial photography for mineral, vegetation, soil and water resources mapping in Brazil). In *International Symposium on Remote Sensing of Environment, 7 th, University of Michigan, Ann Arbor, Mich* (pp. 2303-2306).

Barbosa, F. A. R., Scarano, F. R., Sabará, M. G., & Esteves, F. A. (2004). Brazilian LTER: ecosystem and biodiversity information in support of decision-making. *Environmental Monitoring and Assessment*, *90*(1-3), 121-133.

Barrocas, H. M., Da Gama, M. M., Sousa, J. P., & Ferreira, C. S. (1998). lmpact of reafforestation with Eucalyptus globulus La bi l l. on the edaphic collembolan fauna of Serra de Monchique (Algarve, Portugal). *Misc. Zool*, *2*(1.2), 9-23.

Beckers, J., & Alila, Y. (2004). A model of rapid preferential hillslope runoff contributions to peak flow generation in a temperate rain forest watershed. *Water Resources Research*, *40*(3).

Bernardo, A. L., Reis, M. G., Reis, G. G., Harrison, R. B., & Firme, D. J. (1998). Effect of spacing on growth and biomass distribution in Eucalyptus camaldulensis, E. pellita and E. urophylla plantations in southeastern Brazil. *Forest Ecology and Management*, *104*(1), 1-13.

Brown, M. E., De Beurs, K. M., & Marshall, M. (2012). Global phenological response to climate change in crop areas using satellite remote sensing of vegetation, humidity and temperature over 26years. *Remote Sensing of Environment*, *126*, 174-183.

Cuo, L., Giambelluca, T. W., & Ziegler, A. D. (2011). Lumped parameter sensitivity analysis of a distributed hydrological model within tropical and temperate catchments. *Hydrological Processes*, *25*(15), 2405-2421.

Cuo, L., Giambelluca, T. W., Ziegler, A. D., & Nullet, M. A. (2008). The roles of roads and agricultural land use in altering hydrological processes in Nam Mae Rim watershed, northern Thailand. *Hydrological Processes*, *22*(22), 4339-4354.

Cuo, L., Giambelluca, T. W., & Ziegler, A. D. (2011). Lumped parameter sensitivity analysis of a distributed hydrological model within tropical and temperate catchments. *Hydrological Processes*, *25*(15), 2405-2421.

Dupouey, J. L., Dambrine, E., Laffite, J. D., & Moares, C. (2002). Irreversible impact of past land use on forest soils and biodiversity. *Ecology*, *83*(11), 2978-2984.

de Castro Teixeira, A. H., Bastiaanssen, W. G. M., Ahmad, M. U. D., Moura, M. S. B., & Bos, M. G. (2008). Analysis of energy fluxes and vegetation-atmosphere parameters in irrigated and natural ecosystems of semi-arid Brazil. *Journal of Hydrology*, *362*(1), 110-127.

Galvíncio, J. D., de Barros Corrêa, A. C., & de Araújo, M. D. S. B. (2006). Determinação do albedo no município de Belém do São Francisco, com base em imagens Landsat 7. *Revista de Geografia, Recife*, *23*(3), 103-118.

Giambelluca, T. W. (1996). Tropical land cover change: characterizing the post-forest land surface. *Climate Change: Developing Southern Hemisphere Perspectives. Wiley, Chichester*, 293-318.

Hamza, M. A., & Anderson, W. K. (2005). Soil compaction in cropping systems: A review of the nature, causes and possible solutions. *Soil and tillage research*, *82*(2), 121-145.

Instituto Brasileiro de Geografia e Estatística (IBGE) and Instituto Brasileiro do Desenvolvimento Florestal (IBDF), 1988. In: *Mapa de Vegetação do Brasil. Scale 1:5 000 000*, Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA), Brasilia, DF Brazil.

Jackson, R. B., Jobbágy, E. G., Avissar, R., Roy, S. B., Barrett, D. J., Cook, C. W., ... & Murray, B. C. (2005). Trading water for carbon with biological carbon sequestration. *Science*, *310*(5756), 1944-1947.

Jarvis, A., Reuter, H. I., Nelson, A., & Guevara, E. (2008). Hole-filled SRTM for the globe, Version 4. CGIAR-CSI SRTM 90m Database. *International Center for Tropical Agriculture, Cali, Columbia. http://srtm. csi. cgiar. org*.

Kleidon, A., & Heimann, M. (1998). A method of determining rooting depth from a terrestrial biosphere model and its impacts on the global water and carbon cycle. *Global Change Biology*, *4*(3), 275-286.

La Marche, J. L., & Lettenmaier, D. P. (2001). Effects of forest roads on flood flows in the Deschutes River, Washington. *Earth Surface Processes and Landforms*, *26*(2), 115-134.

Lambin, E. F., Turner, B. L., Geist, H. J., Agbola, S. B., Angelsen, A., Bruce, J. W., ... & Xu, J. (2001). The causes of land-use and land-cover change: moving beyond the myths. *Global environmental change*, *11*(4), 261-269.

Liang, X., Lettenmaier, D. P., Wood, E. F., & Burges, S. J. (1994). A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research – All Series*, *99*, 14-415.

Lohmann, D., Nolte-Holube, R., & Raschke, E. (1996). A large-scale horizontal routing model to be coupled to land surface parametrization schemes. *Tellus A*, *48*(5), 708-721.

Marsden, S. J., Whiffin, M., & Galetti, M. (2001). Bird diversity and abundance in forest fragments and Eucalyptus plantations around an Atlantic forest reserve, Brazil. *Biodiversity & Conservation*, *10*(5), 737-751.

Maurer, E. P., Wood, A. W., Adam, J. C., Lettenmaier, D. P., & Nijssen, B. (2002). A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States*. *Journal of climate*, *15*(22), 3237-3251.

Meyer, P. D., Rockhold, M. L., & Gee, G. W. (1997). *Uncertainty analyses of infiltration and subsurface flow and transport for SDMP sites* (No. NUREG/CR--6565; PNNL--11705). Nuclear Regulatory Commission, Washington, DC (United States). Div. of Regulatory Applications; Pacific Northwest National Lab., Richland, WA (United States).

Myers, N., Mittermeier, R. A., Mittermeier, C. G., Da Fonseca, G. A., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, *403*(6772), 853-858.

Nijssen, B., & Lettenmaier, D. P. (1999). A simplified approach for predicting shortwave radiation transfer through boreal forest canopies. *Journal of Geophysical Research: Atmospheres (1984–2012)*, *104*(D22), 27859-27868.

Pahl-Wostl, C. (2007). Transitions towards adaptive management of water facing climate and global change. *Water resources management*, *21*(1), 49-62.

Pfautsch, S., Bleby, T. M., Rennenberg, H., & Adams, M. A. (2010). Sap flow measurements reveal influence of temperature and stand structure on water use of Eucalyptus regnans forests. *Forest Ecology and Management*, *259*(6), 1190-1199.

Sala, O. E., Chapin, F. S., Armesto, J. J., Berlow, E., Bloomfield, J., Dirzo, R., ... & Wall, D. H. (2000). Global biodiversity scenarios for the year 2100. *science*, *287*(5459), 1770-1774.

Saleska, S. R., Didan, K., Huete, A. R., & Da Rocha, H. R. (2007). Amazon forests green-up during 2005 drought. *Science*, *318*(5850), 612-612.

Soares, J. V., & Almeida, A. C. (2001). Modeling the water balance and soil water fluxes in a fast growing Eucalyptus plantation in Brazil. *Journal of hydrology*, *253*(1), 130-147.

Sharma, M. L. (1984). Evapotranspiration from a Eucalyptus community. *Agricultural Water Management*, *8*(1), 41-56.

Smethurst, P. J., Almeida, A. C., & Loos, R. A. (2014). Stream flow unaffected by Eucalyptus plantation harvesting implicates water use by the native forest streamside reserve. *Journal of Hydrology: Regional Studies*.

Storck P , Bowling L, Wetherbee P , Lettenmaier DP . 1998. Application of a GIS-based distributed hydrology model for prediction of forest harvest effects on peak stream flow in the Pacific Northwest. *Hydrological Processes* **12**: 889–904.

Thanapakpawin, P., Richey, J., Thomas, D., Rodda, S., Campbell, B., & Logsdon, M. (2007). Effects of landuse change on the hydrologic regime of the Mae Chaem river basin, NW Thailand. *Journal of Hydrology*, *334*(1), 215-230.

Thyer M, Beckers J, Spittlehouse D, Alila Y, Winkler R. (2004) Diagnosing a distributed hydrologic model for two high-elevation forested catchments based on detailed stand- and basin-scale data. *Water Resources Research* **40**: W01103, DOI:10.1029/2003WR002414.

Tran, X. T. (1996). Eucalyptus Plantations in Vietnam: Their History and Development Process. *Reports Submitted to the Regional Expert*.

VanShaar, J. R., Haddeland, I., & Lettenmaier, D. P. (2002). Effects of land-cover changes on the hydrological response of interior Columbia River basin forested catchments. *Hydrological Processes*, *16*(13), 2499-2520.

Viola, M. R., Mello, C. R., Beskow, S., & Norton, L. D. (2014). Impacts of Land-use Changes on the Hydrology of the Grande River Basin Headwaters, Southeastern Brazil. *Water Resources Management*, *28*(13), 4537-4550.

Wigmosta, M. S., Vail, L. W., & Lettenmaier, D. P. (1994). A distributed hydrology-vegetation model for complex terrain. *Water resources research*, *30*(6), 1665-1679.

Wigmosta, M. S., Nijssen, B., Storck, P., & Lettenmaier, D. P. (2002). The distributed hydrology soil vegetation model. *Mathematical models of small watershed hydrology and applications*, 7-42.

Wood, E. F., Lettenmaier, D., Liang, X., Nijssen, B., & Wetzel, S. W. (1997). Hydrological modeling of continental-scale basins. *Annual Review of Earth and Planetary Sciences*, *25*(1), 279-300.

Worden, J., Noone, D., Bowman, K., Beer, R., Eldering, A., Fisher, B., ... & Worden, H. (2007). Importance of rain evaporation and continental convection in the tropical water cycle. *Nature*, *445*(7127), 528-532.

IV: CATCHMENT SCALE ASSESSMENT OF SEDIMENT YIELD IN THE SANTA MARIA DA VITORIA RIVER BASINS IN ESPÍRITO SANTO, BRAZIL

Abstract

The Santa Maria da Vitoria (SMV) river basin supplies provides a third of potable water to Vitoria, the most populated city and the capital of Espírito Santo state in Brazil. However, sediment concentrations reach extremely high levels during heavy rainfall such that water sanitation facilities become inoperable. There is also very little sewage treatment in the basin, leading to water pollution and health hazards. The primary motivation for the government of Espírito Santo to explore sediment fluxes and dynamics in the SMV watershed is to inform improved freshwater resource and sanitation management practices. Using a distributed soil, hydrology and vegetation model (DHSVM) and the inherent sediment module, I estimate the sediment yield from the SMV at the main gauging station that is upstream of a dam. Climate data from January 2009 to February 2015 was used to initialize, calibrate and validate the model. Observed field total suspended solids measurements were available in sparse intervals for November 2013 to February 2015. Using three land cover scenarios, I tested the ability of DHSVM to simulate downstream sediment yield for the SMV watershed and to understand the effects of land cover change on sediment yield in the basin. I find that 25% increase in agriculture from the baseline IEMA 2007 landcover increases downstream sediment yield by 19% - 28% for each of our modeled time period while increasing eucalyptus by 50% decreases downstream sediment yield by 23% – 55% for each of our modeled time period. However, simulated sediments are considerably less than the measured sediment yield. I postulate that (1) the basin extent is too large for the DHSVM sediment module to capture basin sediments

dynamics accurately (2) further understanding of basin evolution during storms needs to be investigated and (3) longer term monitoring in a smaller basin (e.g. Rio Mangarai) on a more frequent time-scale would be beneficial in increasing DHSVM sediment predictions either by sediment transport modeling or linear regression calculations.

4.1 Introduction

Water and land resource management decisions have a direct effect on the environmental and economical sustainability of a watershed system. One of the major consequences of unchecked land use change is the impact on water supply and quality, downstream hydrological hazards (e.g. floods) and biodiversity conservation (Dunne, 1997; Tong et al., 2002; Schroter et al., 2005; Bates et al., 2008). Alteration of the landscape and other human-caused disturbances has been shown to be important factors affecting mass transport (loading) of principal plant nutrients (nitrogen and phosphorus) and sediment to lakes (Loeb, 1988). The increase of bioavailable nutrients over time is suspected as a principal cause for the increase in algal growth in the lake, with an associated decrease in water clarity.

Rapidly developing countries, particularly those evolving from rural to urban, frequently lack the resources to adequately monitor and forecast the impact of land use change on biologic, hydrologic and social resources. This leads to a growing need to develop a comprehensive set of tools, capable of accurately predicting the impact of land use changes on small to large spatial scales, as global development continues to steadily increase (Defries et al., 2004). Accurate estimation of mass and chemical export from a watershed is needed to predict the biogeochemical response of a system to changes in both land use and climate (Hope et al., 1994; Tranvik et al., 2002).

The increase in sedimentation and chemical pollutants to the Santa Maria da Vitoria (SMV) river , in the state of Espírito Santo, Brazil has caused the local populace unease, chiefly because the citizens do not understand the correlation between heavy rainfall and water scarcity. This has motivated the government of Espírito Santo to explore tools to quantify sediment fluxes and dynamics in the SMV watershed and to develop suitable responses for improving water quality and sanitation. Accurate estimation of mass and chemical export from a watershed is needed to predict the responses of a system to changes in both land use and climate, and to plan for subsequent water resources and quality infrastructure. This is a challenge, as streams in regions subject to intense storms suddenly mobilize high sediment loads that are difficult to measure. However, virtually nothing is known about sediment fluxes in the SMV. Until that is understood, it is not possible to evaluate such detailed causes and effects.

In this chapter I will explore the ability of the distributed soil vegetation hydrology model (DHSVM) coupled with a sediment module to estimate the sediment yield in the basin and to understand to effects of land cover change on sediment dynamics in the basin. There are two fundamental questions I will address: (a) what are the impacts of changes in the practices of agricultural activities on local and regional water quality and (b) what is the effect of the increase in forest cover on the reduction in erosion potential and turbidity?

4.2 Methods

4.2.1 Study Area

The Santa Maria da Vitoria watershed provides 35% potable water to the capital city of Vitoria in Espírito Santo state in Brazil. It covers an area of roughly 1680 km^2, with a river length of 122 km. Mountainous landscapes and intense whitewater rapids characterize the upper region of the Santa Maria da Vitoria basins. The landscape of the Santa Maria da Vitoria watersheds is composed of roughly 40% natural forested land cover, which is mostly concentrated in the upper regions of the basins. The SMV passes through five municipalities of varying size: Santa Maria de Jetiba, Santa Leopoldina, Cariacica, Serra, and Vitoria. The SMV river mouth empties into the Bay of Vitoria, an important commercial port for the region, and forms the island of Vitoria, the capital city of Espírito Santo (Figure 4.1). The river basin is also influenced by rural development, pasture land, and agricultural export plantations such as banana, coffee, eucalyptus, and sugar cane.

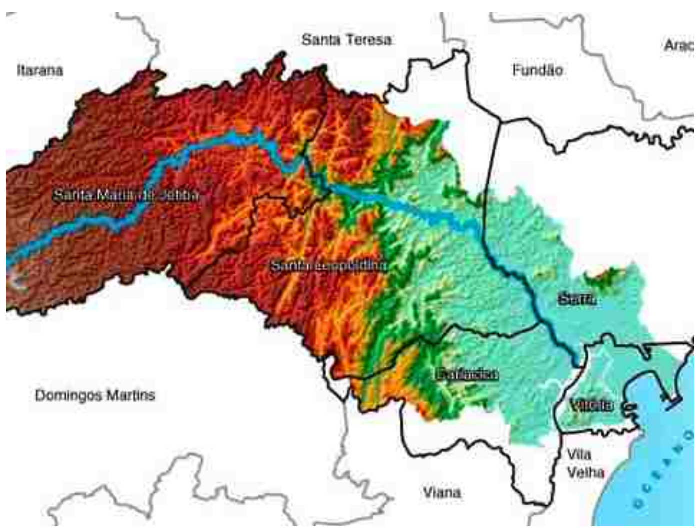

Figure 4.1. Basin extent and drainage municipalities for the Santa Maria da Vitoria basin

Despite the importance of the river basin to the state, land use change has resulted in sediment load increase to the Bay of Vitoria and upstream dams, predominantly during the rainy season. Sediment concentrations reach such high levels that reservoirs become inoperable, causing a decrease in water supply. Further, there is little to no treatment of wastewater in the upper and central regions of the basin. Since the sewage treatment in the region uses septic tanks, septic tank outfall has provided the river with enriched organic nitrogen values. In the lowlands, agricultural activity has caused an increased in fertilizer activity within the SMV river.

4.2.2. Historical sediment records

Two sources of data provided sediment records. Historical records for sediment contrations across SMV were provided by the Instituto Estudal do Meio Ambiente e Recursos Hidricos (IEMA). These records represented bi-monthly sampling, and did not capture storm events. Concentrations of sediments in a stream may change dramatically, from quiet baseflow to major storms.

Much of the sediment transported by a stream occurs during the relatively small period of time of storms. Hence it is critical to have knowledge of these patterns. Joint with CESAN, the project conducted 3 field campaigns in the SMV basin, to make field measurements of sediment movement (and its chemical composition) over short and storm time periods. The concentration of suspended sediments was measured from 30 October 2013 – 06 November 2013 (hereafter refered to as TP1), 25 October 2014 – 28 October 2014 (hereafter refered to as TP2) and 06 February 2015 – 09 February 2015 (hereafter refered to as TP3). Samples were collected with ISCO autosamplers. Each ISCO sequence collected 24 samples at 3-6h intervals in the SMV mainstem and one of its tributaries, the Rio Mangaraí.

4.2.3. The DHSVM Sediment Module

The mechanisms that govern erosion and sediment transport are primarily rainfall, soil permeability, surface runoff, infiltration and throughflow (FAO, 1996). This is pertinent to our study particularly because agriculture and /or forest change influences all these parameters, through changes in leaf area index and root depth. To evaluate the potential impacts of landuse change on sediment generation, a model is needed that represents the processes at work. Doten et al. (2006) developed a sediment algorithm for DHSVM by using the existing slope stability models the Level I Stability Analysis model (LISA) developed by Hammond et al. (1992), and the European Hydrological System sediment (SHESED) model (Burton and Bathurst 1998).

The DHSVM sediment module consists of four primary components: mass wasting, which is stochastic in nature, hillslope erosion, erosion from forest roads, and a channel-routing algorithm (Fig. 4.2). The algorithm redistributes sediments by computing the basin hydrology using overland flow, runoff and mass failure of sediment. The variables used in sediment computations are depth to saturation, saturation and infiltration excess runoff, precipitation, leaf drip and channel flow. This is important to note since the mechanisms that govern land cover change impacts on sediment yield are rain interception and surface and baseflow. For example, a change from forested areas to agriculture would affect leaf drip and infiltration capacity due to transformations in leaf size, rooting depth and changes in soil depth if there is soil compaction. The sediment algorithm in DHSVM redistributes sediments by computing the basin hydrology using overland flow, runoff and mass failure of sediment.

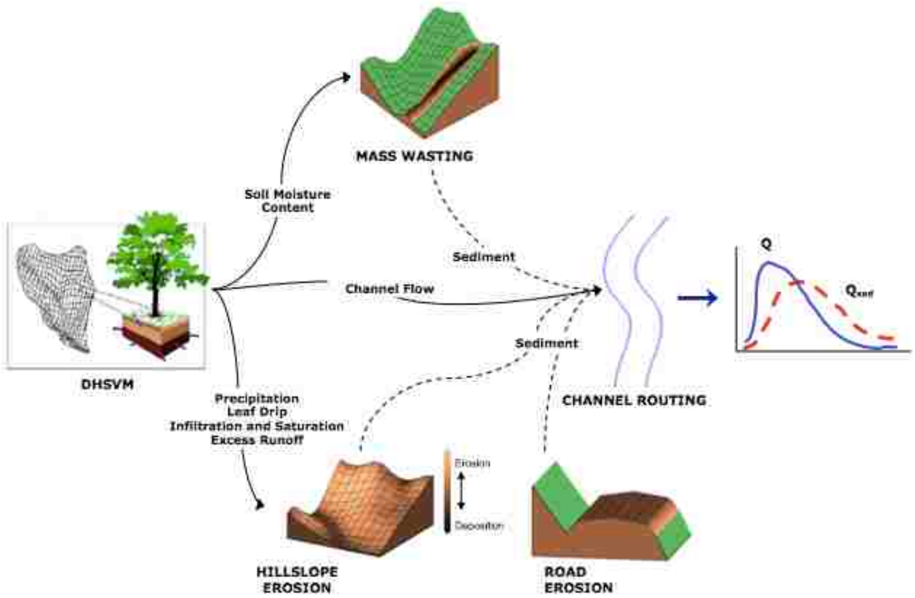

Figure 4.2. Schematic of the DHSVM sediment module (from Doten et al., 2006)

Studies using the DHSVM sediment module have been limited mostly to the Pacific Northwest in order to understand catchment-scale forest road erosion (Surfleet et al., 2008; Surfleet et al., 2015) and post-fire erosion sediment delivery (Lanini et al., 2009). Agricultural land use and its implications were a critical part of this study. Current management practices can influence overland flow, infiltration rates, and erosion during rainstorm events. Runoff erosion and sedimentation depend on the process of entrainment, transport, and deposition of sediment by the forces from raindrop impact and runoff over the soil surface (Rai and Mathur, 2007)

4.2.4 Model setup

The setup in this study only took into account the hillslope erosion and channel routing components since this region is not particularly steep, thus reducing the need to compute sediment loads from landslides (mass wasting). The hillslope erosion is only computed at the hydrology model resolution (10-m) and does no take into account the failure scenarios predicted by the mass-wasting component. Therefore, the hillslope erosion sediment deposit does not need mass-wasting parameters and does not take into account additional sediment load from mass-wasting (failure) events but is rather a product of land surface flow into the stream and channel segments (using the kinematic wave approximation). Essentially, this setup predicts the erosional consequences of vegetation change on the hydrologic regime. There are other mechanisms governing erosion due to vegetation effects such as shear stress that DHSVM cannot predict at this point.

In order to run the sediment module for DHSVM, a 10-m digital elevation model (DEM) and 10-m mask for the SMV were developed. The baseline landcover scheme was from IEMA2007 (see Chapter 3). In order to test the effects of different landcover schemes on sediment yield, I used two different land use scenarios in addition to the baseline scenario (Scenario I). The additional scenarios were increasing eucalyptus by 50% (Scenario II) and increasing agriculture by 25% (Scenario III); these scenarios were chosen based on the results from Chapter 3, which indicated that increasing eucalyptus by 50% and increasing agricultural crops had the most pronounced effect on streamflow in the SMV basin.

The soil and vegetation parameters for the DHSVM set up were obtained from the results of Chapter 3. Long-term, continuous precipitation and discharge data from July 2009 to February 2015 were obtained from the Brazilian Meteorological Agency (INMET), the National Water Agency (ANA) and from the Espírito Santo Sanitation Company (CESAN). For the meteorological data, I used the latest the daily station data for precipitation (data courtesy of CESAN). However, since the most recent data for temperature, wind and humidity was not available publicly, I used the mean daily values of temperature, wind and humidity aggregated from 1970 – 2012. I then used the Variable Infiltration Capacity model (VIC) disaggregation scheme to obtain the 6-hourly meteorological inputs for the SMV. Since sediment yields can change drastically over a short period, I used 6-hour timesteps to capture any sudden events of erosion.

4.2.5. Operational considerations

Since the modeled basin area (>3000km2) is relative large, the sediment module took an extremely long time to produce results. A three-day model spin up took 14-CPU days (on a single quad core processor). This severely limits the ability of the model to produce meaningful results on a feasible timescale for policy making, particularly if longer records are needed. Furthermore, DHSVM cannot be run in parallel and computes the entire basin yield for each time step; this indicates that results will not be obtained until the entire basin run has been completed.

4.3 Results and Discussion

4.3.1. Historical and storm sediment concentrations

Sediment concentrations were maximal at rising and peak high water and minimal at low water (Figure 4.3.). It should be noted, however, that this type of sampling regime largely underestimates the total flux of sediments through the river. Even during high water, samples were typically not taken during periods of extreme rainfall due to logistical difficulties, meaning that peak concentrations were typically not observed in the monthly dataset. Measurements were conducted at a single point in time, once every four to six months. Measurements were also not correlated with events of precipitation – the locations of the gauges make accessibility difficult especially during or after a storm event. However, sediment yield is often the largest after a large storm event (Miller, 1984; Bittencourt et al., 2006).

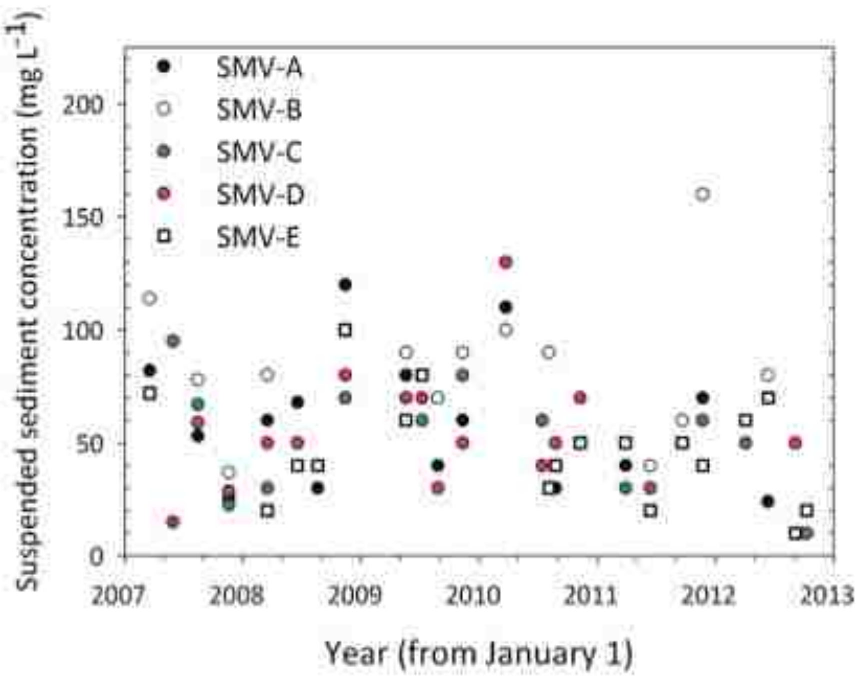

Figure 4.3. Historical measurements of TSS concentrations in the Rio Santa Maria da Vitoria from April 2007 to October 2012 (Station coordinates and data courtesy of IEMA)

Sediment concentrations were maximal at rising and peak high water and minimal at low water (Figure 4.3.). It should be noted, however, that this type of sampling regime largely underestimates the total flux of sediments through the river. Even during high water, samples were typically not taken during periods of extreme rainfall due to logistical difficulties, meaning that peak concentrations were typically not observed in the monthly dataset. Measurements were conducted at a single point in time, once every four to six months. Measurements were also not correlated with events of precipitation – the locations of the gauges make accessibility difficult especially during or after a storm event. However, sediment yield is often the largest after a large storm event (Miller, 1984; Bittencourt et al., 2006).

The detailed ISCO-based storm sampling provides greater insight on sediment dynamics during storm events (Figure 4.4). From October 30-November 5, 2013 there was periodic light rainfall. Sediment concentrations in both the Santa Maria da Vitoria and Rio Mangarai reflected rainfall/river discharge, ranging from roughly 20-60 mg L^{-1}. During this period, sediment concentrations were more variable (i.e. peaked and dropped more often) in the Rio Mangarai than the Santa Maria da Vitoria main channel. The Rio Mangarai is a small second-order stream where river conditions closely reflect a direct connection with the surrounding landscape. The Rio Santa Maria da Vitoria, on the other hand, recieves tributary and direct inputs from a much larger area. Material concentrations in the Santa Maria da Vitoria are, thus, a blend of signals coming from a large landscape with variable weather and landscape conditions. For example, during the October 30-November 5, 2013 time period the Rio Mangarai received localized rainfall that was not consistent across the entire Santa Maria da Vitoria basin. Sediment concentrations in the Santa Maria da Vitoria main channel, thus, reflected both the inputs of tributaries receiving localized rainfall such as the Rio Mangarai and base flow inputs from tributaries across the basin experiencing dry conditions at the time. From November 5-7, 2013 the entire region experienced significant rainfall. During this period, sediment concentrations in the Rio Mangarai increased from roughly 35 to 600 mg L^{-1} at peak discharge. Sediment concentrations in the Santa Maria da Vitoria increased from roughly 25 to 325 mg L^{-1}. Similar to the period of light localized rainfall the week before, sediment concentrations increased proportionally less in the Santa Maria da Vitoria compared to the Rio Mangarai, illustrating the direct connection between small streams and their surrounding landscape and the integration of varying signals in larger river channels (Vannote et al., 1980).

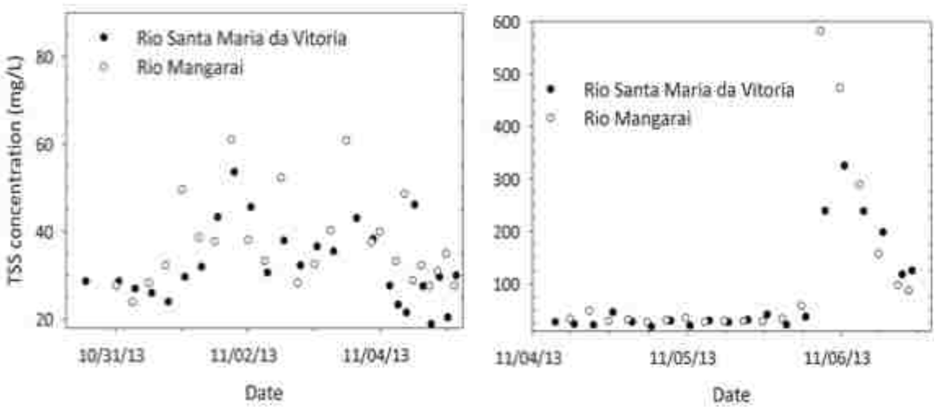

Figure 4.4. Suspended sediment concentrations during storm flow. Measurements of total suspended sediment concentrations during light rainfall (top) and heavy storm flow (bottom) in the Rio Santa Maria da Vitoria and its tributary, Rio Mangarai, from October 30, 2013 to November 6, 2013. Samples were collected on a 3-6h interval.

4.3.2. Extension of DHSVM Runs through 2015

The results from Chapter 3 showed that DHSVM modeled the hydrology of SMV well (E = 0.705 and R^2 =0.728). I extended the model run to February 2015 and found that from 2012 to 2015, DHSVM captured the peak flows (Fig. 4.5) and seasonality of streamflow. Increasing the eucalyptus buffer by 50% following the methods outlined in Chapter 3 reduced mean annual streamflow by 25% and increasing the agricultural buffer by 25% increased streamflow by about 30%; this is consistent with the findings from Chapter 3.

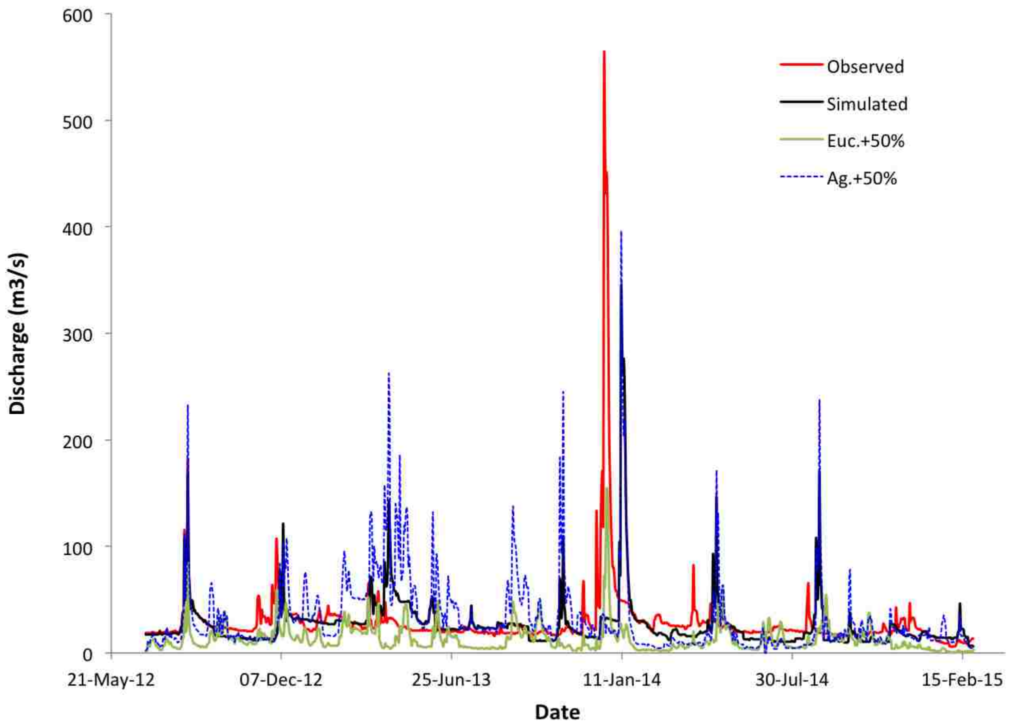

Figure 4.5. Observed and simulated discharge from baseline run (Scenario I) and the different landcover scenarios for Eucalyptus + 50% (Scenario II) and Agriculture + 25% (Scenario III)

4.3.3. Sediment calibration and validation

I used DHSVM to first simulate how well the sediment module might replicate observed sediment yield and subsequently to understand how land cover changes might change sediment dynamics of a watershed. The calibration and validation of the DHSVM sediment module indicated that soil depth and soil cohesion were important parameters in capturing basin sediment yield. Estimation of sediment yield may also be affected by road runoff which was not taken into account in this experiment. Surfleet et al., 2008 suggests that results for sediment yield estimation may be improved if there were better soil depth measurements within the watershed.

I first initialized the model by running DHSVM from January 2009 – February 2015 for five times to generate the sediment and hydrological state files. The sediment module was first initialized by running the DHSVM model with the sediment option turned on for the entire time period of 2009 – 2015 to account for existing sediments in the basin and to reduce the frequency of a sudden mass influx of sediments at the beginning of each run. The observed sediment yield data for November 2013 was used to calibrate the sediments output. Increasing the soil cohesion and decreasing the angle of internal friction of the soils closest to the monitoring station helped achieve this. The subsequent measured total suspended sediments data from October 2014 and February 2015 was used to validate the sediment module.

Modeled sediment yield lags precipitation, as would be expected (Fig. 4.6). For the 11/24 measured point, the model value was within ~10% of the observed, with a lag of several hours. One problem may be that spin-up or initialization time was insufficient to capture the basin sediment amount and dynamics since sediments in rivers are cumulative product. The base data themselves are not of high resolution. The response to the greater rainfall of 11/28 and 11/29 shows a modeled sediment increase at least qualitatively similar to the moderate storm response observed by Ward and Almeda.

For the later two time periods (TP2 and TP3), observed measurements were obtained for a much shorter duration; the measurements taken during in October 2014 missed the major rainfall event that occurred October 31, 2014. While the results of the ISCO-based campaign so far are consistent with the long-term records of IEMA for low-flow and moderate rainfall conditions, it also suggests that sediment measurement should be conducted at longer intervals in order capture any significant rainfall events.

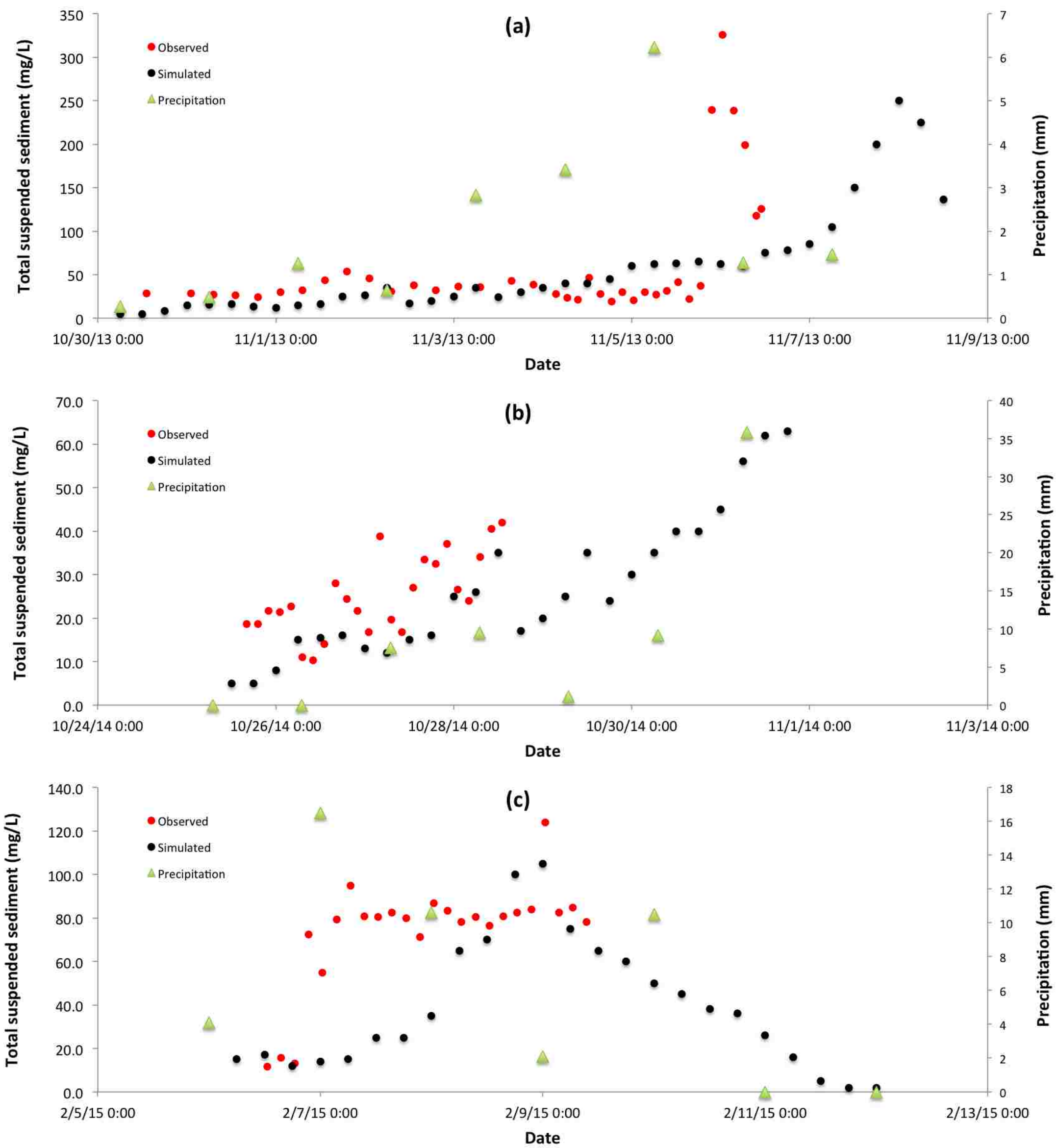

Figure 4.6. Precipitation, observed and simulated sediment yield after calibration and validation for the SMV (a) First time period from 10/30/2013 – 11/6/2013 (b) Second time period from 10/25/2014 – 10/30/214 and (c) Third time period from 02/06/2015 – 02/10/2015

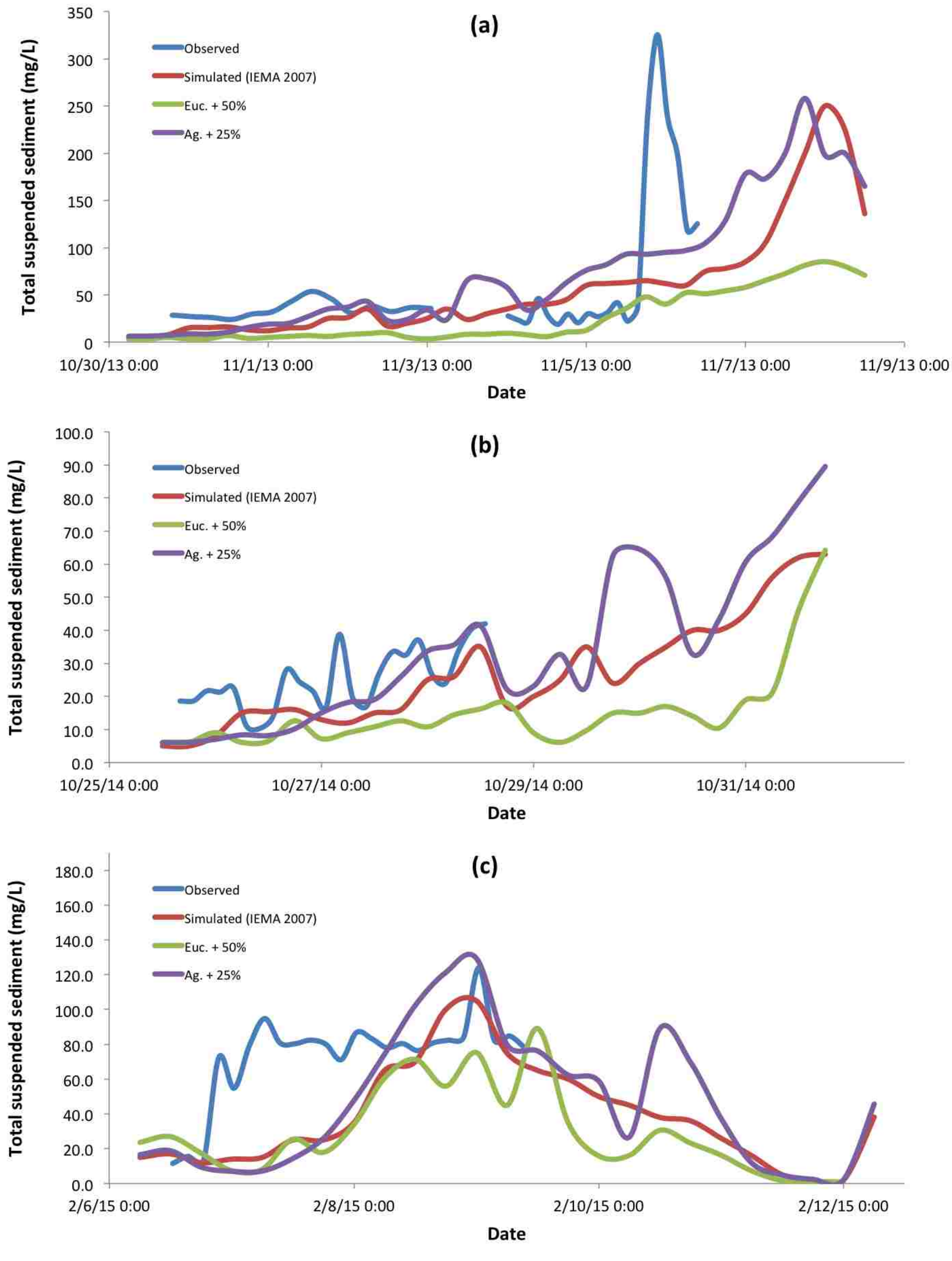

Figure 4.7. Observed and simulated sediment yield for different land cover scenarios (a) First time period from 10/30/2013 – 11/6/2013 (b) Second time period from 10/25/2014 – 10/30/214 and (c) Third time period from 02/06/2015 – 02/10/2015

4.3.4. Scenarios of landuse change effects on sediment yield

Our analysis of different land cover scenarios on sediment yield showed that an increase in agriculture also increases sediment generation and peak sediment generation occurs earlier than for the baseline run (Figure 4.6). For all the time periods (TP1, TP2, and TP3), average sediment yield was increased by 19 – 28% when the agricultural buffers were increased. This is consistent with studies that show a high probablity of erosion and topsoil loss occuring with croplands, especially within urban areas or hillslopes (e.g. Gianessi et al., 1981; Walling, 1983; Nelson and Booth, 2002). Increasing the eucalyptus buffer by 50% however, decreased sediment generation by 55% for TP1, 43% for TP2 and 23% for TP3. This decrease in sediment generation may be due to the fact that eucalyptus behaves like forests in terms of rain interception; erosion and sediment transport is largely influenced by rain interception, overland flow, particle movement and channel geomorphology (Swanson et al., 1982). Also, soil that is not entirely exposed may be less susceptible to erosion (Johansen, 2001). One explanation for the increase in sediment yield from TP1 to TP3 is the seasonal harvesting and thinning of eucalyptus trees which occurs throughout December through February. Another explanation for this increase in sediment generation is the rainfall intensity during TP3 may have been higher than that for TP1 even though the average rainfall occurring in the TP1 time period was higher. Further investigation into factors affecting sediment dynamics in the basin as well as corroboration of rainfall data will be needed.

4.4 Conclusion

The purpose of the sediment trial simulations was to determine if DHSVM could simulate sediment yield efficiently and accurately. However, the modeling work was hampered by the lack of available data and inherent model capabilities in modeling sediments over a large area. The assessment of the impacts of roads on the hydrology and sediment yield of forested catchments also has a high amount of uncertainty. The variability of the hydrologic response of hillslopes and sediment transport and yield makes quantification of these processes difficult.

However, the results from Chapter I, Chapter II and Chapter III show that it is possible to examine specific issues pertinent to the FpV project more quantitatively. For example, land use modeling showed that an increase in agriculture is likely to increase streamflow particularly in the SMV basin. This is corroborated by our analysis, which showed an increase of 19% – 28% in sediment yield when agricultural buffers are increased. An increase in streamflow increases sediment load especially during the heavy rain events, as evidenced by the TSS measurements conducted in November 2013. Chemical evidence shows a strong anthropogenic influence, especially during storm events.

Likewise, modeling efforts show that forest cover, including increasing the eucalyptus buffer, decreases downstream streamflow. Increasing forest cover also reduces the amount of exposed soil susceptible to erosion since forest covers have deeper roots to stabilize soil and reduces the rainfall through the canopy layer. I can surmise from the combination of modeling outputs that priority areas for conservation in order to improve downstream water quality would be dependent on local policies governing agriculture, but ideally, where there are currently low/short crops or exposed soil, a buffer zone should be created. Interspersing plants groundcover with agriculture has been shown to help with erosion in some areas (Reining, 1992; Smolikowski et al, 2001).

It appears that because sediment dynamics vary so greatly between basins, there needs to be a concerted effort to first obtain field measurements over a finer temporal and spatial scale in order to improve confidence in any sediment estimation method. Landuse in the SMV (and its tributaries) have caused very high sediment loads that are far beyond natural especially during storms. This sediment ultimately ends up in the Bay of Vitoria, causing disruption to water supply and sanitation plants, reducing efficiency of the shipping industry due to docking issues and reduces environmental and aesthetic values. Solving and reducing these problems should be an incentive for the Government of Espírito Santo to expand monitoring efforts especially to realize the vision of the FpV project in increasing biodiversity.

4.5 Future Work

The Rio Mangarai is a tributary to the Rio Santa Maria da Vitoria, with considerable agriculture and high sediment loads, and "flashy" response to rainfall events. Due to the small size of the Mangarai basin (about 1200 km^2), the sediment load computation time should be reduced when using DHSVM. The Mangarai basin is also currently the site of a concerted effort to collect sediment, flow and other water quality measurements due to its proposed location as a sanitation site for the state of Espírito Santo.

This increase in field measurement data at a fine temporal and spatial scale would allow for the estimation of sediment yield with higher confidence. Our analysis above indicates that DHSVM and can be used to predict sediment yield but in order to fully understand basin dynamics, more specific measurements of soil depth, soil cohesion and friction angle is needed. A fundamental improvement also needs to be made in computer processing.

References

Bates, B., Kundzewicz, Z. W., Wu, S., & Palutikof, J. (2008). *Climate change and water*. Intergovernmental Panel on Climate Change (IPCC).

Bittencourt, A. C. D. S. P., DOMINGUEZ, J., LANDIM, M., MARTIN, L., & SILVA, I. R. (2000). Patterns of sediment dispersion coastwise the State of Bahia-Brazil. *Anais da Academia Brasileira de Ciências*, *72*(2), 271-287.

Burton, A., & Bathurst, J. C. (1998). Physically based modelling of shallow landslide sediment yield at a catchment scale. *Environmental Geology*, *35*(2-3), 89-99.

Doten, C. O., Bowling, L. C., Lanini, J. S., Maurer, E. P., & Lettenmaier, D. P. (2006). A spatially distributed model for the dynamic prediction of sediment erosion and transport in mountainous forested watersheds. *Water Resources Research*, *42*(4).

DeFries, Ruth, and Keith N. Eshleman. "Land-use change and hydrologic processes: a major focus for the future." *Hydrological processes* 18.11 (2004): 2183-2186.

Dunne, T. (1979). Sediment yield and land use in tropical catchments. *Journal of Hydrology*, *42*(3), 281-300.

Ferguson, R. I. (1987). Accuracy and precision of methods for estimating river loads. *Earth surface processes and landforms*, *12*(1), 95-104.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., ... & Snyder, P. K. (2005). Global consequences of land use. *science*, *309*(5734), 570-574.

Gianessi, L. P., & Peskin, H. M. (1981). Analysis of national water pollution control policies: 2. Agricultural sediment control. *Water Resources Research*, *17*(4), 803-821.

Hope, D., Billett, M. F., & Cresser, M. S. (1994). A review of the export of carbon in river water: fluxes and processes. *Environmental pollution*, *84*(3), 301-324.

Johansen, M. P., Hakonson, T. E., & Breshears, D. D. (2001). Post-fire runoff and erosion from rainfall simulation: contrasting forests with shrublands and grasslands. *Hydrological processes*, *15*(15), 2953-2965.

Loeb, S. L., & Hackley, S. H. (1988). Distribution of Submerged Macrophytes in Lake Tahoe, California and Nevada, and the Possible Influence of Groundwater Seepage. *Internationale Vereinigung fur Theoretische und Angewandte Limnologie, Verhandlungen IVTLAP*, *23*(4).

Lanini, J. S., Clark, E. A., & Lettenmaier, D. P. (2009). Effects of fire-precipitation timing and regime on post-fire sediment delivery in Pacific Northwest forests. *Geophysical Research Letters*, *36*(1).

Level I stability analysis (LISA) documentation for version 2.0. US Department of Agriculture, Forest Service, Intermountain Research Station, 1992.

Loeb, S. L., & Hackley, S. H. (1988). Distribution of Submerged Macrophytes in Lake Tahoe, California and Nevada, and the Possible Influence of Groundwater Seepage. *Internationale Vereinigung fur Theoretische und Angewandte Limnologie, Verhandlungen IVTLAP*, *23*(4).

Maurer, E. P., Wood, A. W., Adam, J. C., Lettenmaier, D. P., & Nijssen, B. (2002). A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States*. *Journal of climate*, *15*(22), 3237-3251.

Miller, E. L. (1984). Sediment Yield and Storm Flow Response to Clear-Cut Harvest and Site Preparation in the Ouachita Mountains. *Water resources research*, *20*(4), 471-475.

Nelson, E. J., & Booth, D. B. (2002). Sediment sources in an urbanizing, mixed land-use watershed. *Journal of Hydrology*, *264*(1), 51-68.

Rai, R. K., & Mathur, B. S. (2007). Event-based soil erosion modeling of small watersheds. *Journal of Hydrologic Engineering*, *12*(6), 559-572.

Reining, L. (1992). *Erosion in Andean hillside farming: characterization and reduction of soil erosion by water in small scale cassava cropping systems in the southern Central Cordillera of Columbia*.

Schröter, D., Cramer, W., Leemans, R., Prentice, I. C., Araújo, M. B., Arnell, N. W., ... & Zierl, B. (2005). Ecosystem service supply and vulnerability to global change in Europe. *Science*, *310*(5752), 1333-1337.

Smolikowski, B., Puig, H., & Roose, E. (2001). Influence of soil protection techniques on runoff, erosion and plant production on semi-arid hillsides of Cabo Verde. *Agriculture, ecosystems & environment*, *87*(1), 67-80.

Swanson, F. J., Fredriksen, R. L., & McCorison, F. M. (1982). Material transfer in a western Oregon forested watershed.

Syvitski JPM, Morehead MD, Bahr DB, Mulder T. 2000. Estimating fluvial sediment transport: the rating parameters. Water Resources Research 36: 2747–2760.

Tong, S. T., & Chen, W. (2002). Modeling the relationship between land use and surface water quality. *Journal of environmental management*, *66*(4), 377-393.

Tranvik, L. J., & Jansson, M. (2002). Climate change (Communication arising): Terrestrial export of organic carbon. *Nature*, *415*(6874), 861-862.

Walling, D. E. (1983). The sediment delivery problem. *Journal of hydrology*, *65*(1), 209-237.

5. GENERAL CONCLUSIONS

This research aimed to improve the understanding of the interactions between climate and hydrology in a data sparse region of Brazil and to evaluate how changes in the climate and future land use change might influence these interactions. I used land surface modeling and developed geospatially consistent dataframes from multiple sources to resolve the structure of the landscape and to produce patterns of water distribution associate with climatic and land use change factors.

In Chapter I, I looked at how precipitation and temperature influences streamflow runoff and I used the future projections from climate models to assess potential changes to the hydrologic regime of the state of Espírito Santo, Brazil.

- By incorporating a sensitivity-based method to predict future streamflow, I showed that this method is a useful 'back-of-the-envelope' tool for water managers to plan for impending changes to the climate system. This is particularly useful for data-sparse regions where technological expertise and the ability to operate full climate models are still lacking.
- The maps of precipitation elasticity and temperature sensitivity also provides an overview of targeted areas where more meteorological stations, modeling efforts or research should be concentrated to provide better data and analysis in helping to narrow the uncertainties. In this case, my research shows that the region is most sensitive to changes in precipitation, and the northern regions of Espírito Santo state would see the highest effects of precipitation changes on streamflow.
- The estimates of future streamflow (ΔQ_{est}) for using the sensitivity-based approach suggest an average increase of 20% to 45% across the region. Differences between each IPCC AR5 scenario are small (<5%). The largest streamflow increase was calculated for Cachoeira

(45% increase), located in the Northern part of the state where temperatures are hottest and has the largest variation in precipitation predictions from the AOGCMs resulting in a large variation of ΔQ_{est}.

- This sort of information is a useful tool in planning the expansion of crops, building infrastructure (such as dams and flood emergency protocols) and narrowing down areas for biodiversity protection. Due to the increase in precipitation from a changing climate, it is anticipated that sedimentation in some major river basins within the state will be on the uptick due to heavier rainfall.

On a smaller scale, I looked at how landcover changes influence the streamflow regime on two major river basins that provide 95% of potable water to the Greater Vitoria area, the most populous county in Espírito Santo state. In Chapter II, I used hypothetical landcover change scenarios coupled with a basin-scale hydrologic model to understand how plantation forests (specifically eucalyptus) and silvaculture changes the hydrologic regime of the river basins.

- Increasing eucalyptus areas decreased discharge (from the IEMA2007 baseline) by an average of 26% in the Jucu and 30% in the SMV. The difference in discharge between Euc.+25% and Euc.+50% was indiscernible in both basins.
- Increased highland agriculture caused higher unregulated annual water yields especially during the low flow season (November - January) for both the Jucu and SMV river basins. Dry season flows increased by 29% in the SMV and 31% in the Jucu while wet season flows increased by 16% in the SMV and 14% in the Jucu. Overall, crop expansion increased annual flows by 22% in the SMV and by 30% in the Jucu. The reason for this can be one of two things: agricultural crops in Brazil, particularly coffee are not shade grown i.e. forests are

clear-cut for monoculture. Espírito Santo is one of Brazil's biggest coffee exporters and a major export crop in the Jucu and SMV watersheds is coffee.

One of the effects of landuse change is a decrease in water quality caused by siltation and erosion. However, data on water quality and sediments is extremely sparse in this region thus reducing the ability to assess the correlation and causation between landuse change and water quality. In Chapter III, I used DHSVM to look how sediment loads increased in the SMV after a rainfall event and how changing landcover affects the sediment load.

- Analysis of different land cover scenarios on sediment yield showed that an increase in agriculture also increases sediment generation and peak sediment generation occurs earlier than for the baseline run. Average sediment yield was increased by 19 – 28% when the agricultural buffers were increased.
- Increasing the eucalyptus buffer by 50% however, decreased sediment generation by 23% - 55% with increased sediment generation occurring as during longer modeling periods. Rainfall intensity and harvesting season is suspected as factors influences this large range of sediment yield.

My research thus shows that in order to increase biodiversity (per the FpV objectives) and to increase water quality, there needs to be a radical rethinking or incentives to change current agricultural practices. The type of monoculture impacts delivery to the coastal zone, depending on the type of landcover replaced. If eucalyptus were to replace primary forest, differences would likely be small. If it replaced low-lying vegetation, discharge would be reduced and ET increased. If the monocultures were a crop, discharge would increase. Results from the modeling efforts show that forest cover decreases downstream streamflow. Increasing forest cover and river buffer areas like wetlands and riparian vegetation also reduces the amount of exposed soil susceptible to erosion since forest covers have deeper roots to stabilize soil and reduces the rainfall through the canopy layer.

The results of this dissertation also show that land surface modeling using existing satellite and climate data is an effective tool in helping policymakers and water manager understand atmosphere-biosphere-land interactions. General conditions found in the Jucu and Santa Maria da Vitória watersheds are relatively common in many parts of the state and in Brazil as well as many tropical countries. This indicates that there is considerable potential for replication of this approach in many other parts of the world where communications, water resources management, hydrologic modeling and melding together local stakeholder inputs would enhance and simplify decision-making.

The process of the hydrologic modeling of scenario futures is based explicitly on the predictions of regional (including global downscaled results). Outputs from regional climate models can be easily coupled to VIC (as demonstrated in the previous chapters) by using either the sensitivity-based method for a back of the envelope calculations or the output from the AOGCMs fed directly into VIC. Further, the hydrologic models (VIC, DHSVM) can be used as the robust base model to provide early warnings. At the longer climate scenario time scale (several decades out), the most sensitive regions could be identified, and options for different crops considered. At shorter time scales, drought indices could be provided with a one-month lead-time.

The primary purpose of this dissertation however, is a more practical one – helping the local Espírito Santo state government form effective policies to address land use change issues that would ultimately impact biodiversity and water resources of the region. The results of this dissertation is readily available through a dynamic information framework (DIF) that has been setup as a website (http://pangaea.ocean.washington.edu). The results are presented using data visualization tools (i.e through charts, graphics and a story flow), making it easier for non-technical stakeholders such as the Governor of ES to envision and understand the results and analysis from the models. Although this portal currently resides on a local machine, the aim is to deploy the entire framework into a cloud platform that would allow public access without the need for local machines and software, administrative setup or long-term technical expertise.

Another valuable implication from this work is the evaluation of future alternatives for landuse in order to help guide policy. Agricultural activities have significant impacts on regional water balances, where conversion of forest to different crops increases runoff. For example, a decision support system such as the "Portal Capixaba de Gestao das Aguas e da Paisagem" (PCGAP) or "Portal for Water and Landuse Management of the Capixaba" can help answer questions such as the impacts of increases in eucalyptus plantations or different agricultural crops on flooding and sediment transfer.

It is the hope that this framework would improve communication and understanding between different local agencies by fully showing the land-atmosphere-and biosphere interactions and offering scientifically based suggestions towards workable policies.