CLIMATE CHANGE IMPACTS ON SURFACE WATER in Central America and Hispaniola
Eric R. Anderson\textsuperscript{1}
Ashutosh Limaye\textsuperscript{2}
Africa I. Flores\textsuperscript{1}
Emil A. Cherrington\textsuperscript{3}

\textsuperscript{1} Department of Atmospheric Sciences, University of Alabama in Huntsville, USA

\textsuperscript{2} Marshall Space Flight Center, National Aeronautics and Space Administration, USA

\textsuperscript{3} Water Center for the Humid Tropics of Latin America and the Caribbean, Panama

May 2011
CLIMATE CHANGE IMPACTS ON SURFACE WATER in Central America and Hispaniola
ABSTRACT

This regional assessment examines the potential impacts of climate change on surface water runoff under a wide range of future precipitation scenarios. Through the employment of a rainfall-runoff model using high resolution interpolated climate change scenarios and a series of data sets on topography, land cover and soil characteristics, this analysis intends to determine changes in the quantity and to a certain extent quality of water in major watersheds from southern Mexico to Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, Panama, Haiti and the Dominican Republic. The results indicate that, despite large disagreement among the various climate models, there is a general trend of drier rainy seasons, resulting in less surface water availability. Erosion analysis identifies upper portions of certain watersheds to be more prone to soil loss and locates watersheds with potentially more turbid waters. Due to the lack of land cover change scenarios available for the region, impacts of changing surface types was not considered, and therefore, results obtained here regarding changes in erosion do not adequately represent any change to be experienced in the future, particularly due to deforestation. While global climate change will likely exacerbate current effects of deforestation and water pollution, measures can be taken on local and regional levels that will not only mitigate climate change but also address more immediate issues such as habitat loss and degrading water quality.
INTRODUCTION

In a region that receives abundant sunlight and rainfall, creating some of the most species-rich habitats in the world, Central American and Caribbean countries are still struggling to provide all of their people with a reliable source of fresh, clean water. On top of this, the Intergovernmental Panel on Climate Change (IPCC) states that “observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems” (2008).

Despite this copious supply of rain water, some populations in Central America are threatened by contaminated freshwater resources or simply do not have adequate access to water, and many Caribbean populations face the challenges that most small islands do in obtaining and retaining freshwater. Environmental and social conditions throughout the region vary greatly, one example being the large contrasts between the Pacific and Caribbean sides of Central America. To start, the majority of the population in Central America is located along or near the Pacific coast (Figure 1).

Figure 1. This map of population density per municipality clearly depicts that the majority of Central America’s population is on the Pacific side of the continental divide. Capital cities have been identified and are among the densest population centers in the region. The small map at the top right shows the same information from a different perspective. Data derived from CIAT et al. (2005) and ORNL (2000).
Due mainly to topography and climate, this is also the drier side of the region in many places. While some areas in the Pacific side may not receive rain for months during the dry season, the Atlantic side receives much more rain overall, to the point that it has inhibited development rates comparable to those on the Pacific side. Most likely due to this abundance of precipitation and lack of infrastructure in Central America and Hispaniola (FAO and NRL 2011), from 80 to 95% of the cropland among Costa Rica, Dominican Republic, El Salvador, Guatemala, Haiti, Honduras, Mexico, Nicaragua and Panama, are rainfed, an indicator of high vulnerability (World Bank 2009). Worldwide, agriculture accounts for roughly 70% of the global water usage, followed by industry and municipal usage at approximately 20% and 10%, respectively (FAO and NRL 2011), and Central American and Caribbean countries generally follow the same pattern (Figure 2).

Perhaps the lack of information on groundwater resources in the region (FAO and NRL 2011) is also an indicator of the huge importance of rain and surface water. Considerate debate can be made on Central America and the Caribbean’s responsibilities in global climate change mitigation, due to their low contribution to greenhouse gas emissions and disproportionately large impacts expected to be felt (Bates et al. 2008). Deforestation—the number one contributor to greenhouse gas emissions in Latin America—has not only implications in terms of climate change but also the more obvious and immediate impacts such as habitat loss (a threat to biodiversity) and soil degradation.

With respect to the general impacts that the IPCC has identified in terms of precipitation change in Central America, a future climate with overall drier conditions, broken up by more intense storm events is expected (Bates et al. 2008). This would undoubtedly increase erosion and potentially impact surface water quality negatively by increasing turbidity and pollutant loads, since higher temperatures would decrease soil moisture, making them more susceptible to erosion. Figure 3 provides an overview of large-scale changes in annual runoff, according to an ensemble, or group of models. Note that the coarseness of this information does not allow for any interpretation of watershed-level impacts in Central America or the Caribbean.

Despite the lack of information on watershed-level impacts of climate change on surface water, previous work has been carried out in the preparation of high resolution interpolated climate projections (Hijmans et al. 2005). One use of this information was the identification of critical areas for biodiversity conservation in Central America, Mexico and the Dominican Republic (Anderson et al. 2008b). This effort laid the groundwork for further applications related to potential impacts of climate change on a regional level, namely those related to the environment and water resources.
OBJECTIVES

The principle objective of this regional assessment is to apply a rainfall-runoff model to quantify the impacts of changing precipitation patterns induced by global climate change on surface runoff at the watershed level in Costa Rica, the Dominican Republic, El Salvador, Guatemala, Honduras and Nicaragua. Additionally, this assessment seeks to gain insight into current erosion patterns and consider what impacts climate change may have on surface water quantity and quality. Given the abundance of global climate models and subsequent large-scale impact assessments, the novelty of this analysis is its attempt to utilize the highest resolution inputs available in order to characterize potential impacts on a much smaller scale. Results are aggregated into commonly known watersheds as well as larger hydrological domains, which also include Belize, Haiti, Panama and southern Mexico for continuity.
METHODS

Using commonly applied equations to measure runoff and erosion, the methodology involved a cell-by-cell analysis of various biophysical factors in the region including topography, land cover, soil characteristics and precipitation. Various inputs were obtained from a number of organizations and initiatives who are acknowledged in this report.

The two main phenomena measured were surface runoff and soil erosion. Runoff, Q, was derived by the following equations (NOAA 2004):

\[ Q = \frac{(P - I_a)^2}{(P - I_a) + S}, \]
\[ I_a = 0.2S, \]
\[ S = \left(\frac{1000}{CN}\right) - 10, \]

Where:
Q = runoff (in)
P = rainfall (in)
S = potential maximum retention after runoff begins (in)
I_a = initial abstraction (in)
CN = runoff curve number

Note: If (P - I_a) = 0, then Q = 0

The rainfall inputs were obtained from WorldClim (Hijmans 2005). The runoff curve numbers were determined by combining ESA’s GlobCover land cover product (Arino et al 2007), redefined to the Coastal Change Analysis Program (C-CAP) classification system (NOAA 2005), with soil hydrological groups (FAO 1998). See Appendix A for details on preparing these inputs.

Erosion, A, was calculated by using a simplified version of the Revised Universal Soil Loss Equation (RUSLE) (Renard et al. 1997):

\[ A = K \times LS \times C \times P \]

Where:
A = average monthly soil loss
K = soil erodibility factor
LS = slope length factor
C = cover management factor
P = rainfall

Unlike most RUSLE calculations, this assessment attempted to estimate monthly erosion using the above equation. The soil erodibility factor, K, was obtained through the same soils data set as above (FAO 1998). The LS factor was derived from hydrological and surface analysis performed on the HydroSHEDS digital elevation model (Lehner et al. 2008), and the cover management factor, C, was obtained from the same land cover data set prepared for the runoff calculations (See Appendix A).

While each of the inputs was prepared in an ESRI ArcGIS Desktop, the actual rainfall-runoff and erosion model calculations were developed in Fortran 95 language and executed in a simple command prompt environment. All inputs above were converted to ASCII files for ingestion into the model. In addition to the Q and A calculated cell-by-cell, an A:Q ratio was also calculated per cell to measure an erosion to surface water runoff ratio. Finally, averaged Q and averaged A values per basin were calculated and documented in a text file. Twelve model runs created the baseline conditions—one for each month. The future conditions included monthly precipitation
generated by three global climate models (GCM): United Kingdom’s Hadley Centre Coupled Model, version 3 (HADCM3), the Canadian Centre for Climate Modelling and Analysis’ Coupled Global Climate Model (CGCM3T47), and Australia’s Commonwealth Scientific and Industrial Research Organisation coupled model (CSIRO Mk3), each GCM running two emissions scenarios: A2 and B2, “business as usual” and a better case scenario, respectively (IPCC 2000). This made a total of 216 future conditions runs. See Appendix B for the complete code.

In order to interpret the results of these model runs, first more generally than all watersheds in the region, the mean Q, A, and A:Q ratios were separated into five broad hydrological domains, derived from the digital elevation model. These domains have been denominated: Pacific slope, Caribbean slope, Usumacinta complex, Southern slope (Hispaniola), Northern slope (Hispaniola), in order to characterize the direction in which surface water flows within a domain (Figure 4).

Figure 4. Five Hydrological Domains for the area of study. These have been defined to characterize the direction in which surface water flows within a domain. For example, any surface water within the Pacific slope will flow towards the Pacific Ocean; the Usumacinta toward the Gulf of Mexico, etc. Note that for Hispaniola, what has been identified here as “Southern slope” is often called “Caribbean slope,” and what has been identified here as “Northern slope” is also referred to as “Atlantic slope.”
Additionally, the results of these model runs were extracted for seven priority watersheds from the large text files generated for each run. These watersheds were identified through a number of consultative processes, usually during training workshops held at CATHALAC (e.g., “Spatial Modeling of Non-point Sources of Pollution and Erosion in the Caribbean,” 2008), and for this study focus on those in CAFTA-DR countries. Many of these are trans-boundary watersheds—those that span two or more countries. Watershed management in these particular basins is particularly important and requires an added amount of attention and international cooperation (Figure 5). See Appendix C for more information about each of these priority watersheds.

Figure 5. The seven selected priority watersheds in CAFTA-DR countries. See Appendix C for more information about each watershed.
RESULTS

The larger Hydrological Domains allow for a more general interpretation of results, at the cost of local variability. This is where the watershed statistics are useful, since they naturally delineate the variables in question; however, any inaccuracies of these high resolution precipitation inputs may be reflected in many of these smaller basins, which in turn is why the larger Hydrological Domains were created.

First, in terms of broader results, Figure 6 and Figure 7 show the baseline annual precipitation per 1 km grid cell and calculated in volume per year. One can see that the larger domains receive greater volumes of rainfall, simply due to their large extent. Conversely, in Figure 6, one can appreciate the heterogeneity of the annual accumulated precipitation, which indicates that this high resolution interpolation has attempted to capture effects from topography.

All of the graphs generated from the results obtained are located in Appendix C. For each priority watershed, monthly Q is shown. Two representative seasonal months are described; in the case of dry season the selected month was March, whereas in the rainy season October was selected.

Each monthly graph contains a comparison of the three global climate models, each run under two emissions scenarios, and models an average runoff, Q, for 2020, 2050 and 2080. Each of the seven priority watershed has a graph for March and October. It is also important to keep in mind that ranges of average monthly runoff vary greatly between the two months. For instances, in some cases, as a result of almost zero precipitation, the average monthly Q for the watershed in question may look like it fluctuates wildly out into the future, but the absolute change is very small. Much higher volumes of runoff are experienced in October in all of the watersheds. In general it can be deduced that the results of the models do not display a trend among each other; however, specific interpretations of each watershed will clarify more about average runoff modeled under different scenarios.

Figure 6. This map depicts the average annual precipitation for the study area, using data from approximately 1950-2000. Data derived from WorldClim (Hijmans et al. 2005)

Figure 7. Given the average annual precipitation and the area of each of the hydrological domains, this figure shows the volume of rain per year for each. Data derived from WorldClim (Hijmans et al. 2005) and HydroSHEDS (Lehner 2008)
Coco watershed In the Coco watershed, the HadCM3, A2 run shows the lowest monthly runoff for March, and in October this same model and scenario represent also some of the lowest values (below the baseline), excepting the HadCM3 B2 run in October in the 2080s. During October, two models show values above the baseline for the 2020s, which differ from the other four, which for the 2020s present runoff volumes below the baseline.

Lempa watershed The Rio Lempa watershed undergoes a drastic change between the dry and wet season, experiencing ten to fifteen times the surface runoff in October, when compared to March. The Canadian models seem to project wetter conditions in this watershed in October, especially towards the 2020s. Besides this, there is a wide range of projections above, below and on par with current surface runoff.

Motagua watershed For the March analysis in the Motagua Watershed, nearly all the projections for 2020, 2050 and 2080 are even with or below the baseline, the lowest monthly average runoff being presented by HadCM3, A2, a characteristically hot, dry model. It seems again that for the 2050s all the models represent a similar value that is closer to the baseline. For the 2080s the models show a variety of values in a wider range. The October graphic shows that the most extreme case was represented by CGCM3T74, B2, one of the wetter models, in the 2020s, where the average monthly runoff reached the highest volume in the entire series of runs.

San Juan watershed In March, nearly all the models show a slight increase in surface runoff, while in October, the majority of the projections are decreasing, most severely the Hadley models. The exceptions to this latter statement are both Canadian models which continue to project a large increase in runoff in October in the 2020s. This is one of the watersheds that undergo a drastic seasonal change in surface runoff, experiencing almost 20 times the runoff in October than in March.

Sixaola watershed In contrast to the San Juan watershed, the Sixaola basin does not undergo a very large seasonal change, due to continuous rains throughout its dry season. This is another case where March projections tend to be increasing, while October projections tend to be decreasing or staying the same. The October graph presents model runs that tend to agree with one another in the nearer future and then begin to diverge greatly towards the 2080s. On the contrary, the March model runs diverge immediately and then converge towards the 2080s, which is unexpected, especially because the Hadley models present unchar-
characteristic wetter conditions (when compared to other parts of the region).

**Usumacinta watershed** In the results generated for March in the largest watershed in this analysis, there is significant variability in all the models for the 2020s, but in the case of the 2050s, all the models return to a similar value, which is very close to the baseline. Nevertheless, for the 2080s projection, the results disagree again significantly at a wide range. For October, dealing with ten times the volume of March, the 2020 projection presents a similar characteristic than that of March, since the future values modeled span from below to above the baseline, but the CGCM3T47 model, B2 scenario is possibly an outlier, showing a very peculiar up-down-up trend, nose-diving toward the 2050s after climbing toward the 2020s. In 2080 CGCM3T47, B2 goes up again.

**Yaque del Sur watershed** Finally, this important Caribbean draining (South) watershed in the Dominican Republic is similar to many other cases in which October runoff is generally decreasing over time, while March is increasing. An important point is that in many of the watersheds, including this one, the October decreases outweigh the March increases, resulting in a net yearly negative change in surface water runoff.

According to the graphics of each watershed, it looks like for the 2020s, the models project disparate values, ranging from above to below the baseline, and then for the 2050s results, many results tend to converge to a runoff volume similar to the baseline. Finally, towards the 2080s, the values among the different models disagree again. Only in the case of the Yaque del Sur watershed do the 2020s projections tend to remain closer to the baseline, and as time passes they tend to diverge in a wider range of runoff values, below and above the baseline, depending of the model-scenario.

**Erosion** Since future land cover information was not available, this was considered to be a constant over time. While unrealistic in the real world, it allows for a clearer analysis of the impacts of changing rainfall patterns independently. Still, A:Q ratios per watershed are displayed in Figure 9 and Figure 10. In both months, greater erosion rates are seen on the Pacific slope, especially in El Salvador and into the

![March Erosion to Runoff ratio per watershed under baseline conditions](image)

**Figure 9. March Erosion to Runoff ratio per watershed under baseline conditions**

![October Erosion to Runoff ratio per watershed under baseline conditions](image)

**Figure 10. October Erosion to Runoff ratio per watershed under baseline conditions**
Gulf of Fonseca. By October, this is magnified, as other watersheds begin to present greater erosion. Haiti stands out against fairly low rates of erosion in the Dominican Republic; however, the Yaque del Sur watershed does have very elevated erosion in the rainy season compared to the rest of the country. Focusing back on Usumacinta, one can appreciate the low relative soil loss in March, but in October, tropical rains appear to have their effect on the large basin. Sixaola does not appear to have such a dichotomous dynamic, maintaining relatively low erosion. Since there is more erosion occurring during the rainy season, a more detailed erosion to runoff ratio is provided in the following page (Figure 14).

Beginning with the Coco watershed, one can appreciate the higher A:Q ratio values in the west, which are the highlands, while the flat, lowlands toward the Caribbean Sea would not be contributing to as much sedimentation in the Coco River and its tributaries. Heavy rains hundreds of kilometers to the west could cause large sediment loads to exit the mouth of this river into the Caribbean Sea, and Figure 14 allows for the identification of those zones that contribute more to the soil loss. There is not as identifiable an upland-lowland trend in the much flatter Usumacinta watershed. This is also reflected in Figure 9 and Figure 10. Regardless, this is a very large watershed and has a great amount of potential sedimentation. The Rio Lempa watershed spans three countries, covering a very large proportion of El Salvador’s territory. The mountain range that separates El Salvador and Honduras has very high erosion to runoff ratio, causing tributaries of the Rio Lempa to carry sediments down from the highlands all the way to the Pacific Ocean.

High erosion-to-runoff ratios are also detectable near Lake Nicaragua in the San Juan watershed. Figure 13 displays impacts of heavy rains in mid to late 2010, which triggered the discharge of tons of sediments into this freshwater system.
October Erosion to Runoff ratio
in priority watersheds Coco, Lempa, Motagua, San Juan, Sixaola, Usumacinta and Yaque del Sur

Figure 14. This Cell-by-cell A:Q ratio identifies high amounts of erosion relative to the volume of runoff per km² ultimately locates sources of sedimentation.
DISCUSSION

Because precipitation was the only test variable, erosion’s response in changes in rainfall was directly proportional to runoff. Nevertheless, a series of maps of the erosion to runoff ratio demonstrate which watersheds and waterways are undergoing sedimentation. Watersheds with current deforestation (CATHALAC-SIMEPAR) will have a higher propensity to erosion and therefore waterways will decline in quality (in terms of clarity). These watersheds are also at a greater risk for decreasing soil productivity.

There are limitations to this type of rainfall-runoff model, and a model can only be as good as its inputs. Precipitation projections vary greatly among the global climate models; Figure 15 shows the range of precipitation values projected across the area of study, highlighting where the greatest disparities lie for March and October in the 2020s. Appendix E also provides graphs of projected precipitation changes for each of the CAFTA-DR capital cities, which demonstrate in yet another manner the disagreement among the models. Uncertainty in the impacts of climate change on surface water is mostly as a result of uncertainties in the projected precipitation, rather than hydrological models (Kaspar 2003). There is yet much to be understood about the global climate system. Regarding the erosion calculations, a simplified version of the commonly used Revised Universal Soil Loss Equation was employed, due to the lack of information on future precipitation intensity, also referred to as the R-factor in the RUSLE methodology (only magnitude was available, in mm). While some global models generate this factor, it appears that efforts have yet to be made in developing higher resolution regional precipitation intensity projections, an important factor in erosion.

Related to rainfall intensity, something else not captured in this model is the general consensus that the IPCC presents in terms of precipitation change, which is a future climate with overall drier conditions, broken up by more intense storm events. This would undoubtedly increase erosion, since higher temperatures would decrease soil moisture, making them more susceptible to erosion (Bates et al. 2008). Today’s rates of soil loss and sedimentation typically induced by poor land use are already alarming, and if this were coupled with larger scale changes in climate, serious actions in soil conservation would be in order.

While interpreting the runoff volumes for each basin, the “middle ground” or average result should not be confused as a scenario more likely to occur. Rather, each result provides a possible characteristic of runoff, assuming the global climate change models and their downscaling are reliable, which is not always the case.

Figure 15. This series of maps shows the range between the six model runs for precipitation in October. From top to bottom: 2020s, 2050s, 2080s; the darker the color, the more disagreement there is among the models in that specific location.
CONCLUSIONS AND RECOMMENDATIONS

On the whole, this assessment considered a range of future climate scenarios, in which precipitation changes affect surface runoff. Due to the lack of agreement among the models, it is impossible to conclude from this analysis probable changes in surface runoff at the watershed scale. This could be remedied by the further development of high resolution climate projections, in order to have a wide array of inputs, rather than just six per time-frame, which could be constructed into an ensemble. Still, the scenarios presented here are useful in that they provide a range of possible futures, albeit a wide one.

Regardless of global climate change due to anthropogenic greenhouse gas emissions, it has been observed in numerous cases that local land use changes have a significant impact on the regional climate, particularly affecting mountains upwind from deforested areas (Nair et al. 2000; Fairman et al. 2011). Also, documented cases show that forests can regulate flow throughout the year, reducing peak flows during storms and allowing for greater flows during the dry seasons (Jones and Grant, 1996). An obvious understanding and application of this theory is demonstrated in Panama Canal Watershed (CICH 2011).

While this regional assessment considered the impacts of changing rainfall patterns on surface water quantity and quality, land cover change must also be incorporated into these scenarios. It is possible that global changes in temperature and precipitation change dominant vegetation in many tropical ecosystems (Cherrington et al. 2011), thereby affecting their rates of rainwater infiltration and runoff. Other more abrupt changes to the land include deforestation, particularly expansion of the agricultural frontier and growth of populated places. This conversion will have a much more direct impact on rainwater infiltration rates (and groundwater recharge), surface runoff and erosion. Greater expanses of impermeable surfaces (e.g., concrete, asphalt) can lead to more flooding and soil loss (Carter 2006). Despite this looming threat of land use change and the fact that deforestation is Latin America’s number one contributor to global climate change, no concerted effort has been made to develop regional land cover change scenarios. While a few do exist, they are either global and too coarse (Alcamo et al. 2008) or only cover a small area (Burke and Sugg 2006), which are not adequate for such watershed-based water quality and quantity projections. Fires also induce greater soil loss, since they remove
vegetation and degrade soils, making them more susceptible to erosion. On a more immediate time-frame, caution should be taken if heavy rains follow fires on steep slopes, since they can even provoke landslides (Cannon 2008).

Remote sensing can be useful in quantifying land cover and land cover change over space and time, but such images and derived products cannot explain the drivers of those changes; they therefore have very limited utility in projecting future land cover / land use. In order to better project surface water quality and quantity in Mesoamerica and the Caribbean, it is recommended that a series of national workshops be held in which land use planners, natural resource managers, demographers or social scientists, ecologists, geographers and GIS practitioners, discuss trends and drivers for historic and current land cover change. Subsequently, different scenarios of population growth, natural resource use, conservation strategies, and drivers behind each of these, should be developed by the group in order to build a sufficient knowledge base upon which future land cover / land use maps may be created. Once land cover projections are created, further studies on future erosion and sedimentation would be possible, providing a much more comprehensive outlook on future surface water quality. Additionally, these land cover projections could be fed into mesoscale climate models in order to understand impacts of land use change on regional climate.

While current rates of deforestation and population growth are contemporary threats to water resources, according to climate projections, this situation is likely to be exacerbated by a changing climate. In the case of Central America and the Caribbean, overall drier conditions may speed up ongoing desertification and land degradation, even changing the ecosystem types which compose the region. The plainest response is to reconsider water consumption habits on agricultural, industrial and municipal levels. Understanding possible future precipitation regimes and the broader climate allows for an appreciation of steps and preparations that should be taken, in light of increasing water stress and scarcity. Even though climate change is perceived as a global phenomenon, many types of climate change mitigation strategies, such as reducing deforestation and conserving water resources, stem from the local level and have more immediate, local impacts, thereby dampening any potential impacts brought about by global climate change.
ACKNOWLEDGEMENTS

This regional assessment was only made possible through the contributions of a number of professionals and institutions and was conducted as one of the components of the project entitled, “Enhancing National Capacities in Disaster Management and Environmental Monitoring in Mesoamerica and the Dominican Republic through Application of the Regional Visualization & Monitoring System (SERVIR).” Implemented by the Water Center for the Humid Tropics of Latin America and the Caribbean, this regional assessment was funded by the United States Agency for International Development (USAID) and overseen by the U.S. National Aeronautics and Space Administration (NASA). In addition to the staff at CATHALAC and NASA-MSFC who contributed to this study, additional thanks go to Daniel Irwin, NASA SERVIR Project Director for his constant encouragement and enthusiasm, to Sundar Christopher, Chair of the Atmospheric Sciences Department at UAHuntsville, for his vision in applied earth systems sciences, and to Tom Sever, Professor at the University of Alabama in Huntsville for his inspiring and enlightening talks on threats to water. This project’s implementation began at CATHALAC in Panama, then received support from NASA-MSFC, and was completed at the National Space Science and Technology Center at UAHuntsville. During the initial phases in Panama, several international workshops related to climate change and water were held, and specifically to thank are the enthusiastic and inquisitive students with diverse perspectives from the “Spatial Modeling of Non-point Sources of Pollution and Erosion in the Caribbean,” held in February of 2008 and “Modelación de la contaminación por fuentes difusas y dinámica de sedimentos aplicando SIG” held in October the same year.

This study would not have been possible without the wealth of publicly accessible environmental data sets from a variety of sources mentioned previously.
REFERENCES


APPENDIX A

Runoff and erosion calculation input preparation
Mapping CN (curve numbers) and C (cover factors), utilizing C-CAP and soil hydrological groups

<table>
<thead>
<tr>
<th>C-CAP Value</th>
<th>C-CAP Class</th>
<th>Group A</th>
<th>Group B</th>
<th>Group C</th>
<th>Group D</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>High-Intensity Developed</td>
<td>89</td>
<td>92</td>
<td>94</td>
<td>95</td>
<td>0.000</td>
</tr>
<tr>
<td>3</td>
<td>Low-Intensity Developed</td>
<td>61</td>
<td>75</td>
<td>83</td>
<td>87</td>
<td>0.030</td>
</tr>
<tr>
<td>4</td>
<td>Cultivated Land</td>
<td>67</td>
<td>78</td>
<td>85</td>
<td>89</td>
<td>0.240</td>
</tr>
<tr>
<td>5</td>
<td>Grassland</td>
<td>39</td>
<td>61</td>
<td>74</td>
<td>80</td>
<td>0.050</td>
</tr>
<tr>
<td>6</td>
<td>Deciduous Forest</td>
<td>30</td>
<td>55</td>
<td>70</td>
<td>77</td>
<td>0.009</td>
</tr>
<tr>
<td>7</td>
<td>Evergreen Forest</td>
<td>30</td>
<td>55</td>
<td>70</td>
<td>77</td>
<td>0.004</td>
</tr>
<tr>
<td>8</td>
<td>Mixed Forest</td>
<td>30</td>
<td>55</td>
<td>70</td>
<td>77</td>
<td>0.007</td>
</tr>
<tr>
<td>9</td>
<td>Scrub/Shrub</td>
<td>30</td>
<td>48</td>
<td>65</td>
<td>73</td>
<td>0.014</td>
</tr>
<tr>
<td>10</td>
<td>Palustrine Forested Wetland</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.003</td>
</tr>
<tr>
<td>11</td>
<td>Palustrine Scrub/Shrub Wetland</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>12</td>
<td>Palustrine Emergent Wetland</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>13</td>
<td>Estuarine Forested Wetland</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.003</td>
</tr>
<tr>
<td>14</td>
<td>Estuarine Scrub/Shrub Wetland</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>15</td>
<td>Estuarine Emergent Wetland</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>16</td>
<td>Unconsolidated Shore</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.500</td>
</tr>
<tr>
<td>17</td>
<td>Bare Land</td>
<td>77</td>
<td>86</td>
<td>91</td>
<td>94</td>
<td>0.700</td>
</tr>
<tr>
<td>18</td>
<td>Water</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>19</td>
<td>Palustrine Aquatic Bed</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.000</td>
</tr>
<tr>
<td>20</td>
<td>Estuarine Aquatic Bed</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Source: USDA-NRCS, 1986
APPENDIX B

Fortran 95 code used to calculate Q, A, A:Q ratio and basic statistics per basin
Required inputs in “curve_inputs” directory: LCClass.txt, landcover.asc, soils.asc, [precipitation_file].asc, k_factor.asc, ls_grid.asc, and basins.asc

```fortran
character :: al*20,b*80,fname*80,KFile*80,LSFile*80,WatershedIDfile*80,LCFile*80,OutFile*80,comma*1
real, allocatable :: Q(:,:), Rain(:,:), CN(:,:), K(:,:), LS(:,:), C(:,:), A(:,:)
real, allocatable :: AvgQ(:,), MaxQ(:,), AvgA(:,), MaxA(:,), AQRatio(:,:)
integer, allocatable :: Soil(:,:), LC(:,:), WSID(:,:), iWSSize(:,:)
integer, parameter :: k11=1,k22=2
real P, CN2, Ia, S
real*4 tarray(2), ttotal
logical :: FE

if(iargc().ne.2)then
    write(*,*)'2 Arguments needed. Provided ',iargc()
    write(*,*),'Syntax: CN_Grids_v2.exe PrecipFile LandCoverFile'
    stop
endif

call getarg(k11,fname)
call getarg(k22,LCFile)

fname='annual_prec.asc'
KFile='k_factor.asc'
LSFile='ls_grid.asc'
comma=',
WatershedIDfile='basins.asc'

LCFile='landcover.asc'
OutFile=trim(fname(:len(trim(fname))-4))//'_'//trim(LCFile(:len(trim(LCFile))-4))//'.asc'
inquire(file='curve_inputs\LCClass.txt',exist=FE)
if(FE.eq. F)then
    write(*,*)'Trouble opening landcover file'
    stop
endif

! Open LC Class file, read Curve numbers for each soil type
! Read the LC, soil and rain file
!
open(1,file='curve_inputs\LCClass.txt',status='old')
open(2,file='curve_inputs\'+trim(LCFile),status='old')
open(3,file='curve_inputs\soils.asc',status='old')
open(4,file='curve_inputs\'+trim(fname),status='old')
open(5,file='curve_inputs\Q_'//trim(OutFile),status='unknown')
open(6,file='curve_inputs\'+trim(KFile),status='old')
open(7,file='curve_inputs\'+trim(LSFile),status='old')
open(9,file='curve_inputs\'+trim(WatershedIDfile),status='old')
```

Climate Change Impacts on Surface Water in Central America and Hispaniola

```
open(10,file='curve_inputs\WS_AvgMax_Q&A_'//trim(OutFile(:len(trim(OutFile))-4))//'.txt',status='unknown')
open(11,file='curve_inputs\A_'//trim(OutFile),status='unknown')
open(12,file='curve_inputs\A_Q_Ratio'//trim(OutFile),status='unknown')

read(1,*)a1
! allocate array memory
allocate(CN(100,4),C(100))

! read the data and assign to the CN matrix
do 1 i=1,1000
   read(1,*,end=1)ix1,iclass,ix2,CNA,CNB,CNC,CND,C1
   CN(iclass,1)=CNA*100
   CN(iclass,2)=CNB*100
   CN(iclass,3)=CNC*100
   CN(iclass,4)=CND*100
   C(iclass)=C1
1 continue

read(2,*)a1,ncols
read(2,*)a1,nrows
rewind(2)
allocate(Soil(nrows,ncols),LC(nrows,ncols),Q(nrows,ncols),Rain(nrows,ncols),AQRatio(nrows,ncols))
allocate(K(nrows,ncols),LS(nrows,ncols),A(nrows,ncols),WSID(nrows,ncols))

! For each grid cell, read the LC, soil and rainfall data
do irow=1,nrows
   read(2,*)(LC(irow,j),j=1,ncols)
   read(3,*)(Soil(irow,j),j=1,ncols)
   read(4,*)(Rain(irow,j),j=1,ncols)
   read(6,*)(K(irow,j),j=1,ncols)
   read(7,*)(LS(irow,j),j=1,ncols)
   read(9,*)(WSID(irow,j),j=1,ncols)
   do icol=i,ncols
```

if(WSID(irow,icol).ge.0)WSID(irow,icol)=WSID(irow,icol)+1

enddo
endo
totall=dtime(tarray)
imaxID=0
do 2 i=1,nrows
do 2 j=1,ncols
    if(WSID(i,j).gt.imaxID)imaxID=WSID(i,j)
2 continue
allocate(AvgQ(imaxID), MaxQ(imaxID), AvgA(imaxID), MaxA(imaxID), iWSSize(imaxID))

! Calculate Q based on data for each pixel

do irow=1,nrows
    ! write(*,*)irow

do icol=1,ncols
    CN2=0.
    C2=0.
    if(LC(irow,icol).gt.0.and.Soil(irow,icol).gt.0) then
        CN2=CN(LC(irow,icol),Soil(irow,icol))
        C2 = C(LC(irow,icol))
    endif
    P=Rain(irow,icol)
    ! calculate Q only for CN > 0, non water pixels
    if(CN2.gt.0) then
        S=(1000/CN2) - 10.
        Ia=0.2*S
        Q(irow,icol)=(P-Ia)**2/((P-Ia) + S)
        ! if the rainfall is less than initial abstraction, set Q to zero
        if((P-Ia).le.0) Q(irow,icol)=0.
    ! Compute the erosion
    A(irow,icol)=K(irow,icol)*C2*LS(irow,icol)*P

    ! Compute AQ ratio
    AQRatio(irow,icol)=A(irow,icol)/Q(irow,icol)

    ! attach the Q and A values to the avg and max stats
    if(Q(irow,icol).ge.0.and.A(irow,icol).ge.0)then
        AvgQ(WSID(irow,icol))= AvgQ(WSID(irow,icol))+Q(irow,icol)
        if(Q(irow,icol).gt.MaxQ(WSID(irow,icol)))MaxQ(WSID(irow,icol))=Q(irow,icol)
        AvgA(WSID(irow,icol))= AvgA(WSID(irow,icol))+A(irow,icol)
        if(A(irow,icol).gt.MaxA(WSID(irow,icol)))MaxA(WSID(irow,icol))=A(irow,icol)
        iWSSize(WSID(irow,icol))=iWSSize(WSID(irow,icol))+1
    endif
! endif for CN>0
endif

! enddo for icol loop
enddo

! write the Q data out to ascii file
write(5,'(10000(f7.3,1x))') (Q(irow,icol),icol=1,ncols)
write(11,'(10000(f7.3,1x))') (A(irow,icol),icol=1,ncols)
write(12,'(10000(f7.3,1x))') (AQRatio(irow,icol),icol=1,ncols)

! enddo for irow loop
enddo

write(10,*)'WatershedID, AverageQ, MaxQ, AverageA, MaxA'
do i=1,iMaxID
   if(iWSSize(i).gt.0)then
      AvgQ(i)=AvgQ(i)/iWSSize(i)
      AvgA(i)=AvgA(i)/iWSSize(i)
      write(10,'(i7.7,a1,f12.2,a1,f12.2,a1,f12.2)')
i,comma,AvgQ(i),comma,MaxQ(i),&
      comma,AvgA(i),comma,MaxA(i)
   endif
enddo

ttotal = etime(tarray)
write(*,'(a19,f5.2,a4)')'Total time spent = ',ttotal,' sec'
write(*,*)' of which ',total1,' seconds spent on I/O'
end
### APPENDIX C

#### Selected priority watersheds

<table>
<thead>
<tr>
<th>HydroSHEDS Basin ID</th>
<th>Name</th>
<th>Countries</th>
<th>Area</th>
<th>Baseline volume precipitation/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>46660</td>
<td>Usumacinta</td>
<td>Guatemala, Mexico, Belize</td>
<td>123,566 km²</td>
<td>356 km³/yr</td>
</tr>
<tr>
<td>49783</td>
<td>Yaque del Sur</td>
<td>Dominican Republic</td>
<td>5,201 km²</td>
<td>6.53 km³/yr</td>
</tr>
<tr>
<td>59101</td>
<td>Motagua</td>
<td>Guatemala, Honduras</td>
<td>16,372 km²</td>
<td>39.5 km³/yr</td>
</tr>
<tr>
<td>60156</td>
<td>Coco</td>
<td>Honduras, Nicaragua</td>
<td>24,563 km²</td>
<td>61.9 km³/yr</td>
</tr>
<tr>
<td>61541</td>
<td>Lempa</td>
<td>El Salvador, Honduras, Guatemala</td>
<td>18,042 km²</td>
<td>52.5 km³/yr</td>
</tr>
<tr>
<td>63729</td>
<td>San Juan</td>
<td>Nicaragua, Costa Rica</td>
<td>41,228 km²</td>
<td>117 km³/yr</td>
</tr>
<tr>
<td>65048</td>
<td>Sixaola</td>
<td>Costa Rica, Panama</td>
<td>2,845 km²</td>
<td>8.36 km³/yr</td>
</tr>
</tbody>
</table>
APPENDIX E

Monthly precipitation anomalies according to the models considered in this study (reproduced from Anderson et al. 2008a).

In order to present the wide range of precipitation projections, precipitation anomalies are presented based on data provided by WorldClim (Hijmans et al. 2005) for capital cities. These graphics demonstrate the similarities and differences among different climate change scenarios and global climate models for one particular point in each CAFTA-DR country.

It is worth noting that given the emission scenarios supplied by the IPCC, the temperature is almost always projected to be lower in the B2 scenario than in the A2 scenario. In terms of temperature, there is not high variation or disagreement among the models, but precipitation is much more difficult to model than temperature. The different models begin to deviate from each other further into the future. Precipitation projections range greatly, both in the next decade as well as in the furthest projections. While one general trend evident in the Mesoamerican analyses performed here is the commonly projected drying of the wet season, there are not enough sample points in the Caribbean to make such a generalization.

The six lines represent the A2 and B2 scenario runs from the United Kingdom’s Hadley Centre Coupled Model, version 3 (HADCM3), the Canadian Centre for Climate Modelling and Analysis’ Coupled Global Climate Model (CGCM3T47), and Australia’s Commonwealth Scientific and Industrial Research Organisation coupled model (CSIRO Mk3).
Precipitation Anomalies in Santo Domingo, Dominican Republic

- HadCM3, A2
- HadCM3, B2
- CSIRO Mk3, A2
- CSIRO Mk3, B2
- CGCM3T47, A2
- CGCM3T47, B2

Precipitation Anomalies in San Salvador, El Salvador

- HadCM3, A2
- HadCM3, B2
- CSIRO Mk3, A2
- CSIRO Mk3, B2
- CGCM3T47, A2
- CGCM3T47, B2
Precipitation Anomalies in Guatemala City, Guatemala

Precipitation Anomalies in Tegucigalpa, Honduras
Precipitation Anomalies in Managua, Nicaragua

Reproduced from Anderson et al. 2008a