IMPACT ANALYSIS OF CHANGING RIVERINE FLOOD FREQUENCIES CAUSED BY CLIMATE CHANGE ON TRANSPORTATION INFRASTRUCTURE AND LAND USE —A CASE STUDY OF PENSACOLA, FLORIDA

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
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To my loving grandparents

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The National Research Council recently announced that climate change would greatly affect the performance of transportation and urban infrastructures. More frequent precipitations and storms will significantly increase the frequency and magnitude of flooding, which in turn threatens the reliability of urban infrastructures. With intent to help decision makers better understand the impacts of increasing precipitation and consider adaptation strategies, this study develops a methodology using historical rainfall and discharge records to estimate the area and frequency of future riverine flood. Pensacola in Florida is used as a case study. Unlike previous impact studies, which are often general and qualitative, this paper explores the possibility to use downscaled global climate model output (in forms of daily rainfall realizations) to conduct quantitative impact analysis that could assist transportation and land use planning practice at the local level. Areas and infrastructures within projected floodplain are identified, showing that in Pensacola single family developments are most

vulnerable to the increase of precipitation compared with other land use types. Future flood exceedance probability is calculated and compared, indicating that new design and planning standards should be developed, adapting to the future increase of precipitation. The estimated flood map could be used as a guide for land use planning, and the calculated frequency increase could help to adjust the drainage design frequency standard. The multidisciplinary methodology in this study could be applied to other MPOs and region, providing a procedure for using hydrological data to estimate the impacts of changing precipitation on urban infrastructure.

CHAPTER 1
INTRODUCTION

Recent studies and reports conclude that climate change is an undeniable challenge for the current transportation system (National Research Council, 2008; Meyer, 2008; Committee on Climate Change, 2008). According to the Transportation Research Board Special Report 290 (National Research Council, 2008), changes in precipitation, sea level, storms and heat waves will have significant impacts on the performance of the transportation and urban system. As a result, it is especially important that climate change should be taken into consideration in the long-range transportation and land use planning process (National Research Council, 2008; ICF, 2008).

Among the five types of climate extremes (i.e. very hot days and heat waves, increases in Arctic temperatures, rising sea levels, intense precipitation, and extreme hurricanes) through which climate change will have primary effects on transportation (National Research Council, 2008), precipitation change will have much broader impacts than the others on transportation and other infrastructure systems. It is highly likely (with probability of greater than 90%) that most of the United States will suffer more intense and frequent precipitation events, which have an average annual increase rate of 6.1 percent per century with regional variations (National Research Council, 2008; IPCC, 2007; Environmental Protection Agency). Changing precipitation levels could challenge the transportation system through increases in flooding levels and the moisture levels in soils, which will affect the stability of pavement subgrades, foundations, and drainage designs (National Research Council, 2008; Meyer, 2008). The National Research Council (2008) uses the Great Flood of 1993, which occurred in the Mississippi and Missouri River system, to illustrate the potential impacts of such increase. During this event, a catastrophic flood caused disruptions to the surface transportation system within 500 miles of the river system, affecting rail, truck, and marine traffic (National Research Council, 2008). However, regardless of the potential severity of this challenge, research questions such as the extent to what the changing precipitation would affect the magnitude and frequency of riverine flooding and, the surrounding development and transportation infrastructure remain unexplored at the moment, due to the lack of climate projections and future flooding predictions at the local level.

In order to answer these research questions and help transportation planners better adapt to potential precipitation change, this thesis provides an impact assessment of the changing riverine flood frequencies caused by climate change on transportation infrastructure and land use, using Pensacola, Florida, as a case study. Unlike previous, qualitative assessment, this paper focuses on detailed, quantitative analysis at the local level with the intent to help local practitioners adapt to climate change. The paper proposes an innovative methodology through which the global climate change forecasting results could be converted to flood projection at the local level. In the research process, first, the current flood frequency information is extended regionally to estimate flood frequencies at any unmonitored locations of interest in the basin. Then, using historic daily rainfall and flood data, the antecedent precipitation conditions which would likely give rise to flood events are established. Based on the extracted relationship and realization of daily rainfalls under future climate change scenario, and the impacts of future flooding on transportation and land use in the study area is finally estimated. Due to the lack of daily rainfall realization at the local level, historical rainfall records in other geographical area is used as the proxy of a future scenario. In this study the historical rainfall pattern in Upper Shillong, India is selected as the proxy for future simulation in the study area, as its annual rainfall is similar to the projected future annual rainfall in the study area. This is explained in detail later.

This paper includes five parts. The first part (Introduction) briefly explains the reasons for conducting this study. The second part (Literature Review) introduces background research, as well as summarizing what has been done and need to be done in regards to assessing the impact of changing precipitation caused by climate change on transportation and land use infrastructure. The third part (Data and Methodology) introduces the data selection, analysis scenarios, methodologies and analysis procedures. Basic assumptions of the analysis are also encapsulated in this section. The fourth part (Results) summarizes the increase of floodplain, inundation area by different land use type, and critical transportation infrastructures at risk. The final section (Conclusions and Discussions) illustrates how the methodology and results can help local decision makers make decisions to protect crucial infrastructures and development against changing precipitation and shed a light on what needs to be done in the future.

CHAPTER 2
LITERATURE REVIEW

Debate regarding the inevitability of climate change has raised concerns in society as to the potential impacts of climate change. Even if the greenhouse gas (GHG) emissions do not increase further, the accumulation of GHG emissions over past centuries is enough to cause climate changes that will quite likely increase both the frequency and intensity of extreme weathers in the near future (National Research Council, 2008; Environmental Protection Agency, 2005). Consequently, it is important to understand how changing climate variables interact with the current transportation system, so as to minimize the potential negative impacts of climate change in the long range transportation planning process.

Warm temperatures, temperature extremes, heavy precipitation, sea level rise, and more intense tropical storms have been identified as several important factors through which climate change will challenge the transportation system (National Research Council, 2008). While warm temperatures and temperature extreme would challenge the material of our infrastructure, the sea level rise, precipitation and more intense storms will impose more threats on how we plan and maintain our network with the increase of flood risk (Maantay and Maroko, 2009; Zimmerman, 2001). However, flood risk is not given proper attention in either the transportation or land use planning process or previous climate change impact assessment studies, in part because of the difficulties of collecting sufficient, accurate data across disciplines to produce flood prediction and impact assessments at the local level.

Considering the complexity of flood generation process, studies in this paper will be narrowed down to discuss the impacts of riverine flood generated by intense precipitation on transportation and land use planning only. Even estimating the impacts of changing precipitation on transportation infrastructure and land use requires intensive interdisciplinary cooperation among planners, transportation engineers, geographers, and climatologists. Specifically, in the cooperation process, the following research questions need to be answered:

1. How does traditional transportation land use planning incorporate flood information? Are the existing tools capable to provide guidance for future flood prediction/modeling?

2. What are the state-of-the-art methods in estimating the impact of climate change? What are implications for practitioners? What are the existing research gaps?

3. Regarding precipitation, what is the state-of-the-art methodology for future prediction? How could we use the results of precipitation prediction to estimate the change of riverine discharge? How could we predict the spatial (location and area) and temporal change (flood frequency) of flood plain based on the change of riverine discharge?

4. What are the implications of these changes to transportation and land use planning?

The remaining of this chapter provides a literature review trying to answer questions one, two and three, which constitute the foundation on which the research method in chapter three is developed. Chapter three provides a detailed description of the methods and data used to overcome these research gaps, and the remaining chapters will throw some lights on question four specifically for the study area.

2.1 Traditional Flood Prevention in Transportation Planning and Engineering

Flood protection was traditionally viewed as an engineering task through the design of flood defense systems with a specific exceedance probability (probability of at least one exceedance per year) (Apel et al., 2004; Buchele et al., 2006). For instance, the frequency, intensity, and duration of extreme precipitation of different return periods have been used by civil engineers to design transportation infrastructures (National

Research Council, 2008). The Project Development and Design Manual proposed by the United States Department of Transportation (U.S. Department of Transportation, 2008) provides detailed standards, criteria and recommended methods of dealing with hydrology-related issues in highway and bridge design. There are also specific requirements regarding roadway hydraulics in respect to the culverts, ditches, pavement drainage, storm drains, energy dissipaters, and alternative pipe materials (U.S. Department of Transportation, 2008). However, these standards are based solely on a number of assumption, statistical stationarity and historical records of flood magnitude and runoff. If the meteorological (e.g. intensity and frequency of precipitation), hydrological (e.g. river profile), socio-economic (e.g. agriculture activity) conditions change, the runoff and the magnitude of the flood will change correspondingly, impairing the effectiveness of these standards. Consequently, more comprehensive design procedures have been proposed (Apel et al., 2004).

Extending the flood protection to planning, Flood Insurance Rate Maps (FIRM), are used as the guideline for land use and transportation planning. Hazard zones are identified in FIRM, and developments in these areas are restricted. However, traditional planning does not place strong emphasis on flood protection (Zimmerman, 2001). The FIRMs are widely criticized as being outdated, inaccurate, underestimating both the size and the depth of the flood (Burby, 2001). Additionally, many infrastructures are located within low-lying areas that are vulnerable to flood even without climate change to pursue operational benefits at the sacrifice of increasing flood risk (Zimmerman, 2001). This situation puts a large amount of infrastructure at high risk considering the increase of frequency and magnitude of flood caused by climate change (Jacob et al., 2001).

In the past decades, with increased attention in flood protection, risk-based design has been identified as a complete approach to deal with flooding, taking both the probability of the flooding and the consequences of flooding into consideration (Apel et al., 2004). Usually, all flooding scenarios with associated probabilities and potential damages will be considered in the risk assessment, and a flood risk curve would be generated as the final product, demonstrating the distribution of flood damage in the study area within acceptable uncertainty boundaries (Apel et al., 2004). The parameters and techniques considered in risk assessment have been categorized into four types, namely meteorological (e.g. rainfall, temperature), hydrological (e.g. river runoff), socio-economic (e.g. land use change), and a combination of the three (Ologunorisa and Abawua, 2005). Using different parameters, researchers have explored different causality and consequences of flood risk. For example, Single et al. (1990, cited by Ologunorisa and Abawua, 2005) use the total summer rainfall as an indicator to explore the relationship between flood/drought and the amount of regional rainfall. Apel et al. (2004) develop a flood risk model to explore the probabilities of occurrence for flood events with different magnitudes and economic damages, using historical gauged hydrological data and stochastic modeling method. Their model take hydrological load, flood routing, levee failure and outflow, and damage estimation into account in the process (Apel, 2004). Buchele et al. (2006) incorporated risk assessment in their regionalization model to study flood with return period of 200 to 10000 years at small ungauged basin. However, these figures themselves are the indicators of the low confidence of these estimations, especially considering their usefulness in planning area.

Both traditional planning and engineering approach and risk assessment suffer some limitations when applied to studies regarding climate change. Generally, most of these studies use the extreme value distribution of discharge as their start point, and only a few consider the effect of rainfall runoff. The lack of consideration for the causality relationship between rainfall and flood limits their ability to incorporate the change precipitation trend in the model process. Furthermore, considering it is difficult to get the probability of each climate change scenarios (especially at the downscaled regional level), it is hard to incorporate the risk assessment techniques in climate change impact assessment. In recent years, many studies have been conducted to assess the impact of climate change on transportation infrastructures and land use, with the intent to provide decision makers with information to adapt to climate change. Most of these studies use scenario based methods rather than risk based methods, due to the aforementioned difficulties.

2.2 Climate Change Impact Assessment and Research Gaps

Recently many studies estimated the impacts of climate change on transportation infrastructure and land use, and draw valuable conclusions with respect to riverine flooding, storm, and sea level rise's influence on transportation (Suarez et al., 2005; ICF International, 2007; U.S. Climate Change Science Program, 2008; Peterson et al., 2008; Jacob et al., 2007; Burkett, 2002; Titus, 2002; James et al., 2009). However, in spite of these studies that focus on estimating climate change's impacts on transportation system, research in this area is still at an early stage. Most of these studies focus on large scale, qualitative level analysis (ICF International, 2007; U.S. Climate Change Science Program, 2008; Peterson et al., 2008; Jacob et al., 2007). In another word, those quantitative studies are not specific or accurate enough to assist local practitioners to develop local adaptation strategies to climate change (U.S. Climate Change Science Program, 2008; Suarez et al., 2005). Detailed impact assessments of climate change on transportation and land use infrastructures are needed at the local level.

The impact of precipitation varies at difference scales of study. From planning perspective, most of the research was focused on national scale and regional scale assessment, while from the engineering perspective the focus needs to be at local scale analysis. Koetse and Rietveld (2009) summarize existing transportation engineering research directions in estimating the impact of increased precipitation on transportation. Their review demonstrates that most of the existing studies focus on operation aspects, trying to analyze the impacts of precipitation on trip production, mode choice, and accident rate. There is a requirement for intermediate level research, which could provide local planners and project managers with estimation of the direct impact of increasing precipitation on infrastructure disruption.

The biggest challenge in estimating the impact of climate change on land use and transportation infrastructure, especially in term of changing precipitation, is the lack of accurate flooding prediction at the local level. Local flood prediction requires both rainfall projections and the extraction of the regional relationship between flooding and precipitation at the local level. Both of these conditions are currently lacking. As a result, two research gaps must be overcome. First, the regional association between flooding and precipitation needs to be extracted from empirical data. Second, local rainfall simulations rather than global average projections should be used. Most previous studies use global average projections, rather than local projection to conduct impact assessment (Jerry et al., 2000; National Research Council, 2008; Peterson et al., 2008). While the global average projection delivers a simple and general idea about climate change, it does not provide an accurate depiction of climate change at the local level, considering the differences in terrain, land use, coastal erosion, local subsidence and other factors. In order to bridge these two research gaps, the next section will provide a review of the existing data and methods regarding precipitation prediction and flood estimation.

2.3 Precipitation Prediction and Flood Estimation

Flood generation is a complicated process, involving the interactions among meteorological, hydrological, and socio-economic factors (Ologunorisa and Abawua, 2005). Specifically, Durotoye (2000, cited by Ologunorisa and Abawua, 2005) elaborates that river peak discharge, heavy rainfall peaks, stream channel change, and tidal flooding are four major factors that cause inundation in deltaic plains. Furthermore, study shows that there is a positive coincidence between the changes of the frequency, magnitude, duration of heavy rainfall and the change of the frequency of extreme floods (McEwen, 1999 cited by Ologunorisa and Abawua, 2005), which indicate that the change in precipitation will definitely influence the magnitude and recurrence probability of flood events.

According to Fowler and Hennessy (1995), it is widely acknowledged that climate change will substantially change the frequency and magnitude of extreme daily precipitation. Milly et al. (2002) further extend this conclusion to the substantial increase of the frequency of large floods in the twentieth century. All of these studies demonstrate that precipitation is a factor that could not be overlooked in the flood estimation process.

There are a number of models and GIS techniques regarding flood estimation, but only a few take rainfall-runoff simulations into account. Buchele et al. (2006) constructs a model with consideration for the effect of precipitation and compared that with detailed rainfall-runoff simulation. However, the limitation of their research is that their regression model uses mean annual precipitation depth, which is not a good indicator to reflect the change of the frequency of precipitation, while the rainfall-runoff simulation uses intensive historical data and computation capabilities. Other models considering rainfall simulation use precipitation forecasting rather than prediction with a focus on real time or near term forecasting (e.g. within 30 days), which is not suitable for long term planning activities (Todini, 1999; Frei et al., 2000). Consequently, there is a demand for studies to bridge the gaps between the large scale, qualitative analysis and real time simulations.

Global climate models could provide a general simulation of precipitation frequency distribution changes (Simonovic et al., 2003). General circulation models (GCMs) such as Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) four-atmosphere-layer GCM (CSIRO4), nine-atmosphere-layer GCM (CSIRO9), and the United kingdom Meteorological Office high-resolution GCM (UKHI), could provide decades of daily precipitation data of each of the greenhouse gas emission conditions (Fowler and Hennessy, 1995). The simulation results are generally consistent, indicating that the change of precipitation is more significant in frequency and intensity than in total amount (Fowler and Hennessy, 1995). Researchers have interpreted the significance of these results in return periods to generate implications for flood planning (Fowler and Hennessy, 1995). However, because GCMs use coarse grids, this limits the application of the model results to large scale flood protection system (Simonovic et al., 2003).

Currently, the production of downscaled simulation data is in progress. For example, California Reanalysis Downscaling at 10 km (CaRD10) has been produced to produce hourly, 10-km resolution downscaled analysis for California to support regional-scale climate change applications (Kanamitsu and Kanamaru, 2007). In Southeastern United States, dynamical downscaling results at 20km resolution has been compared with the coarse resolution (2.5° latitude/longitude) large-scale atmospheric variables from the National Center for Environmental Prediction (NCEP)/DOE reanalysis (R2) for 16 summer seasons (1990-2005), indicating a better prediction over shorter time scales (Lim et al., 2010). Although the downscaled modeling results for the study area are not available at present, it is said that downscaled 10km gridded rainfall for Southeast U.S. reanalysis will be available within several months.

This study is designed with the intent to incorporate both the downscaled climate projection results and regional hydrological parameters (e.g. lag times, stream channel, etc.) in the flood impact assessment. To achieve this objective, the following steps are taken in the flood prediction process:

1. Estimation of current discharge and rainfall data. Daily discharge and rainfall data are recorded at specific stations, therefore spatial interpolation is needed to estimate discharge and rainfall at other locations of potential interest.

2. Establish the relationship between rainfall pattern and riverine discharge values, which require an estimation of regional hydrologic lag time,

3. Based on precipitation simulation, estimate the magnitude of future extreme precipitation with a certain return period, and

4. Delineate a hydrological data inventory (including e.g. river bank, stream line, land use, river cross section…) so as to convert the discharge value into flooding map in GIS software.

Specifically, this study uses regional empirical data to 1)estimate flood frequency at ungauged locations in the study area, 2)extracting the lag time between precipitation events and discharge fluctuation and 3)establishing antecedent precipitation conditions which would likely give rise to flood events. Estimates as to the change of future flood frequency based on this antecedent precipitation condition and daily rainfall realizations are made, and finally analyzed with respect to corresponding transportation and land use impacts.

CHAPTER 3
DATA AND METHODOLOGY

Pensacola (Figure 3-1), the seat of Escambia County, Florida is selected as a case study, as it has experienced rapid population growth, intensive coastal development and exposure to heavy precipitation events. In addition, all major hydrological networks in Escambia County are natural flows without artificial intervention, minimizing the external control over riverine floods.

Figure 3-1. City of Pensacola

As mentioned above, current climate change projections can provide daily simulations for future rainfall patterns. In order to estimate the flood frequency characteristics in Pensacola, the relationship between rainfall and riverine discharge must first be estimated. Then, realizations of future daily rainfalls may be passed through this relationship to empirically derive future flood frequencies. This paper uses rainfall data, discharge data, hydrological characteristics, and Geographical Information System (GIS) analysis to establish those relationships for the Escambia River System.

The results are put into hydrology models to delineate floodplain and to estimate future flood impact on transportation and land use. There are three major parts in the research process, namely flood prediction, terrain data processing (flood map generation), and transportation and land use impact analysis (Figure 3-2, below). The following paragraphs provide a detailed description of the data and methodology used in each part.

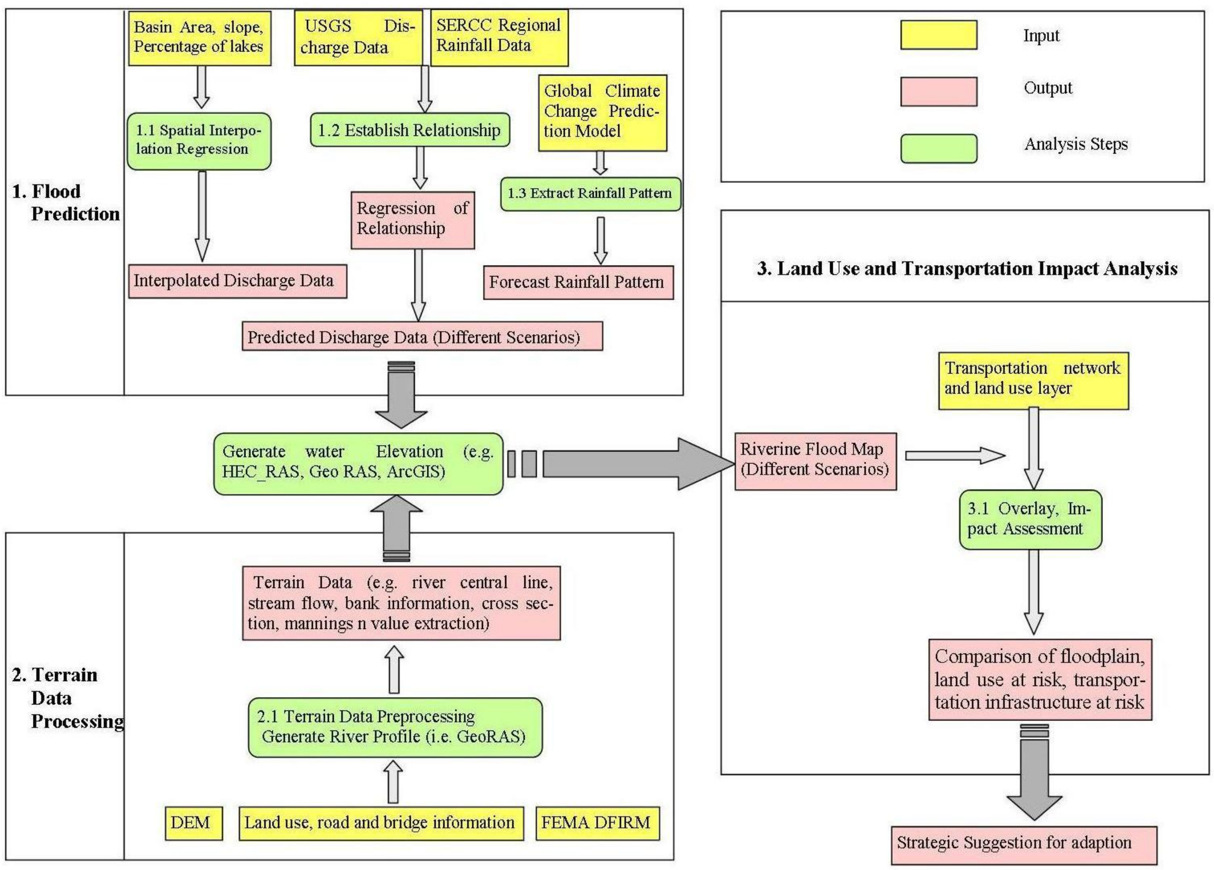


Figure 3-2. Overall research framework

3.1 Flood Prediction

This section uses the historical discharge data and observed rainfall data to establish the relationship between rainfall data and flood discharge records in the Escambia River Basin. Using the established relationship, the most likely future discharge pattern is predicted based on future rainfall projections. Daily discharge data and daily rainfall data are obtained from U.S. Geological Survey (USGS) and the Southeast Regional Climate Center. These include 10 discharge stations with more than 30 years records, and 55 rainfall stations within the basin area.

3.1.1 Spatial Interpolation Regression

In Escambia County there are only six gauge stations with discharge records. The small sample size makes it difficult to interpolate discharge values at the points of interest in study area. This paper uses the regression provided by National Streamflow Statistics (NSS), which is developed by USGS, to estimate the current discharge values at ungauged points in our study area (see Figure 3-2, below). The estimation is specifically for Northwest Florida region.

$$Q2 = 58.9 DA^{0,824} SL^{0.387} (LK+3)^{-0.785}$$

$$Q5 = 117 DA^{0,844} SL^{0.482} (LK+3)^{-1.06}$$

$$Q10 = 164 DA^{0,860} SL^{0.534} (LK+3)^{-1.21}$$

$$Q25 = 234 DA^{0,882} SL^{0.586} (LK+3)^{-1.37}$$

$$Q50 = 291 DA^{0,900} SL^{0.626} (LK+3)^{-1.48}$$

$$Q100 = 351 DA^{0,918} SL^{0.658} (LK+3)^{-1.58}$$

$$Q500 = 507 DA^{0,960} SL^{0.725} (LK+3)^{-1.79} \tag{3-1}$$

where QT is the discharge value for a recurrence interval of T-years in cubic feet per second, DA is the contributing drainage area in square miles, and LK is the percent lakes and ponds (Bridges, 1982).

Using these equations, the current discharge values with different return periods are calculated for our study area, specifically Site A and Site B (Figure 3-3). The results are provided in Table 3-1.

Figure 3-3. Ungauged points within the study area.

Table 3-1. Current discharge with different return periods in the study area

Return Period (Years)	Site A Discharge (cubic feet per second)	Standard Error (%)	Equivalent Years	Site B Discharge (cubic feet per second)	Standard Error (%)	Equivalent Years
2	502	44	3	813	44	3
5	998	46	4	1630	46	4
10	1420	49	5	2340	49	5
25	2050	55	6	3440	55	6
50	2630	59	6	4450	59	6
100	3230	65	6	5520	65	6
200	3890	70	6	6740	70	6
500	4890	77	6	8580	77	6

3.1.2 Establish the Relationship between Antecedent Precipitation and Floods

Within the region, flood sizes are strongly controlled by the amount of precipitation during certain preceding period. That period and the nature of the relationship need to be determined. Historic daily rainfall records from Southeast Regional Climate Center and discharge values from USGS within the Escambia river system are first obtained to estimate the length of that significant preceding period. Table 3-2 provides the location information of the eight discharge stations with more than 30 years records and associated rainfall records (within Escambia River Basin). Dates and magnitudes of the ten largest annual floods observed in each of eight streamflow records in the region are then extracted. Next, partial sums of weighted basin inputs up to 14 days prior to the peak flow are computed and correlated to peak discharge. Plots of correlation versus length of partial sum indicate that ten days prior is sufficient regardless the size of basin area (Table 3-3, for detail please refer to Appendix B). The weight of each rainfall station is determined by the size of the Thiessen Polygon.

Table 3-2. Location of the discharge stations used in the study

Name	Longitude	Latitude
Escambia River near Century	-87.2342	30.965
Escambia River near Molino	-87.2667	30.66806
Big Coldwater Creek	-86.9722	30.70833
Murder Creek near Evergreen AL	-86.9867	31.41833
Perdido River at Barrineau Park	-87.4403	30.69028
Shoal River near Mossy Head	-86.3069	30.79583
Shoal River near Crestview, FL	-86.5708	30.69722
Yellow River at Milligan, FL	-86.6292	30.75278

Table 3-3. Preceding period with maximum correlation between accumulated rainfall amount and discharge values

Name and size of the basin area	Critical time (days)
Shoal River near Mossy Head, FL (basin: 122 sq miles)	3
Murder Creek near Evergreen AL (basin: 176 sq miles)	6
Big Coldwater Creek (basin: 237 sq miles)	4
Perdido River at Barrineau park (basin: 378 sq miles)	3
Shoal River near Crestview, FL (basin: 468 sq miles)	1
Yellow River at Milligan, FL (basin: 635 sq miles)	4
Escambia River near Century (basin: 3825 sq miles)	4
Escambia River near Molino (basin: 4139 sq miles)	10

The discharge value is assumed to be primarily influenced by the magnitude of the rain within the influential period (10 days in Escambia Basin Area) and the size of the basin area. As a result, for each of the eight streamflow stations with discharge records in Escambia River Basin, the 10 largest floods at each station is converted to a standardized measure of runoff by dividing discharge values by basin area to get units of specific discharge (cfs/sq miles) to discover the relationship among discharge, rainfall, and the size of basin area. The runoff is then plotted against the rainfall total of preceding 10 days (Figure 3-4). The plot reveals that the relationships between standard runoff and the amount of 10 days accumulated rainfall are generally linear. Therefore, by forcing the intercept to be zero to simplify the model, the slopes and R-squared of the linear regression model for each of the basin area are calculated (Table 3-4). Finally, logarithm model are used to regress the relationship among discharge values, 10 days accumulated rainfall and the size of the basin area.

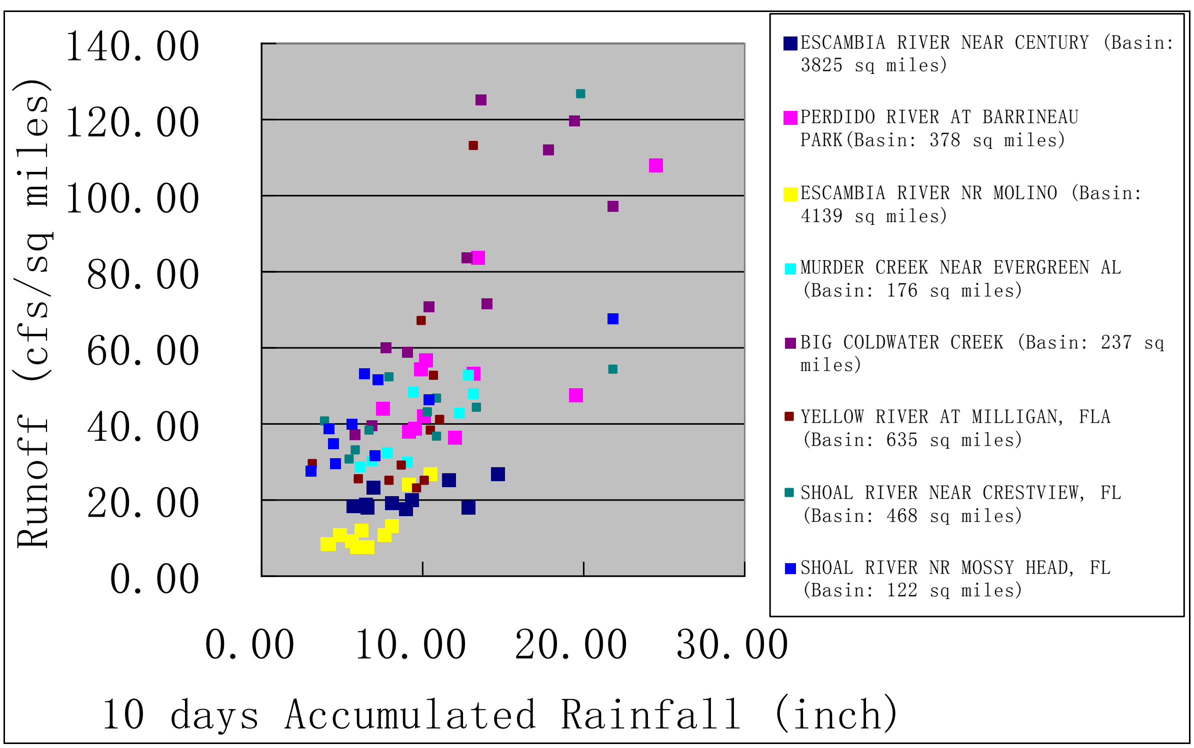


Figure 3-4. Relationship between standard runoff and 10 days accumulated rainfall

Table 3-4. Linear regression model parameters for each basin

Name of the Basin	Linear Regression slope (intercept=0)	R-squared	basin area (sq miles)	log(Basin Area)
Escambia River near Century	2.11	0.94	3825	3.58
Perdido River at Barrineau Park	4.19	0.93	378	2.58
Escambia River near Molino	1.97	0.93	4139	3.62
Murder Creek near Evergreen AL	3.98	0.98	176	2.25
Big Coldwater Creek	6.08	0.96	237	2.37
Yellow River at Milligan	4.7	0.82	635	2.8
Shoal River near Crestview	4.28	0.86	468	2.67
Shoal River near Mossy Head	4.43	0.84	122	2.09

Regression yields functions that permit the establishment of an anticipated peak discharge in response to antecedent precipitation totals.

The regression result is as below.

$Discharge = AR * (9.212 - 1.911 \log(Area)) * BasinArea$, correspondingly

$$AR = Discharge / BasinArea / (9.212 - 1.911 \log(Area)) \quad (3\text{-}2)$$

Where AR is the ten-days accumulated rainfall in inches, discharge is the peak daily discharge in cubic feet per second, and area is the size of the basin area in square miles. The R-square of the regression is 0.660, standard error is 0.852.

Using this equation and the calculated current discharge values, the ten-days accumulated rainfall that will give rise to 50- and 100-year flood estimates at Basins A and B are estimated (Table 3-5). According to the results generated through this process, 34.30 inches ten-days accumulated rainfall will be enough to generate 50 year return period flood at Basin A, while 34.49 inches ten-days accumulated rainfall will be enough to generate 50 year return period flood at Basin B.

3.1.3 Extract Future Rainfall Pattern

The third step is to extract future extreme distribution of ten-days accumulated rainfall using future daily rainfall simulation. Currently, the down-scaling of global climate projection is still under the process, and no future daily rainfall simulation is available in our study area. To overcome this difficulty, historic precipitation series from other climate regions are used as the proxy for future rainfall simulation in study area. According to global projections, the precipitation of Gulf area will increase by 20%-30% by 2060 (U.S. Climate Change Science Program, 2008; Louisiana Coastal Wetlands Planning, 2003). As a result, the selected region should have at least 20%-30% more precipitation than that of the current Pensacola. The average annual rainfall values are calculated for stations in 2005 Global Historical Climatology Network (GHCN) database and compared. Finally, historic daily records in Upper Shillong in India, which has about 35% more annual rainfall than Pensacola, are selected as the proxy of future simulation for Pensacola.

Table 3-5. Estimated rainfall sufficient to generate floods with varying return periods

Site	50-year Flood		100-year Flood	
	Discharge (cfs)	Rainfall (inches)	Discharge (cfs)	Rainfall (inches)
Site A	2630	34.30	3230	42.12
Site B	4450	34.79	5520	43.16

To extract the rainfall pattern in Upper Shillong, historical daily rainfall record from the 2005 Global Historical Climatology Network (GHCN) database are used to generate the ten-days accumulated rainfall series. Then, after extracting the annual maximum ten-days accumulated rainfall, generalized extreme value distribution is used to calculate the maximum annual ten-days accumulated rainfall with different return period:

$$F(x) = EXP(\frac{-\{1-k(x-\varepsilon)\}}{a})^{\frac{1}{k}} \tag{3-3}$$

Where $k = 0.04887$, $\varepsilon = 144.29$ and $\alpha = 392.78$. The Chi-Squared statistic is 3.9063.

The recorded historic annual maximum 10-days accumulated precipitation data can be seen in Figure 3-5. Figure 3-6 illustrates the generalized extreme value distribution of the annual maximum ten-day accumulated precipitation in Upper Shillong.

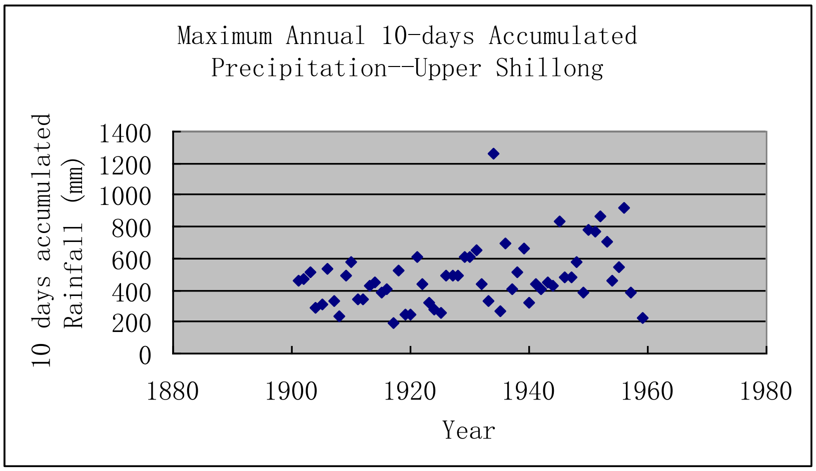


Figure 3-5. Annual maximum ten-day accumulated precipitation—Upper Shillong

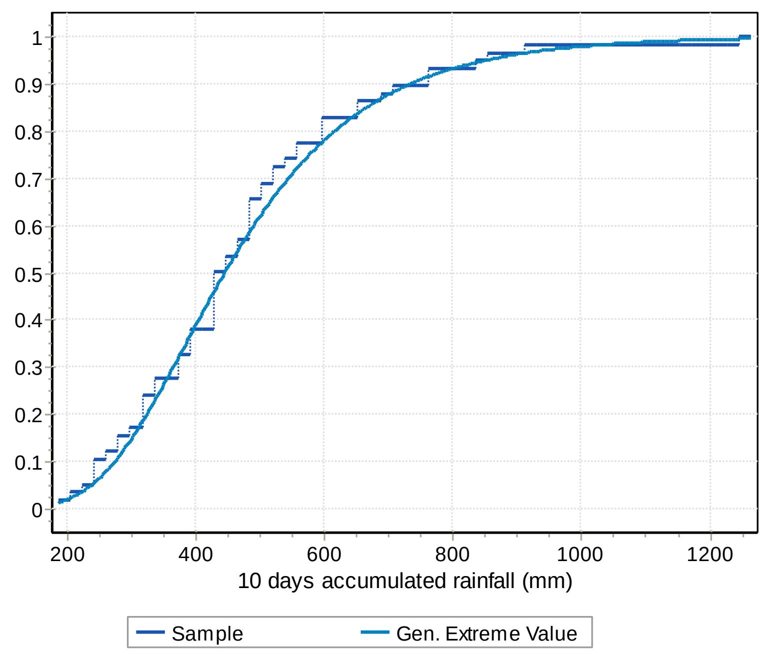


Figure 3-6. Generalized value extreme distribution of ten-day accumulated rainfall in Upper Shillong

According to the General Extreme Value distribution, the accumulated ten-days annual maximum rainfall with 50 year return period is 41.35 inch (1013.08 mm), and the accumulated ten-days annual maximum rainfall with 100 year return period is 46.41 inch (1137.05mm). Using equation (2), the future discharge value at Site A and B can then be calculated (Table 3-6). Figure 3-7 shows the change between current discharge values and future discharge values at Basins A and B, which indicating an increase of magnitude of floods with the same recurrent possibility, or in another word, the increase of recurrent possibility of floods with the same level of magnitude.

Table 3-6. Future rainfall and discharge values with different return periods

Site	50-year Flood		100-year Flood	
	Discharge (cfs)	Rainfall (inches)	Discharge (cfs)	Rainfall (inches)
Site A	3171	41.35	3559	46.41
Site B	5288	41.35	5935	46.41

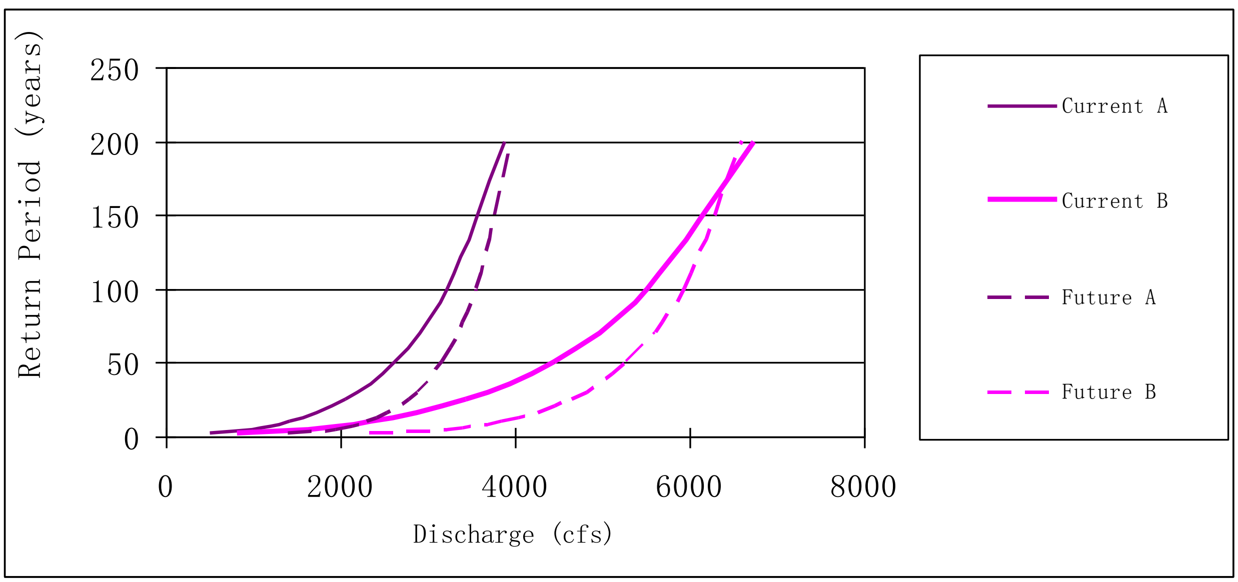


Figure 3-7. Change of discharge at study area

3.2 Terrain Data Processing (Flood Map Generation)

In this step, the results from Step One, together with land use data, terrain data, river profiles, and road and bridge information are inputs to hydrology software, so that flood maps under different scenarios can be delineated. In the study, Digital Flood Insurance Rate Map (DFIRM) from Federal Emergency Management Agency (FEMA) Map Service Center is used to extract the river profile for the study area in ArcGIS and HEC-GeoRAS. The profile includes river central line, stream flow lines, and bank information. Digital Elevation Model data from USGS are used to extract 0.3m Triangular Irregular Network (TIN), which generates cross section information. Land use data (2004) from the Florida Geographical Data Library (FGDL) is used to assign the Mannings N (roughness) values for each cross section. HEC-RAS software is used to conduct steady flow analysis, which produces results that could be converted to flood map in ArcGIS (Figure 3-8, 3-9 and Figure 3-10, 3-11), where the light blue boundary represents the increase of future flood.

3.3 Impact Assessment

Finally, using spatial analysis in ArcGIS, an assessment of the change in floodplain area identifies transportation infrastructure at risk, and estimates the vulnerability of different land use types in respect to the increase of precipitation in the study area. The transit route data are obtained from Florida Transit Information System for the year 2008. The land Use data is 2004 land use and land cover data from FDGL, developed by Florida Department of Environmental Protection’s Bureau of Watershed Restoration. The highway data comes from Florida Department of Transportation Roads Characteristics inventory (RCI) dataset, including major roads in 2009 version. The impact assessment includes two perspectives, spatial and temporal. From the spatial perspective, the impact assessment focuses on the number of infrastructures and the amount of land will be inundated directly, while from the temporal perspective, the impact assessment focus on estimating the future flood frequency and comparing that with the existing design standards. The results are provided in the following chapter.

Figure 3-8. Current and future 50 year return period flood maps

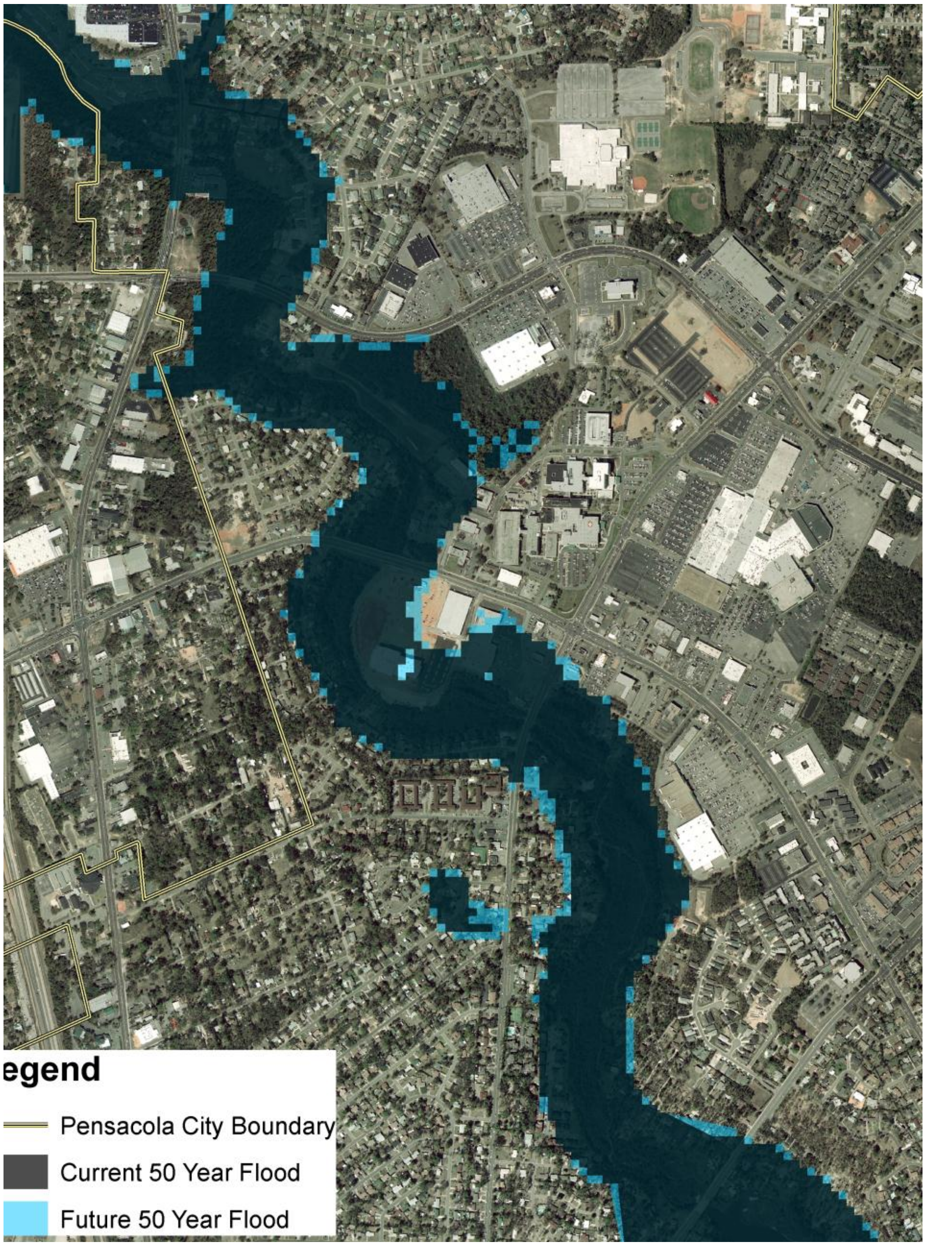


Figure 3-9. Current and future 50 year return period flood maps (small scale)

Figure 3-10. Current and future 100 year return period flood maps

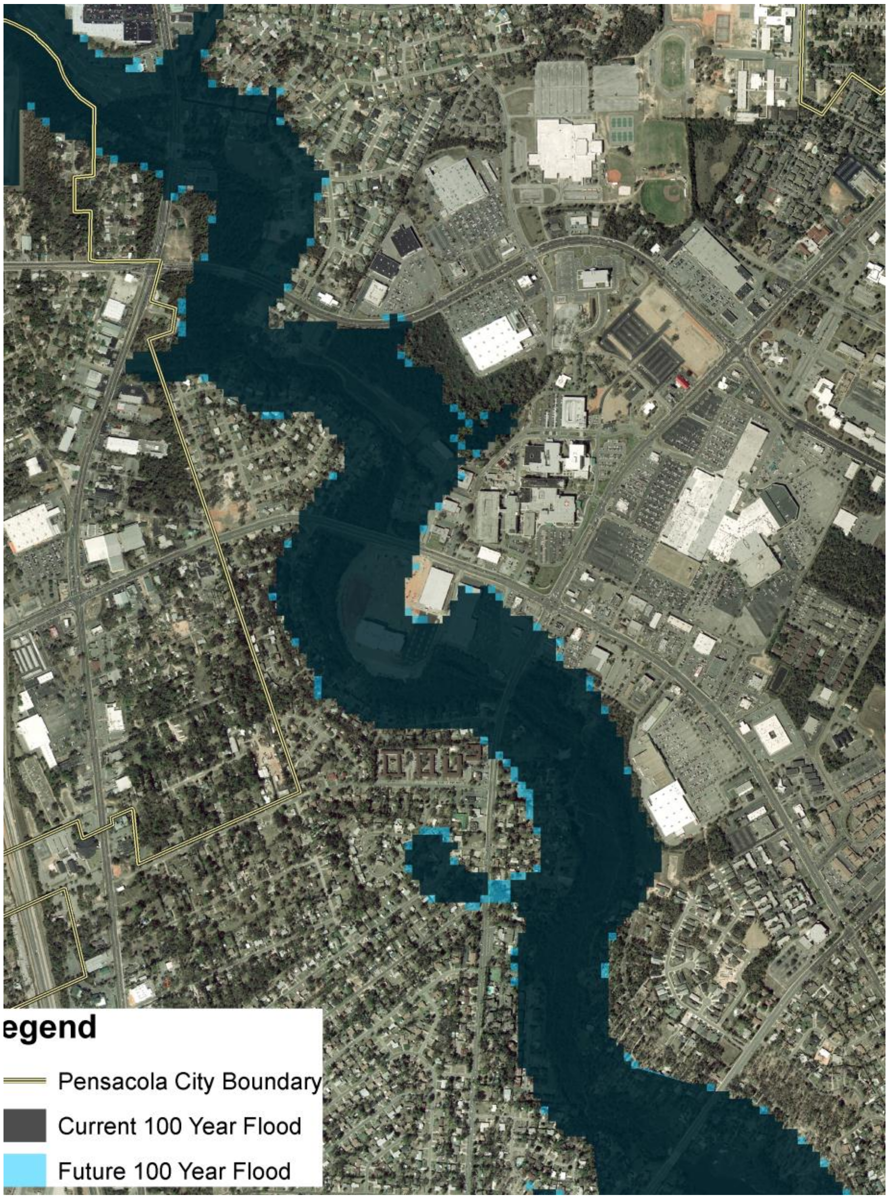


Figure 3-11. Current and future 100 year return period flood maps (small scale)

CHAPTER 4
RESULTS

4.1 Impact Assessment

The increase of precipitation in the study area will increase the size of the floodplain, thereby putting increasing numbers of transportation and urban infrastructure at greater risk. This section provides a detailed impact assessment by quantifying the increase of floodplain, estimating different land use at risk, identifying transportation infrastructures that are most vulnerable to flood increases.

First, an increase in the frequency and magnitude of precipitation will directly increase the size of the floodplain. Table 4-1 and Figure 4-1 show that in the study area, the size of 50-year floodplain will increase by five percent from 2.25 square miles to 2.37 square miles, and the size of 100-year floodplain will increase by 2.89 percent from 2.42 square miles to 2.49 square miles.

Table 4-1. Floodplain increases

	Total Flood Area (Square Miles)		Percentage of Increase
	Current	Future	
50 year flood	2.25	2.37	5%
100 year flood	2.42	2.49	2.89%

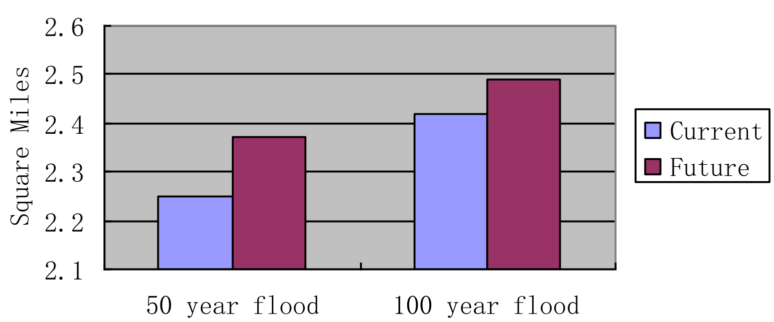


Figure 4-1. Change of flood area

Second, the increase of precipitation will put more urban land (Level 1 land use description, based on Florida Department of Transportation classification schema) at risk. Figures 4-2 and 4-3 show the varying land use types vulnerable to 50- and 100-year floods, respectively. Results indicate that urban and built-up environments are most susceptible to floods caused by increases in precipitation, as compared to other land use types.

Third, the increase of precipitation will also affect transportation infrastructure (e.g. highway and transit), increasing the failure possibilities of transportation infrastructure. Table 4-2 summarizes the number of transportation infrastructures vulnerable (direct intersect with floodplain) to flooding in the study area. Because the location of most infrastructures happens not to be in the flood zone, the number of vulnerable transportation infrastructure is not as much affected by future 100 year flood as the land inundation.

Table 4-2. Transportation infrastructures at risk

	Major Highway			Major Roads					Affected Bus Routes
	Sum	Interstate	Other Urban Arterial	Sum	Roadway	Urban Collector	Urban Local	Urban Minor Arterial	
Current 50y flood	3	2	1	19	5	4	2	8	5
Future 50y flood	3	2	1	21	5	6	2	8	5
Current 100y flood	4	2	2	21	5	6	2	8	5
Future 100y flood	4	2	2	21	5	6	2	8	5

4.2 Implications to Urban Planning and Transportation Engineering

The results of this study provide valuable implications for the development of climate change adaptation strategies in Pensacola. As Figure 4-2 and Figure 4-3 indicates, urban and built-up environment will be affected most by the floods caused by increasing precipitation. Within the urban and built up land use category, single family dwelling units would be the most vulnerable sector to an increase in flooding in terms of having the largest amount of area at risk (Table 4-3). As a result, in order to reduce the cost of maintenance and protection in future, adaptation strategies should focus on restricting single family residential development within the projected floodplain, and reallocating the current residential development in the following decades.

Table 4-3. Inundation land By different land use types (urban and built-up)

Land Use Types (Urban and Built-up)	Area (Acres) Current 50y Flood	Future 50y Flood	Current 100y Flood	Future 100y Flood
Commercial and Services	40.45	46.29	49.59	55.82
Extractive	22.68	23.00	23.00	23.00
Fixed Single Family Units	468.23	520.78	538.22	569.46
Inactive Land with Street Pattern without Structures	11.22	12.58	13.00	13.61
Institutional	28.99	31.81	31.94	33.27
Marinas and Fish Camps	2.23	2.23	2.23	2.23
Multiple Dwelling Units, Low Rise	25.04	26.27	27.02	28.26
Residential Mixed Units	7.00	7.08	7.25	7.25
Undeveloped Land within Urban Areas	0.07	0.07	0.25	0.25

Second, the results of the study demonstrate that current design standards are not sufficient to prepare transportation infrastructures for future extreme events. Currently, according to the Project Development and Design Manual proposed by United States Department of Transportation (U.S. Department of Transportation, 2008), most transportation infrastructures within the study area are designed to convey runoff of existing 50 year return period or 25-year return period flood. However, for the same magnitude of flood, the return period will be become short in future. Table 4-4 shows that the current 50-year return period flood will become an 18 year return period flood for Basin A and 20 year return period flood for Basin B, while the current 100-year return period flood will become 56 return period flood for basin A and 64 return period flood for Basin B. Therefore, an update of design specifications should be developed in the near future.

Table 4-4. Projected flood return periods

Site	50-year Flood				100-year Flood			
	Rainfall inch	mm	Future Cumulative Probability	Future Return Period	Rainfall inch	mm	Future Cumulative Probability	Future Return Period
Site A	34.30	840.35	0.9458	18	42.12	1031.94	0.9820	56
Site B	34.79	852.36	0.9495	20	43.16	1057.42	0.9844	64

The most important impact of flood caused by increased precipitation will be on cross section and drainage designs (Meyer, 2008). For example, in order to accommodate the increase of flooding, the slope of paved surface may need to be changed higher in order to remove water to the side of the road as soon as possible (Meyer, 2008). In addition, drainage systems, open channels, pipes and culverts should be adjusted to provide larger capacity system for the increase of water discharge at the given design frequency. The parameters of the design standards are determined by the selected design frequency, which are usually defined in drainage manual. For instance, in the Florida Department of Transportation’s drainage manual, the design frequency of cross drain hydraulics, including culverts, bridge-culverts, and bridges, for mainline interstate and high use culverts are 50 years return period (Florida Department of Transportation, 2010). The selection of the design frequency is determined based on the consideration of damage to property, structure and roadway, traffic interruption, hazard to human life and damage to stream and floodplain environment (Virginia Department of Transportation, 2002). Therefore, in order to keep the risk of route interruptions at the current level, the design frequency should be increased to accommodate the increase of precipitation. To determine how to increase the design frequency in our study area, probability distributions are used to fit the current discharges at Site A and Site B (Figure 4-4, 4-5). Johnson Sb distribution (Equation 4-1) best fits the trend of current discharge at Site A, with $\gamma = 2.2928$, $\delta = 0.808$, $\lambda = 6043.4$, $\xi = 340.28$. The Kolmogorov-Smirnov Test statistic is 0.3, and P value is 0.39012. The Inverse Gaussian distribution (Equation 4-2) best fits the current discharge trend at site B, with $\lambda = 2758.9, \mu = 1481.4$, $\gamma = 0$. The Kolmogorov-Smirnov Test statistic is 0.292, and P value is 0.42008. Using these distributions, the equivalent current frequencies of future 50-year return period floods and 100-year return period floods are calculated (Table 4-5). The results indicate that to keep the damage the same as the current 50 year return period flood level, the design frequency in Basin A should be raised to 70 years, and to 85 years in Basin B. To keep the damage equivalent to the current 100 year return period flood level, the design frequency should be raised to 120 years in Basin A, and 145 years in Basin B.

$$F(x) = \phi(\gamma + \delta \ln(\frac{z}{1-z})), \quad z = \frac{x-\xi}{\lambda} \tag{4-1}$$

$$F(x) = \phi(\sqrt{\frac{\lambda}{x-\gamma}}(\frac{x-\gamma}{\mu} - 1)) + \phi(-\sqrt{\frac{\lambda}{x-\gamma}}(\frac{x-\gamma}{\mu} + 1)) \exp(2\lambda / \mu) \tag{4-2}$$

Table 4-5. Increase of flood design frequency

Site	Future 50-year Flood			Future 100-year Flood		
	Discharge	Current Cumulative Probability	Current Return Period	Discharge	Current Cumulative Probability	Current Return Period
A	3171	0.985752	70	3559	0.991766	120
B	5288	0.98827	85	5935	0.99311	145

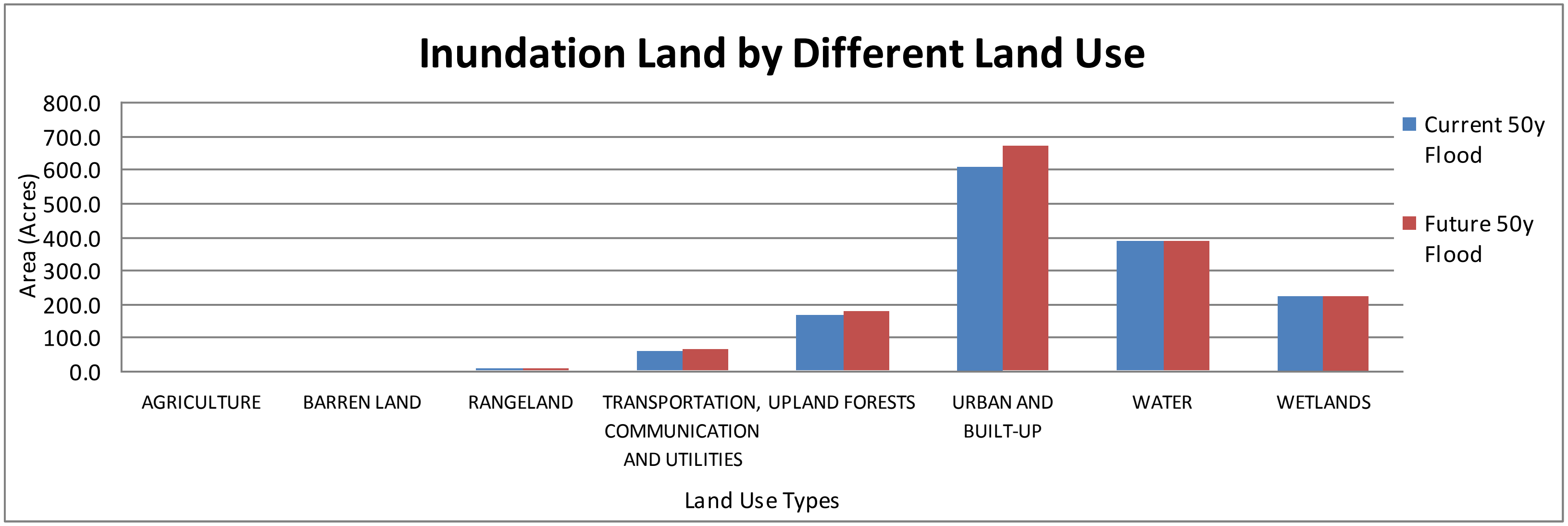


Figure 4-2. Inundation land by different land use type (50-year flood)

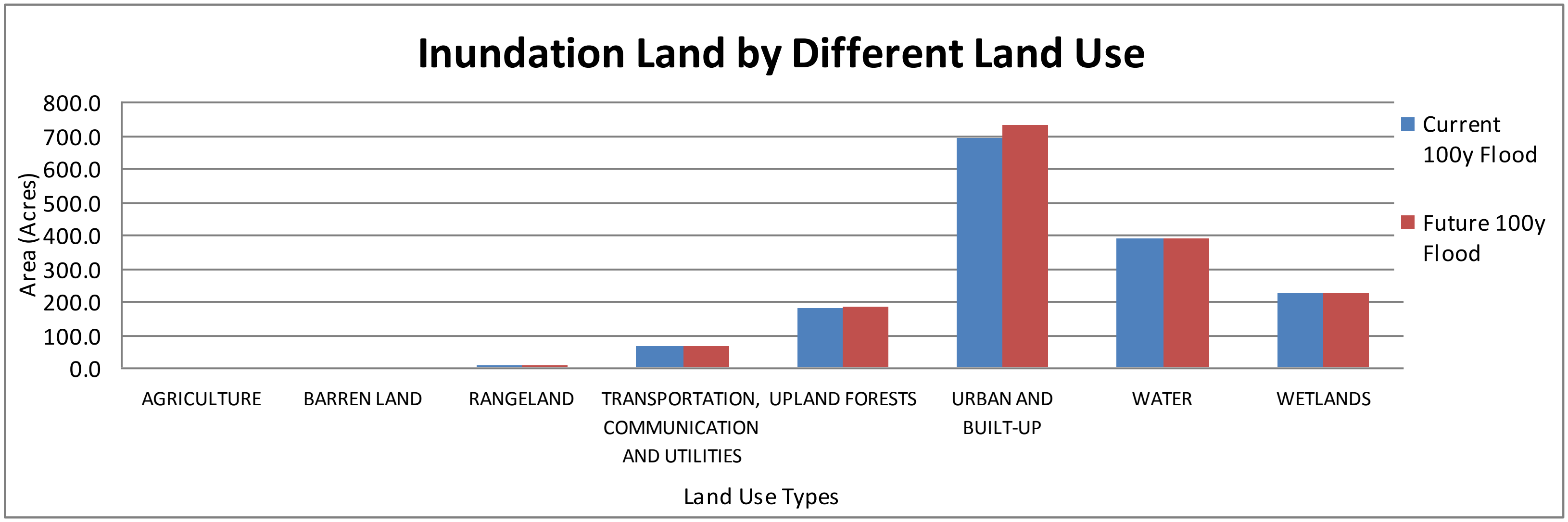


Figure 4-3. Inundation land by different land use type (100-year flood)

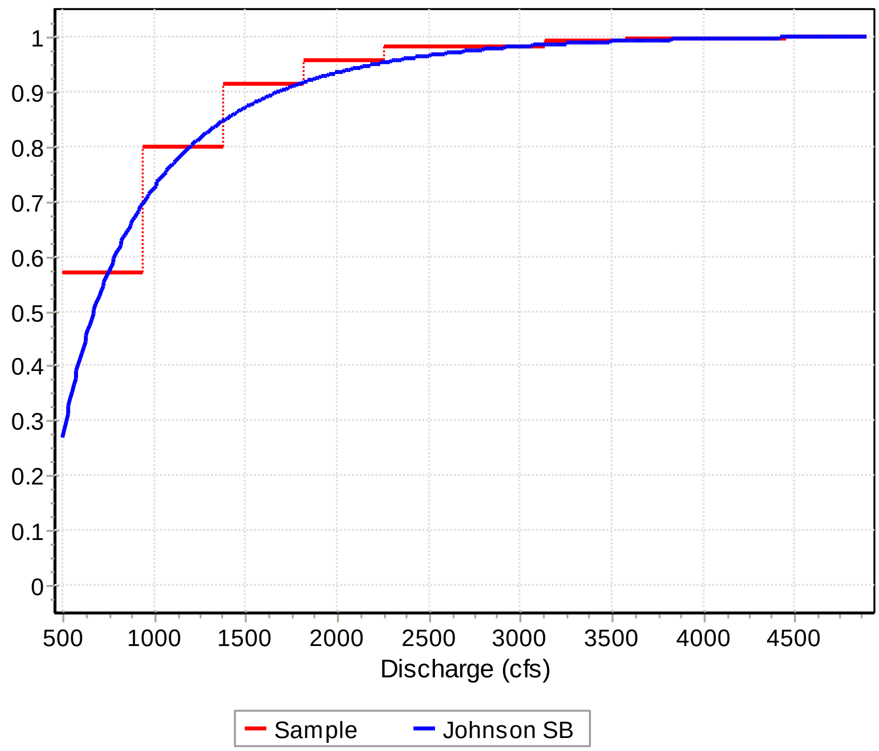


Figure 4-4. Probability distribution of current discharge at site A

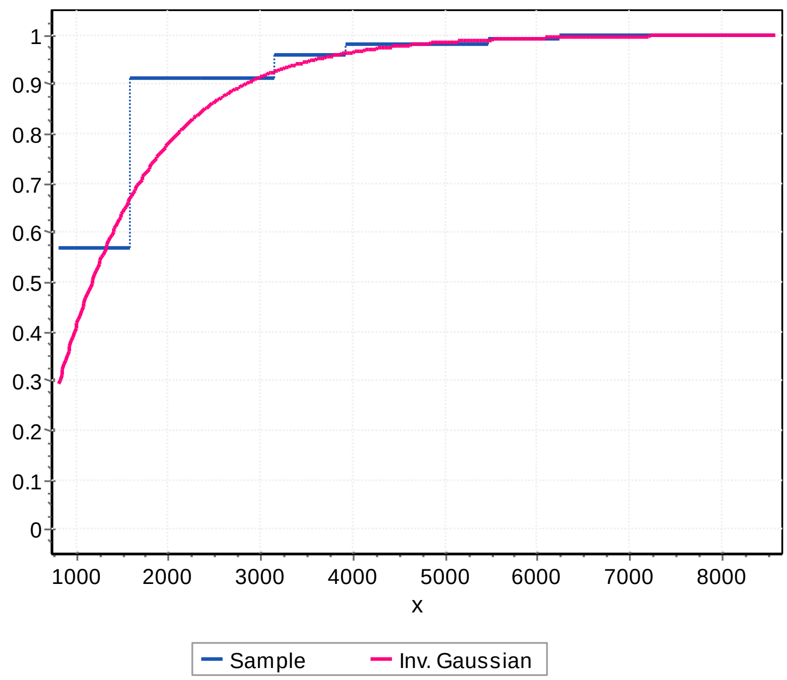


Figure 4-5. Probability distribution of current discharge at site B

CHAPTER 5
CONCLUSIONS AND DISCUSSIONS

In conclusion, increase of precipitation will affect both transportation and land use development in City of Pensacola, Florida from two aspects. First, increase of precipitation will generate riverine flood that will inundate more urban and built-up environment, especially single family dwelling units. Corresponding adaptation strategies could be developed based on this finding. For example, land use control policy could be implemented or flood proofing or residential house raising could be applied. The adaptation strategies could be either structural or non structural. The structural adaptations include building levees, dams, dikes, channel improvements and so on. The non structural strategies involve land use control, public participation, information sharing, open space and wetland preservation, and community activities such as flood preparedness. The objectives of both structural and non structural adaptations are to reduce the amount of impervious surface, limit the development within floodplain, and preserve natural resources that reduce flooding. However, compared with non structural strategies, structural adaptations are usually costly with certain environmental negative effects (e.g. disruption of hydrological cycles) and the potential to encourage development within the protected area. Furthermore, considering the total increase of floodplain in the study area is not enormous, it is recommended that local planners and decision makers would better seek non structural mitigation strategies. The mitigation could be focused on three sides 1) natural preservation 2) governmental regulation 3) public participation. First, through acquisition and preservation of the open space and wetland within the projected floodplain, the increase of impervious surface could be effectively controlled to reduce further increase of runoff.

Second, through zoning, comprehensive floodplain management plan, the total amount, density, and design standard (e.g. height of the lowest floor) of the housing units with in the projected floodplain could be regulated, reducing the total amount of potential risk. Finally, through public information sharing and education and modification of insurance regulations, homeowner involvement could be promoted, which plays a crucial and active role in flood mitigation. For undeveloped area within the projected floodplain, mitigation strategy one is proposed, that is the government should acquire the open land and preserve them. For developed area, mitigation strategy two and three is recommended to increase public attention and reduce the flooding risk though change of standards. Furthermore, I recommend the local government consider the update of floodplain to change the flood insurance policy and the premium. Decision makers could also consider the use of incentives for relocation.

Second, increase of precipitation will increase the frequency of the flood, which requires an update of the drainage design frequency for transportation infrastructure. The analysis results could be used to update the flood zone map, or serve as a guideline for design standard update, which could strengthen the protection of human health and safety, reduce infrastructure disruption, and reduce stress.

The innovative methodology used in the study successfully links climate change model outputs with the flood projection and detailed impact assessment at the local level. Although the inputs (daily realization) to the analysis remain a large amount of uncertainty, the study at least provides a way to describe the potential situation of climate change scenario at the local level. Furthermore, the study not only provides a quantification of the impacts of changing riverine flooding on transportation and urban infrastructures, but also a foundation for further risk assessment and economic cost analysis. In the future, land use models could be incorporated in this process to simulate the reallocation of development within the projected flood area, and the potential economic cost could be quantified. In addition, the study could be integrated with both land use model and transportation models to quantify the indirect cost on transportation system, taking the land use change and restriction of development in the flooding area into consideration. Finally, the multidisciplinary methodology in this study could be applied to other MPOs and region to help decision makers make more informed decisions about adaptation strategies for climate change.

The limitation of the study is the requirement of large amount of precipitation and rainfall data and manual work. However, considering the hydrological pattern are similar within a relative large area (e.g. Escambia River Basin in this study), which often includes several states, researches could be achieved through cooperation between states. The establishment of such cooperation will provide a possibility for small cities with limited resources to prepare for climate change.

Another limitation is the uncertainty of the data and modeling process. In addition to the uncertainty in climate change projection data and the variability in statistic model, incomplete knowledge of the complicated flood generation process produce additional epistemic uncertainties. For example, the model does not consider the probability of levee failure and other additional activity that could change the stream channel. Risk assessment may throw a light on these issues, but more accurate climate projection at the local level is the premise for such application.

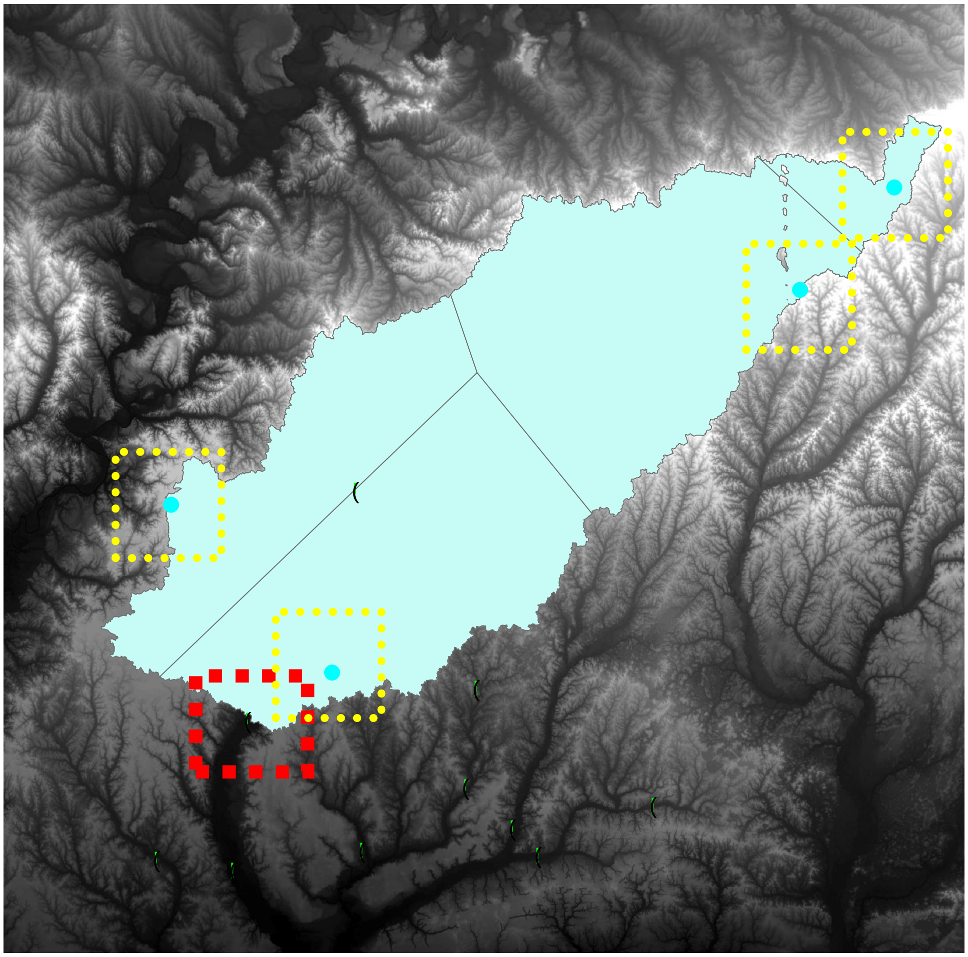
Further improvements could be made towards the understanding of causality of riverine flooding, simulating the effects of variable such as rainfall statistics with different duration classes (e.g. 0.5 h to 72 h). Impact assessment could be enriched by estimating the ground-floor elevation of the building and stage-damage functions by building types, usage, and structure.

APPENDIX
PLOTS OF PEARSON CORRELATION BETWEEN PARTIAL WEIGHTED RAINFALL SUM AND DISCHARGE VERSUS LENGTH OF PARTIAL SUM FOR EACH OF THE BASIN AREA

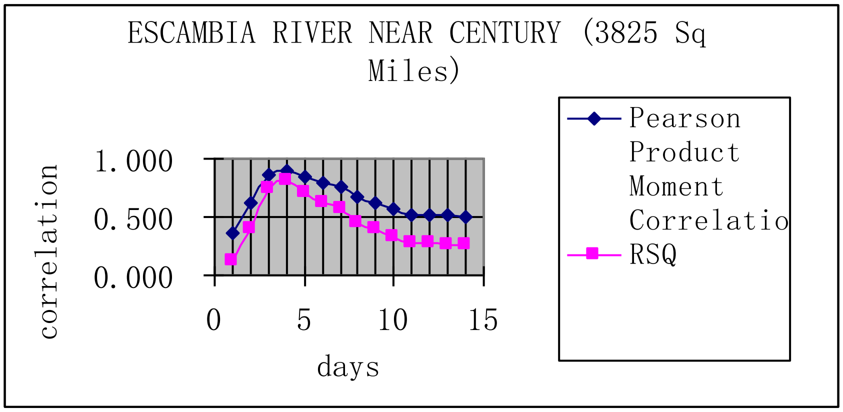
The following maps show the location of each discharge station and the valid rainfall station contributing to the streamflow in the basin area. The Digital Elevation Model data and discharge records come from U.S. Geological Survey (USGS) and the rainfall station comes from both USGS and Southeast regional climate center. The red rectangles show the location of the discharge stations, and dashed yellow rectangles show the location of rainfall stations. The diagrams demonstrate the Pearson product moment correlation coefficient and the square of the Pearson correlation coefficient.

Station 1 Escambia River near Century

Size of the basin area: 3825sq miles
Partial sum lengths with maximum correlation: 4 days
Location of the station and valid rainfall record stations

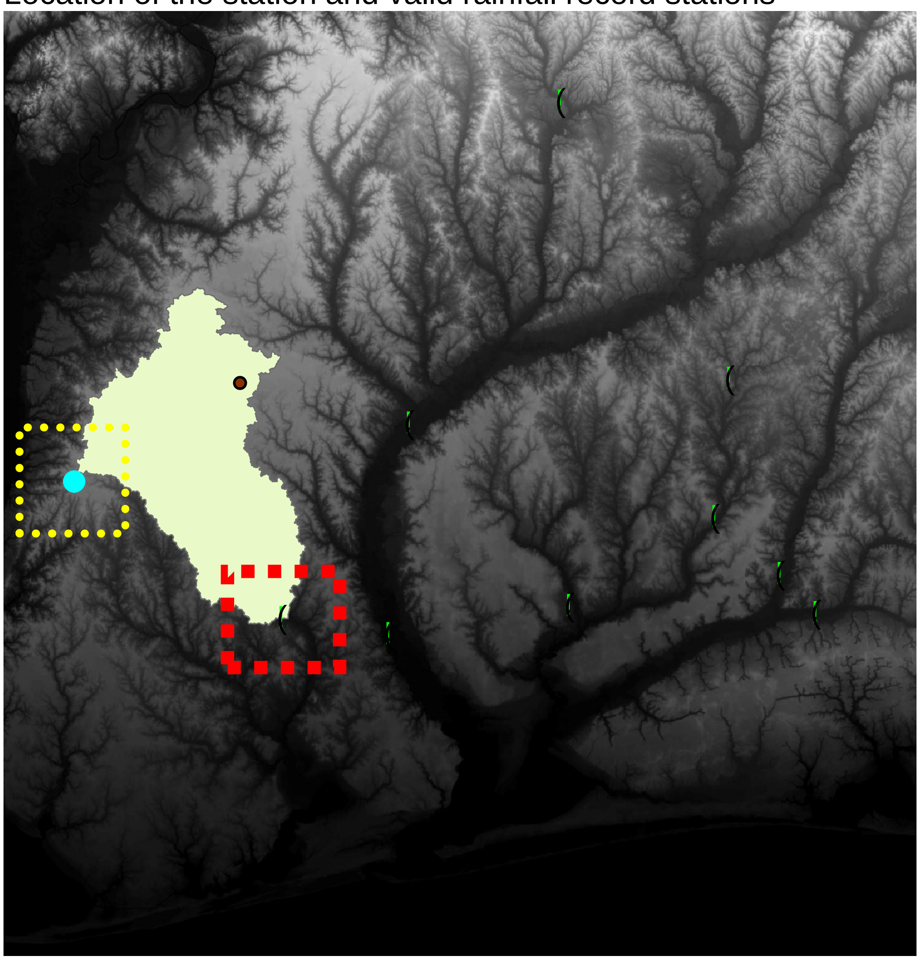


Plots of Pearson correlation versus length of partial sum for each of the basin area

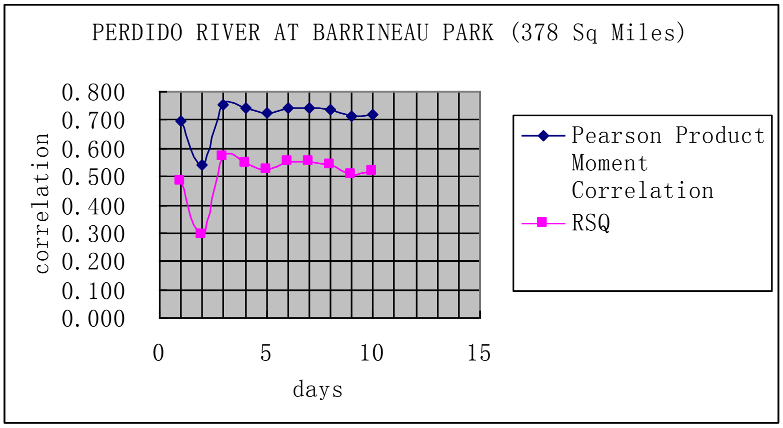


Station 2 Perdido River at Barrineau Park

Size of the basin area: 378 sq miles
Partial sum lengths with maximum correlation: 3 days
Location of the station and valid rainfall record stations

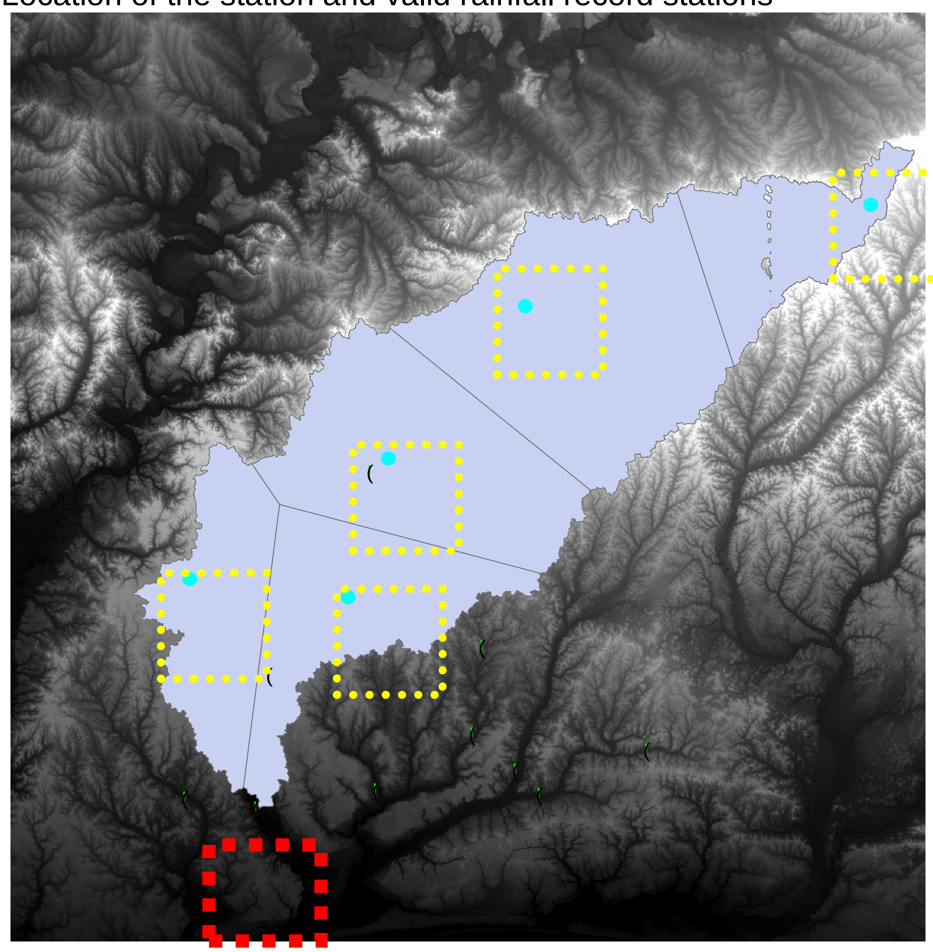


Plots of Pearson correlation versus length of partial sum for each of the basin area

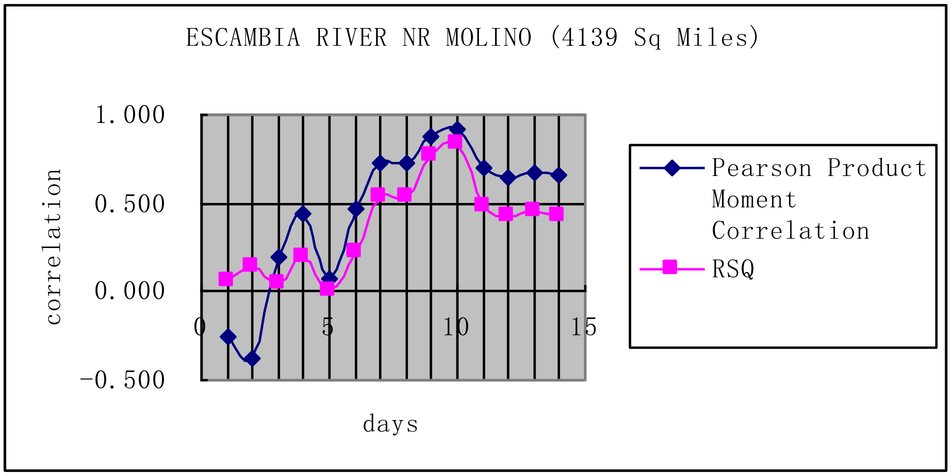


Station 3 Escambia River near Molino

Size of the basin area: 4139 sq miles
Partial sum lengths with maximum correlation: 10 days
Location of the station and valid rainfall record stations

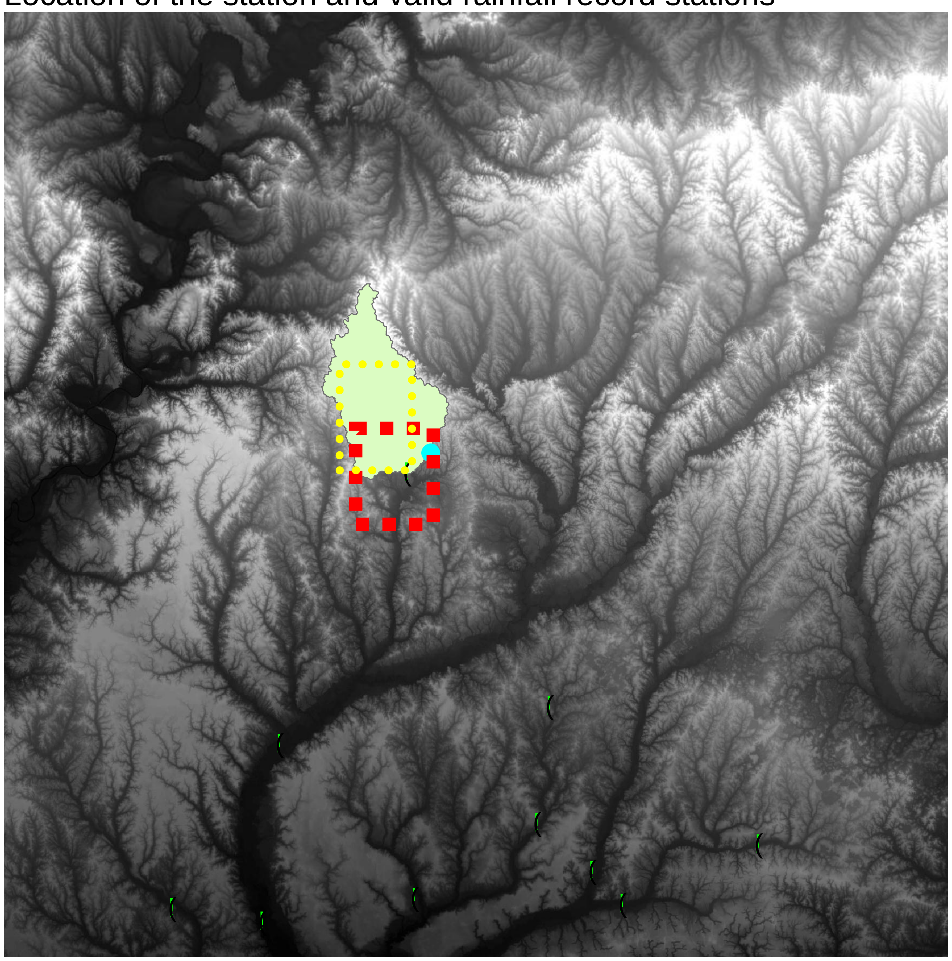


Plots of Pearson correlation versus length of partial sum for each of the basin area

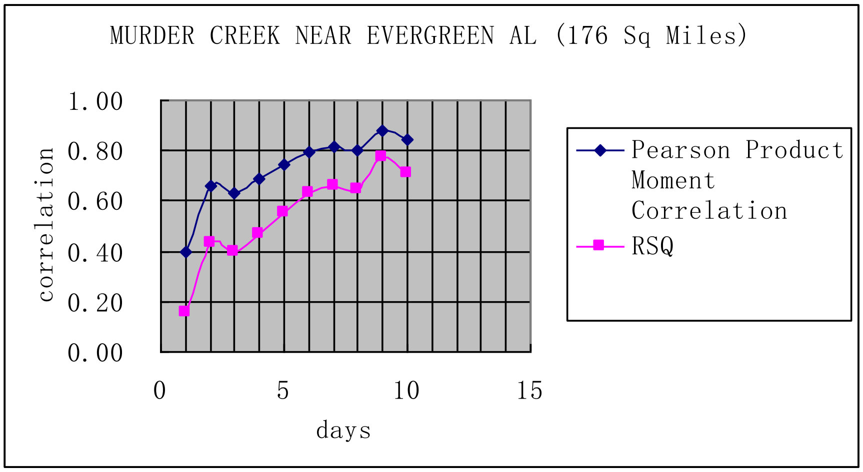


Station 4 Murder Creek near Evergreen AL

Size of the basin area: 176 sq miles
Partial sum lengths with maximum correlation: 6 days
Location of the station and valid rainfall record stations

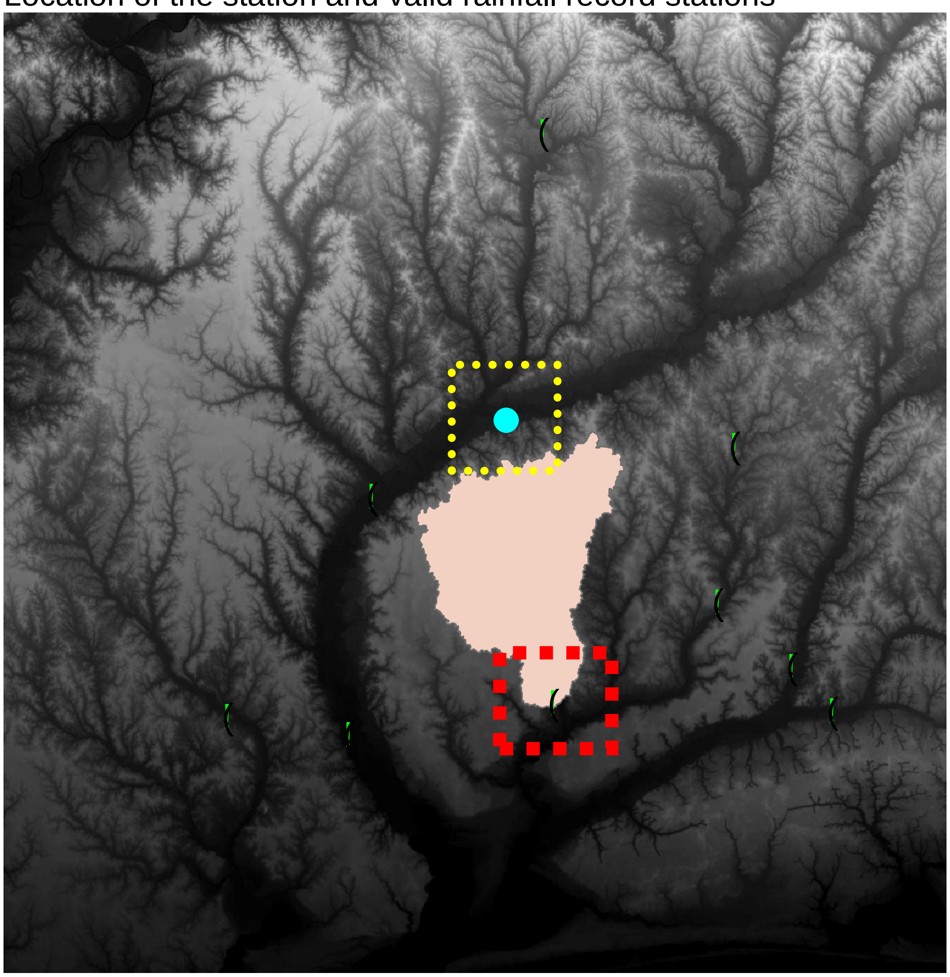


Plots of Pearson correlation versus length of partial sum for each of the basin area

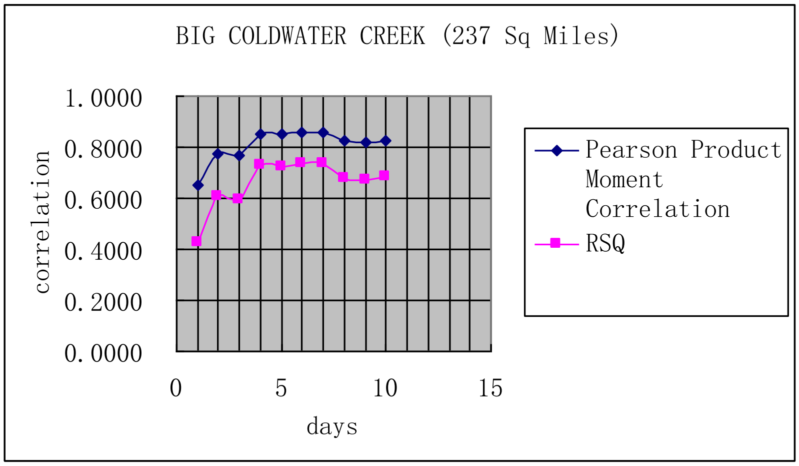


Station 5 Big Coldwater Creek

Size of the basin area: 237 sq miles
Partial sum lengths with maximum correlation: 4 days
Location of the station and valid rainfall record stations

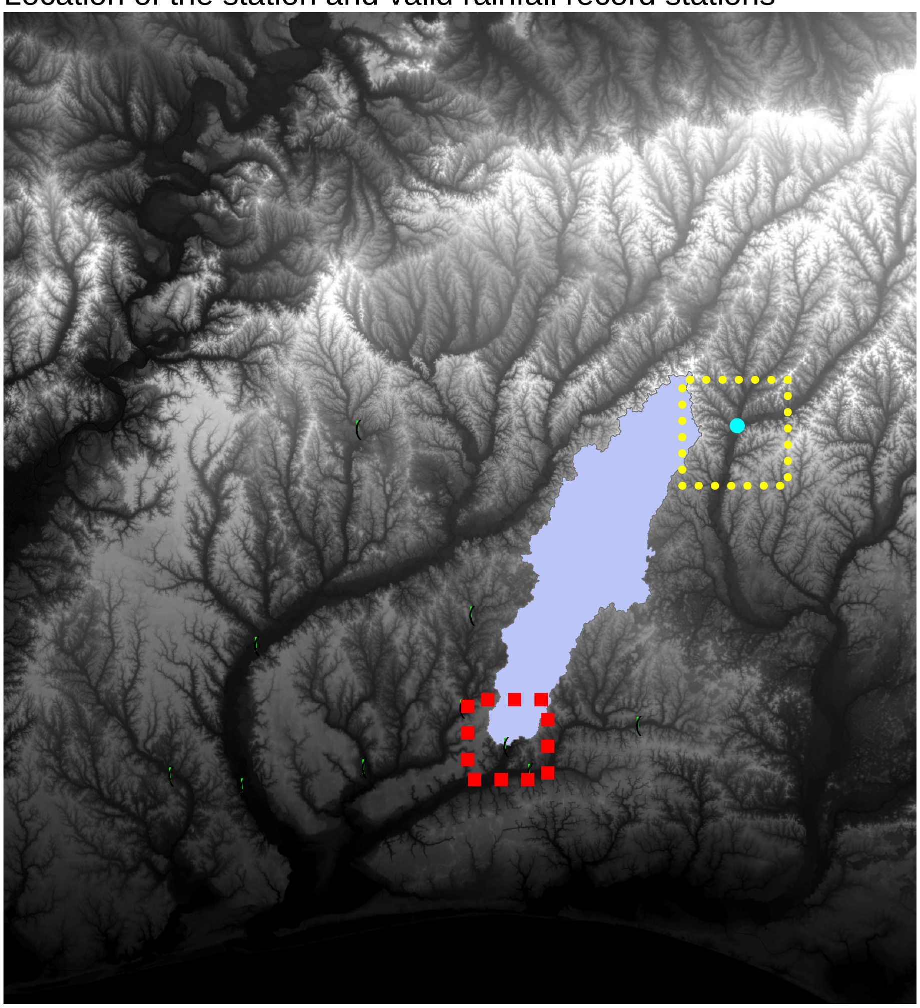


Plots of Pearson correlation versus length of partial sum for each of the basin area

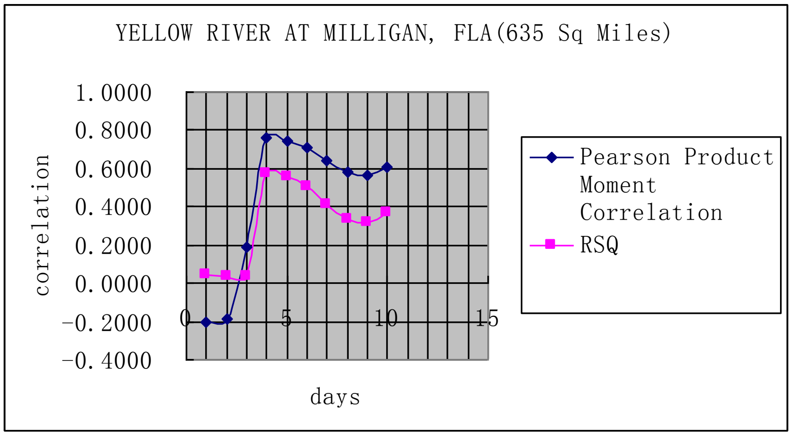


Station 6 Yellow River at Milligan, FLA

Size of the basin area: 635 sq miles
Partial sum lengths with maximum correlation: 4 days
Location of the station and valid rainfall record stations

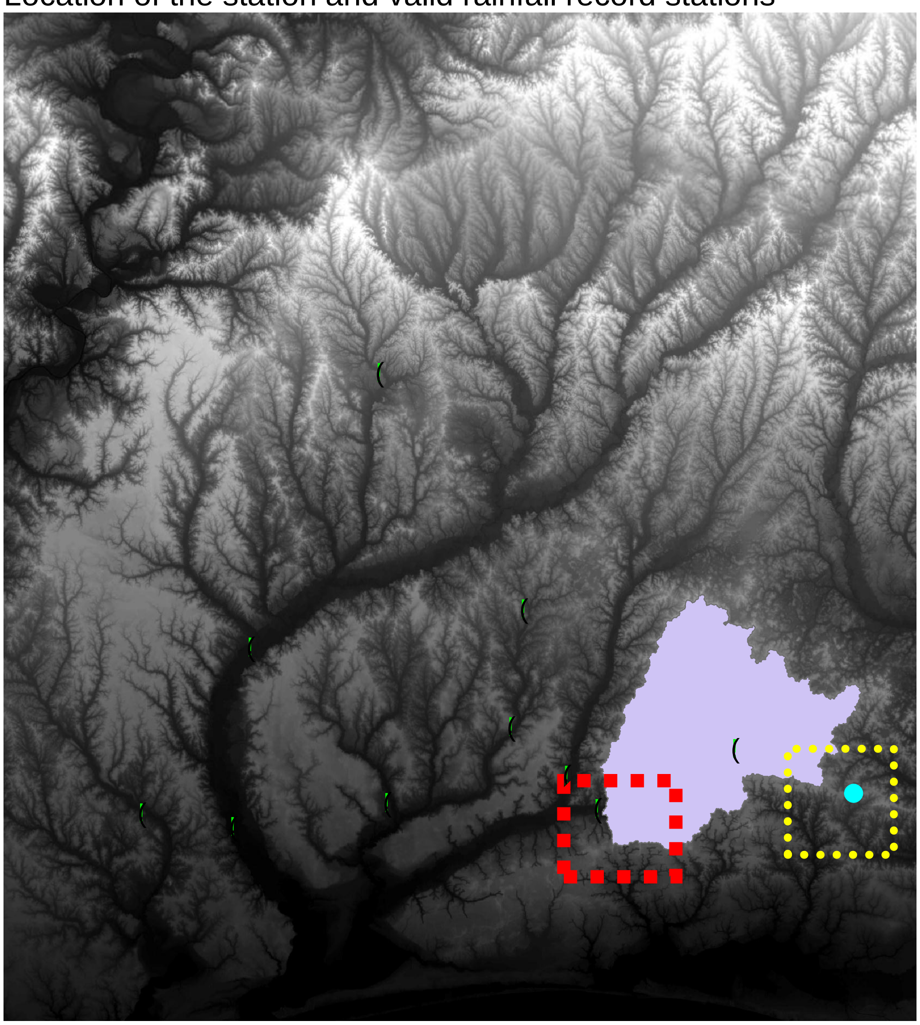


Plots of Pearson correlation versus length of partial sum for each of the basin area

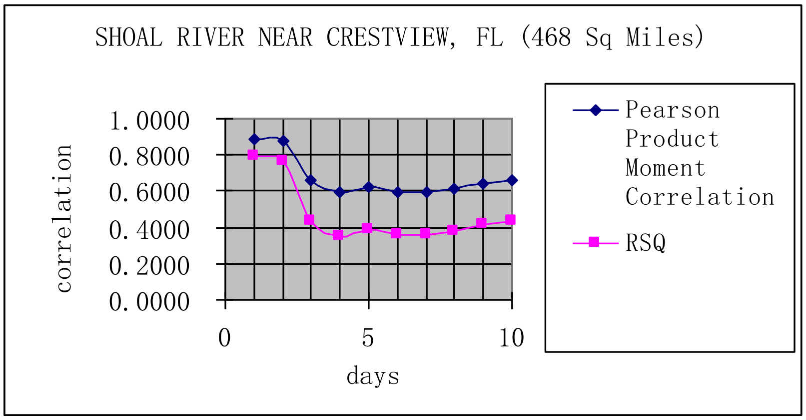


Station 7 Shoal River near Crestview, FL

Size of the basin area: 468 sq miles
Partial sum lengths with maximum correlation: 1 day
Location of the station and valid rainfall record stations

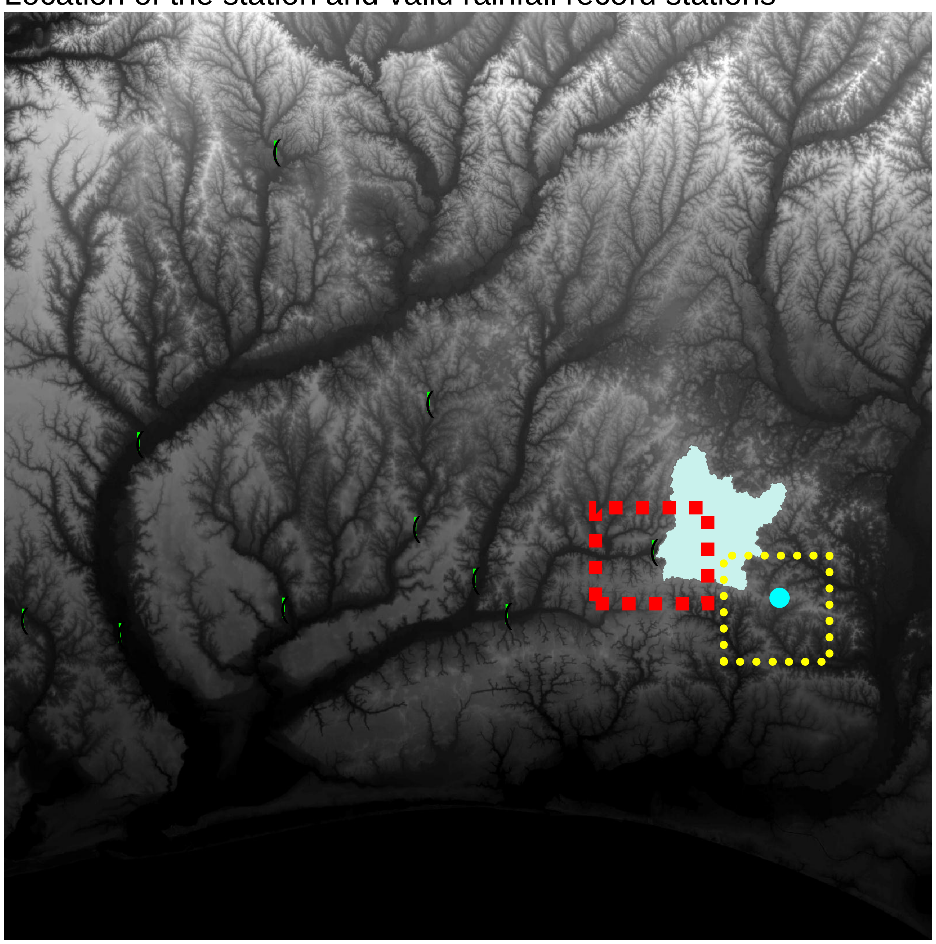


Plots of Pearson correlation versus length of partial sum for each of the basin area

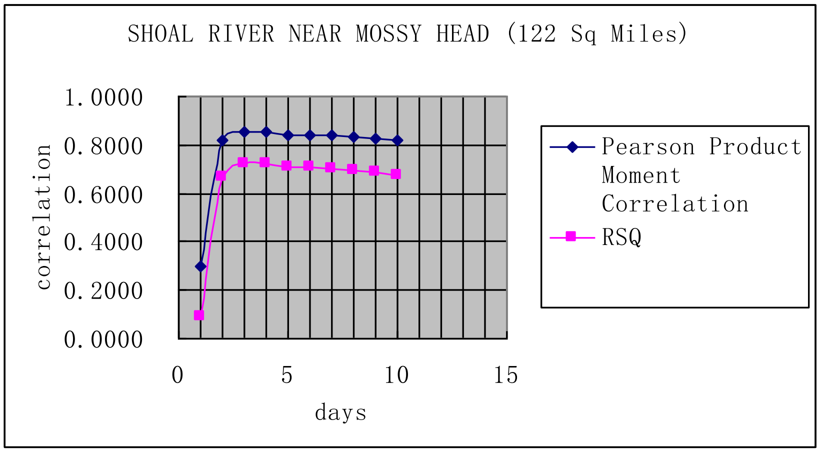


Station 8 Shoal River near Mossy Head

Size of the basin area: 122 sq miles
Partial sum lengths with maximum correlation: 3 day
Location of the station and valid rainfall record stations



Plots of Pearson correlation versus length of partial sum for each of the basin area



LIST OF REFERENCES

Apel et al.. (2004). Flood risk assessment and associated uncertainty. *Natural Hazards and Earth System Sciences* (2004). Vol. 4, pp. 295-308.

Bridges. (1982). Technique for estimating magnitude and frequency of floods on natural-flow streams in Florida. U.S. Geological Survey Water-Resources Investigations Report 82-4012. USGS, 1982.

Buchele et al.. (2006). Flood-risk mapping: contributions towards an enhanced assessment of extreme events and associated risks. *Natural Hazards and Earth System Sciences (2006)*, vol. 6, pp. 485-503.

Burby R.J. (2001). Insurance and Floodplain Management: The US Experience. *Flood Environmental Hazards*, Vol. 3, pp. 111-122.

Burkett. (2002). Potential Impacts of Climate Change and Variability on Transportation in the Gulf Coast/Mississippi Delta Region. In The Potential Impacts of Climate Change on Transportation Workshop Summary. U.S. Department of Transportation, Workshop, 2002.

Drainage Manual. Florida Department of Transportation, March 2010. www.dot.state.fl.us/rddesign/dr/files/2010DrainageManual.pdf Accessed June 5th, 2010

Environmental Protection Agency*. Precipitation and Storm Changes*. Environmental Protection Agency. http://www.epa.gov/climatechange/science/recentpsc.html Accessed June 5th, 2010

Environmental Protection Agency. 2005. *Emission Facts: Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel*. EPA420-F-05-001, http://www.epa.gov/otaq/climate/420f05001.htm Accessed June 1st, 2010.

Fowler and Hennessy. (1995). Potential Impacts of Global Warming on the Frequency and Magnitude of Heavy Precipitation. *Natural Hazards*. Vol. 11, pp 283-303.

Frei et al.. (2000). Climate dynamics and extreme precipitation and flood events in Central Europe. Integrated Assessment. Vol. 1, pp. 281-299.

ICF International. (2007). The Potential Impacts of Global Sea Level Rise on Transportation Infrastructure. Phase 1 - Final Report: the District of Columbia, Maryland, North Carolina and Virginia. http://www.bv.transports.gouv.qc.ca/mono/0965210.pdf Accessed June 20th, 2010.

ICF. (2008). *Integrating Climate Change into the Transportation Planning Process*. Federal Highway Administration, 2008. http://www.fhwa.dot.gov/hep/climatechange/climatechange.pdf Accessed May 15th, 2010.

IPCC. (2007). Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf Accessed June 15th, 2010.

Jacob, Edelblum, and Arnold. (2001) Infrastructure. Chapter 4 in *Climate Change and a Global City: The Potential Consequences of Climate Variability and Change- Metro East Coast*, edited by C. Rosenzweig and W. D. Solecki. Columbia Earth Institute. New York, pp. 47-65.

Jacob, Gornitz, and Rosenzweig. (2007). Vulnerability of the New York City metropolitan area to coastal hazards, including sea-level rise: Inferences for urban coastal risk management and adaptation policies. In *Managing Coastal Vulnerability*. L. McFadden, R. Nicholls, and E. Penning-Rowsell, Eds. Elsevier, pp. 139-156.

James et al.. (2009). Coastal Sensitivity to Sea Level Rise: A Focus on the Mid-Atlantic Region. Synthesis and Assessment Product 4.1 Report by the U.S. Climate Change Science Program and the Subcommitte on Global Change Research. Jan, 2009.http://www.climatescience.gov/Library/sap/sap4-1/final-report/default.htm Accessed May 1st, 2010.

Jerry et al.. (2000). U.S. Global Change Research Program: National assessments of the potential consequences of climate variability and change. National Assessment Synthesis Team, U.S. Global Change Research Program, 2000. http://www.gcrio.org/NationalAssessment/overpdf/overview.html Accessed June 30th, 2010.

Kanamitsu and Kanamaru. (2007). Fifty-Seven-Year California Reanalysis Downscaling at 10 km (CaRD10). Part I: System Detail and Validation with Observations. *Journal of Climate*. Vol. 20, Issue 22. pp.5553-5571.

Koetse and Rietvel. (2009). The impact of climate change and weather on transport: an overview of empirical findings. *Transportation Research Part D.* Vol. 14, pp 205-221.

Lim et al.. (2010). High-resolution subtropical summer precipitation derived from dynamical downscaling of the NCEP/DOE reanalysis: how much small-scale information is added by a regional model? *Climate Dynamics*. Available at http://dx.doi.org/10.1007/s00382-010-0891-2

Louisiana Coastal Wetlands Planning. (2003). *Protection and Restoration News*. Feb, 2003. No. 22. http://lacoast.gov/new/Data/WaterMarks/Watermarks-2003-02.pdf Accessed June 1st, 2010.

Maantay J and Maroko A. (2009). Mapping Urban Risk: Flood Hazards, Race, & Environmental Justice in New York. *Applied Geography*, Vol. 29, pp. 111-124.

Meyer, M.D. (2008). *Design Standards for U.S. Transportation Infrastructure: The Implications of Climate Change*. Transportation Research Board. http://onlinepubs.trb.org/onlinepubs/sr/sr290Meyer.pdf Accessed May 1st, 2010.

Milly et al.. (2002). Increasing risk of great floods in a changing climate. *Nature*. Vol. 415, pp. 514-517.

National Research Council, 2008. *Potential Impacts of Climate Change on U.S. Transportation.* Transportation Research Board Special Report 290. Transportation Research Board, Washington, D.C. http://onlinepubs.trb.org/onlinepubs/sr/sr290.pdf Accessed May 5th, 2010.

Ologunorisa and Abawua. (2005). Flood Risk Assessment: A Review. *Journal of Applied Sciences and Environmental Management.* Vol. 9(1), pp 57-63

Peterson T. C., McGuirk M., Houston T. G., Horvitz A. H., and Wehner M. F. (2008). Climate Variability and Change with Implications for Transportation.http://onlinepubs.trb.org/onlinepubs/sr/sr290Many.pdf Accessed June 15th, 2010.

Project Development and Design Manual. U.S. Department of Transportation, Federal Highway Administration, March 2008.http://flh.fhwa.dot.gov/resources/manuals/pddm/Chapter_07.pdf#7.1.1. Accessed June 1st, 2010.

Simonovic et al.. (2003). Methodology for Assessment of Climate Change Impacts on Large-Scale Flood Protection System. *Journal of Water Resources Planning and Management.* Vol. 129, No. 5, pp. 361-371.

Suarez et al.. (2005). Impacts of Flooding and Climate Change on Urban Transportation: A Systemwide Performance Assessment of the Boston Metro Area. In *Transportation Research Part D Transport and Environment.* Vol. 10, 2005. pp. 231-244.

Titus. (2002). Does Sea Level Rise Matter to Transportation Along the Atlantic Coast? In The Potential Impacts of Climate Change on Transportation, Summary and Discussion Papers, Federal Research Partnership Workshop, Brookings Institution, Washington, D.C., Oct. 1–2, 2002. pp. 135–150.

Todini. (1999). An operational decision support system for flood risk mapping, forecasting and management. *Urban Water*. Vol.1, pp 131-143.

U.S. Climate Change Science Program. (2008). *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I*. U.S. Department of Transportation, Center for Climate Change and Environmental Forecasting. Washington, D.C. http://www.climatescience.gov/Library/sap/sap4-7/final-report/ Accessed June 1st, 2010.

Virginia Department of Transportation Drainage Manual. Location and Design Division, Hydraulics Section, Virginia DOT, 2002.http://www.extranet.vdot.state.va.us/locdes/electronic%20pubs/2002%20Drainage%20Manual/pdf/_Start%20VDOT%20Drainage%20Manual.pdf Accessed June 10th, 2010.

Zimmerman, R. (2001). Global Climate Change and Transportation Infrastructure: Lessons from the New York Area, in *The Potential Impacts of Climate Change on Transportation: Workshop Summary and Proceedings*, Washington, U.S. Department of Transportation, pp. 91-101. 2002. http://climate.dot.gov/documents/workshop1002/zimmermanrch.pdf Accessed May 20th, 2010.

BIOGRAPHICAL SKETCH

Suwan Shen is currently a student at the University of Florida, with a major in urban and regional planning and a special interest in transportation planning. She got her undergraduate degree in Geographical Information System (GIS) from Southeast University, Nanjing, China. During her studies in the master's degree program at the University of Florida, she presented her works in three international conferences: Transportation Research Board 2009 meeting, the Association of Collegiate Schools of Planning 2010 meeting, and International Association for China Planning, and has won the Karen R. Polenske Best Student Award. She also volunteers herself as an intern working for the North Central Florida Regional Planning Council (NCFRPC) in spring 2010. Suwan is preparing herself for a career in transportation planning. Her future research plans include exploring travel behavior and GIS application in transportation fields.