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# Incorporating Potential Climate Change Impacts in Bridge and Culvert Design

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Each contract report is peer reviewed and accepted for publication by staff of the Virginia Transportation Research Council with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

## ABSTRACT

This project examined the potential impact of changing climatic conditions on structural designs in Virginia. A methodology was developed for producing intensity-duration-frequency (IDF) curves verified against the standard Atlas 14 values. The results suggest increases in rainfall depth for a 24-hour rainfall event. The second objective used a 2-dimensional hydrodynamic model to assess increased rainfall volumes on peak runoff volumes, suggesting smaller watersheds have a constant relationship between peak runoff and watershed size, while larger watersheds have less than 1% increase in peak runoff as the watershed size increases. The third objective illustrated average annual risk over the lifespan of a culvert and a bridge. Finally, the IDF approach showed significant variability across individual stations, but no obvious spatial trend. It is recommended that VDOT use the findings from this study to update the design standards involving storm water runoff and stream flows. When VDOT assets are designed using rainfall data, the values should be increased to account for the greater rainfall predicted and reported in this study. When VDOT assets are designed using discharge data not derived from rainfall, the values should be increased to account for the greater discharges predicted and reported in this study.

**FINAL REPORT**

# INCORPORATING POTENTIAL CLIMATE CHANGE IMPACTS IN BRIDGE AND CULVERT DESIGN

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## INTRODUCTION

Bridges and culverts have traditionally been designed assuming stationarity in rainfall records, meaning that there will be no significant long-term changes in rainfall intensities and patterns (Bhatkoti et al., 2016). Evidence suggests, however, that the climate is changing and this will result in different rainfall intensities and patterns from those experienced in the past (Milly et al., 2008). The effect that changes in climate will have on existing and future bridges and culverts is uncertain (Hui et al., 2018), but using current scientific understanding and engineering judgement, this change can be estimated and incorporated into bridge and culvert designs to balance risk across a structure's lifespan.

There are many viewpoints on the topic of climate change and its implication on infrastructure design in the literature. Most scientists agree that the assumption of stationarity must be questioned based on recorded and projected changes in climate (Milly et al., 2008), however, the practical implications of this are less agreed upon. For example, Montanari and Koutsoyiannis (2014) suggest it imprudent to disregard the assumption of stationarity and the past data record completely. A report by Galloway (2011) suggests that, although climatologists demonstrate evidence of climate change, hydrologists are less certain regarding exactly how climate changes will impact rivers and streams and what should be done in engineering practice to adjust.

Despite this uncertainty, the field has begun to offer engineering approaches to account for changing climatic conditions. One practical approach to account for non-stationarity in infrastructure design is to adjust precipitation intensity-duration-frequency (IDF) curves (Cheng and Aghakouchak, 2014). IDF curves define an exceedance probability for extreme precipitation events and are a common design tool for civil infrastructure design. A return period is the expected or average estimated time between two events of the same intensity or magnitude. IDF curves are typically developed assuming stationarity, however several studies have examined the updating or adjusting of IDF curves with a non-stationarity viewpoint. These studies have had mixed conclusions. Though recognizing statistically significant trends in climate and rainfall data, studies by Yilmaz and Perrera (2013) and Ganguli and Coulibaly (2017) suggest that adopting a non-stationary approach does not lead to practical benefit. On the other hand, results from Cheng and Aghakouchak (2014) suggest a significant underestimation of design storms if stationarity is assumed compared to non-stationarity. A key point of these studies is that historical records and climate projects must be considered for specific places to determine the right course of action.

A study on updating IDF curves recently completed by the engineering firm, Dewberry (Smirnov et al., 2018) (hereafter, the “Dewberry study”), is particularly relevant due to the study area being in Virginia. The Dewberry study, funded by the City of Virginia Beach, recommended changes to the IDF curves used by the City of Virginia Beach for engineering design. The report recommended that the city increase all of the volumes of their design storms by 20% given the historic trend and simulated future climate conditions, which suggest that extreme rainfall events will be occurring more frequently in coming decades.

## PURPOSE AND SCOPE

This study extends the Dewberry study in several ways to make it more relevant to VDOT design needs. First, an approach similar to the Dewberry methodology is used to estimate future IDF curves for a longer time period — to the end of the century. Second, a 2-dimensional hydrodynamic model is employed to project the impact of future changes of rainfall on peak streamflow volumes for watersheds of varying sizes, as these streamflow peaks are critical for the design of bridges and culverts. The model used for this analysis covers a large area (1720 sq km) of southeastern Virginia. Third, a methodology is suggested for balancing risk given the changing IDF and peak flow values expected in the future. Fourth, the methodology for estimating future IDF curves is applied to rainfall observation stations across the Commonwealth to investigate the potential changes in rainfall events for stations outside of Norfolk.

**Objective 1**: Evaluate/validate the existing Dewberry study and extend to time spans (through 2100) and return periods (100-year) of interest to VDOT.

**Objective 2**: Investigate the relationship between increased rainfall, runoff, and watershed area for a variety of storm events

**Objective 3:** Provide equivalent risk assessment methodology to determine appropriate design criteria.

**Objective 4:** Repeat the rainfall analysis for other regions in the state to better understand potential impacts of regional variability in rainfall.

## METHODS

### Objective 1: Future IDF Analysis for Norfolk Airport Station

#### IDF Statistical Methods

Daily rainfall data was collected from the Norfolk International Station, in Norfolk VA, to calculate precipitation IDF. To be consistent with NOAA Atlas 14, partial duration series (PDS) was used, which was done by choosing the largest N daily rainfall observations in the entire period of record, where N is the number of years of data. It is more likely that an unconstrained 24-hr rainfall would be much higher than a constrained daily rainfall. Therefore, in accordance with NOAA Atlas 14, the partial duration series was multiplied by a factor of 1.13 to convert from daily to 24-hr precipitation. NOAA Atlas 14 found Generalized Extreme Value (GEV) to be the most appropriate statistical distribution for the Norfolk station and used it for calculating IDF. Therefore, the partial duration series was fit to the GEV distribution using L-moments to derive distribution parameters.

#### Historical IDF

Historical precipitation IDF values were calculated using 24-hour duration precipitation data until 2000 for return periods of 1 to 100 yrs. The values of historical IDF were compared with the NOAA Atlas 14 values and values reported in the Dewberry study.

#### Global Climate Models and Regional Climate Models

Global Climate Models (GCM) from the World Climate Research Programme’s (WCRP’s) Coupled Model Intercomparison Project Phase 5 (CMIP5) were used to project changes in future precipitation IDF (source: https://esgf-node.llnl.gov/projects/esgf-llnl/). Due to spatially coarse resolution of the raw GCM outputs, downscaled regional climate model (RCM) outputs were obtained from the Coordinated Regional Climate Downscaling Experiment (Cordex; source: https://www.cordex.org ). Daily model precipitation time series was obtained from 1950 to 2100 considering 1950-2005 the historic period and 2006-2100 as the future period, consistent with prior studies.

The modeled precipitation data was collected for two emission scenarios or Representative Concentration Pathways: RCP 4.5 and RCP 8.5. RCP 4.5 and RCP 8.5 are two of four total RCPs defined by the Intergovernmental Panel on Climate Change (IPCC). In their Fifth Assessment report, IPCC defines RCP 4.5 as a scenario with intermediate greenhouse gas emissions and RCP 8.5 as a scenario with very high greenhouse gas emissions. (IPCC 2014)

**Bias Correction**

The historical model rainfall data (1950-2005) from RCMs and for both RCP8.5 and RCP4.5 was compared with historical observation data at NOAA rainfall stations followed by bias correction. The empirical quantile mapping method was used for bias correction. The empirical quantile mapping is a bias correction method that consists of calibrating the simulated Cumulative Distribution Function (CDF) by adding to the observed quantiles both the mean delta change and the individual delta changes in the corresponding quantile. This method was performed using the downscaleR package in R (https://github.com/SantanderMetGroup/downscaleR/wiki). Figure 1 shows an example of a quantile-quantile plot (qq-plot) bias correction performed for the CanESM2_CanRCM4 RCM (see Table 1 for model details) where the modeled data was only slightly biased. Figure 2 shows the correction for the CanESM2_CRCM5-UQAM RCM (see Table 1 for model detail) where the modeled data was more biased.

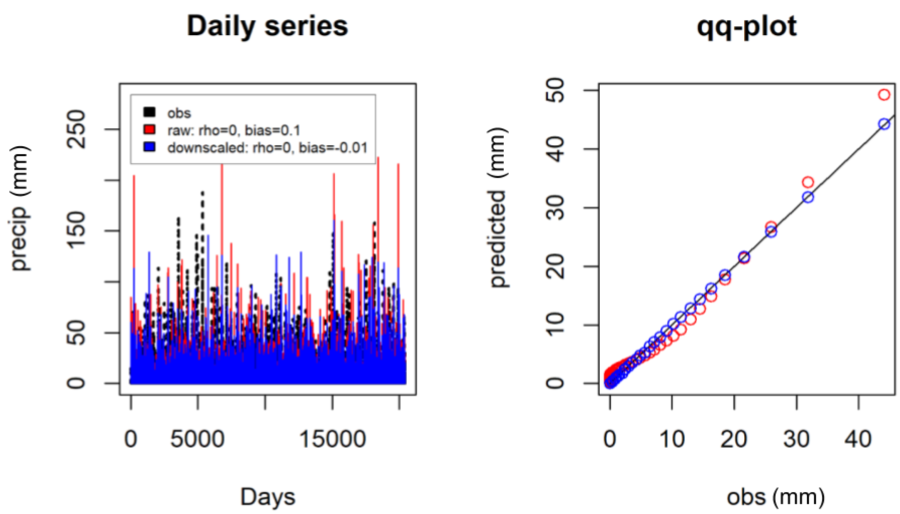


**Figure 1: Bias correction using quantile-quantile approach for CanESM2_CanRCM4 regional climate model (see Table 1 for model details). The red data is the original model output and the blue data is the bias-corrected output.**

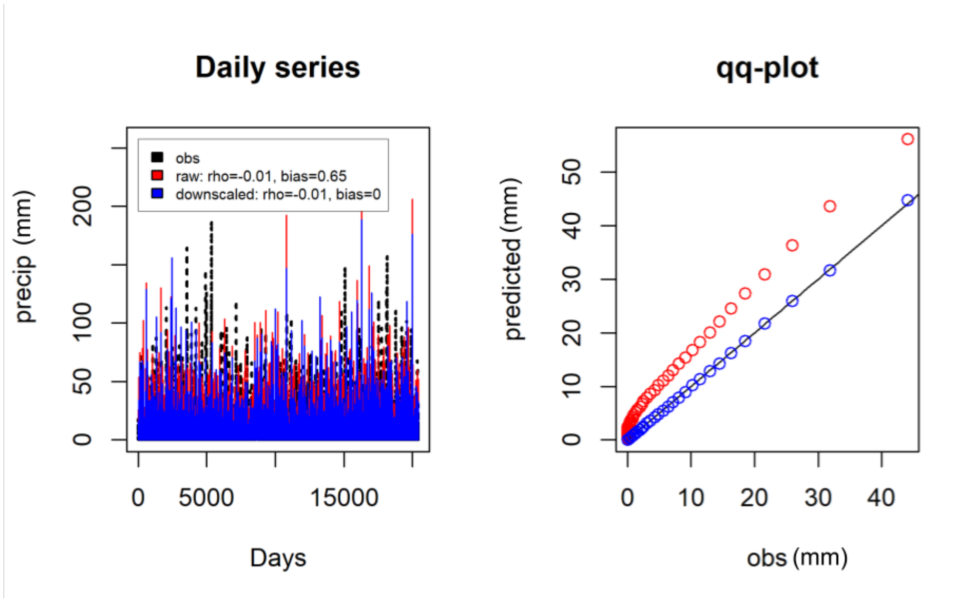


**Figure 2: Bias correction using quantile-quantile approach for CanESM2_CRCM5-UQAM regional climate model (see Table 1 for model details). The red data is the original model output and the blue data is the bias-corrected output.**

## Future Rainfall IDF

To produce an estimated future IDF curve for the Norfolk station, the time series rainfall projections from RCMs within the region were extracted at the Norfolk station for the time period 2006-2100. This modeled rainfall data was bias corrected using the quantile-quantile approach obtained from the historic model as illustrated in the prior section. The models used for RCP4.5 and RCP8.5 are given in Table 1 and Table 2, respectively. Using the GEV distribution, projected IDF curves were calculated for the mid-century (2045) and end century (2085) periods for both the RCP4.5 and RCP8.5 scenarios. A 30-year time window was used to calculate future precipitation IDF curves, i.e., 2045 represents the period 2030-2060 and 2085 represents the period 2070-2100.

**Table 1. Models Used for RCP4.5**

| **GCM Modeling Agency** | **GCM** | **RCM** | **Resolution (km)** |
|---|---|---|---|
| Canadian Centre for Climate Modeling and Analysis | CanESM2 | CanRCM4 | 22 |
| Canadian Centre for Climate Modeling and Analysis | CanESM2 | CRCM5-UQAM | 44 |
| Canadian Centre for Climate Modeling and Analysis | CanESM2 | RCA4 | 44 |
| European Centre for Medium-Range Weather Forecasts | EC-EARTH | HIRHAM5 | 44 |
| European Centre for Medium-Range Weather Forecasts | EC-EARTH | RCA4 | 44 |

**Table 2. Models Used for RCP8.5**

| GCM Modeling Agency | GCM | RCM | Resolution (km) |
|---|---|---|---|
| Canadian Centre for Climate Modeling and Analysis | CanESM2 | CanRCM4 | 22 |
| Canadian Centre for Climate Modeling and Analysis | CanESM2 | CRCM5-OUR | 22 |
| Canadian Centre for Climate Modeling and Analysis | CanESM2 | CRCM5-UQAM | 22 |
| Canadian Centre for Climate Modeling and Analysis | CanESM2 | RCA4 | 44 |
| Geophysical Fluid Dynamics Lab | GFDL-ESM2M | CRCM5-OUR | 22 |
| Geophysical Fluid Dynamics Lab | GFDL-ESM2M | WRF | 44 |
| Max Planck Institute for Meteorology | MPI-ESM-LR | WRF | 22 |
| Max Planck Institute for Meteorology | MPI-ESM-LR | RegCM4 | 22 |
| Met Office Hadley Centre | HadGEM2-ES | WRF | 22 |
| European Centre for Medium-Range Weather Forecasts | EC-EARTH | RCA4 | 44 |

## Objective 2: Impacts of Future IDF Curves on Peak Runoff

### Blackwater Watershed 2-Dimensional Hydrodynamic Model

For Objective 2, the two-dimensional (2D) hydrodynamic model TUFLOW (Two-Dimensional Unsteady Flow) was used. TUFLOW (https://www.tuflow.com/) solves the shallow water equations (SWE), making it powerful in complex 2D flow pattern applications such as in the Coastal Plain of Virginia. The model domain is located in the southeastern part of Virginia (see Figure 3). The TUFLOW model for this study region was developed and calibrated in a previous VDOT project (Morsy et al., 2019).

Various scenarios were simulated using the TUFLOW model as described below to investigate the relationship between increased rainfall, runoff, and watershed area for a variety of storm events.

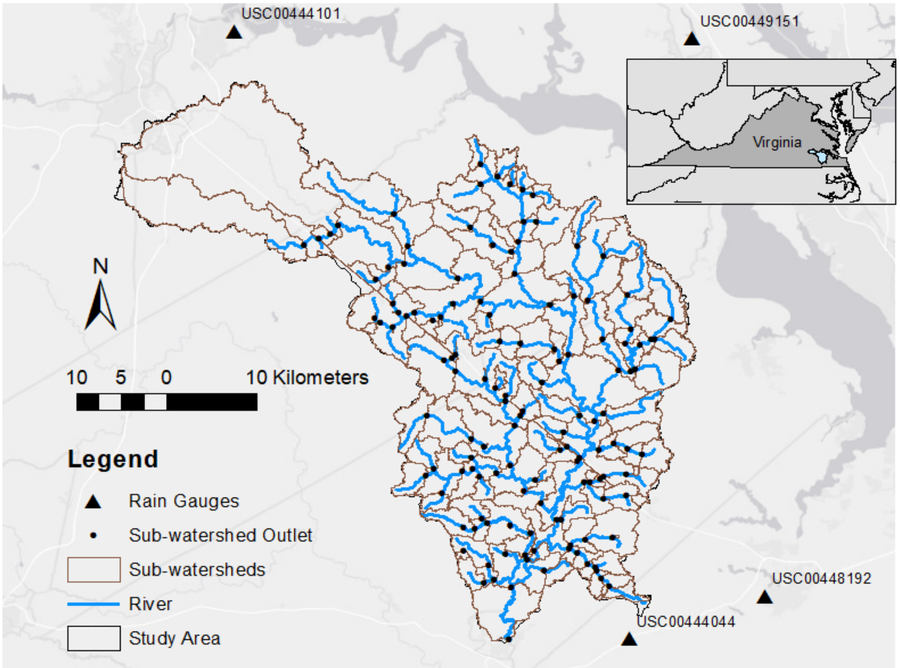


**Figure 3. TUFLOW model domain and sub watershed outlets where peak flows were recorded under current and future conditions.**

### Variety of Storm Events

As shown in Figure 3, four NOAA rain gauges in the region were used as the rainfall input for the TUFLOW model. Seven 24-hr design storms (1-, 2-, 5-, 10-, 25-, 50-, and 100-year) were derived using these four rain gauges and two climate scenarios: RCP 4.5 and RCP 8.5. These rainfall inputs were used within TUFLOW simulations to estimate the increase in peak flow resulting under different future rainfall conditions for both the mid-century (2045) and end-century (2085) time periods. The rainfall was distributed spatially from the four rain gauges (shown in Figure 3) across the study domain using the inverse distance weighting method. The 24-hr design rainfall hyetograph was constructed from the IDF curves using NOAA type B unit hyetograph, as shown in Figure 4.

### Relationship Between Peak Flow Increase and Watershed Area

Because the increase of peak flow can vary across different sizes of watersheds, the study area is divided into sub-watersheds with various watershed areas to investigate the relationship between peak flow increase and watershed area. To do so, 131 bridge locations were selected and the corresponding sub-watershed for each bridge was delineated. The area of the sub-watersheds ranged from 0.003 to 1696 sq km. The distribution of watershed areas is shown in Figure 5.

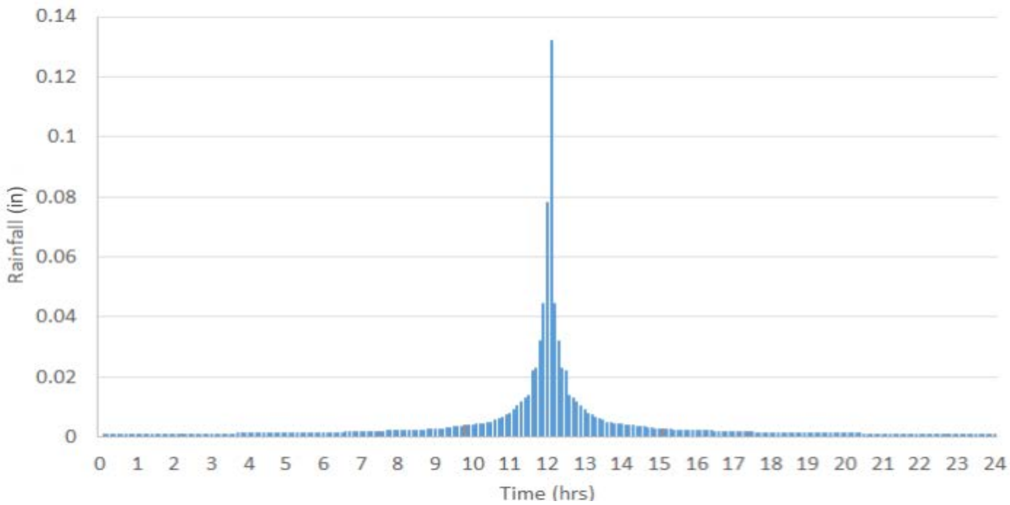


**Figure 4. NOAA type B unit hyetograph of 24-hour design rainfall**

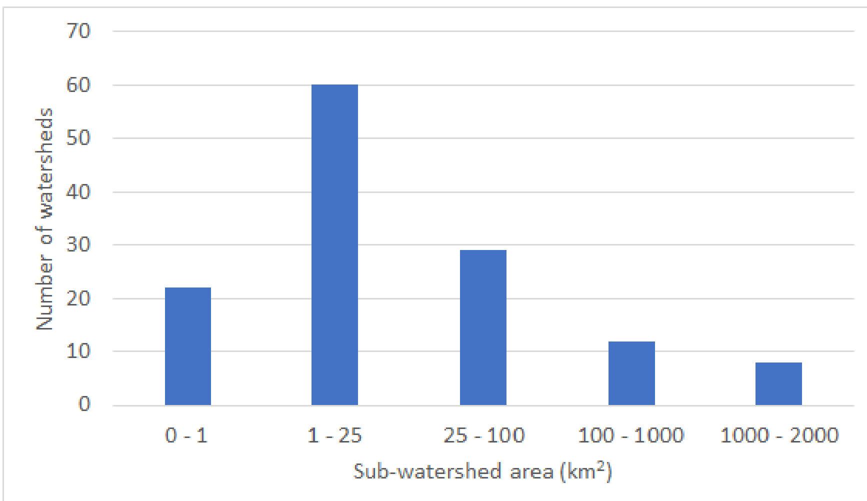


**Figure 5. The distribution of sub-watershed area at 131 bridge locations**

## Computing the Peak Flow Increase

To obtain the peak flow increase (Q-peak Increase), baseline values were obtained by first running the model using the design storms based on the historical model runs. This was done for both the RCP 4.5 and RCP 8.5 scenarios. Then the future scenarios were simulated using estimated future IDF curves for the two emission scenarios and the two-time spans centered on 2045 and 2085. A total of 28 future scenarios Q-peak increase results (seven return period design storms under two future climate scenarios on two target years) were obtained comparing the Q-peak of future scenario simulation results to the baseline results. For each sub-watershed outlet, the computed percent Q-peak increase is computed as

$$\text{Q-peak Increase (\%)} = \frac{Qf - Qc}{Qc} * 100$$

where $Q_f$ and $Q_c$ are the future and baseline peak flow values, respectively.

## Objective 3: Equivalent Risk Design Approach

Several alternatives for accounting for non-stationarity in the design of civil infrastructure have been suggested in the literature (Yan et al., 2017). These include design-life level (DLL) (Rootzén and Katz, 2013), non-stationary extreme value analysis (NEVA) (Cheng et al., 2014), average annual reliability (Read and Vogel, 2015), and average annual risk (AAR) (Stedinger and Crainiceanu, 2008). Average annual risk (AAR) was chosen and demonstrated as a simple but effective approach for balancing risk over the life of a structure assuming non-stationarity conditions. AAR was selected because it also complements the results of the other objectives in this study.

AAR is simply the average risk of exceeding a threshold over a given design or planning period. It is defined as

$$AAR(n) = \frac{1}{n}\sum_{i=1}^{n} p_i$$

where $n$ is the number of years in the design or planning period and $p$ is the exceedance probability. Under the assumption of stationarity, the exceedance probability is constant, meaning that $AAR$ would simply be $p$. However, in non-stationary conditions, the exceedance probability changes with time. The non-stationary AAR approach is demonstrated in the results section for two design cases: 1) a culvert with a design life of 25 years designed to pass a 10-year storm, and 2) a bridge with a design life of 50 years designed to pass a 100-year storm. The updated IDF curves for the Norfolk station resulting from Objective 1 are used and linear increases in risk between design storms is assumed.

## Objective 4: Future IDF Rainfall Forecasts Across Virginia

To explore spatial trends across the Commonwealth of Virginia, the IDF analysis presented in Objective 1 was performed using the historical rainfall records from 29 rainfall observation stations across the Commonwealth with records available through the NOAA National Climatic Data Center (see Figure 6). These 29 stations were all the stations in Virginia which had a period of record of at least 50 years without more than two years of missing data. As with the Norfolk station described above, at these stations the historical data was used in the bias correction of RCM hindcasts, which correction was then applied to the 2045 and 2085 climate forecasts of design storms. This was done for both the RCP 4.5 and RCP 8.5 emission scenarios. The modeled historical storm values were compared to the future design storm values to get a picture of the projected increases in storm design magnitudes across Virginia.

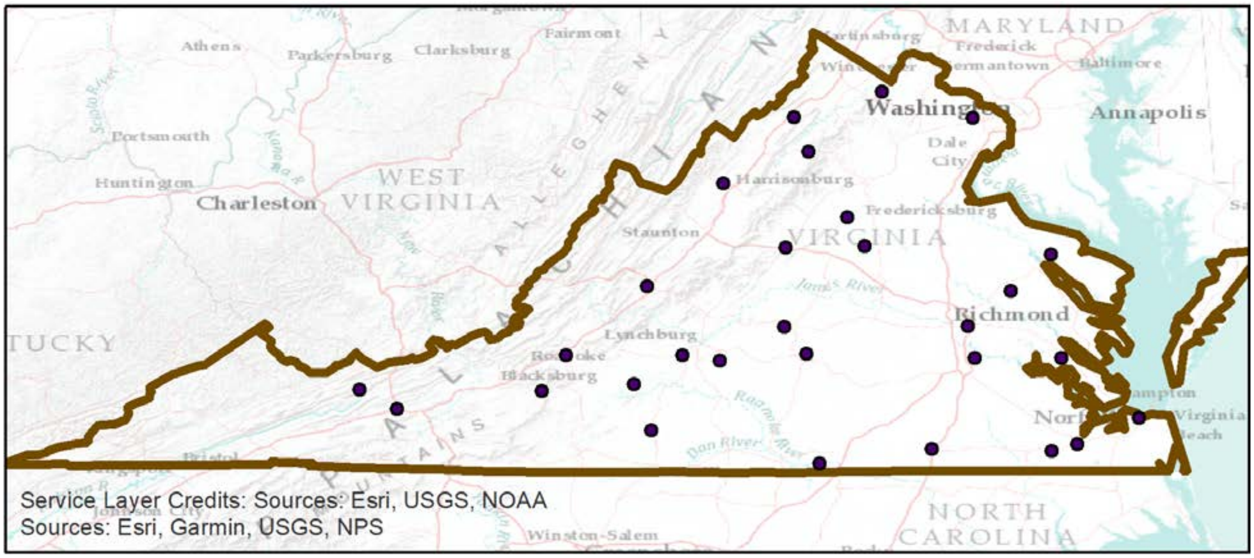


**Figure 6. Locations across Virginia where the future IDF analysis was performed.**

## RESULTS

### Objective 1: Future IDF Analysis for Norfolk Airport Station

The first step in accomplishing Objective 1 was to replicate the design storm values using the historical data from the Norfolk observation station. Figure 7 shows the design storm values from the analysis compared to the design storm values from Atlas 14 (the currently accepted standard) and those in the Dewberry study. As shown in the figure, the values obtained were very similar to the Atlas 14 values. The largest difference (in magnitude and percent difference) between the calculated design storm values in this study and the Atlas 14 values was for the 100-year storm: 0.4 inches, 4% higher than the Atlas 14. The values generated in this analysis were also similar to the values reported in the Dewberry report.

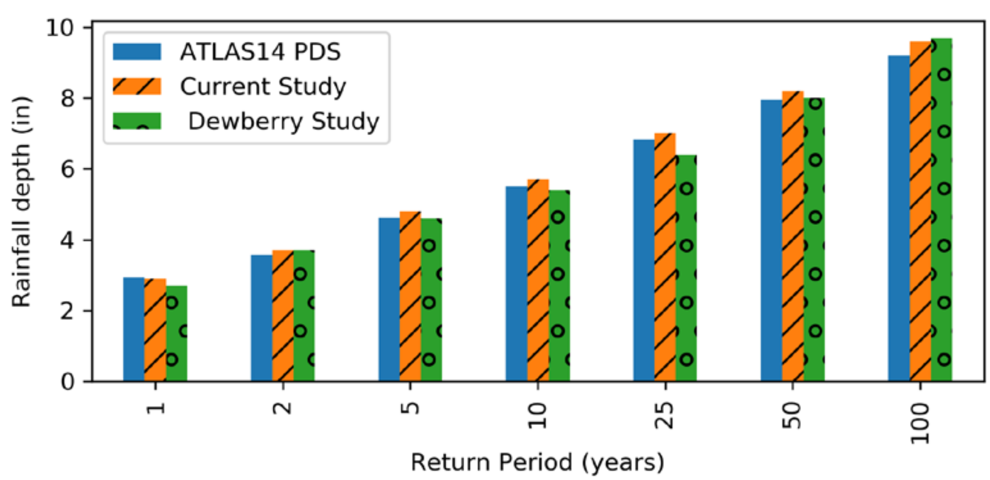


**Figure 7. Comparison between Atlas14, the historical IDF values in the current study and the IDF values from the Dewberry report for the RCP 8.5 emission scenario**

In addition to calculating the IDF values using the historical data, the methods were validated by calculating the annual maximum series (AMS) at the Norfolk Airport. Figure 8 shows the comparison between the values in the current study and the values reported in the Dewberry report including calculating the trend of the data. The results are nearly identical including the slope of the calculated trend line at the same confidence interval. This further verified the methodology of the current study.

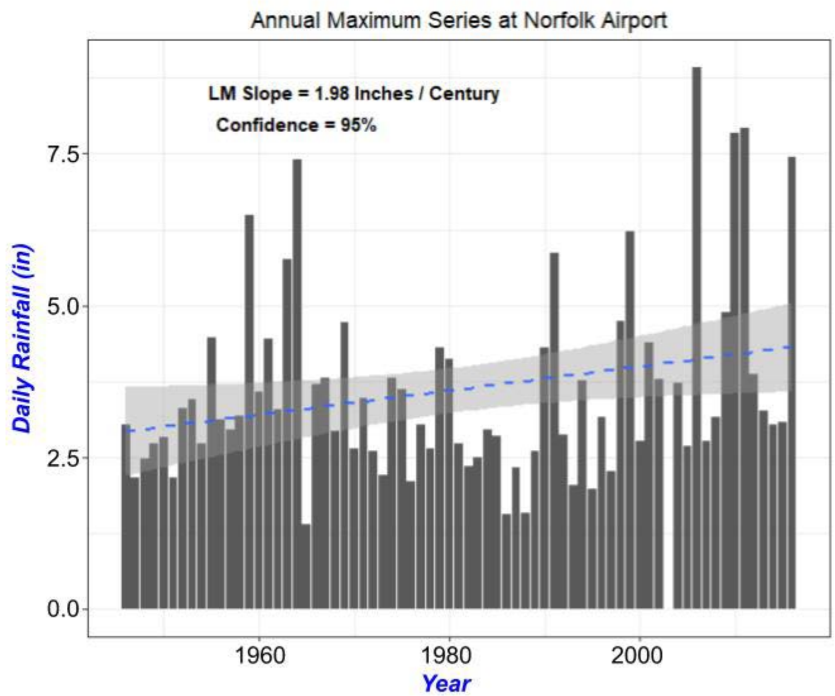


**Figure 8. Trend in annual maximum series rainfall 1950-2015**

With the methods validated against Atlas 14 and the Dewberry report, they were extended to estimate the IDF values using the projected climate data from the RCMs. Table 3 shows the IDF values using the RCM data for periods 2045 and 2085 and the percent increase compared to Atlas 14 under the RCP 4.5 emission scenario. Note that the historical model values for the current study are not the same as those in Figure 7 because the RCMs used in the RCP 4.5 emission scenario were different than those used in the RCP 8.5 emission scenario.

The percent increases in rainfall depth in the modeled future data under the RCP 4.5 emission scenario are all less than 10% in year 2045. Generally, the percent increases are smaller with smaller design storms and even decrease or remain the same in the 5-year, 2-year, and 1-year events. In the year 2085, however, the percent increases are significantly larger, ranging from 8% to 20%, and again are generally smaller for lower return period design storms.

**Table 3. IDF Values (in) for Norfolk Airport Station for Years Centered on 2045 and 2085 Based on RCMs Compared to Historical Model Assuming the RCP 4.5 Emission Scenario.**

| | Historical Model | | 2045 | | 2085 | |
|---|---|---|---|---|---|---|
| Return Period | ATLAS14 PDS | Current Study | Current Study | Increase (%) | Current Study | Increase (%) |
| 1yr | 2.9 | 2.8 | 2.8 | 0 | 3.1 | 11 |
| 2yr | 3.6 | 3.6 | 3.5 | -3 | 3.9 | 8 |
| 5yr | 4.6 | 4.6 | 4.5 | -2 | 5.0 | 9 |
| 10yr | 5.5 | 5.3 | 5.4 | 2 | 6.0 | 13 |
| 25yr | 6.8 | 6.6 | 6.8 | 3 | 7.5 | 14 |
| 50yr | 8.0 | 7.6 | 8.1 | 7 | 9.0 | 18 |
| 100yr | 9.2 | 8.9 | 9.7 | 9 | 10.7 | 20 |

Table 4 shows the IDF values using the RCM data for years 2045 and the percent increase compared to Atlas 14 under the RCP 8.5 emission scenario. Table 5 shows the same for the years 2075 (for comparison against the Dewberry study) and 2085. The increases are much larger for the RCP 8.5 scenario compared to the RCP 4.5 scenario. In the year 2045, the 5 largest of the 7 design storms have increases of between 20-30%. In the year 2085, these increases are all between 30-40%. When comparing the year 2075 and the year 2085, the values did not increase at all for the largest (100-year) and smallest (1-year) storms, however there was a slight increase in the remainder of the design storms.

In addition to the values estimated in this study, the values reported by Dewberry are included in Tables 4 and 5 for comparison. In general, the values that were estimated in this study are comparable to the Dewberry study. The estimates for the year 2085 were nearly identical. The estimates for the year 2045, however, the differences are larger. The larger return period storms had larger increases in the current study compared to the Dewberry report. The 100-year event had a 5% higher rainfall volume increase compared to the Dewberry study.

**Table 4. IDF Values (in) for Norfolk Airport Station for Years Centered on 2045 Based on RCMs Compared to Historical Model and Dewberry Study Given with the RCP 8.5 Emission Scenario**

| | Historical Model | | | 2045 | | | |
|---|---|---|---|---|---|---|---|
| Return Period | ATLAS14 PDS | Current Study | Dewberry Study | Current Study | Increase (%) | Dewberry Study | Increase (%) |
| 1yr | 2.9 | 2.9 | 2.7 | 3.1 | 7 | 3.0 | 11 |
| 2yr | 3.6 | 3.7 | 3.7 | 4.3 | 16 | 4.4 | 19 |
| 5yr | 4.6 | 4.8 | 4.6 | 5.8 | 21 | 5.5 | 20 |
| 10yr | 5.5 | 5.7 | 5.4 | 7.0 | 23 | 6.5 | 20 |
| 25yr | 6.8 | 7.0 | 6.4 | 8.8 | 26 | 7.8 | 22 |
| 50yr | 8.0 | 8.2 | 8.0 | 10.4 | 27 | 9.9 | 24 |
| 100yr | 9.2 | 9.6 | 9.7 | 12.3 | 28 | 11.9 | 23 |

**Table 5. IDF Values (in) for Norfolk Airport Station for Years Centered on 2075 and 2085 Based on RCMs Compared to Historical Model and Dewberry Study**

| | Historical Model | | | 2075 | | | | 2085 | |
|---|---|---|---|---|---|---|---|---|---|
| Return Period | ATLAS14 PDS | Current Study | Dewberry Study | Current Study | Increase (%) | Dewberry Study | Increase (%) | Current Study | Increase (%) |
| 1yr | 2.9 | 2.9 | 2.7 | 3.3 | 14 | 3.2 | 19 | 3.3 | 14 |
| 2yr | 3.6 | 3.7 | 3.7 | 4.6 | 24 | 4.6 | 24 | 4.7 | 27 |
| 5yr | 4.6 | 4.8 | 4.6 | 6.2 | 29 | 5.9 | 28 | 6.4 | 33 |
| 10yr | 5.5 | 5.7 | 5.4 | 7.4 | 30 | 7.1 | 31 | 7.6 | 33 |
| 25yr | 6.8 | 7.0 | 6.4 | 9.4 | 34 | 8.5 | 33 | 9.5 | 36 |
| 50yr | 8.0 | 8.2 | 8.0 | 11.2 | 37 | 10.9 | 36 | 11.2 | 37 |
| 100yr | 9.2 | 9.6 | 9.7 | 13.2 | 38 | 13.2 | 36 | 13.2 | 38 |

The results in Table 4 suggest that the recommendation made in the Dewberry report to increase design storms by 20% may underestimate the increase that will be seen by climate change for higher return period storms. The estimates from the current study for the higher return period storms centered around 2045 were closer to 30%. Additionally, for infrastructure with a longer design life (e.g., 50 years), the results suggest that a larger percent increase would be more appropriate with percent increases centered on 2075 of nearly 30% or more for all design storms larger than the 2-year event. The difference between these results and the Dewberry study results may be explained by differences in the use of RCMs.

The results also suggest that future emissions will have a large impact on the future design storms. The differences between the future IDF estimates under the RCP 8.5 emission scenario were nearly double those estimates under the RCP 4.5 scenario. This impact was much larger than the impact of the time frame. In fact, the estimates centered on 2045 for the RCP 8.5 scenario were greater than those centered on 2085 under the RCP 4.5 scenario.

## Objective 2: Impacts of Future IDF Curves on Peak Runoff

Figure 9 shows the percent increase of peak runoff volumes from the 100-year rainfall event in the year 2045. Appendix A shows the increases in design storms for the rain gauges input into the TUFLOW model. From Figure 9, it can be seen that the change in peak runoff is much more scattered in the watersheds with smaller drainage areas. When looking only at the smaller watersheds (area<25 km) (see Figure 9b), there is no clear trend with drainage areas. Overall, however, larger watersheds had a smaller percent increase. This is consistent with findings by Ganguli & Coulibaly (2017). One possible reason for this is that in larger watersheds, the runoff has more space (longer reach lengths and wider floodplains) and time (longer response times). This would allow the water to spread out more, thus reducing the peak runoff (though may not reduce the total runoff volumes).

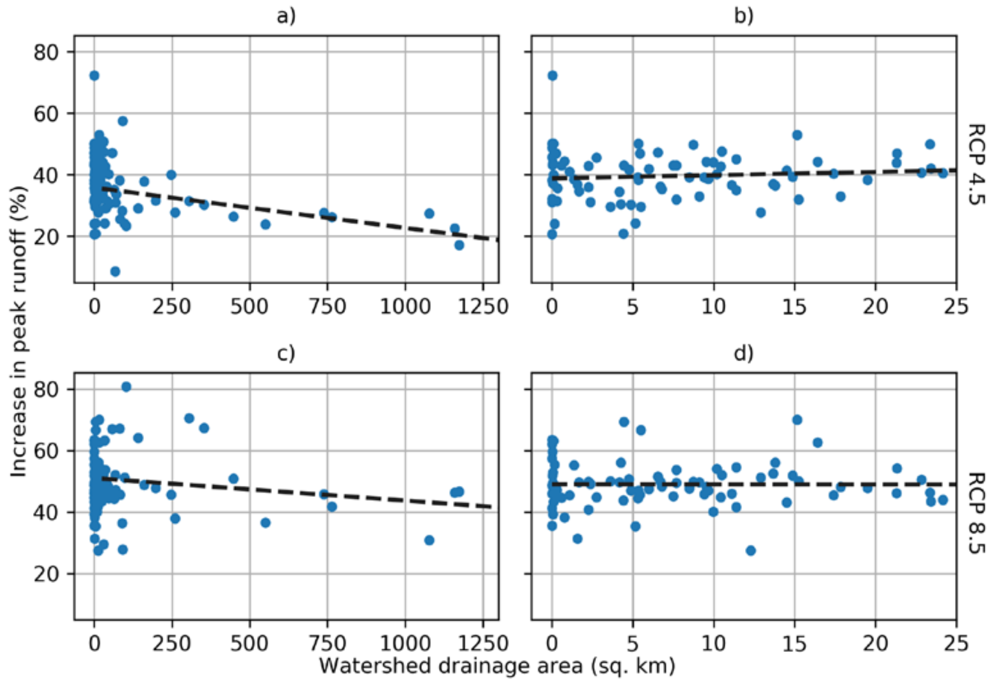


**Figure 9. Percent increase in peak runoff from the 100-year, 24-hour storm event in the year 2045 for all watersheds (a and c) and watersheds with drainage areas less than 25 square km (b and d).**

The pattern of a general trend with larger watersheds and little or no trend with smaller ones was seen to a greater degree with larger design storms. For example, Figure 10 shows the percent increase in peak flow given the 1-year, 10-year, and 100-year design storms compared to the watershed area under the RCP 4.5 emission scenario for the year 2045 and year 2085. The same plots for all seven design storms are given in Appendix B. Included in these plots is a linear trend line that is fit to the points with drainage areas greater than 25 km. In the 1-year event, the trend line is basically flat with a higher magnitude slope in the runoff response to the 100-year event. The main difference in the responses between these two watersheds is a larger percent increase in the runoff in the smaller watersheds compared to the larger watersheds. This suggests that the smaller watersheds will be more sensitive to increased rainfall volumes than large watersheds.

The equations for the trend lines fit to the percent increases in peak flow versus watershed area for RCP 4.5 are given in Table 6. The equations are divided based on watershed area. Watersheds with a drainage area less than 25 square km have a constant estimated percent increase in peak runoff regardless of area. The estimated percent increase in peak runoff for watersheds with a drainage area greater than 25 square km is a function of the drainage area (represented as X within the equations). The slopes for all but 4 of the 14 equations are negative. Additionally, the magnitude of the negative slopes generally increases with larger storm events. This again suggests that the smaller watersheds will be affected more significantly than larger ones in the RCP 4.5 emission scenario.

Another result is that the largest percent increase between the two time periods, year 2045 and 2085, occurs in the mid-range of the design storms (Figure 10). When comparing the increase in peak runoff between year 2045 and 2085, there is only a small change in the 1-year event and the 100-year event compared to the 10-year event where there is a greater percent increase from year 2045 to year 2085 in many of the watersheds. This suggests that climate change may most impact mid-range storms in this region; those with return periods around 10 years compared to smaller (1-year) and larger (100-year) storms.

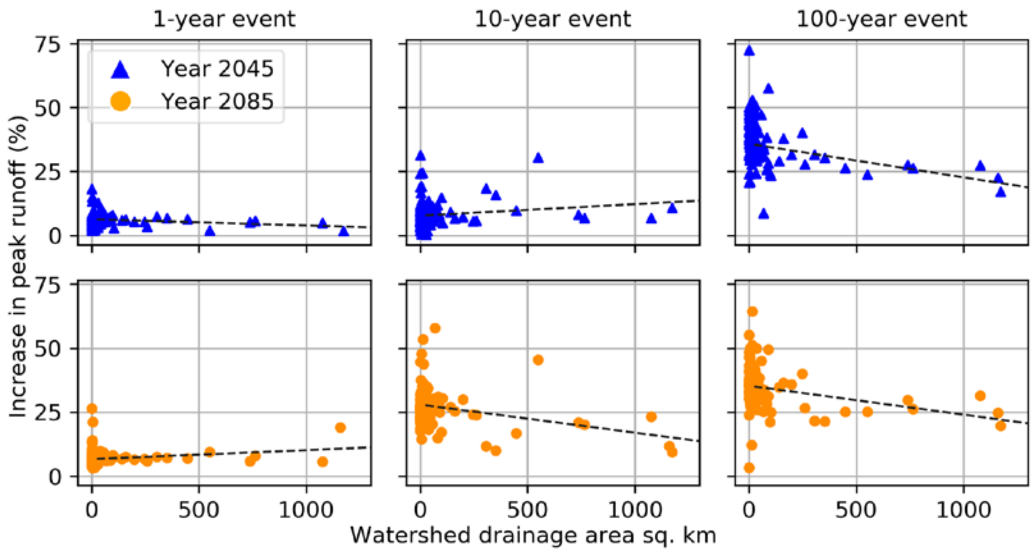


**Figure 10. Percent increase in peak runoff over watershed area for the 1-year, 10-year, and 100-year rainfall events under the RCP 4.5 emission scenario.**

**Table 6. Percent increase in Peak Flow as a Function of Watershed Drainage Area for Years 2045 and 2085 Under the RCP 4.5 Emissions Scenario. The equations are divided based on watershed area. Watersheds with a drainage area less than 25 square km have a constant estimated percent increase in peak runoff regardless of area. The estimated percent increase in peak runoff for watersheds with a drainage area greater than 25 square km is a function of the drainage area (represented as X within the equations).**

| | | Increase in Q-peak (%) | | Correlation coeff, r |
|---|---|---|---|---|
| | | Drainage Area ≤ 25 $Km^2$ | Drainage Area > 25 $Km^2$ | |
| **2045** | **1-Yr** | 7 | Y = -0.0024X + 6.37 | -0.35 |
| | **2-Yr** | 5 | Y = 0.002X + 2.4 | 0.31 |
| | **5-Yr** | 6 | Y = 0.0001X + 5.13 | 0.01 |
| | **10-Yr** | 9 | Y = 0.0045X + 7.77 | 0.26 |
| | **25-Yr** | 17 | Y = -0.0036X + 16.59 | -0.24 |
| | **50-Yr** | 28 | Y = -0.0128X + 26.2 | -0.69 |
| | **100-Yr** | 39 | Y = -0.0131X + 35.8 | -0.45 |
| **2085** | **1-Yr** | 8 | Y = 0.0035X + 6.66 | 0.46 |
| | **2-Yr** | 18 | Y = -0.0028X + 18.56 | -0.24 |
| | **5-Yr** | 31 | Y = -0.0099X + 33.8 | -0.33 |
| | **10-Yr** | 27 | Y = -0.0109X + 27.95 | -0.39 |
| | **25-Yr** | 35 | Y = -0.0118X + 34.58 | -0.55 |
| | **50-Yr** | 36 | Y = -0.013X + 36.5 | -0.51 |
| | **100-Yr** | 36 | Y = -0.0113X + 35.32 | -0.48 |

Figure 11 shows the percent increase in peak runoff for the 1-, 10-, and 100-year events over the watershed areas for RCP 8.5 and Table 7 shows the equations corresponding to the linear trend lines. The percent increases in the RCP 8.5 are much greater compared to the RCP 4.5 scenario, reaching past 100% for some watersheds and design storms. The increase from the 100-year event is 52% in the RCP 8.5 compared to 36% in the RCP 4.5 for the smaller watersheds. In general, the magnitude of the slopes of the trend lines are also greater in the RCP 8.5 scenario (though in Figure 11 it does not appear so because the range of the y-axis is considerably larger than that of the Figure 10). This suggests that the difference in impact between smaller watersheds and larger watersheds will be more pronounced in the RCP 8.5 scenario.

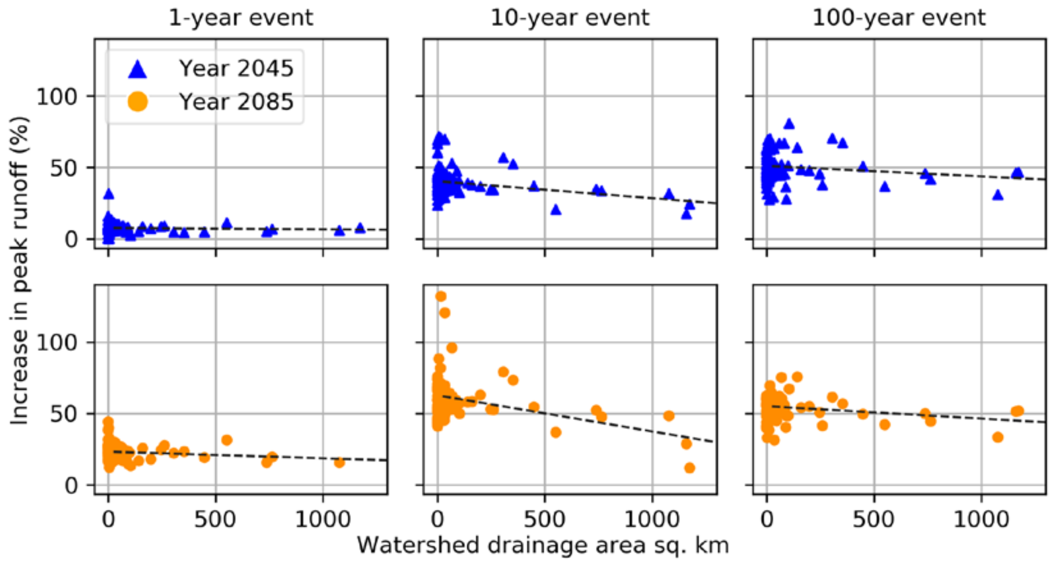


**Figure 11. Percent increase in rainfall volumes for the 1-year, 10-year, and 100-year rainfall events under the RCP 8.5 emission scenario.**

**Table 7. Percent Increase in Peak Flow as a Function of Watershed Drainage Area for Years 2045 and 2085 Under the RCP 8.5 Emissions Scenario. The equations are divided based on watershed area. Watersheds with a drainage area less than 25 square km have a constant estimated percent increase in peak runoff regardless of area. The estimated percent increase in peak runoff for watersheds with a drainage area greater than 25 square km is a function of the drainage area (represented as X within the equations)**

| | | Increase in Q-peak (%) | | |
|---|---|---|---|---|
| | | **Drainage Area ≤ 25 sq. km** | **Drainage Area > 25 sq. km** | **Correlation coeff, r** |
| **2045** | **1-Yr** | 8 | Y = -0.001X + 7.6 | -0.14 |
| | **2-Yr** | 21 | Y = 0.0004X + 21.32 | 0.03 |
| | **5-Yr** | 32 | Y = -0.008X + 33.7 | -0.43 |
| | **10-Yr** | 41 | Y = -0.0119X + 40.31 | -0.41 |
| | **25-Yr** | 46 | Y = -0.0196X + 48.41 | -0.49 |
| | **50-Yr** | 48 | Y = -0.0209X + 52.12 | -0.41 |
| | **100-Yr** | 49 | Y = -0.0073X + 51.02 | -0.22 |
| **2085** | **1-Yr** | 25 | Y = -0.0046X + 23.21 | -0.24 |
| | **2-Yr** | 47 | Y = -0.0133X + 47.28 | -0.56 |
| | **5-Yr** | 54 | Y = -0.018X + 57.43 | -0.43 |
| | **10-Yr** | 58 | Y = -0.0252X + 62.58 | -0.49 |
| | **25-Yr** | 62 | Y = -0.027X + 63.82 | -0.56 |
| | **50-Yr** | 57 | Y = -0.0287X + 65.98 | -0.39 |
| | **100-Yr** | 52 | Y = -0.0087X + 54.99 | -0.31 |

## Objective 3: Equivalent Risk Design Approach

Both of the illustrations of the average annual risk (AAR) method use the updated and non-stationary IDF curves shown in Figure 12 from the Norfolk airport station given in Objective 1. A design value is needed so that the AAR over the design life does not exceed the design standard. The approach can be thought of in a graphical sense. If the non-stationary exceedance probability curve is plotted against time (as in Figure 12) the design storm value can be thought of as a horizontal line which intersects the curve so that the area above the curve equals the area beneath it.

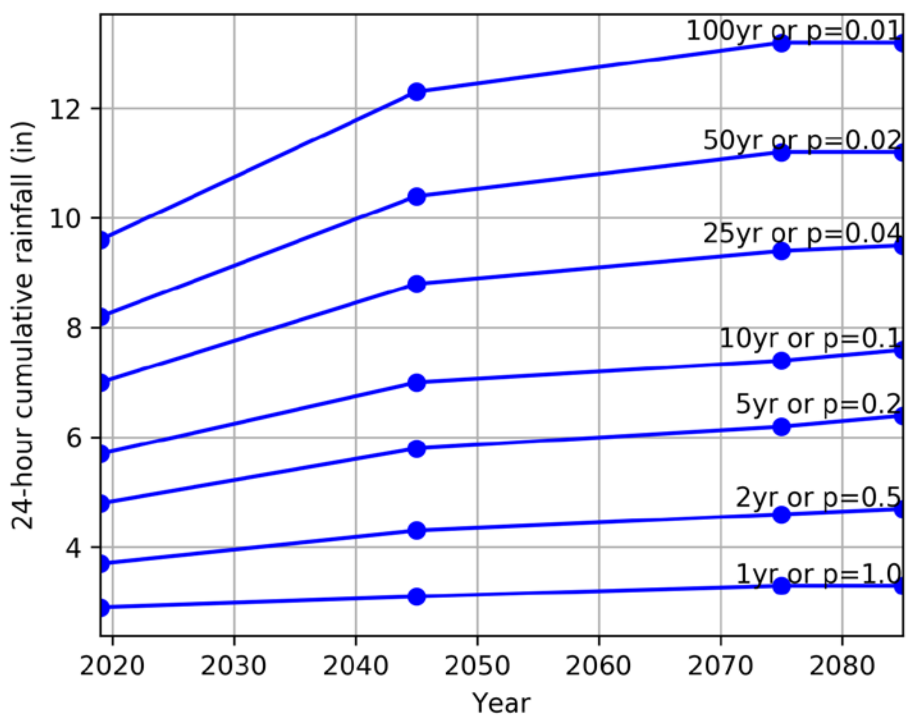


**Figure 12. Graphical representation of increasing IDF values for Norfolk Airport station through 2085.**

### Illustration 1: 25 years design life, passing a 10-year design storm

In the first illustration, the AAR must not exceed 10% (the annual exceedance probability of the 10-year storm) for a design life of 25-years. A constant (linear) increase in risk is assumed for the design life since the end of the design life is before 2045, the somewhat arbitrary year where the analysis in other objectives was divided. To find the value of rainfall that will produce an AAR of 0.1, the engineer simply needs to take the value from the line at the halfway point of the design life (see Figure 13). If an engineer was designing starting at the year 2020, the halfway point of the design life is midway through 2032. Therefore, adding the initial value to the slope of the line gives the design storm value of 6.38 inches. This is also the average of the design storm value at the beginning of the design life and the design storm value at the end of the design life. Based on the exceedance probability curve, for the first half of the design life the structure will be over-designed and for the second half the structure will be under-designed. Assuming a linear difference and equal spacing between exceedance probability curves (not an outlandish assumption based on Figure 12) the amount of over-design will equal the amount of under-design so on average the risk will be 0.1.

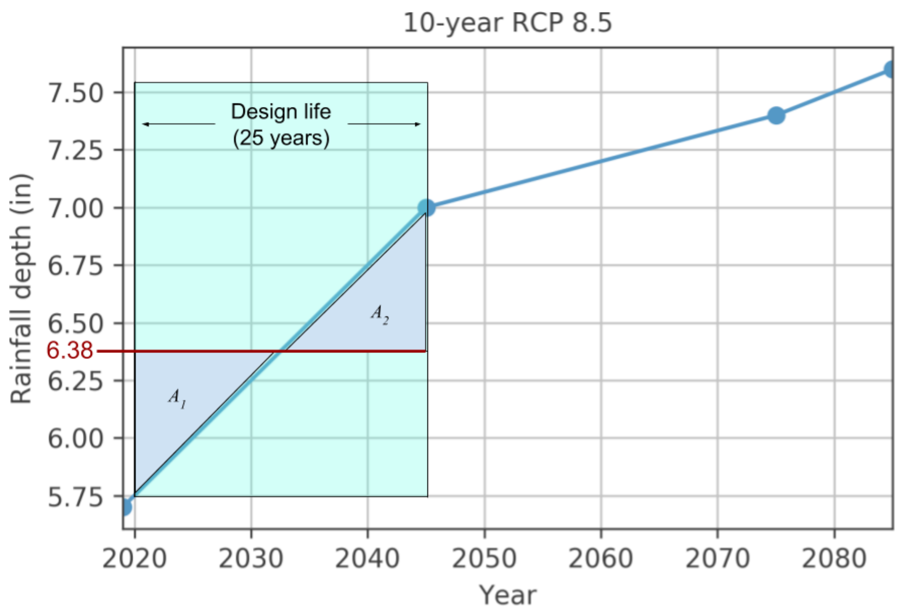


**Figure 13. Graphical representation of AAR for Illustration 1**

### Illustration 2: 50-year design life, passing as 100-year design storm

The second illustration, a design storm for a 100-year storm with a 50-year design life, is more complex. Because the design life is longer, there is more variability in the changes to the design storms. Simply bisecting the return period is not enough because the rate of increase in rainfall is different at the end of the design life compared to the beginning (again, based on the somewhat arbitrary division of the century centered around the year 2045). For this case a system of equations has to be used to develop a solution that will produce the design value where the average will equal the desired risk amount. This was done in a spreadsheet software for this illustration and the solution was found using the spreadsheet's solver functionality. The design value that balanced the over- and under-design (making the AAR=0.01) was 11.8 inches. Details on this analysis are provided in Appendix C.

## Objective 4: Future IDF Rainfall Forecasts across Virginia

Figures 14 and 15 show the spatial variation of rainfall increases across the Commonwealth of Virginia in absolute increase and percent increase respectively. These results are based on the RCM output for the 100-year event in the year 2085 and the RCP 8.5 emission scenario. There is substantial variability but no clear spatial trend in the variation of increases across the Commonwealth. The increases range from 1.2 and 6.6 inches and percent increases from 15.2 to 77.8 percent. Both the coastal plain region and the piedmont region have stations with larger increases and others with smaller increases, with no obvious spatial pattern. For example, the largest increase in terms of inches is 6.6 and is located in the Middle Peninsula of the Hampton Roads region. However, the station closest to it has an increase of only 2.3 inches.

Similarly, in the Piedmont region, stations near Lynchburg have increases of 3.8 and 4.9 inches while a nearby station only has an increase of 1.7 inches.

The percent increases (Figure 15) provide an additional perspective that may better represent the degree to which the increases in rain vary across the Commonwealth. For example, although the increase in inches is much smaller than the 6.6 inches increase in the Hampton Roads region, the two most southwesterly stations have the largest percent increase (65.3% and 77.8%). Therefore, even though the absolute increase in rainfall is similar to many other stations in the Commonwealth, the effect of the increase may be felt more substantially in these two stations where there has been less rain historically.

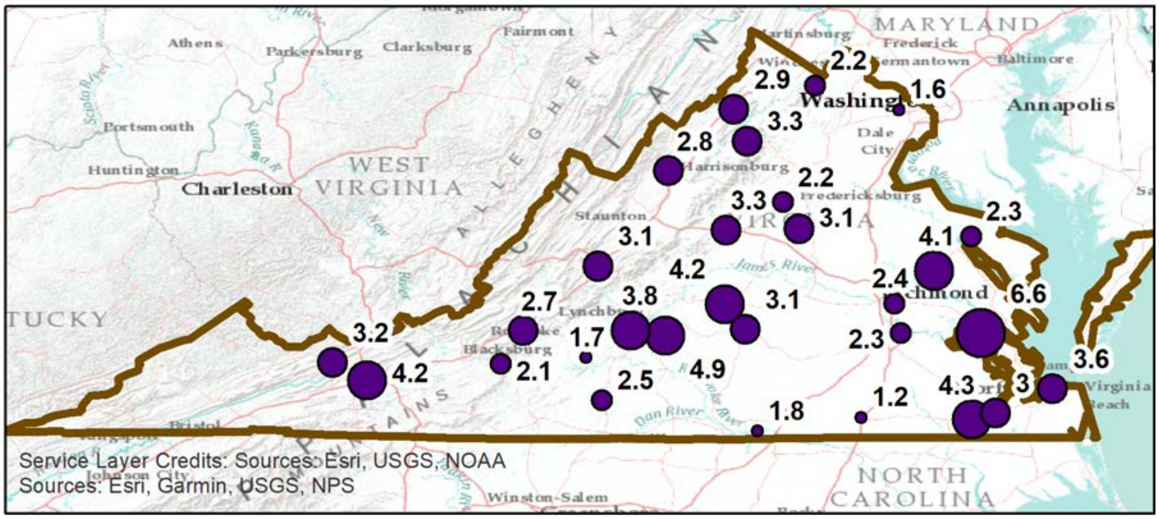


**Figure 14. Increase in the 100-year event in inches across the Commonwealth of Virginia for the year 2085 and the RCP 8.5 emission scenario.**

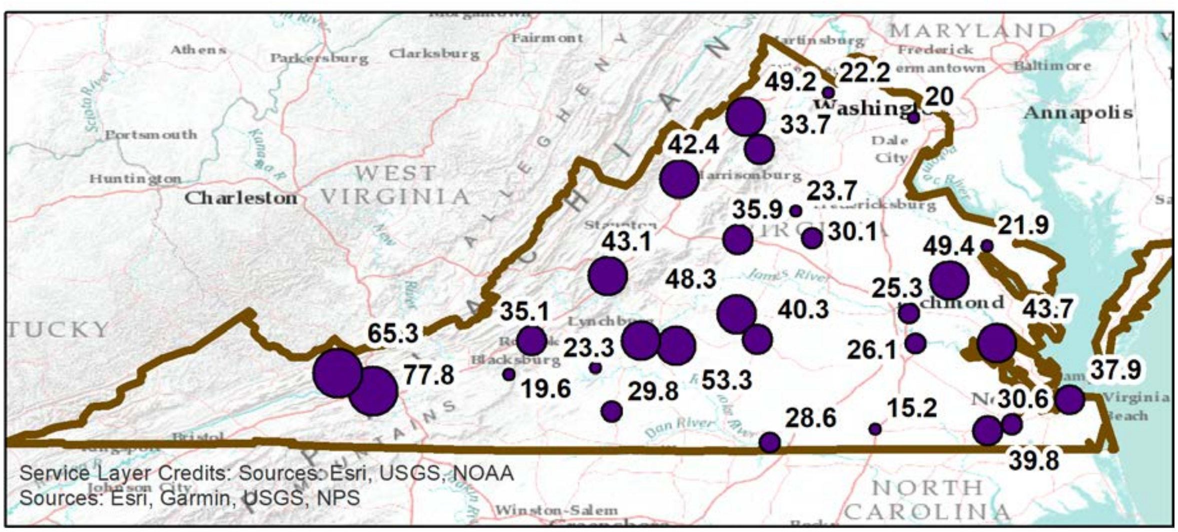


**Figure 15. Percent increase in 100-year storm event across the Commonwealth of Virginia for the year 2085 and the RCP 8.5 emission scenario.**

Figure 16 shows the statistical distribution of increases across all observation stations for all of the design storms. This plot shows that over all of the stations, the median increase in design storm depth is well over 20% by mid-century in the RCP 8.5 scenario. This reinforces the results found in Objective 1 for the Norfolk Airport station alone. The median increase for most of the design storms is close to, or above, 40% by the end-of-century.

Figure 16 also highlights variation across the stations for the different scenarios. The variability in predictions in the RCP 4.5 emission scenario is much greater than that in the RCP 8.5 scenario. There are far more outliers in the RCP 4.5 scenario and most of these outliers are on the upper end of the distribution. The median of the percent increases in the RCP 8.5 scenario are all greater than those of the RCP 4.5 scenario. However, the extreme increases of the RCP 4.5 are greater than those of the RCP 8.5 in the higher return period storms. This may be an artifact of the differences in models that were available for use in the RCP 4.5 scenario versus in the RCP 8.5 scenario.

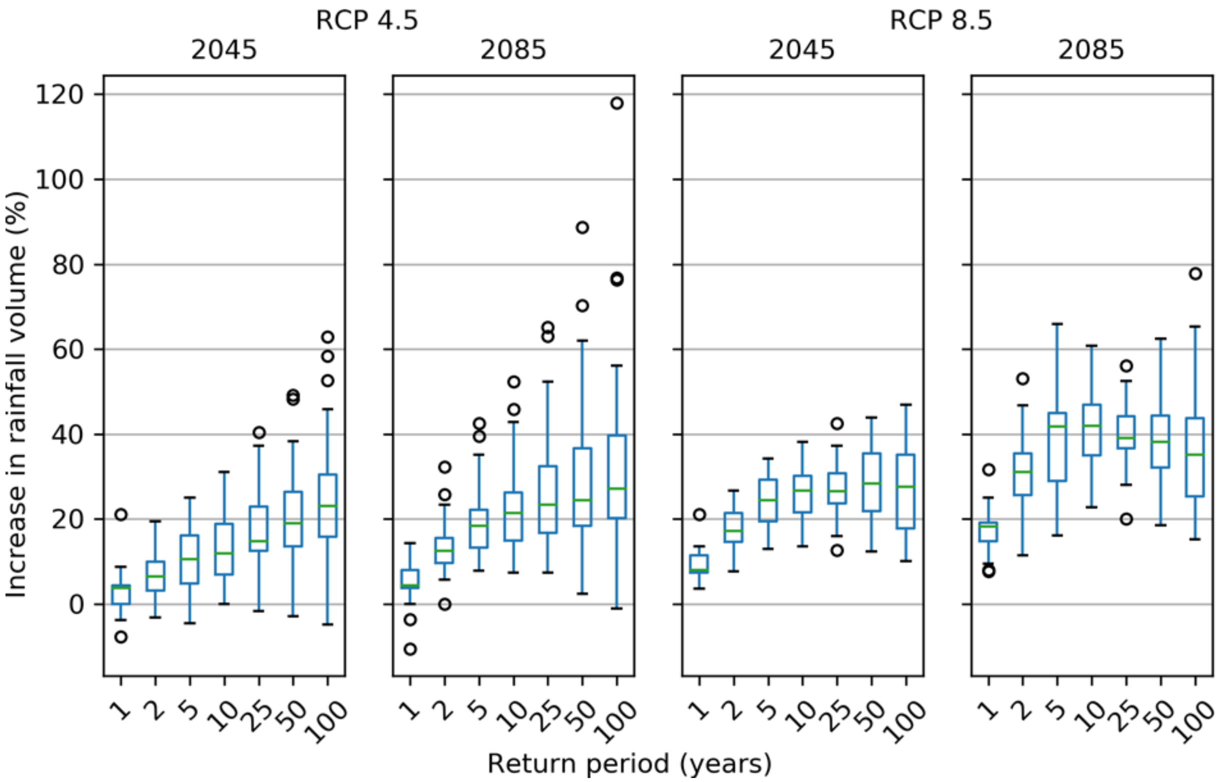


**Figure 16. Distribution of increases in design storm volumes across the 29 observations selected in Virginia.**

## General Discussion

One of the major sources of uncertainty in this study originates from the models used. In Objectives 1 and 4, the IDF curves were derived from an ensemble of RCMs. These IDF curves were also used in Objective 2 as input for the 2-dimensional streamflow model. Each RCM has parameters and simplifications of reality that introduce uncertainty. Although the ability of the RCMs to model future conditions with accuracy is uncertain, the models have been shown to adequately replicate historic climatic patterns lending confidence in their use.

In Objective 2, the TUFLOW model is used extensively. As with the RCMs, how accurately TUFLOW represents the behavior of streamflow in such a large basin is uncertain and the results must be understood in that light. That said, as with the RCMs, the TUFLOW model has been calibrated and demonstrated to adequately represent the physical behavior of the stream flow (Morsy et al., 2019). Additionally, these findings are based on a model of only one area of the Commonwealth. Watersheds with different physical characteristics may respond differently to increases in design storm volumes.

## CONCLUSIONS

- *By mid-century, rainfall depths for 5-year design storms and larger increased by 20-30% (avg. 25%) for the Norfolk airport station using the RCP 8.5 emission scenario. By the end-of-century, the increases the same design storms were between 30-40% (avg. 35%) under this emission scenario.*

- *Modeled increases are much smaller for the RCP 4.5 scenario compared to the RCP 8.5 scenario for the Norfolk airport station. By mid-century, modeled rainfall depths for all design storms increased by less than 10%. By the end-of-century, the increases ranged from 8% to 20% with an average of 13%.*

- *The emissions scenario had a large impact on the estimated future IDF curves with the IDF values for the RCP 8.5 scenario being roughly double those of the RCP 4.5 scenario.*

- *Estimated increases in design storm magnitudes are predicted to increase peak runoff values for watersheds as a function of the watershed's drainage area for watersheds larger than 25 sq km. Smaller watersheds will have increases in peak flow that are not a function of the watershed's drainage area. Overall, the percent increases in peak flow were greater in the smaller watersheds compared to larger watersheds.*

- *The average annual risk (AAR) method can be combined with updated mid-century and end-of-century IDF curves to determine design storm rainfall depths that account for a non-stationary climate.*

- *Results suggest there is a consistent increase in rainfall depth for future IDF curves at rainfall stations across the Commonwealth. There was a large variability in increases across these stations, however no apparent spatial trend was found in the records.*

- *The median increase across all stations in the Commonwealth was generally between 10-30% for the mid-century period for both emission scenarios. The increase was most pronounced for storms with larger return periods. For the end-century period, median increases were more sensitive to emission scenario and ranged generally between 10-40%.*

## RECOMMENDATIONS

1. *VDOT's Structure and Bridge Division and Location and Design Division should use the findings from this study to update the design standards involving storm water runoff.* When VDOT assets are designed using rainfall data, the values should be increased to account for the greater rainfall predicted and reported in this study.

2. *VDOT's Structure and Bridge Division and Location and Design Division should use the findings from this study to update the design standards involving stream flows*. When VDOT assets are designed using discharge data not derived from rainfall, the values should be increased to account for the greater discharges predicted and reported in this study.

## IMPLEMENTATION AND BENEFITS

### Implementation

With regard to Recommendation 1, VDOT's Structure and Bridge Division and Location and Design Division will use the findings from this study as the basis for decisions on updating the design standards for VDOT roadway drainage, storm water management and BMPs. The updated standards will be released by January 1, 2021.

With regard to Recommendation 2, VDOT's Structure and Bridge Division and Location and Design Division will use the findings from this study as the basis for decisions on updating the design standards for VDOT culverts and bridges. The updated standards will be released by September 1, 2020.

For these recommendations, VDOT Structure and Bridge Division will contact the Special Assistant to the Governor for Coastal Adaptation and Protection to verify that the upcoming changes to the design standards generally align with climate change models/scenarios that will be adopted by the state government. This review will be completed within 6 months of the release Virginia's Climate Action Plan report.

### Benefits

Implementing Recommendation 1 will ensure that new VDOT roadway drainage elements better accommodate increased precipitation volumes and associated discharges predicted over the lifetime of the structures. Integrating the estimated non-stationarity values reported in this study into structure design can maintain the originally-specified level of risk over the course of a structure's design life.

Implementing Recommendation 2 will ensure that new VDOT stream crossings elements better accommodate increased discharges predicted over the lifetime of the structures.

Integrating the estimated non-stationarity values reported in this study into structure design can maintain the originally-specified level of risk over the course of a structure's design life.

## ACKNOWLEDGEMENTS

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## APPENDIX A. INCREASES IN DESIGN STORMS APPLIED TO TUFLOW MODEL IN OBJECTIVE 2

**Table A1. IDF Values (in) for Station USC00444101 for Years Centered on 2045 and 2085 Based on RCMs Compared to Historical Model Assuming the RCP 4.5 Emission Scenario.**

| | Historical Model | | 2045 | | 2085 | |
|---|---|---|---|---|---|---|
| Return Period (Yrs) | ATLAS14 PDS | Current Study | Current Study | Increase (%) | Current Study | Increase (%) |
| 100yr | 8.48 | 8.2 | 9.7 | 18 | 9 | 10 |
| 50yr | 7.36 | 6.8 | 8 | 18 | 7.9 | 16 |
| 25yr | 6.33 | 5.8 | 6.6 | 14 | 6.8 | 17 |
| 10yr | 5.14 | 4.6 | 5.2 | 13 | 5.6 | 22 |
| 5yr | 4.33 | 3.9 | 4.3 | 10 | 4.8 | 23 |
| 2yr | 3.38 | 3.2 | 3.4 | 6 | 3.7 | 16 |
| 1yr | 2.79 | 2.5 | 2.7 | 8 | 2.7 | 8 |

**Table A2. IDF Values (in) for Station USC00444101 for Years Centered on 2045 and 2085 Based on RCMs Compared to Historical Model Assuming the RCP 8.5 Emission Scenario.**

| | Historical Model | | 2045 | | 2085 | |
|---|---|---|---|---|---|---|
| Return Period (Yrs) | ATLAS14 PDS | Current Study | Current Study | Increase (%) | Current Study | Increase (%) |
| 100yr | 8.48 | 8.8 | 11.9 | 35 | 11.1 | 26 |
| 50yr | 7.36 | 7.2 | 9.8 | 36 | 9.7 | 35 |
| 25yr | 6.33 | 5.9 | 8.1 | 37 | 8.4 | 42 |
| 10yr | 5.14 | 4.7 | 6.3 | 34 | 6.8 | 45 |
| 5yr | 4.33 | 4 | 5.2 | 30 | 5.7 | 43 |
| 2yr | 3.38 | 3.2 | 3.8 | 19 | 4.4 | 38 |
| 1yr | 2.79 | 2.6 | 2.7 | 4 | 3.1 | 19 |

**Table A3. IDF Values (in) for Station USC00449151 for Years Centered on 2045 and 2085 Based on RCMs Compared to Historical Model Assuming the RCP 4.5 Emission Scenario.**

| | Historical Model | | 2045 | | 2085 | |
|---|---|---|---|---|---|---|
| Return Period (Yrs) | ATLAS14 PDS | Current Study | Current Study | Increase (%) | Current Study | Increase (%) |
| 100yr | 9.24 | 13.2 | 15.8 | 20 | 17.3 | 31 |
| 50yr | 7.97 | 9.8 | 11.2 | 14 | 13 | 33 |
| 25yr | 6.83 | 7.4 | 8.2 | 11 | 9.8 | 32 |
| 10yr | 5.51 | 5.3 | 5.6 | 6 | 6.9 | 30 |
| 5yr | 4.62 | 4.2 | 4.4 | 5 | 5.3 | 26 |
| 2yr | 3.57 | 3.2 | 3.3 | 3 | 3.8 | 19 |
| 1yr | 2.94 | 2.6 | 2.7 | 4 | 2.7 | 4 |

**Table A4. IDF Values (in) for Station USC00449151 for Years Centered on 2045 and 2085 Based on RCMs Compared to Historical Model Assuming the RCP 8.5 Emission Scenario.**

| | Historical Model | | 2045 | | 2085 | |
|---|---|---|---|---|---|---|
| Return Period (Yrs) | ATLAS14 PDS | Current Study | Current Study | Increase (%) | Current Study | Increase (%) |
| 100yr | 9.24 | 15.1 | 20.8 | 38 | 21.7 | 44 |
| 50yr | 7.97 | 11 | 15.1 | 37 | 16.4 | 49 |
| 25yr | 6.83 | 8.2 | 11.1 | 35 | 12.4 | 51 |
| 10yr | 5.51 | 5.8 | 7.5 | 29 | 8.7 | 50 |
| 5yr | 4.62 | 4.5 | 5.6 | 24 | 6.7 | 49 |
| 2yr | 3.57 | 3.4 | 3.9 | 15 | 4.6 | 35 |
| 1yr | 2.94 | 2.7 | 2.8 | 4 | 3.2 | 19 |

**Table A5. IDF Values (in) for Station USC00448192 for Years Centered on 2045 and 2085 Based on RCMs Compared to Historical Model Assuming the RCP 4.5 Emission Scenario.**

| | Historical Model | | 2045 | | 2085 | |
|---|---|---|---|---|---|---|
| Return Period (Yrs) | ATLAS14 PDS | Current Study | Current Study | Increase (%) | Current Study | Increase (%) |
| 100yr | 9.28 | 9 | 11.5 | 28 | 11.1 | 23 |
| 50yr | 8.04 | 7.6 | 9.1 | 20 | 9.3 | 22 |
| 25yr | 6.91 | 6.4 | 7.2 | 13 | 7.8 | 22 |
| 10yr | 5.59 | 5.1 | 5.4 | 6 | 6.2 | 22 |
| 5yr | 4.69 | 4.3 | 4.4 | 2 | 5.1 | 19 |
| 2yr | 3.64 | 3.4 | 3.3 | -3 | 3.8 | 12 |
| 1yr | 2.99 | 2.6 | 2.6 | 0 | 2.7 | 4 |

**Table A6. IDF Values (in) for Station USC00448192 for Years Centered on 2045 and 2085 Based on RCMs Compared to Historical Model Assuming the RCP 8.5 Emission Scenario.**

| | Historical Model | | 2045 | | 2085 | |
|---|---|---|---|---|---|---|
| Return Period (Yrs) | ATLAS14 PDS | Current Study | Current Study | Increase (%) | Current Study | Increase (%) |
| 100yr | 9.28 | 9.8 | 12.5 | 28 | 12.8 | 31 |
| 50yr | 8.04 | 8.1 | 10.4 | 28 | 10.7 | 32 |
| 25yr | 6.91 | 6.8 | 8.6 | 26 | 8.9 | 31 |
| 10yr | 5.59 | 5.3 | 6.7 | 26 | 7 | 32 |
| 5yr | 4.69 | 4.5 | 5.5 | 22 | 5.8 | 29 |
| 2yr | 3.64 | 3.5 | 4 | 14 | 4.4 | 26 |
| 1yr | 2.99 | 2.8 | 2.9 | 4 | 3.2 | 14 |

**Table A7. IDF Values (in) for Station USC00444044 for Years Centered on 2045 and 2085 Based on RCMs Compared to Historical Model Assuming the RCP 4.5 Emission Scenario.**

| | Historical Model | | 2045 | | 2085 | |
|---|---|---|---|---|---|---|
| Return Period (Yrs) | ATLAS14 PDS | Current Study | Current Study | Increase (%) | Current Study | Increase (%) |
| 100yr | 9.22 | 9.5 | 12.4 | 31 | 12.1 | 27 |
| 50yr | 7.99 | 7.9 | 9.4 | 19 | 9.7 | 23 |
| 25yr | 6.87 | 6.6 | 7.2 | 9 | 7.9 | 20 |
| 10yr | 5.56 | 5.2 | 5.2 | 0 | 6 | 15 |
| 5yr | 4.67 | 4.4 | 4.2 | -5 | 4.9 | 11 |
| 2yr | 3.62 | 3.4 | 3.3 | -3 | 3.6 | 6 |
| 1yr | 2.98 | 2.6 | 2.7 | 4 | 2.7 | 4 |

**Table A8. IDF Values (in) for Station USC00444044 for Years Centered on 2045 and 2085 Based on RCMs Compared to Historical Model Assuming the RCP 8.5 Emission Scenario.**

| | Historical Model | | 2045 | | 2085 | |
|---|---|---|---|---|---|---|
| Return Period (Yrs) | ATLAS14 PDS | Current Study | Current Study | Increase (%) | Current Study | Increase (%) |
| 100yr | 9.22 | 10.8 | 14.3 | 32 | 15.1 | 40 |
| 50yr | 7.99 | 8.8 | 11.2 | 27 | 12 | 36 |
| 25yr | 6.87 | 7.1 | 8.8 | 24 | 9.6 | 35 |
| 10yr | 5.56 | 5.5 | 6.5 | 18 | 7.2 | 31 |
| 5yr | 4.67 | 4.5 | 5.2 | 16 | 5.7 | 27 |
| 2yr | 3.62 | 3.4 | 3.8 | 12 | 4.2 | 24 |
| 1yr | 2.98 | 2.6 | 2.8 | 8 | 3.1 | 19 |

# APPENDIX B: SUPPLEMENTARY MATERIALS

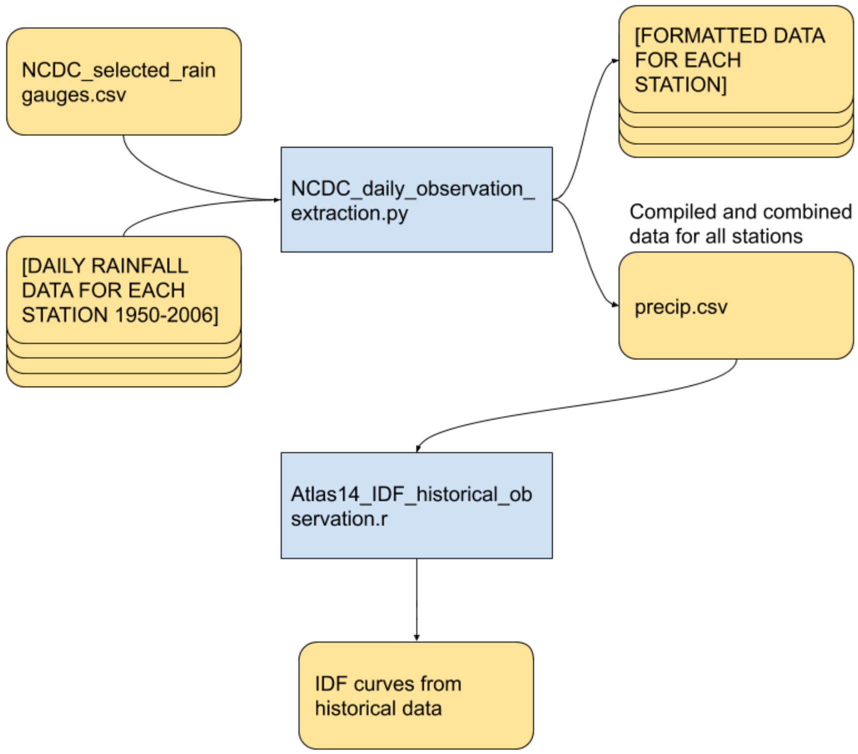


**Figure B1. Workflow for producing IDF curves from historical data**

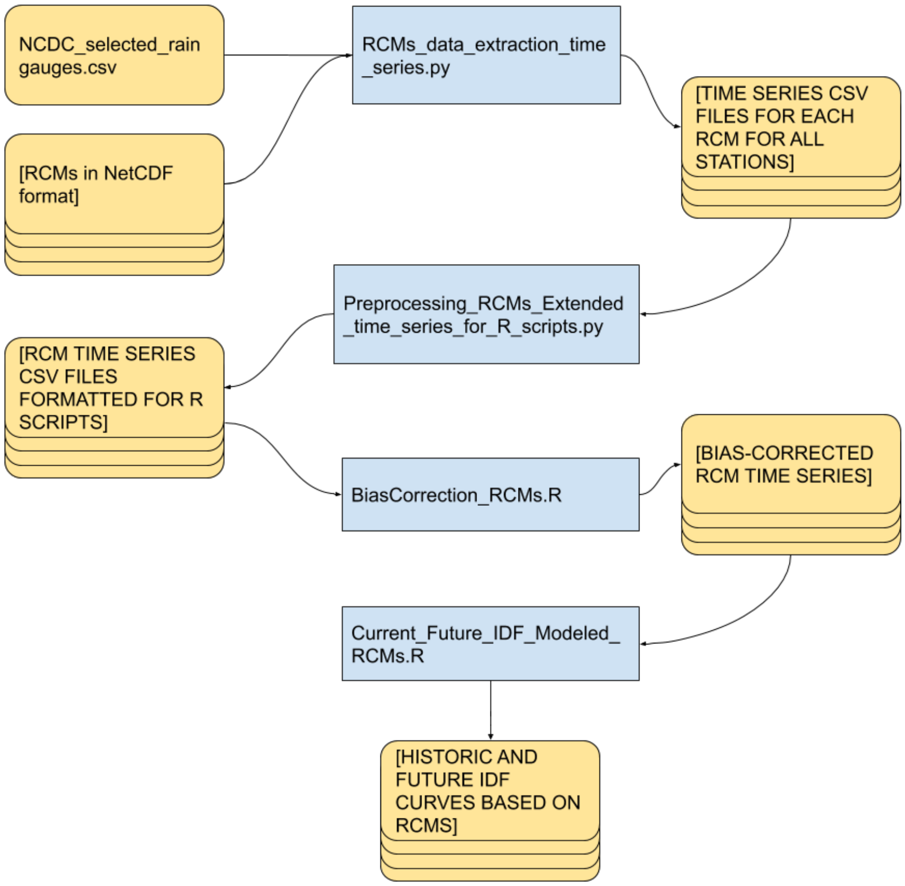


**Figure B2. Workflow for obtaining future IDF values**

**Table B1. NOAA rain gauges used for precipitation IDF**

| Station ID | Station Name | Latitude | Longitude | Elevation | Start | End | Record Length (years) |
|---|---|---|---|---|---|---|---|
| USC00445851 | Mount Weather | 39.0643 | -77.8883 | 505.7 | 1914 | 2017 | 103 |
| USC00445050 | Louisa | 38.0421 | -78.0061 | 128 | 1916 | 2019 | 103 |
| USC00444101 | Hopewell | 37.2992 | -77.2775 | 12.2 | 1916 | 2019 | 103 |
| USC00441614 | Chatham | 36.8224 | -79.4104 | 198.4 | 1922 | 2019 | 97 |
| USC00448737 | Vienna | 38.8922 | -77.2892 | 127.4 | 1925 | 2019 | 94 |
| USC00448829 | Walkerton 2 NW | 37.7434 | -77.04 | 15.2 | 1932 | 2019 | 87 |
| USC00444044 | Holland 1 E | 36.683 | -76.7684 | 24.4 | 1933 | 2018 | 85 |
| USW00013740 | Richmond International Airport | 37.51151 | -77.32344 | 50 | 1939 | 2019 | 80 |
| USC00441999 | Copper Hill | 37.08169 | -80.13486 | 870.8 | 1940 | 2019 | 79 |
| USC00445096 | Luray 5 E | 38.6661 | -78.3727 | 426.7 | 1941 | 2019 | 78 |
| USW00013733 | Lynchburg International Airport | 37.3208 | -79.2067 | 286.5 | 1944 | 2019 | 75 |
| USC00448192 | Suffolk Lake Kilby | 36.7297 | -76.6015 | 6.7 | 1945 | 2019 | 74 |
| USW00013737 | Norfolk International Airport | 36.9033 | -76.1922 | 9.1 | 1945 | 2019 | 74 |
| USC00446712 | Piedmont Research Station | 38.2323 | -78.1202 | 158.5 | 1946 | 2019 | 73 |
| USW00013741 | Roanoke International Airport | 37.3169 | -79.9741 | 358.1 | 1947 | 2019 | 72 |
| USC00444414 | John H Kerr Dam | 36.6002 | -78.3011 | 76.2 | 1948 | 2019 | 71 |
| USC00449151 | Williamsburg 2 N | 37.3017 | -76.7039 | 21.3 | 1948 | 2019 | 71 |
| USC00441955 | Concord 4 SSW | 37.2819 | -78.9591 | 248.4 | 1950 | 2019 | 69 |
| USC00444148 | Huddleston 4 SW | 37.12587 | -79.5251 | 273.4 | 1950 | 2019 | 69 |
| USC00444876 | Lexington | 37.7767 | -79.4385 | 334.4 | 1889 | 2019 | 130 |
| USC00449263 | Woodstock 2 NE | 38.8969 | -78.4679 | 205.7 | 1889 | 2019 | 130 |
| USC00441593 | Charlottesville 2 W | 38.0329 | -78.5226 | 264 | 1892 | 2019 | 127 |
| USC00442208 | Dale Enterprise | 38.4547 | -78.9352 | 413.9 | 1892 | 2019 | 127 |
| USC00442790 | Emporia 1 WNW | 36.6983 | -77.5597 | 30.5 | 1892 | 2019 | 127 |
| USC00448894 | Warsaw 2 NW | 37.9881 | -76.7769 | 42.7 | 1892 | 2019 | 127 |
| USC00449301 | Wytheville | 36.9617 | -81.087 | 749.2 | 1892 | 2019 | 127 |
| USC00441136 | Buckingham | 37.5083 | -78.5333 | 176.8 | 1894 | 2019 | 125 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| USC00441209 | Burkes Garden | 37.0908 | -81.33639 | 935.1 | 1896 | 2019 | 123 |
| USC00442941 | Farmville 2 N | 37.3263 | -78.3864 | 137.2 | 1897 | 2019 | 122 |

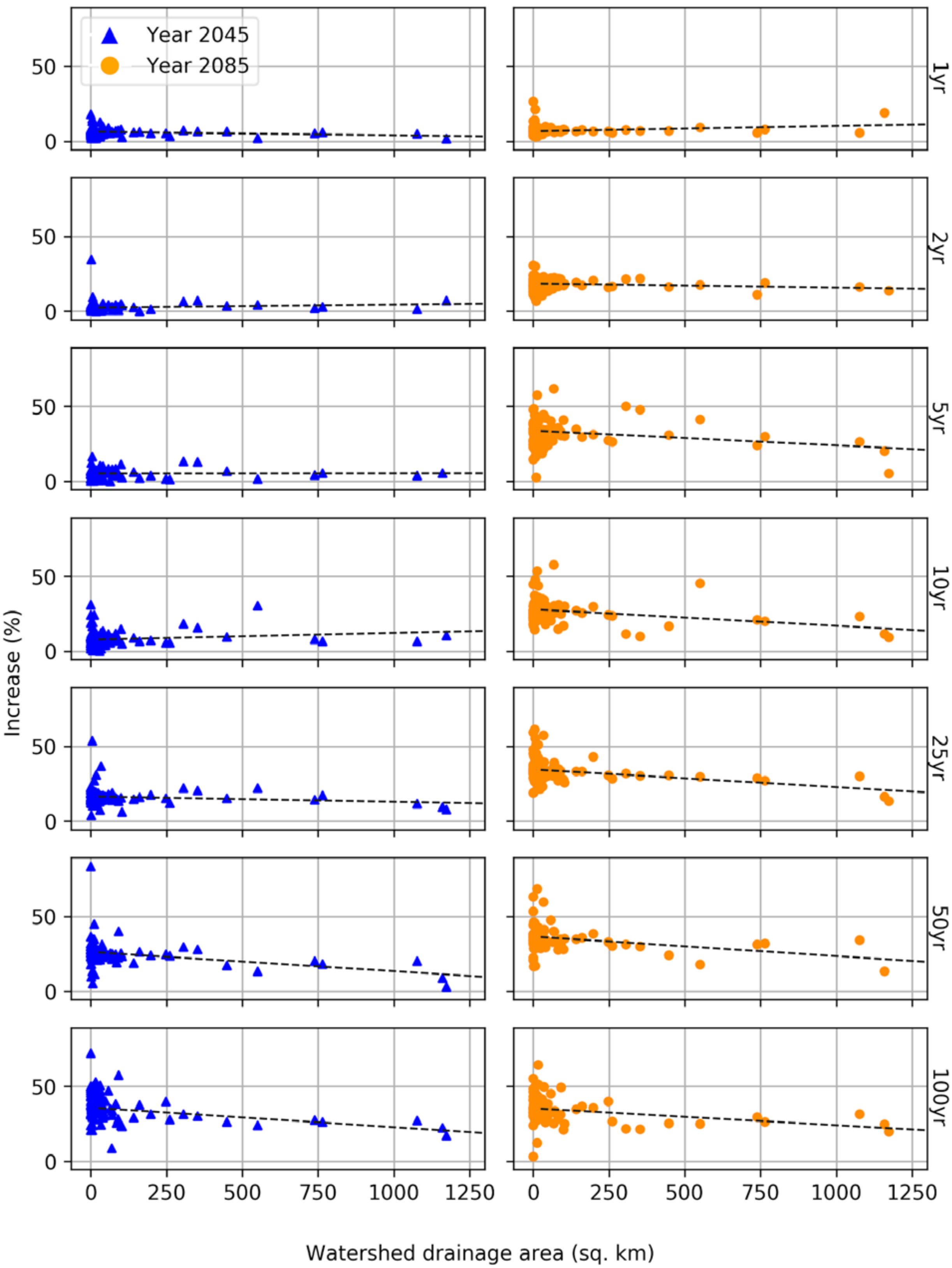


**Figure B3. Percent increase of peak flow for design storms versus watershed drainage area for watersheds in TUFLOW model domain under RCP 4.5**

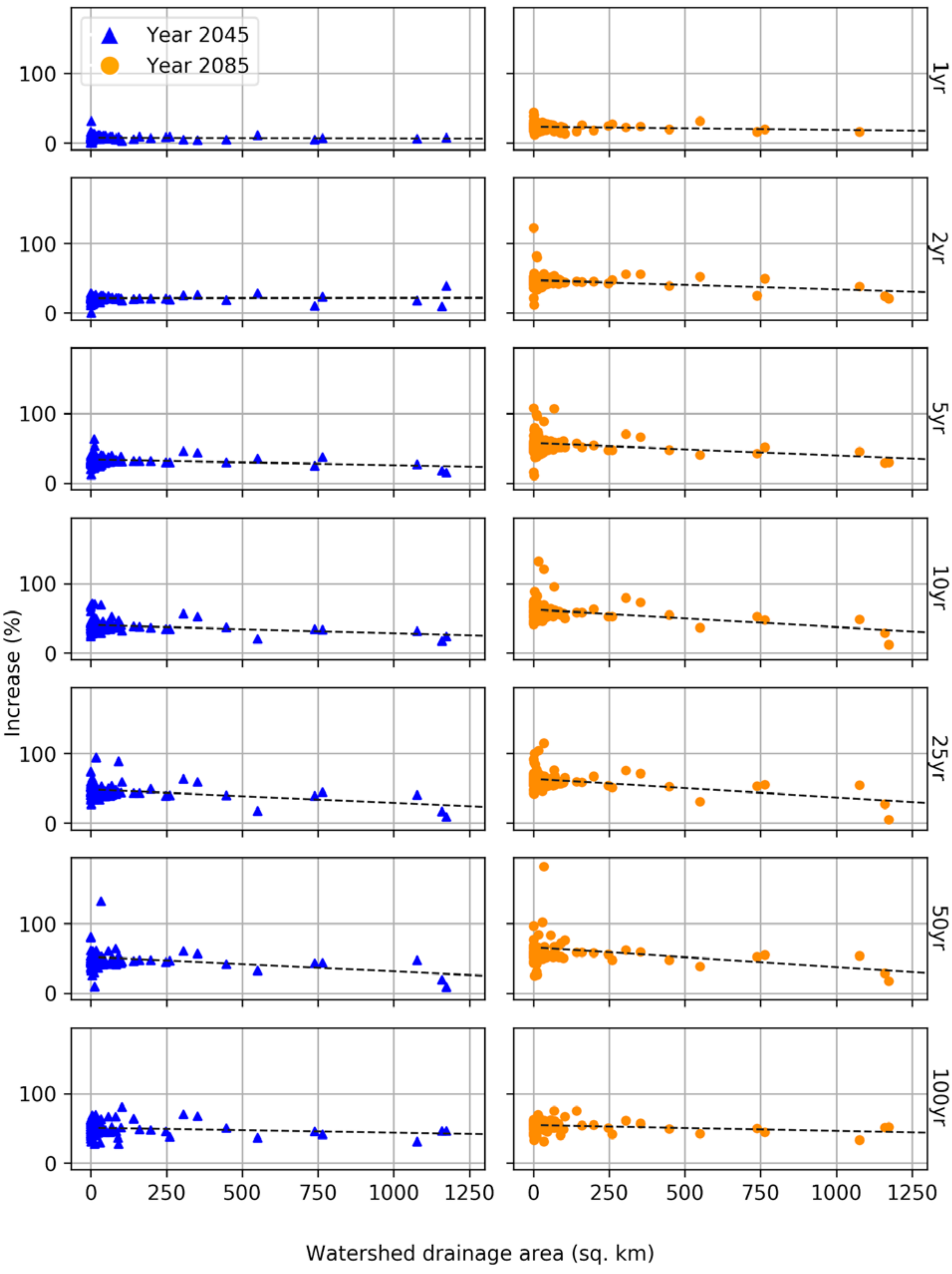


**Figure B4. Percent increase of peak flow for design storms versus watershed drainage area for watersheds in TUFLOW model domain under RCP 8.5**

## APPENDIX C. AAR CALCULATIONS FOR ILLUSTRATION 2

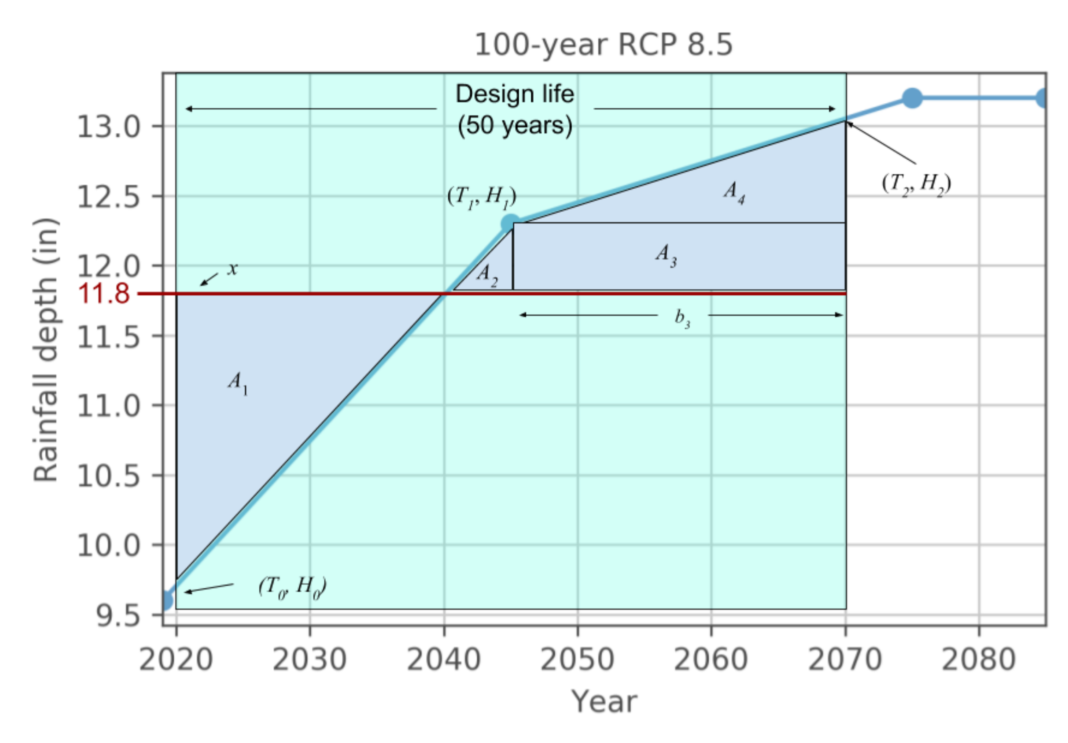


**Figure C1. Diagram illustrating AAR for Illustration 2**

Known equations (referring to Figure B1).

$$A_1 = A_2 + A_3 + A_4 \qquad (1)$$

Assume that the design rainfall depth, $x$, is less than the depth at $T_1$ , $H_1$.

Put area equations in terms of $H_0$, $H_1$,, $H_2$, $m_1$, and, $b_3$ where $m_1$ is the slope of the exceedance probability curve between $T_0$ *and* $T_1$.

$$A_1 = \frac{(x - H_0)^2}{2m_1}$$

$$A_2 = \frac{(H_1 - x)^2}{2m_1}$$

$$A_3 = (H_1 - x) * b_3$$

$$A_4 = (H_2 - H_1) * b_3 \quad * 0.5$$

You can substitute these into (1), set equal to zero and use a solver to find $x$ that satisfies the equation. In the example case, $x$ ends up being 11.8 inches.