Extreme Precipitation and Runoff under Changing Climate in Southern Maine

Environmental Science Division

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1. Introduction

The quantification of extreme precipitation events is vitally important for designing and engineering water and flood sensitive infrastructure. Since this kind of infrastructure is usually built to last much longer than 10, 50, or even 100 years, there is great need for statistically sound estimates of the intensity of 10-, 50-, 100-, and 500-year rainstorms and associated floods.

The recent assessment indicated that the intensity of the most extreme precipitation events (or the heaviest 1% of all daily events) have increased in every region of the contiguous states since the 1950s (Melillo et al. 2014). The maximum change in precipitation intensity of extreme events occurred in the northeast region reaching 71%. The precipitation extremes can be characterized using intensity-duration-frequency analysis (IDF). However, the current IDFs in this region were developed around the assumption that climate condition remains stationary over the next 50 or 100 years. To better characterize the potential flood risk, this project will (1) develop precipitation IDFs on the basis of both historical observations and future climate projections from dynamic downscaling with Argonne National Laboratory's (Argonne's) regional climate model and (2) develop runoff IDFs using precipitation IDFs for the Casco Bay Watershed. IDF development also considers non-stationary distribution models and snowmelt effects that are not incorporated in the current IDFs.

The IDF curves can be used for many engineering designs: (1) urban drainage system (e.g., stormwater system, sewer system), which may require conveyance capacity for 5- to 10-year rainfall events; (2) road designs, which may need to meet criteria for 50-year storm events for culverts and 10-year events for pavement drainage; and (3) hydraulic structures along the rivers (bridges, dams, etc.). These curves can also be used to evaluate flood risk and management such as floodplain delineation and determination of urban flood hazard zones. Environmental management projects involving floodplain management or remediation will also often require design flood estimates from IDF curves.

The potential improvements of the new IDF curves incorporate the following:

- Bias-corrected future climate projections for 2035–2064,
- Snowmelt effects using a dynamic energy balance snowmelt model,
- Nonstationary distribution models to capture the increasing trend in precipitation over 90 years,
- Multiple distribution models and estimates of distribution parameters, as well as parameter uncertainty with a Bayesian approach, and
- Runoff IDFs that use a calibrated hydrologic model to address the issue of limited stream flow records.

This study is a part of the Department of Homeland Security's (DHS's) Regional Resiliency Assessment Program (RRAP), which addresses a range of hazards that could have regionally significant consequences for the Casco Bay Watershed region in southern Maine. Argonne is a partner in the RRAP project for Portland, Maine.

1.1 Project Area

The project area surrounds the Casco Bay Watershed with a wide buffer for data collection. The total area extends for 28,571 mi², of which Casco Bay Watershed is 904.841 mi². The watershed drains into Casco Bay on the Atlantic Ocean. Major lakes and rivers are shown in Figure 1.

1.2 Products

The final data products provided by the project include the following:

- Gridded precipitation IDF's considering bias-corrected future climate projections and snowmelt,
- At-station and gridded precipitation IDF's considering snowmelt effects using historical data only,
- Graphic plots for IDF's at all gauge stations,
- Precipitation IDF for the major cities in the study area,
- Maps for the selected gridded IDF's, and
- Runoff IDF's at 11 sub-basins in Casco Bay Watershed.

Figure 1 Casco Bay Watershed (outlined in red). Rivers are shown as colored lines, lakes are outlined in light blue, and dams are represented by colored points.

2. Intensity-Duration-Frequency Analysis

The IDF analysis estimates the statistical probability that a precipitation event of a given intensity over a given duration will occur. This information is widely used for designing precipitation-affected infrastructure systems, engineering standards, building codes, and maintenance standards. This study extends the analysis to incorporate (1) snowmelt as part of the rainfall that potentially contributes to the flood hazard, (2) effects of future climate change projected through the middle of the century, and (3) runoff IDF at the Casco Bay Watershed. This section outlines the general process the analyses followed. The Casco Bay Watershed is shown in Figure 1.

2.1 General Framework

The analyses framework includes four main components: (a) bias correction of future climate projections, (b) snowmelt modeling, (c) IDF development, and (d) hydrologic modeling (Figure 2). The bias correction and snowmelt modeling provide additional information that is currently not considered during IDF development. Hydrologic modeling is applied specifically for runoff IDF in the Casco Bay Watershed. All the analysis processes were developed to maximize automated computations. The details of each analysis component are briefly discussed in the following sections.

Figure 2 Process of IDF development including four analysis components.

2.2 Bias Correction of Downscaled Future Climate Projections

This analysis is designed to evaluate and improve the quality of dynamically downscaled future climate projections prior to incorporating them in IDF development. The bias was identified through comparisons between the observation data and simulation data from the regional climate model for the same historical time period (30 years: 1975–2004). A quantile-quantile method of bias correction (Amengual et al. 2012) was adapted in this study to adjust the future projections individually according to the difference between the historical and simulation data at every quantile. The adjustment includes both the mean value and variation for daily data over 30 years at each quantile interval.

The future climate projections were obtained by dynamically downscaling using a regional climate model (RCM) with the Weather Research and Forecasting (WRF) modeling tool by Argonne (Kotamarthi et al. 2016). The Argonne RCM, a WRF model, was developed using Community Climate System Model, version 4 (CCSM4), output data for the RCP8.5 emission scenario as model boundary conditions. The CCSM4 is a global climate model (GCM) developed by the National Center for Atmospheric Research (Gent et al. 2011). The RCM using the WRF considered the regional/local topography, land surface processes, detailed cloud physics, and radiative transfer schemes (Giorgi et al. 2012); this may facilitate modeling of the localized advection processes that determine the magnitude of extreme precipitation events. The output of the RCM may result in increased interannual variability (Mo et al. 2005) and precipitation intensity (Roads et al. 2003) compared to the results from GCMs.

The Argonne RCM has a high spatial resolution of 12 km. The model results used for this study include projections for a 30-year historical period of 1975–2004 and a 30-year period in the middle of the century (2035–2064). The simulation results for 1975–2004 were evaluated based on the observation data to identify potential bias of the dynamical downscaling with the Argonne RCM model. The observation data for 1981–2014 were mainly collected from the PRISM (Parameter-elevation Relationships on Independent Slopes Model) developed by Daly et al. (2008). The PRISM 1-km gridded data were aggregated to the Argonne's RCM model grid. The data gap (1975–1980) in PRISM was filled using an advanced inverse distance weighting method, a two dimensional interpolation algorithm for irregularly spaced data (Shepard 1968), to interpolate the daily rain gauge station data to the Argonne's RCM model grids (Figure 3). The RCM model's bias, which was identified by comparison between simulation and observation results for the same 30-year period (1975–2004), was used with the quantile-quantile method to correct future WRF model projections for 2035–2064.

The historical data and bias-corrected future projections were combined to form one dataset at each grid cell, which has a limited data gap of 2015–2034 (20 years). This dataset was used to develop IDFs with non-stationary distribution models. The details are presented in Section 2.4.

Figure 3 The subset of grid cells from the Argonne regional climate model for developing future precipitation IDFs (gray). The precipitation time series at each grid cell was bias corrected. The Casco Bay Watershed is shown in blue and daily rain gauge stations are shown in red.

2.3 Snowmelt Modeling

Runoff from rainfall over snow cover is associated with a significant flood hazard in many parts of the United States. It causes mass wasting of hill slopes, damage to river banks, and downstream flooding; these effects are responsible for losses of infrastructure, property, and lives. Rain-on-snow events are a common feature in various parts of the United States, and they play a significant role in generating high stream flows and flooding. One of the worst rain-on-snow events on record occurred during January 1996, causing flooding across much of the mid-Atlantic and northeast United States. The rapid snowmelt of unusually thick snowpack combined with intense rainfall to contribute to catastrophic flooding, which was responsible for as many as 30 deaths and \$1.5 billion in damage (Anderson and Larson 1996). Engineers and scientists involved in infrastructure designs

(bridges, culverts, dams, etc.) often need to know the runoff volume and frequency associated with rain-on-snow events, which were not considered in the existing IDFs.

To better understand the runoff behavior associated with rain-on-snow events, we used the Utah Energy Balance (UEB) snowmelt model (Tarboton et al. 1995; Mahat and Tarboton 2012). The UEB is a physical, process-based model that accounts for exchanges more than air temperature (such as fluxes of energy due to incoming and outgoing short- and long-wave radiation, thermal or heat conduction, evaporation and condensation, and horizontal heat transport) to calculate snow accumulation and snowmelt.

The UEB model was driven by air temperature, precipitation, wind speed, humidity, and radiation inputs at an hourly time scale. The model output of snow water equivalent (SWE: the amount of water contained within the snowpack if it were all melted without evaporation) was compared with the observed SWE for locations in the study area where observed SWE data were available. The comparison showed that the modeled SWE agreed with the observed SWE. This agreement indicates that the model is able to capture the snowmelt processes.

The UEB model projects hourly snowmelt, which is combined with precipitation to form the total amount of water that contributes to the surface runoff. The combined datasets were used to develop IDFs.

2.4 IDF Development

Developing IDFs for precipitation includes three major steps: (1) data pre-processing and regionalization, (2) determination of distribution models and model parameters, and (3) model performance evaluation. The IDFs were developed for five sub-daily durations (1-, 2-, 3-, 6-, and 12-hour durations) and 10 day durations (1-, 2-, 3-, 4-, 7-, 10-, 20-, 30-, 45-, and 60-day durations). For each duration, precipitation intensity was computed for return periods of 2, 5, 10, 25, 50, 100, 200, 500, and 1,000 years with an appropriate distribution model. The return period reflects the probability that a given precipitation event over a given duration would occur.

Data Pre-Processing and Regionalization. Daily and hourly precipitation data were collected from National Oceanic and Atmospheric Administration (NOAA) Climate Data Online (CDO). Although there are 900 daily and 300 hourly rain gauge stations in the project area, only 85 daily and 42 hourly stations had adequate continuous data available to merit IDF (Figure 4). In order to maintain the minimum quality of the dataset, all selected stations require a minimum of 20 years of records with at least 80% of all possible observations for each year. These data were used in the snowmelt modeling process and the part of data was also used in future data bias-correction process as discussed in

Sections 2.2 and 2.3. The resultant data were used to generate annual maximum series (AMS), which are sets of maximum precipitation in observations for each duration from every complete year of time series.

Figure 4. Rain gauge stations (daily record in red and hourly record in yellow) were collected over entire project area. The Casco Bay Watershed is outlined in blue, and encompasses Portland and South Portland.

The AMS were created for 5 hourly durations (1-, 2-, 3-, 6-, and 12-hour durations) and 10 day durations (1-, 2-, 3-, 4-, 7-, 10-, 20-, 30-, 45-, and 60-day durations). Two sets of AMS data were generated for IDF analysis: one dataset was generated at gauge stations from the snowmelt model without considering future projections, and the other dataset (gridded data over the subset of the Argonne RCM grid cells for the study area, Figure 3) includes combined data for both historical observations and bias-corrected future projections, as discussed in Section 2.2.

The results of snowmelt modeling indicate that the snowmelt affected the determination of the AMS dataset at gauge stations. Figure 5 shows that the maximum value in 1992 occurred in April (82 mm) instead of June (61 mm) if the effects of snowmelt are considered. The AMS data at gauge stations were further processed to group them into a homogeneous region if they share the similar distribution characteristics. This regionalization process was performed with the L-moment approach using two statistic criteria (the H-statistic and D-statistic) (Hosking and Wallace 1993).

Figure 5. Simulated snowpack (shown as SWE) and snowmelt for a station (USW00014764). The 1992 results indicate that the snowmelt will affect the AMS at this gauge station. The annual maximum precipitation was 82 mm in April (instead of 61 mm in June) if the effect of snowmelt is considered.

Determination of Distribution Models and Parameters. In order to develop IDFs, the key is to identify an appropriate distribution model and estimate the distribution parameters. The selected distribution model can be used to find the probability that a given precipitation event over a given duration will occur. In this study, we included all distribution models (generalized extreme value, lognormal, generalized logistic, Pearson Type 3, and generalized Pareto) used in NOAA Atlas 14 and one (Beta-K) of Beta family distributions used by the Northeast Regional Climate Center (NRCC) (Wilks 1993; DeGaetano and Zarrow 2016). The distribution models were initially screened with L-moment approach to identify the top three distribution models.

Once the top three distributions were identified, the distribution parameters were determined using the Bayesian approach, which can directly incorporate multiple types of information and provide the entire parameter posterior distribution. The Bayesian procedure is computationally intensive and was implemented through the Markov Chain Monte Carlo (MCMC) using the Metropolis algorithm (DREAM) (Vrugt and Ter Braak, 2011), which has proven effective at sampling multi-model and nonlinear distributions.

Bayesian model averaging (BMA) was also applied to pool the top three competing distributions to make a consensus prediction using weighted averaging (e.g., Raftery et al. 2005; Moges et al. 2016). The weights are derived from model posterior performance. The method used in this study is advantageous because it can accommodate multiple distributions—thereby avoiding the subjectivity in distribution selection—and can directly address distribution parameter uncertainty. The final distribution model derived from BMA can provide IDF and upper and lower bounds of the intensity based on the parameter uncertainty range.

For the AMS dataset with the combined historical and bias-corrected future projection data, a significant increasing trend was identified in the initial evaluation. All the distributions were modified to non-stationary distributions for IDF development.

Model Performance Evaluation. Several model performance measures were identified. These include the Taylor diagram (Taylor 2001), which is composed of correlation coefficient, standard deviation, and centered root mean square errors; the modified Anderson-Darling metric (Ahmad et al. 1988); and bootstrap analysis. Using this BMA approach, all of these measures have exhibited performances that are better than or similar to any single best distribution.

2.5 Hydrologic Modeling

In order to compute the runoff IDFs, a hydrologic model was developed for the Casco Bay Watershed with the HEC-HMS (Hydrologic Engineering Center Hydrologic Modeling System) version 4.2 (USACE 2016). The Casco Bay Watershed model includes five major rivers in southern Maine: Royal River, Presumpscot River, Stroudwater River, Dunstan River, and Nonesuch River. The outlet locations of 11 sub-basins were defined based on the locations of U.S. Geological Survey (USGS) streamflow gauges, dams, and the outlets of these major rivers into Casco Bay (Figure 6).

The largest lake and corresponding dam within the area, Sebago Lake and Eel Weir, were included in the model by defining an elevation-area relationship for the lake and an outlet structure to imitate outflow from the dam. The elevation-area relationship was determined using information on a water budget of Sebago Lake from the USGS. The dam outlet size and location were defined using characteristics of the dam spillway, and calibrated using observed lake stage.

The model precipitation (initial) losses were determined using the Soil Conservation Service (SCS)'s Curve Number method. In this method, precipitation is partitioned to runoff using a curve number and the initial loss of water prior to infiltration, which is affected by the sub-basin area covered by impervious surfaces. There are three types of CNs to be

estimated that correspond to an average, dry, or wet antecedent moisture condition (AMC); see Table 1 for definitions. To consider the uncertainty of the AMC, the uncertainty band of the runoff IDF was calculated. The CN corresponding to an average AMC was used along with the average precipitation IDFs; the dry AMC CN was used along with lower-bound precipitation IDFs; and the wet AMC CN was used with the upper-bound precipitation IDFs.

Table 1 Antecedent moisture condition definitions

Antecedent Moisture Condition	Amount of precipitation in the previous five days
Dry	<1.4 in. in growing season, <0.5 in. in dormant season
Average	1.4–2 in. in growing season, 0.5–1 in. in dormant season
Wet	>2 in. in growing season, >1 in. in dormant season

The runoff from each sub-basin is translated into a streamflow hydrograph using the Clark Unit Hydrograph method. This method used the equilibrium time for rainfall occurring at the most remote portion of the basin to contribute flow at the outlet and the storage delay time.

Flow is routed between sub-basins using the Muskingum method. The base flow within each sub-basin was modeled as recession base flow, in which base flow exponentially decreases within the channel flow after a storm event (USACE 2016). Three parameters were used: the initial flow; rate at which the base flow recedes between storm events; and the ratio to the peak streamflow at which base flow is reset on the receding limb of the hydrograph.

To ensure the model's performance and predictability, model calibration was performed. Eleven daily and 44 hourly rain gauges in the modeled area were used to provide model forcing data (precipitation) for simulating historical large runoff event during calibration. Due to the limited number of stream gauges available in this area, three streamflow gauges with 15-minute streamflow data, two along the Presumpscot River and one along Royal River, were used for model calibration. The sub-basin parameters discussed above were adjusted in model calibration until we found the best agreement between simulated and observed stream flows over the large storm events. For the ungauged sub-basin, an adjustment from a sub-basin with similar characteristics was applied.

The peak streamflow IDF values were determined with the calibrated model using precipitation IDFs as the input precipitation. For each of the return periods of 1, 2, 5, 10, 25,

50, 100, and 200 years, precipitation intensity with durations less than or similar to the maximum travel time were used as model input to estimate the peak flow. After running the model with these inputs, the lower bound, average, and upper bound of peak streamflow were generated as runoff IDF's for 11 sub-basins.

Figure 6. Casco Bay Watershed model including 11 sub-basins. The stream flows are simulated at the outlets of all the sub-basins (yellow and blue circles).

3. Results of IDF Analyses

The results from the IDF analyses include (1) IDFs at gauge stations considering snowmelt effect only and (2) IDFs at the WRF model grid cells considering effects of both snowmelt and bias-corrected future projections. The second set of IDFs is discussed in this section.

3.1 IDF at Gauge Stations

The IDFs derived in this study are generally higher than the NOAA IDFs but vary depending on the gauge stations. The changes in IDFs mainly are contributed by non-stationary change based on future climate projections, the snowmelt effects, and a Bayesian approach to incorporate multiple distribution models. Figure 7 shows precipitation intensities at gauge stations from NOAA IDFs (in red) and at the WRF grid cells closest to the corresponding gauge stations from the IDFs derived in this study (in blue) for the return periods of 10, 50, and 100 years, respectively, over 1-day durations. The change in precipitation is more significant for extreme, low-frequency events (Figure 8). The percent increase in mean value of the updated IDFs over the 85 stations is 10% (10 years), 19% (50 years), and 25% (100 years). The maximum percent increase is 56% for a 100-year event.

Figure 7. Comparison of 1-day precipitation intensity between NOAA IDFs and IDFs from this study at 85 gauge stations for return periods of 10, 50, and 100 years. The IDFs from this study considered snowmelt effects and future climate projections, and the intensity was selected at the Argonne RCM model grid cells closest to the corresponding stations.

Figure 8. Statistic comparison of 1-day precipitation intensity between NOAA IDFs and updated IDFs from this study at 85 gauge stations for return periods of 10, 50, and 100 years.

3.2 IDFs for Casco Bay Watershed

For comparison, the gridded IDFs within the Casco Bay Watershed were averaged to generate aggregated IDF curves for the watershed (Figure 9). The IDF curves for the Casco Bay Watershed indicates that precipitation intensity considering both snowmelt and future projections increased for all events with all durations and return periods. The results will affect the runoff IDFs in the watershed.

3.3 Gridded IDFs for the Southern Maine

The IDFs from this study were also interpolated to the same grids as NOAA's. Figure 10 shows that the precipitation intensity increases in the southern part of the study region for extreme events (50- and 100-year events) based on both NOAA and updated IDFs. However, the updated IDFs show a more significant increase along the high-elevation area near the headwater (most upstream part) of the Casco Bay Watershed, as well as the southeast coastal area.

Figure 9. Aggregated IDF curves for the Casco Bay Watershed.

Figure 10. Precipitation intensity maps of 1-day duration event for return periods of 10, 50, and 100 years. The upper maps are based on NOAA IDFs. The lower maps are from this study, and take into account for both the snowmelt effects and the bias-corrected future climate projections.

3.4 Runoff IDFs for the Casco Bay Watershed

The runoff IDFs were computed in this study for outlet locations of 11 sub-basins using the calibrated hydrologic model for the Casco Bay Watershed. The outlet at Presumpscot River near the City of Portland receives stream flow from the largest drainage area in the watershed (more than 600 mi², Figure 6). Figure 11 shows the runoff IDF based on the peak stream flows calculated by the calibrated Casco Bay model. The peak stream flow for a 100-year storm event (return period of 100 years) is 25,480 cfs (cubic feet per second), which is 68% higher than the Federal Emergency Management Agency (FEMA) results (FEMA 2013). The peak stream flow for 50-storm event is 21080 cfs, 55% higher than the FEMA results and the peak stream flow for 10-storm event is 12430 cfs, 27% higher than the FEMA results (FEMA 2013). The upper and lower bounds of runoff IDF considered an uncertainty of (1) precipitation uncertainty based on the upper and lower bounds of precipitation IDF and (2) the uncertainty of antecedent moisture conditions used in the Casco Bay Watershed model. All the runoff IDFs will be included in the data products (Section 1.2) for easy access.

Figure 11. Runoff IDF at the outlet of Presumpscot River near the City of Portland, Maine. The FEMA results are represented by the yellow curve.

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