EXECUTIVE SUMMARY

Linked Rainfall and Runoff Intensity-Duration-Frequency in the Face of Climate Change and Uncertainty

SERDP Project RC-2514

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ACRONYMS AND ABBREVIATIONS

CCSM	Community Climate System Model
CMIP5	Coupled Model Intercomparison Project Phase 5
DoD	Department of Defense
GCM	General Circulation Model
GFDL	Geophysical Fluid Dynamics Laboratory
GIS	Geographic Information System
HEC-HMS	Hydrologic Engineering Center – Hydrologic Modeling System
IDF	Intensity-Duration-Frequency
RCP	Representative Concentration Pathways
SERDP	Strategic Environmental Research and Development Program
SMA	Soil Moisture Accounting
UEB	Utah Energy Balance
WRF	Weather Research and Forecasting

1.0 INTRODUCTION

The increase in intensity and frequency of extreme weather events, likely due to a warming climate and the consequent increase in the water-holding capacity of the atmosphere, is expected to have adverse effects on critical military installations and operations unless these effects are incorporated into the planning, design, and operations of the military. The majority of military installations worldwide have already faced a rising threat from flooding that can be partly attributed to the increase in storm intensities and frequencies, and the inadequacy of stormwater infrastructures. A recent vulnerability assessment report by the Department of Defense (DoD) found that, in the United States alone, more than 930 military sites (Figure 1) have been hit by floods in the past 30 years (DoD 2018). A similar report on the effects of a changing climate on military bases across the country found that two-thirds of the 79 installations reviewed are vulnerable to flooding (DoD 2019). An estimated $5 billion is needed to repair and rebuild two air force bases (Tyndall and Offutt) from storms and flood damage that occurred this year, underscoring the need for DoD to better plan and account for the risks posed by flooding and extreme weather. In response to this growing national security issue, Congress recently passed legislation (H.R.5515 - John S. McCain National Defense Authorization Act for Fiscal Year 2019, 115th Congress (2017-2018)) directing the DoD to assess the flood risk and consider future environmental conditions in the design and modification of its military facilities.

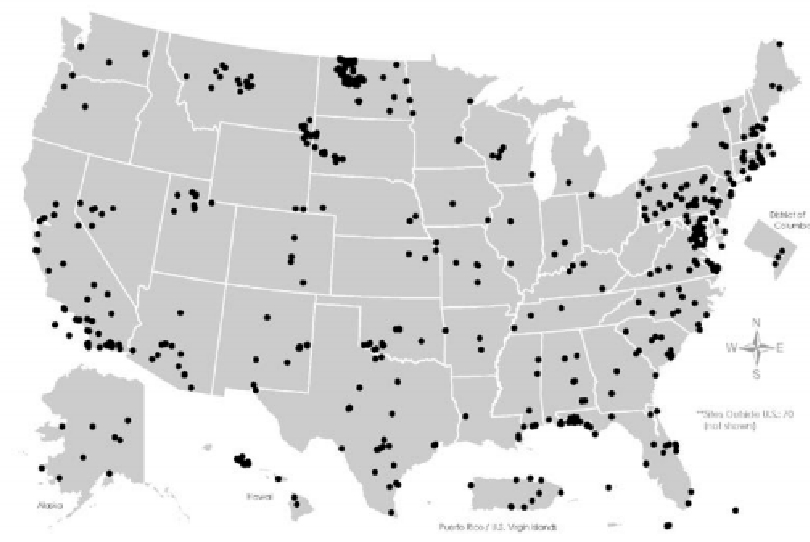

Figure 1. Military Sites Affected by Flooding from Non-storm Surge Events Over the Past 30 Years (adopted from DoD 2018)

Adaptation to a rising flood risk starts with quantifying the changes in design storms and their associated impacts on hydrologic processes under a non-stationary and substantially uncertain future climate, and incorporating these changes into future engineering designs and planning. The design storm, often obtained from an intensity-duration-frequency (IDF) curve, needs to reflect the change in extreme rainfall patterns and the various sources of uncertainty involved in constructing the curves. Traditionally, stormwater and flood control infrastructure design relied on the stationarity of the storms and peak flows over the design life-time of the infrastructure, lasting beyond 100 and 500 years. However, during the last century, more intense and frequent precipitation extremes have been observed in several regions resulting from either a warming climate or long-term climatic variations (Westra et al. 2013). Based on an ensemble of climate model projections and the basic physical relationship between atmospheric water vapor and storms, a warming climate is expected to further increase the intensity and frequency of precipitation extremes in the future (Sillmann et al. 2013). Consequently, the traditional IDF curves can substantially underestimate precipitation extremes and thus, may not be suitable for infrastructure design in a changing climate. For example, many of the drainage systems installed over the last several decades used IDF curves that were outdated by as much as half a century, making the systems potentially inadequate and vulnerable for flooding under strongly non-stationary precipitation conditions (Mailhot and Duchesne 2010, Rosenberg et al. 2010). It is therefore critical to update the IDF curves so they reflect the potential changes in rainfall extremes in engineering standards and designs.

The IDF curves, which are commonly constructed using relatively limited records of precipitation extremes, are subjected to bias and uncertainties. The return periods of design storms usually exceed the record length, making extrapolation of the observed data essential to estimate the storm magnitude corresponding to higher return periods. The frequency analysis methodologies used to construct the IDF curves also contain uncertainties resulted from the choice of homogenous regions, probability distributions, and parameter estimations. In addition, there is a considerable level of uncertainty in climate model predictions of precipitation extremes at the required temporal and spatial resolutions for constructing the IDF curves. Consequently, uncertainty is inherent to the IDF curves and needs to be properly quantified for engineering design and risk assessment applications.

The underlying assumption of using the IDF curves for designing stormwater and flood control structures is that there is a direct relationship between the design storms and design floods. But in reality, other watershed factors or runoff response dynamics, not only precipitation, are important causes of floods. The assumption may be valid for regions where soil saturation and precipitation extreme are strongly coupled and for regions that are prone to flash floods (e.g., arid and high-slope regions). In these areas, the rainfall amount can be a reasonable indicator of the runoff generated from a given drainage. On the other hand, floods can be caused by non-extreme rainfall falling on saturated soil, as in the Mississippi River Basin, or by the melting of accumulated snow, as in the Rocky Mountains, or by rain on snow, as in the western United States (Berghuijs et al. 2016). Thus, the complexity of floods as a temporal and spatial aggregation of water over a landscape, in comparison to extreme precipitation, necessitates additional considerations other than simply applying the rainfall IDF curves.

2.0 OBJECTIVES

The main objective of the project is to revise and update the storm and flood IDF curves for selected military installations by considering the changes in observed and future storm and flood events, effect of snowmelt, modeling, and data uncertainties. The project involves six interrelated tasks.

The objective for Task 1 is to update the current IDF curves using a regional frequency analysis, the most complete precipitation record available, and future projections. The regionalization approach combines data from nearby climatologically similar stations to improve the accuracy of the IDF curves. Incorporation of future precipitation helps to better represent the effects of the changing climate.

The objective for Task 2 is to quantify both the intra-model uncertainty (due to different probability distributions and climate simulations) and inter-model uncertainty (due to parameter estimation) associated with the estimation of the IDF values. Risk evaluation should account for these uncertainties to avoid under-design of critical infrastructures dealing with flooding and storm.

The objectives for Task 3 are to perform dynamic downscaling from General Circulation Models (GCMs) to better capture extremes associated with local topographic effects and convective patterns with the Weather Research and Forecasting (WRF) modeling tool, and develop a methodology that can identify and correct the biases in extreme precipitation projections.

The objectives for Task 4 are to effectively update existing IDF curves whenever new precipitation records or projections are available. Instead of reconstructing the IDF curves to incorporate newly available data, a seamless updating approach is required to integrate available precipitation data on a frequent basis. In addition, the project would develop non-stationary IDF curves when the precipitation extremes exhibit significant trends.

The objectives for Task 5 are to develop the runoff IDF curves by considering different site-specific flood-causing mechanisms. The runoff IDF curves allow us to directly characterize the flooding risks and improve the design of stormwater and flood control structures. In addition, this task aims to incorporate snowmelt and accumulation into the IDF curves to better characterize the amount of rainfall that is available for runoff.

The objective for Task 6 is to develop and implement an interactive web-based Geographic Information System (GIS) geodatabase and tool to provide convenient access to the rainfall and runoff IDF curves under various climate scenarios for the 13 DoD installations considered in the study. The web-based tool will aid in decision making and planning exercises, especially to assess the vulnerability of existing military installations to extreme rainfall and runoff events, and to adopt design codes for more resilient infrastructure that accounts for climate change. The framework can be easily extended to other military installations or regions of interest.

Moreover, the validity of the current IDF curves was assessed based on the changes in the magnitude and frequency of precipitation extremes under current and future storm conditions. The study provides data and information necessary for assessing the local flood risks at the installation level and for design guidelines modification to make the installations more resilient to floods taking into consideration the impact of changing climatic conditions.

3.0 TECHNICAL APPROACH

Various statistical and modeling approaches were employed to evaluate, construct, and update the IDF curves, quantify the uncertainty ranges, and incorporate future simulations of precipitation extremes and effects of snow accumulation and melt. The Mann-Kendell and likelihood ratio tests were used to evaluate linear and nonlinear trends in the magnitude and frequency of precipitation extremes. Regional frequency analysis coupled with Bayesian model averaging and parameter estimation methods were used to develop the IDF curves and associated uncertainty intervals. Nonstationary probability distributions with time-varying parameters were used to account for future precipitation and the effect of climate change on the IDF curves. Also, a Bayesian hierarchical method was developed for the frequent update of the IDF curves whenever new precipitation data is available.

A dynamic downscale method using the WRF model was performed to generate high-resolution spatial (12 km) and temporal (30 min) precipitation from climate model projections. The bias in the projections was corrected using a hybridized quantile mapping (HQM) method which was designed to correct extremes in the right tail of the precipitation distribution while preserving the long-term precipitation patterns projected by climate models. The Hydrologic Engineering Center – Hydrologic Modeling System (HEC-HMS) hydrological model, with Soil Moisture Accounting (SMA) method for rainfall excess simulation, was used to construct the runoff IDF curves from given rainfall IDF curves. The Utah Energy Balance (UEB) snowmelt model was applied to better understand the runoff behavior associated with snowmelt and rain-on-snow events; these effects were incorporated in the IDF curves. Finally, a project website and web-based GIS mapping tool was developed and populated with the study results for the planned geographic regions and climate scenarios.

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4.0 RESULTS AND DISCUSSIONS

The project provides updated IDF curves with 95% confidence intervals for rainfall durations from 1-hour to 10-day and return periods from 2 years to 500 years for 13 military installations across the United States. Unlike the traditional IDF curves, which heavily rely on observed (or historical) precipitation extremes and their stationarity in the future, the updated IDF curves represent the nonstationarity impacts of climate change and effects of snowmelt and accumulation. The curves were used to assess flooding risk under stationary and nonstationary climate conditions.

For all the installations and storm durations (1hr–10day) we have considered, the historical records of annual maximum precipitation showed no significant spatially consistent trends at either the station or regional levels. Approximately 10%–16% of stations showed statistically significant increasing trends, while only 4%–6% of stations showed decreasing trends in the past. None of the climatologically homogenous regions within our study sites showed significant trends. Relatively more stations in the Midwest (Ft. McCoy and Ft. Riley) and Northeast (Ft. Drum and Aberdeen Proving Ground) showed increasing trends, particularly for storms with daily and longer durations. However, when future precipitations are considered, considerably more stations (> 50%) showed an increasing trend in storms with daily and longer durations while there was a decreasing trend in storms of sub-daily magnitude at the majority of installations. The differences are not clearly evident in the resulting trends from either the Community Climate System Model (CCSM) or Geophysical Fluid Dynamics Laboratory (GFDL) climate models or the Representative Concentration Pathways (RCP) 8.5 and 4.5 emission scenarios. Compared to the trend in extreme precipitation of magnitude, relatively more weather stations (50%–90%) showed an increasing trend in the frequency of occurrence of daily extreme precipitation events (heaviest 1% daily precipitation).

Comparing the stationary and nonstationary IDF values, the storm magnitudes corresponding to longer durations increased for most of the installations, with the increase being higher for the installations located in the central and eastern parts of the country. For the installations in the south and southwest, the storm magnitudes with sub-daily durations have decreased, while they have increased for storms of daily and longer durations.

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5.0 IMPLICATIONS FOR FUTURE RESEARCH AND BENEFITS

Adaptation to a rising flood risk entails quantifying the changes in the characteristics of design storms and their associated impacts on hydrologic processes under a substantially uncertain future climate, and incorporating these changes into future engineering designs and planning. The results from our study sites across the United States provide improved and updated IDF curves that can be used to assess the flood risk posed by climate change and its uncertainty on military installations. The updated curves are expected to be used as a scientific basis for understanding the vulnerability of military installations to flooding and contribute to military resilience against the increasing flood trends. Despite the progresses so far, additional research is still needed to identify the level and nature of changes in hydroclimatological extremes, to represent those changes in our design standards and planning, and to provide an accurate assessment of the risks posed by severe storms and floods. There is also a research need to develop a readily available and easy-to-use tool and database to aid in decision-making and planning exercises, especially to assess the vulnerability of existing military installations to extreme rainfall and runoff events, and to adopt design codes for more resilient infrastructure that accounts for climate change. The interactive web-based GIS tool from this project has the potential to meet this research need with the inclusion of more military sites into the database and incorporation of advances in the procedures involved for the development of IDF curves and the assessment of flood risk.

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