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Climate Change Risk to Coastal Airfield Stormwater Systems

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THESIS

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Abstract

Climate change is resulting in rising sea levels and increased rainfall, posing new challenges to stormwater management, particularly along coastlines. The airfield stormwater systems of Tyndall Air Force Base discharge directly into an interior bay of the Gulf of Mexico through tidal canals and ditches, creating a risk of system inundation from high tidewater conditions from sea-level rise (SLR). This study explores the performance and consequences of an inundated stormwater system from SLR during rainfall events using the EPA's Stormwater Management Model (SWMM). One hundred and fifty-three combinations of SLR and return year storms were applied to a model of an independent stormwater system primarily servicing the Bravo taxiway, and analysis of the results indicate that SLR projections associated with 2065 under high emissions and 2100 under medium emissions will result in widespread flooding, surcharging, and capacity limitation in stormwater inlets and conduits adjacent to airfield pavements and proximate to the system outfall. The results of this model warrant future study and validation, while indicating that the Department of Defense needs to account for the dual threat of SLR and intensified rainfall in stormwater planning.

Dedication

Thanks to the friends I came here with, the friends I made here, and the friends I left here with.

Acknowledgments

Thank you to Tyndall Air Force Base for providing information critical to this undertaking. Thank you to Dr. Christopher Chini for the inspiration, encouragement, and opportunities to broaden my horizons and succeed.

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I. Introduction

Motivation

The Department of Defense (DoD) and the United States Air Force (USAF) rely on airbases to project air power in support of foreign policy. Mission requirements, geography, and necessity force many airbases to be located adjacent to bodies of water. Whether ocean, river, lake, and more, these bodies of water carry inherent risks to the neighboring bases and airfields. Swelling waters from wind, precipitation, and tides can cause flooding and interrupt operations, and examples abound in recent years. Figure 1 illustrates extensive flooding from the swollen Missouri River at Offutt Air Force Base in Nebraska, which inundated a third of the installation and covered much of the runway in 2019 (Losey 2019).

Figure 1: Airfield Flooding at Offutt AFB (55th Wing Public Affairs 2019)

At Norfolk Naval Station in Virginia, encroaching high tides often flood roadways and impede access to the installation's gates (Yale Climate Connections 2020). Also in Virginia, Langley Air Force Base has installed millions of dollars in flooding mitigation infrastructure including sea walls and stormwater system pumps as sea-level rise threatens the peninsular installation (Dietrich 2018). Climate change is anticipated to alter the sea level and precipitation amounts worldwide and could threaten coastal DoD assets. Tyndall Air Force Base is at particular risk, as it is bounded by both the Gulf of Mexico and an interior bay, with an airfield stormwater system that empties directly to tidal canals. This study will take a unique approach by researching how the airfield stormwater system of Tyndall Air Force Base will perform as sea-level rise and intense rainfall threatens these tidal outfalls.

Climate change is anticipated to alter the intensity and frequency of storms. Water vapor concentrations are projected to rise due to a warmer climate, which will lead to an accelerated water cycle with intensifying extreme rains. Research produces varying estimates of the projected increase; for example, one research team predicts the continental U.S. average daily precipitation of 2071-2100 to be 10-30% higher than the current average under business-as-usual worldwide emissions levels (Kunkel et al. 2013). This increase in rainfall is anticipated to come mostly in the form of stronger short duration, high-intensity storms (Zhu 2013). In addition to these storms being stronger, research suggests that these intensifying storms will occur with more frequency (Kunkel et al. 2013).

Warmer temperatures are causing sea level rise as ice melts in the regions surrounding the Earth's northern and southern poles. The United Nations Intergovernmental Panel on Climate Change predicts the global mean sea level to rise 0.25-0.50 meters, 0.375-0.75 meters, or 0.50-1.1 meters by the year 2100, based on climate scenarios RCP 4.5, RCP 6.0, and RCP 8.5. (IPCC 2019). Projections are commonly shown under varying scenarios, often to represent changes in level of human contributions to climate change. Additionally, a rising sea-level affects areas differently based on geography, an effect known as relative sea-level rise. For example, the geography of southeast Virginia is widely recognized as being at higher risk to inundation from sea-level rise than other areas (Sadler et al. 2017). Sea level rise is a concern of the DoD, as the DoD acknowledged that sea-level rise can exacerbate storm surge and potentially result in

land becoming irrevocably uninhabitable due to inundation (Department of Defense (DoD) 2019).

Recurrent Flooding

Sea-level rise and intensified storms are anticipated to increase the frequency of recurrent flooding. Recurrent flooding can be defined as an increase in the frequency of flooding events. This manner of flooding is of special interest in a report prepared by the DoD in 2019 on the expected impacts of climate change on operations:

> "Coastal flooding may result from storm surge during severe weather events. Over time, gradual sea level changes magnify the impacts of storm surge, and may eventually result in permanent inundation of property. Increasing coverage of land from nuisance flooding during high tides, also called 'sunny day' flooding, is already affecting many coastal communities." (DoD 2019)

The threat or occurrence of recurrent flooding may prompt installations to consider the implementation of mitigation strategies. Strategies can include physically enlarging stormwater systems, pumping stations, low impact development, levees, flood walls, channel modifications, and seawalls (Wright 2007). A stormwater pumping station at Langley AFB can be seen in Figure 2. All of these methods carry varying levels of efficacy and implementation cost, and they require an understanding of current and future risks prior to implementation. Risks can include nuisance flooding as mentioned above, such as in Naples, Florida where tidal stormwater outfalls occasionally backup and flood roadways (Erickson et al. 2019). Research by Johnston et al. (2014) found that recurrent flooding

from SLR and surging tides in the coastal community of Scarborough, Maine, would threaten roadways, sewer infrastructure, water supply infrastructure, stormwater infrastructure, communications infrastructure, natural gas pipelines, and other community infrastructure including emergency response, schools, and medical facilities, while the ocean water's salinity would pose additional risks to the structural integrity of infrastructure itself.

Figure 2: Demonstration of Stormwater Pump at Langley AFB (Stannard 2016)

Case Study Overview

In this research, the effects of climate change in the form of intensified storms and sea-level rise on a stormwater system will be studied. Specifically, this study asks if sea-

level rise and intense rainfall can lead to ponding or flooding from coastal airfield stormwater systems that drain directly to the sea. The main effect being studied is a pincer effect of a sea level that is high enough to cause backflow into a tidal stormwater outfall while increasingly intense rainfall events are applied. Furthermore, this research will explore how these risks can be communicated. In this study, a portion of the airfield stormwater system at Tyndall Air Force Base will be modeled. Variations of sea-level rise projections and increasingly intense storms will be applied to the Stormwater Management Model (SWMM) replication of the stormwater system.

Tyndall Air Force Base is located on Florida panhandle, on a peninsula parallel to the mainland. The peninsula is bounded by two bays and the Gulf of Mexico. The base airfield has an elevation of 5.18 meters above mean sea level as of 2019. The base is bisected by US Highway 98, with the airfield and aviation related functions located closer to the bay between the peninsula and the mainland, and support functions located closer to the Gulf of Mexico. The airfield features two runways of over 3,000 meters. The dual runways, taxiways, and maintenance pads are nonpermeable, and generate a considerable amount of stormwater runoff. Some of this runoff is vectored off the airfield by subterranean culverts and into a system of open-air drainage ditches, which ultimately flow into canals and bayous before flowing into East Bay between the peninsula and the mainland. There are two prominent bayous used for stormwater discharge: Fred Bayou and Little Cedar Bayou. Fred Bayou stretches roughly 1,200 meters from the coast to where a series of drainage ditches begin. Little Cedar Bayou reaches roughly 450 meters

inland before connecting to a canal that runs approximately 1,150 meters to a separate series of drainage ditches. These two bayous and the airfield stormwater drainage ditches that flow into them can be seen in Figure 3. The stormwater system is divided into multiple independent systems servicing different parts of the airfield. Of sections that discharge into drainage ditches for ultimate discharge to the sea, outfall heights range from 0.061 meters above sea level to 0.856 meters above sea level, with a mean of 0.229 meters above sea level. The climate of the base is classified as warm and temperate, with nearby Panama City Beach averaging 134.62 centimeters of rain per year (Climate-Data.org 2021). Additionally, Tyndall AFB's location on the Gulf Coast makes it susceptible to tropical storms. Sea-level rise projections are available for Tyndall Air Force Base, compiled in 2016 by the Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) (Hall et al. 2016). SLR projections for Tyndall AFB for 2035, 2065, and 2100 can be seen in Table 1. The range in these projections is highly dependent on global emissions levels.

Figure 3: Satellite Image of Tyndall AFB airfield

Table 1: Tyndall AFB SLR Projections

SLR Projections, Tyndall AFB FL		
Range (meters)		Year
Low	High	
0.1	0.3	2035
0.1	0.9	2065
0.1	2.1	2100

Coastal Infrastructure Threats and Policy

The threats posed by sea-level rise to stormwater infrastructure are numerous. For example, as the sea-level rises, stormwater tailwater pipes can become submerged during high tide events, inhibiting outflow from these pipes during storm events (Sadler et al. 2017). An example of this scenario can be seen in Figure 4. In addition to tailwater lowering the discharge capability of stormwater systems, the salinity of tidal water would exacerbate the material degradation of stormwater infrastructure, such as culverts and flap gates (Johnston et al. 2014). Johnston et al (2014) also hypothesize that a maximum flooding scenario (sea level rise combined with high tides and storm surge) could overwhelm traditional road culverts close to the coast, potentially leading to the inundation degradation or destruction of roadways.

Figure 4: Inundated Stormwater Outfall at Naples Beach, FL (Naples, FL 2021)

Federal Aviation Administration (FAA) Advisory Circular 150/5320-5D provides guidance on the design and construction of airfield drainage systems, and it speaks to several stormwater system flooding mitigation practices relevant to this study. For example, flap gates are discussed as a method of preventing backflow into a stormwater system, and encourages their use to defend from high tide events and when the discharge area itself may be flooded (FAA 2013). The Circular echoes the concern of Johnston et al. (2014) when it states the corrosive danger of tidal water on stormwater systems if backflow is not prevented, and advises that flap gates require consistent inspection and maintenance to ensure that corrosion and sediment build up does not degrade their working condition. Stormwater detention basins are recommended to provide an additional layer of safety and allow for uniform discharge of stormwater. Additionally, the Circular states that, in a storm event exceeding the design level, ponding cannot be allowed on the center 50% of runways and taxiways during ten-year return storms. These conditions help to establish assumptions and failure states for this study. For example, in this study it will be assumed that the modeled stormwater system does not have flap gates preventing tidal or storm surge backflow into its airfield stormwater system, or that any flap gates are ineffectual due to corrosion or lack of maintenance. Further, it will be assumed that flooding will result from system inlets, rather than overflowing detention basins or drainage channels.

Thesis Overview

In this introduction, climate change, recurrent flooding, coastal stormwater infrastructure, and objectives of this research were briefly discussed. In the following background section, these topics will be further explored. Examples of climate change-based stormwater risk modeling will be discussed, and how this study is unique in its objectives and methods. Climate change and its anticipated effects on weather events, stormwater infrastructure, and infrastructure design requirements will be discussed. Finally, SWMM's advantages, disadvantages, and examples of its application will be discussed.

II. Literature Review

Risk Modeling of Stormwater

Current and future stormwater risks can be conveyed through stormwater risk modeling. Modeling is often used to further the understanding of the risks posed by a changing climate. These models are popular areas of study; the understanding of projected climate change effects is necessary to guide the implementation of adaptation and mitigation strategies to protect life, infrastructure, and quality of life. A variety of techniques are available for modeling the climate change risk factors of sea-level rise and intensified storms. The most common approach to model the impact of sea-level rise is to raise the sea level for a coastal area using geographical information system (GIS) maps, and analyze the extent of inundated infrastructure. To model the impact of intensified storms, a common approach is to first model a stormwater system and then apply projections of future storms to the model the system's performance under increasingly heavy load.

Modeling the effects of sea-level rise is a very common research topic, as the effects of sea-level rise can be experienced along every coastline on the Earth. For example, one study by Johnston et al. (2014) modeled the effects of SLR at the scale of the town of Scarborough, Maine, with eight miles of oceanfront and a large tidal salt marsh. GIS was used in conjunction with LIDAR and digital elevation models (DEM) to study the effects of three climate scenarios and three respective sea-level rise figures. A survey of the area and GIS data was used to identify critical infrastructure such as roadways, sewers,

stormwater, water supply, communications, schools, emergency response facilities, and more that would be flooded in the scenarios. This study serves to identify critical infrastructure in the locality that would be inundated in the future. However, it does not explore the response or performance of each infrastructure type, especially the sewer or stormwater infrastructure.

Similarly, a study by Yesudian and Dawson (2021) researched the effects sea-level rise could have on airports worldwide. A list of all airports was subset to airports within the lowest elevation coastal zone. Using GIS, three projections of sea-level rise were applied to the model to analyze which airports became inundated. Following the identification of vulnerable airports, the trade and stability implications of the flooding were analyzed. This study serves to identify the airports most at risk from global sea-level rise, but they did not study any of the system responses of the airports as sea levels gradually rise. Studies such as this are useful for showing what areas are covered by water in SLR scenarios, but ignore the potential for flooding under lower SLR scenarios when combined with storms.

The state of Virginia is a common case study for the effect of sea-level rise. A study by Sadler et al. (2017) used GIS data of Virginia Department of Transportation roadways and traffic flow data combined with several estimates of sea level rise to identify the vulnerability of roadways. This study also factored tidal fluctuations into the projections of sea-level rise. Similarly, Li et al. (2013) used a coastal modeling suite and GIS to model the level of landcover inundation at Naval Station Norfolk resulting from

sea-level rise combined with simulated hurricanes and winter storms. Furthermore, research was conducted into roadway and bridge access inundation and general landcover inundation in the Hampton Roads region of Virginia by Tahviladari and Castrucci (2021) using GIS and several projections of sea-level rise in addition to tidal fluctuations. These heavily GIS-based studies continue the trend of sea-level rise studies focusing on identifying infrastructure that will become inundated, without studying the response of systems as the inundation levels increase.

Additionally, a study by Storlazzi et al. (2018) analyzed the risk of inundation at Pacific atolls using GIS and wave modeling software. This study used three future climate projections with corresponding sea-level rise estimates. For each projection, the amount of landcover inundated was found. Furthermore, the effects of tidal inundation on the atoll aquifers were studied. While this study looked at the aquifer system response to flooding, the general trend of using GIS to simply look at elevations prone to inundation was continued.

There are numerous studies studying the effects of stronger storms from climate change on infrastructure. For example, Kuo and Gan (2015) analyzed the risk of exceeding the IDF storm used in design in Edmonton, in Alberta, Canada, and proposed a new methodology for a climate change-adapted risk chart comprised of design life, rainfall intensity, and the risk of a storm occurring that exceeds the design, based on projected future rainfall amounts. However, this study did not focus on individual infrastructure, as it revolved around IDF curves directly. Furthermore, Forsee and Ahmad (2011) applied

stronger storms to a watershed model of the Las Vegas Valley, in Nevada. The scale of this study included the entire Las Vegas metropolitan area, and analyzed the performance of stormwater infrastructure including inflow, discharge, and detention basin storage amounts and elevation. Several climate scenarios were used to project future rainfall amounts. The extreme breadth of this study comes at a cost of removing individual system-level analysis, but it serves as an example of the study of system response to climate change.

A study by William and Stillwell (2017) studied the probability of failure of green roofs under precipitation loading. A failure state was determined, which was the inability of the green roof to lower the roof's runoff by a set percent. Fragility curves were produced following simulations of stormwater loading and determining when the green roof failed to meet the reduction percentage. This study provides an outstanding methodology into visualizing the probability of failure of a stormwater asset under increasing load, but is conducted at a minor component scale and does not convey overall system risk. It would be necessary to scale this study in order to visualize how the stormwater loading on a stormwater system would be affected by multiple failures of green stormwater infrastructure.

There are many examples of research using SWMM to model stormwater applications without climate change effects. For example, Wang et al. (2018) used SWMM to model the quantity and quality of stormwater runoff adjacent to a highway in Maryland. The total subcatchment area studied comprised just over seven acres, illustrating SWMM's

modeling ability for small-scale studies. Brendel et al. (2021) used SWMM to model the performance of the stormwater network of Roanoke, Virginia. The model contained 57 subcatchments ranging in area from 1.75 acres to over 400 acres, and helped the locality determine where to implement flooding mitigation infrastructure. Shahrokh Hamedani et al. (2021) used SWMM in conjunction with elevation data to study the performance of low impact development in a small watershed comprised of testbeds. All of these studies were validated and calibrated prior to publication. Through these studies, it is clear that SWMM provides accurate simulations in scale from under an acre to hundreds of acres.

One can see several trends in climate change-based stormwater risk modeling research. Many studies on sea-level rise have a focus area of a township-equivalent or larger, up to a world-wide scale. In many studies GIS tools are used to produce an overview of landcover or specific infrastructure points at risk of temporary or permanent inundation, without studying the system response to additional loading. A range of climate scenarios producing varying levels of sea-level rise is almost always used in models. Some studies account for tidal fluctuations in their sea-level rise projections, adding a potential additional layer of height to estimates. Several of these best-practices are applicable and utilized in this specific research, such as using a range of sea-level rise estimates to reflect multiple emissions levels. Additionally, there are specific knowledge gaps that this study aims to bridge. For example, there appears to be a lack of climate change-based risk modeling research into the response and performance of stormwater systems at the scale this study

is modeling. Additionally, this research is modeling a coastal airfield directly affected by sea-level rise through its outfall.

Climate Change

As previously discussed, climate change is anticipated to result in higher temperatures worldwide. As a result of these higher temperatures, the water cycle will be altered and more frequent precipitation will occur, and with higher intensity. Furthermore, higher temperatures are anticipated to melt ice frozen near the planet's poles, resulting in a slowly rising sea-level (EPA 2021). Although there are more risks posed by climate change, these two factors of intensifying rainfall and rising seas are most prevalent to stormwater infrastructure and stormwater research.

Climate change effects are typically reported in intervals to account for differing future climate scenarios. Representation Concentration Pathways (RCP) are used to describe human factors that contribute to climate change. For example, RCP 4.5 describes a scenario in which greenhouse gas emissions are curbed and lowered by 2100. RCP 8.5 describes a "business-as-usual" scenario in which emissions continue to rise by 2100. This climate scenario is typically used as the "highest emissions" scenario in research (EPA 2017).

IDF Curves and DoD Design Requirements

Changes in the intensity and frequency of precipitation are projected to have cascading effects on infrastructure. Precipitation data is commonly modeled using IDF curves, where intensity is typically measured in depth per unit of time and the duration is

measured using the same unit of time. Modeled on these graphs are curves representing return-period storms, often two-year storms all the way up to 100-year storms. An IDF curve can be seen in Figure 5, which was also used to create simulated return year storms for this study. A return year storm is defined as the probability that a storm of a given or greater intensity occurs in a year. For example, a 100-year storm would mean there is a 1 in 100 (or 1%) chance of a storm of that intensity occurring in any given year. Thus, as increasingly intense storms occur with higher frequency, the chances rise of a 100-year storm happening more frequently with an actual 100-year storm being underestimated.

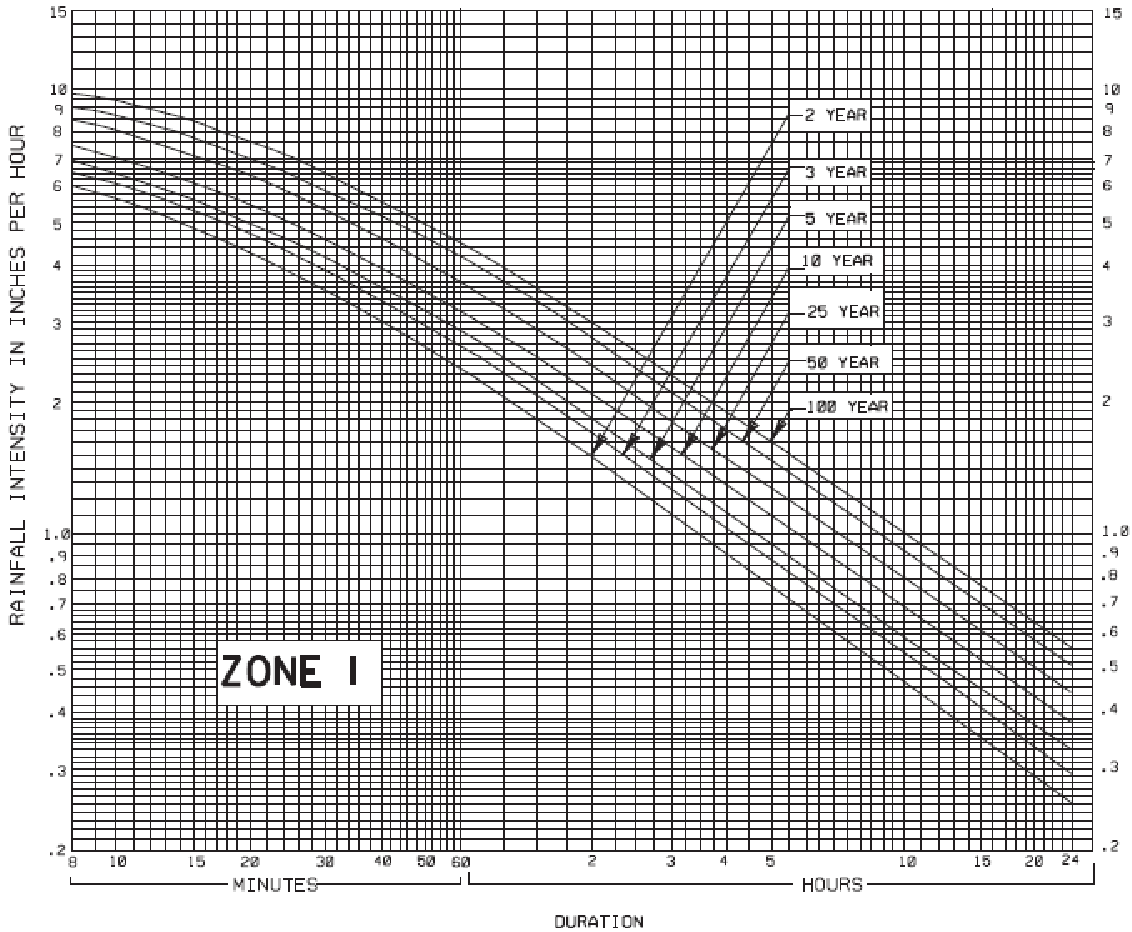

Figure 5: Florida DOT IDF Curve used in Study (FDOT 2022)

Though localities may choose to produce their own curves, the most used IDF data in the US is generated by the National Oceanic and Atmospheric Administration (NOAA). NOAA uses rainfall frequency distribution characteristics that are extracted from the historical records and these estimates of return frequency and IDF are applied in the design of future projects, assuming the climate will remain the same as during the historical period, known as stationarity. Rainfall records for each geographic region of the US are

kept by NOAA and published in the Atlas 14 series (Bonnin et al. 2006). Areas without Atlas 14 curves rely on older publications, such as Atlas 2, published in 1973, which covers portions of the Western United States.

Wernstedt and Carlet (2014) note that the IDF curves used to design infrastructure are based on historical data, and therefore use a stationary climate. In other words, IDF curves are being generated for a snapshot in time of the climate, with no consideration of how the climate could change and how the changed climate could affect precipitation levels. As such, depending on how the precipitation patterns shift, new construction could be over or underprepared for future precipitation levels. Kuo and Gan (2015) suggest that current IDF curves do not convey the actual level of risk of exceeding design storms under climate change scenarios. As increasingly intense storms occur with higher frequency, the chances rise of a storm happening more frequently than its associated IDF probability. Researchers expect the 2-year return period to be shortened to 1.8 years (O'Neill 2010). Other researchers believe that across the continental U.S., a 20-year return-period storm of 2000 could be a 7-year return-period storm by 2090 (Trenberth et al. 2003). These researched concerns echo the Government Accountability Office's (GAO) concern that the DoD is not incorporating future climate projections in design, as IDF curves are based on a stationary climate and are suggested to not accurately convey risk as the climate changes (GAO 2019).

The DoD designs its infrastructure based on the Unified Facility Criteria (UFC) and state requirements, with stormwater drainage designs based on NOAA IDF curves when

available. UFC 3-201-01, *Civil Engineering* (2021), lists airfield stormwater design requirements:

> "Runways, taxiways, heliports, and aprons use the minimum required by the local governing authority for airfields and heliports or a minimum 5 year storm frequency. Retrofit projects on existing runways, taxiways, heliports, and aprons should be designed using a 5 year storm. Where an engineering and cost analysis indicates that it is advantageous to the project, a minimum 2 year storm frequency may be used for retrofit projects" (DoD 2021)

In other words, DoD airfields are designed with low return-storms. The UFC also contains information on the acceptable amount of airfield ponding on runways, taxiways, and aircraft aprons:

> "The maximum spread for airfields must not encroach on the center 50 percent, along the centerline, of runways, taxiways, or helipad surfaces using a 10 year storm frequency."
>
> "The maximum spread for aprons is a depth of 4 inches (100 mm) using a 5 year storm frequency. The maximum ponding depth is 4 inches (100 mm) around apron inlets." (DoD 2021)

To summarize, DoD airfield stormwater systems are to be built to either the state minimum or a 5-year return storm, with ponding not to be allowed on the middle 50% of runways and taxiways during a 10-year return storm and ponding not to exceed four inches of depth on aprons during 5-year return storms. Other design publications do not raise these

requirements. UFC 3-260-01, *Airport and Heliport Planning and Design,* simply defers to UFC 3-201-01 for airfield drainage design (DoD 2020). The FAA's Advisory Circular on Airport Drainage Design, AC 150/5320-5D (2013), incorporates the now archived Surface Drainage Design UFC draft, which lists a minimum two-year storm requirement for DoD airfields, but echoes the requirement of avoiding ponding on the center of runways and taxiways in a 10-year return storm. The DoD could theoretically have airfields worldwide designed with a range from two-to-five-year return storms, with possible higher variations as required by states or other local authorities. Because airfields can have vast areas of impervious area, it can be economically justified to have low design requirements, as more stringent design requirements could result in rapidly rising construction costs. The FAA's airfield drainage manual states this succinctly:

> "The damage or inconvenience that may be caused by storms greater than the 5-year event may not warrant the increased cost of a drainage system large enough to accommodate that storm" (FAA 2013)

However, storms rising far above these frequencies could result in ponding levels widespread enough to slow or halt operations if the center 50% of runways and taxiways become ponded. As the climate warms and storms with higher intensities than NOAA IDF curves occur more frequently, the downtime in operations caused by excess stormwater runoff and ponding could reach unacceptable levels. As such, one could argue that NOAA's current IDF curve methodology is too conservative for use on DoD airfields and installations.

Sea Level Rise

Additionally, climate change is anticipated to affect the sea level. As the sea level rises, tides pose an additional threat to infrastructure and infrastructure planning. As noted previously, sea-level rise is commonly modeled with GIS to glean what infrastructure or landcover is at risk of inundation. However, baseline estimates such as the ones prepared by the UN IPCC can be influenced by tides, geography, and weather. For example, Bloetscher et al. (2014) noted that tidal fluctuations can add an additional layer of risk to sea level rise estimates. When preparing an estimate of sea level rise for the year 2100, Bloetscher et al. used a tidal fluctuation of two feet, which, when combined with an estimated three feet of sea level rise, assumed that elevations of below five feet above sea level would be inundated. The combination of high tides with storm surge is noted as causing the highest potential of flooding possible (Tahvildari and Castrucci 2021). Similar to how storm events can have attached probabilities of annual exceedance, tides can be similarly measured. A 1% annual exceedance probability is known as a king tide, and was used by Sadler et al. (2017) when modeling sea-level rise risk to transportation networks. Therefore, maximum sea-level rise can be modeled by combining baseline estimates of rise, king tide events, and storm surge.

SWMM

To build a model of the stormwater system of interest, Stormwater Management Model (SWMM) can be used. SWMM is a freely available stormwater modeling program, currently in its fifth version. SWMM was initially released as a public domain software in 1971 by the Environmental Protection Agency (EPA) to provide rainfall runoff quantity and quality simulations (Niazi et al. 2017). Through the evolution of the program over the last 50 years, SWMM has been upgraded to improve modeling and simulation capability. SWMM is used primarily for planning, analysis, and design of stormwater runoff, combined sewers, and sanitary sewers (Niazi et al. 2017). SWMM is also used for flooding analysis, usually resulting from backed up or inundated stormwater systems (Niazi et al. 2017). The user's manual for the latest generation of the program, published in 2015, describes SWMM as a "dynamic rainfall-runoff simulation model used for single event or long-term simulation of runoff quantity" (Rossman 2015). The extensive literature review and gap analysis of SWMM authored by Niazi et al was relied upon heavily in this research.

SWMM has several strengths and applications that make it ideal for this study. It is proposed that SWMM be used to create a model of Tyndall Air Force Base airfield stormwater system, relying on drawings of the system and a local engineering contact. The ubiquity of the program, thanks in part to its status as free to download and use, has led to the program being among the most common stormwater management programs in the world. Other programs can be interfaced with SWMM to further enhance its applicability to specialized scenarios, such as SWAT, BreZo, Dinamica-Environment for Geoprocessing

Objects, GIS, and National Oceanic and Atmospheric Administration data (Niazi et al. 2017). In addition, researchers have found that SWMM can process model simulations faster than competing programs, such as Gridded Surface Subsurface Hydrologic Analysis (GSSHA) (Brendel et al. 2021). This study also found that SWMM was strong at providing detailed simulation results that mirrored real world storm sewer hydraulic conditions. SWMM has a history of being used to model the effects of climate change and resultant increase in storm water quantity. For example, researchers have used SWMM in studies of flood risk, drainage, runoff, precipitation changes, and SLR, with concentration towards flood frequency, water quality, and stormwater system overflows (Niazi et al. 2017).

Compared to other stormwater modeling programs, SWMM has several drawbacks. For example, compared to the Urban Snow Model (USM), SWMM was found to not model snow-melt as well (Niazi et al. 2017). In addition, SWMM is not as effective or accurate at modeling nonlinear reservoir routing for overland flow as the dynamic watershed simulation model (DWSM) (Niazi et al. 2017). SWMM has a reputation of tediousness and complexity, which is balanced against the accurate results it can achieve with its flexibility (Niazi et al. 2017). SWMM has a notable drawback in its inability to model resultant flooding from inundated inlets. For example, for each inlet the user must define the area that will flood, if the inlet floods. If the inlet floods during a simulation, the simulation results generate the volume of water flooded for that inlet. Essentially, the predetermined flooding area acts as a graduated cylinder over each inlet, with the simulation results showing the maximum volume the cylinder will hold during a simulated

rainstorm. This is useful for comparing flooding intensity at each junction, but provides no information on how the flooding will affect other inlets or how land cover will be affected. Despite these drawbacks, SWMM remains the best choice for modeling the airfield stormwater system, as its customizability allows for a close replication of the stormwater system.

Models created in SWMM require calibration. SWMM model calibration is the process of tuning the model parameters so that the simulation results mirror real world observations. This process is commonly done manually, but is a time intensive and daunting task when there are many parameters in the model (Niazi et al. 2017). Optimization algorithms are available to streamline the calibration process, and some commercial versions of SWMM will automatically calibrate a SWMM model based on these algorithms (Niazi et al. 2017). For example, Wang et al (2018) found that manually performing calibration consistently resulted in worse performance than when an automatic calibration was performed using Monte Carlo techniques to optimize the parameters. SWMM models can be calibrated with single events or with continuous events, each with respective strengths. For example, calibrating SWMM models with single events is the more common approach and provides peak flow rate, time to peak flow rate, and hydrograph results of a higher accuracy than continuous event calibration. On the other hand, continuous calibration provides more accurate results in terms of estimating runoff volume (Niazi et al. 2017). However, due to a lack of system performance data for real-

world storms, this specific model cannot be calibrated. Calibration of the model remains an option for future research.

After calibration, SWMM models require validation. Validation is the process of assessing the accuracy of a model using different event data than used for the calibration. Niazi notes that among studies where SWMM models were validated, the validation performance tended to be lower than the calibration performance, which can raise issues when using the model to simulate hypothetical scenarios (Niazi et al. 2017). This highlights the need for an accurate validation of the SWMM model that is going to be created for this study, as the created model will be extrapolated with varying intensity storms and used to model risk. However, as this model cannot be calibrated during the duration of the study, this model also cannot be validated. Validation of the model remains an option for future research, if real-world system performance statistics can be attained. In the previous discussion of stormwater risk modeling, the importance of calibration and validation of models for publication was discussed.

In this background review, several topics were discussed and points established. Stormwater modeling strategies reviewed, revealing a lack of research into the gradual response of individual stormwater systems when increased rainfall and SLR effects are applied. The climate change topics of intensified rainfall and SLR were explored, along with IDF curves and how slow or non-existent updates to these curves puts infrastructure at risk, especially infrastructure designed for low return-year storms. Finally, the requirements, strengths, and weaknesses of SWMM were reviewed, along with its efficacy

and applicability to this study. In the next section, the methods used in this study to analyze Tyndall's airfield stormwater system response to climate change effects will be outlined and explained in detail.

III. Methods

The methodology of this study is introduced in Figure 6. There are seven steps in the methodology, beginning with the selection and familiarization of SWMM and finishing with using SWMM to simulate a wide range of sea-level scenarios and storms. The following sections mirror this Figure and provide the basis for analysis.

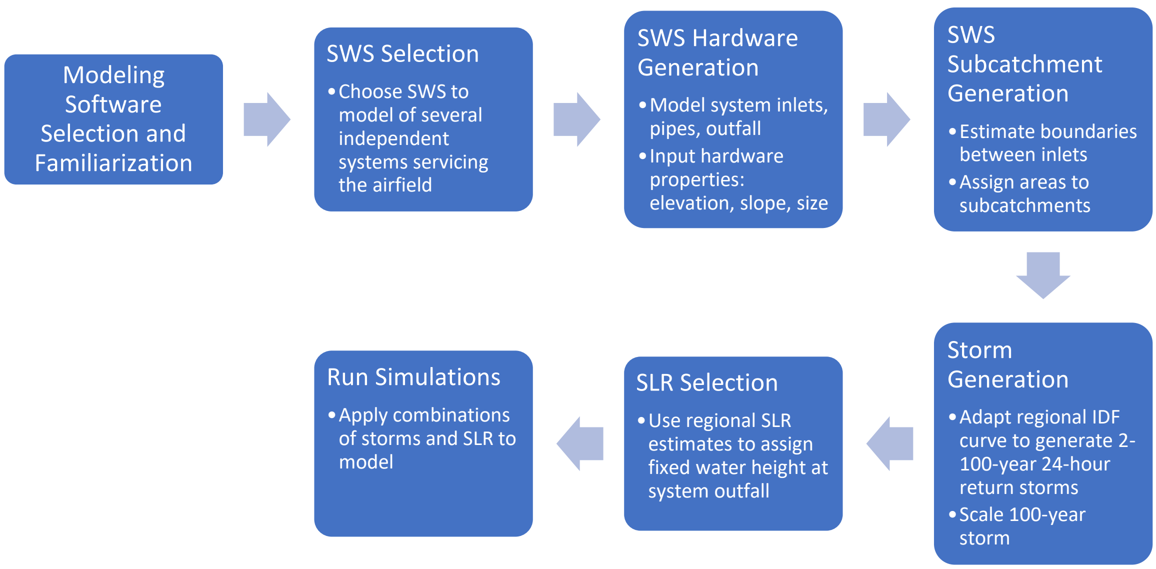

Figure 6: Methodology Flowchart

1. Modeling Software Selection and Familiarization

SWMM was chosen as the stormwater modeling software to be used in this research. SWMM version 5.1 was used, with guidance primarily coming from the SWMM 5.1 user's manual written by Lewis Rossman of the EPA. Initial work in SWMM was comprised of becoming familiarized with the program and its uses while researching

SWMM's uses and efficacy. The manual includes a step-by-step walkthrough of the creation of a basic stormwater system. This tutorial also includes applying a time-series precipitation event to the model, and how to interpret the results of the simulation. The tutorial was a valuable introduction into the basics of the program.

2. Stormwater System Selection

Points-of-contact at Tyndall AFB provided design-build request for proposal (RFP) drawings of the airfield drainage system for the airfield, produced through a joint venture of Otie RS&H for the US Army Corp of Engineers in April 2020. The drawings detail both existing conditions and changes to be made to the airfield stormwater system. Analysis of the drawings revealed that independent systems service various portions of the airfield, with varying degrees of size and complexity. An independent system servicing primarily the Bravo taxiway at the north end of the airfield was selected. This stormwater system drains into Fred Bayou. This system also services small portions of the Delta, Golf, and Foxtrot taxiways and Runway 14L-32R. This system was chosen to be modeled for several reasons. First, this system is less complex than other systems, as all conduits are single-barrel only, whereas other systems have double- and even triple-barrel culverts. Second, this system services a diverse mix of interior airfield grass, taxiways, and runway. Third, this system discharges into a ditch draining into a bayou, with an outfall elevation of .0914 meters above sea level. Overall, this system was the ideal and obvious choice for study. An illustration of the system overlaid on satellite imagery can be seen in Figure 7.

Figure 7: Modeled Stormwater System

3. Stormwater System Hardware Generation

Following the decision to model the north Bravo taxiway system, generation of the model in SWMM could begin. Junctions and conduits were sequentially added, beginning with the end of the stormwater system opposite the outfall. The SWMM manual describes junctions:

> "Junctions are drainage system nodes where links join together. Physically they can represent the confluence of natural surface channels, manholes in a sewer system, or pipe connection fittings. External inflows can enter the system at junctions. Excess water at a junction can become partially pressurized while

> connecting conduits are surcharged and can either be lost from the system or be allowed to pond atop the junction and subsequently drain back into the junction." (Rossman 2015)

The terms "node" and "junction" are used interchangeably in both the manual and this study. All hardware generated for the SWMM model was done in feet to avoid converting units from the construction drawings. The invert elevation and maximum water depth was specified for each junction. The invert elevation gleaned directly from the drawings, as conduits listed starting and ending invert elevation. The maximum water depth for each junction was calculated by subtracting the invert elevation from the rim elevation listed in the drawings. As discussed previously, a drawback of SWMM is its inability to model overland flooding resulting from inundated inlets. A circular ponded area with a diameter of 200 feet was assigned for each inlet in this model, for a total defined ponded area of 31,416 square feet for each inlet. When flooding happens in a simulation, the results return the maximum volume of ponding occurring within the defined area. Conduits were added to link junctions. The SWMM manual defines conduits as "pipes or channels that move water from one node to another in the conveyance system" (Rossman 2015). For each conduit, the inlet and outlet nodes (junctions) were specified. Additionally, the shape of each conduit was specified. Generally, the further from the terminus, conduits are circular pipes with two-foot diameters. As runoff quantity increases, circular conduits increase to three-foot diameters, and then become rectangular closed culverts with three-foot depths. Regardless of material, the Manning's roughness coefficient for each conduit was left at

the default value of 0.01. On some conduits, outlet offsets were specified where junctions featured decreases in invert elevation. Additionally, conduits in SWMM are not drawn to scale. Therefore, the user must simply draw a conduit to a length that makes visual sense, and then manually input the length of the conduit. Finally, following the generation of all junctions and conduits, the system outfall was added. The invert elevation of 0.30 feet was specified. Overall, 27 conduits and 28 junctions were generated. Example junction and conduit properties dialog boxes can be seen in Figure 8.

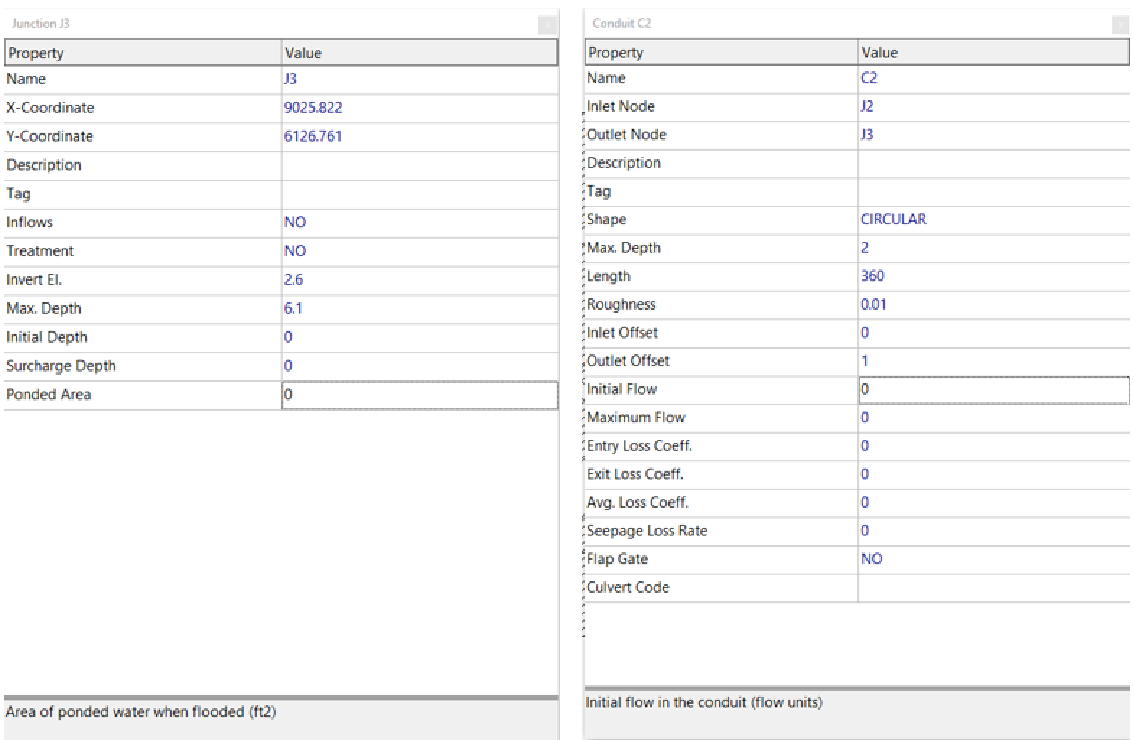

Figure 8: Junction and Conduit Properties Dialog Boxes

4. Stormwater System Subcatchment Generation

After junctions, conduits, and the outfall were generated, subcatchments were added. The SWMM manual defines a subcatchment as “an area of land containing a mix of pervious and impervious surfaces whose runoff drains to a common outlet point, which could be either a node of the drainage network or another subcatchment.” On the airfield, stormwater drains are located off paved areas, surrounded by interior airfield grass. Therefore, runoff from paved areas flows from the pavement, onto the grass, and into the stormwater system. Subcatchments in SWMM, like conduits, are not drawn to scale. Users free-draw subcatchments to the best of their ability to roughly mimic areas that would drain into junctions. Starting with the highest point in the stormwater system, subcatchments were drawn to represent portions of the taxiway in intervals that mimicked the average distance between junctions. Parallel to these pavement subcatchments, grass subcatchments were drawn surrounding the junctions. Subcatchments offer a plethora of customizable characteristics. Notably, for paved subcatchments the percent sloped was specified as 0.5%, the percent impervious was specified as 100%, and the percent of impervious area with no depression storage was specified as 100%. For grass subcatchments, the percent slope was specified as 2%, the percent impervious was specified as 40%, and the percent of impervious area with no depression storage was specified as 25%. An example subcatchment properties dialog box can be seen in Figure 9.

Subcatchment S39

Property	Value
Name	S39
X-Coordinate	9147.092
Y-Coordinate	8694.072
Description	
Tag	
Rain Gage	Gage1
Outlet	s2
Area	.43
Width	250
% Slope	0.5
% Imperv	100
N-Imperv	0.01
N-Perv	0.1
Dstore-Imperv	0.05
Dstore-Perv	0.05
%Zero-Imperv	100
Subarea Routing	OUTLET
Percent Routed	100
Infiltration Data	MODIFIED_GREEN_AMPT
Groundwater	NO
Snow Pack	
LID Controls	0
Land Uses	0
Initial Buildup	NONE
Curb Length	0
N-Perv Pattern	
Dstore Pattern	
Infil. Pattern	

Mannings N for impervious area

Figure 9: Subcatchment Properties Dialog Box

Following the generation of subcatchments, the user must then assign areas to the subcatchments. Acres were used to denote area. As SWMM is not drawn to scale, this process can require a blending of methods to assign acceptable estimates of area to each subcatchment. Further complicating this process is the user-defined nature of the

subcatchments. The construction drawings were used to create a tracing of the stormwater system of study, including junctions and conduits. Subcatchments were added to mirror the estimated location of subcatchments in the SWMM model. Known system dimensions were measured using a ruler to find a common metric. In this case, a 250-foot conduit was closely comparable to a half-inch. Satellite imagery from Google Earth was used to approximate runway and taxiway locations and dimensions, which served to help determine subcatchment boundaries. With this estimating standard developed, dimensions could then be assigned to subcatchment boundaries, and from these boundary estimates basic geometry was used to calculate the area in square feet of the subcatchments. These square footage totals were converted to acres and input into the individual subcatchment properties. This method was especially useful for non-uniformly shaped subcatchments. For subcatchments of relatively uniform dimensions, two acres emerged as a common estimate. Overall, 51 subcatchments were generated. A conglomerate image of the complete SWMM model can be seen in Figure 10.

Figure 10: SWMM Model

5. **Storm Generation**

To run simulations in the model, initial rainfall levels needed to be established. It was decided that 24-hour storms would be applied to the model for the baseline, using Florida Department of Transportation (FDOT) IDF curves. FDOT divides the state into eleven zones, each with their own IDF curve for all standard return storm periods. Tyndall AFB is located in Zone 1, along with all other counties in the far west corner of the state. This IDF curve was previously referenced and can be seen in Figure 5. From the Zone 1

IDF curve, the rainfall intensity in inches per hour for 10, 25, 50, and 100-year 24-hour storms were recorded. These intensities were multiplied by 24 hours to find the cumulative amount of rainfall, in inches, for the 24-hour storms. The FDOT also provides mass rainfall curves for all storm durations, accompanied by precipitation totals and intensities for each hour (FDOT 2022). The IDF intensities and corresponding cumulative rainfall totals were multiplied by the pre-calculated totals and intensities in order to generate hyetographs of 24-hour storms for all return periods. A hyetograph for the 24-hour, 100-year storm can be seen in Figure 11.

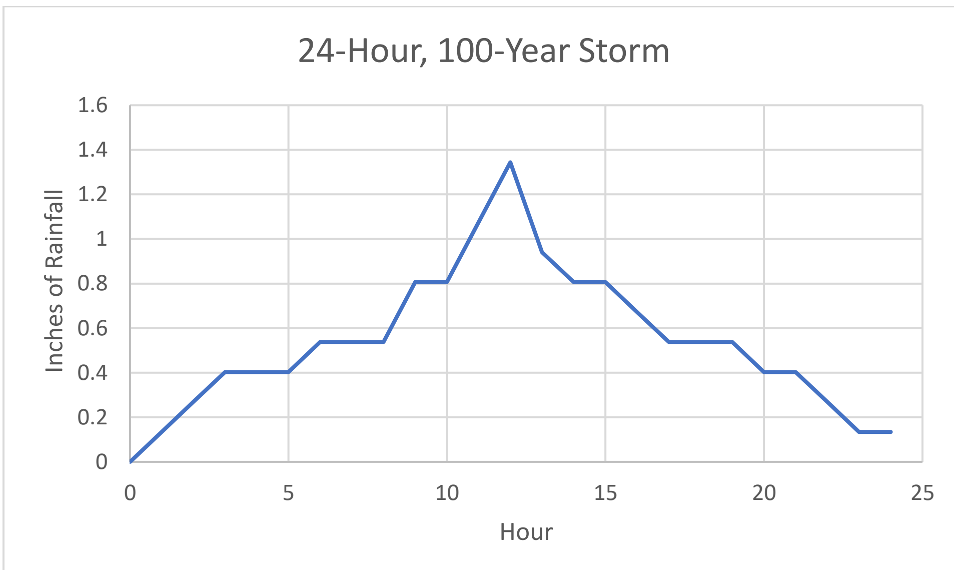

Figure 11: Hyetograph for 24-Hour, 100-Year Storm

To model intensified storms under climate change scenarios, the 24-hour, 100-year storm from the FDOT IDF curve was mathematically scaled. The hyetograph was multiplied to produce storms that have 10% larger precipitation depth than the previous storm. This

range of potential future storms offers several benefits. First, it satisfies projections of intensifying storms in the United States. Second, it offers insights into the stormwater system's performance under increasingly heavy loading of storms roughly equivalent to NOAA 200-year storms and higher. As the amount of rainfall exceeds the stormwater system's design, ponding can be expected to occur with more frequency. A summary of the simulated storms can be seen in Table 2, with an example of how the intensified storms were generated.

Table 2: Model Storms

Storm Return-Year Period	Rainfall Intensity (in/hr)	Total Precipitation Depth (inches)
10	0.38	9.12
25	0.45	10.8
50	0.51	12.24
100	0.56	13.44
100+10%	0.616	14.78
100+20%	0.672	16.13
100+30%	0.728	17.47
100+40%	0.784	18.82
100+50%	0.84	20.16

100-yr +10% storm intensity = (100-yr in/hr)*(1.1)

100-yr +10% storm intensity = (0.56 in/hr)*(1.1)

100-yr +10% storm intensity = .616 in/hr

100-yr +10% storm depth = (0.616 in/hr)*(24 hr)

100-yr +10% storm depth = 14.78 in

With all storms generated, the storms could then be manually entered into SWMM as time series data reflecting the depth of precipitation per hour of storm. An example for a 24-hour, 100-year storm used in the study can be seen in Figure 12.

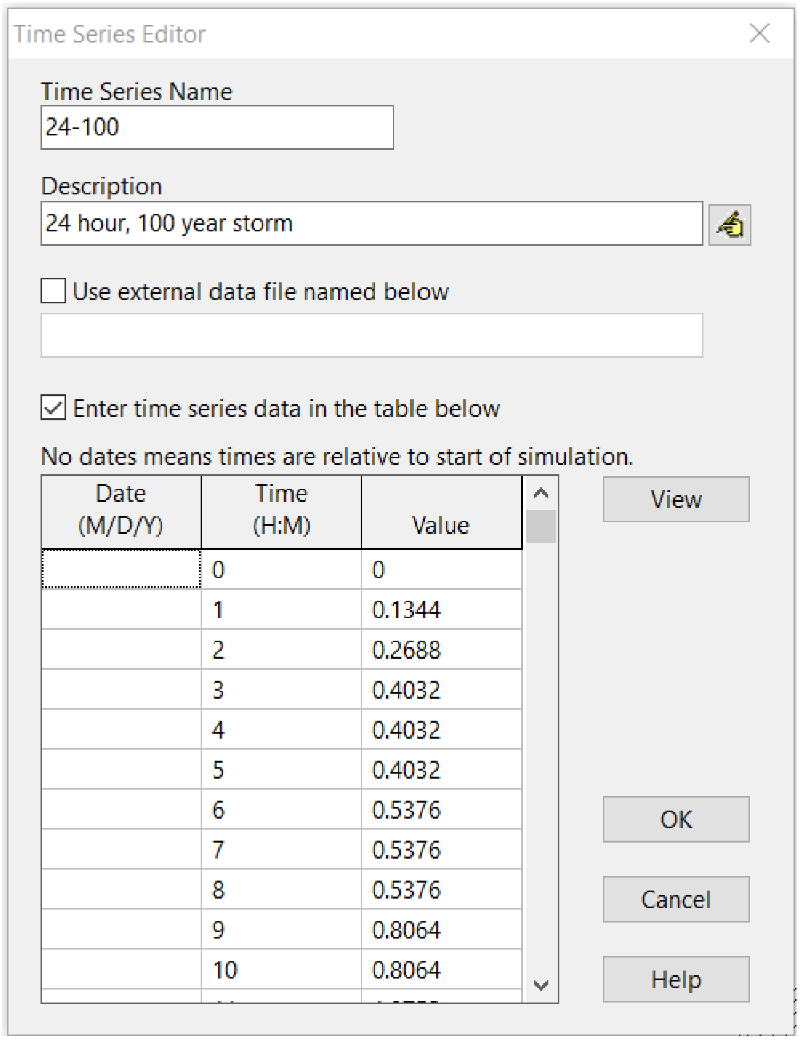

Figure 12: SWMM Time Series for 24-Hour, 100-Year Storm

6. SLR Selection

Sea-level rise for this study was modeled through fixed outfall heights at the system terminus, where the last culvert of the stormwater system flows into the drainage ditch leading to Fred Bayou. A fixed outfall height represents a specific water level of a water body that the stormwater system is emptying into. Sea-level rise projections for Tyndall Air Force Base from the Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) were added into the outfall properties as a fixed outfall. These future projections as a fixed outfall height allowed for the outfall to be partially or fully submerged. Zero sea level rise was used initially, scaling by 0.1 meters increments up to a maximum of 2.1 meters. As the SWMM model was created using Imperial units, these SLR estimates were converted to feet when applied to the system outfall. A list of SLR heights used as fixed outfall heights can be seen in Table 3.

Table 3: SLR Projections Used in Study and Associated Timeframes

<table>
<tr><th>SLR (meters)</th><th>SLR (feet)</th><th colspan="3">Timeframe</th></tr>
<tr><td>0.00</td><td>0.00</td><td colspan="3">2016 (Baseline)</td></tr>
<tr><td>0.10</td><td>0.33</td><td rowspan="3">2035</td><td rowspan="9">2065</td><td rowspan="17">2100</td></tr>
<tr><td>0.20</td><td>0.66</td></tr>
<tr><td>0.30</td><td>0.98</td></tr>
<tr><td>0.40</td><td>1.31</td><td></td></tr>
<tr><td>0.50</td><td>1.64</td><td></td></tr>
<tr><td>0.60</td><td>1.97</td><td></td></tr>
<tr><td>0.70</td><td>2.30</td><td></td></tr>
<tr><td>0.80</td><td>2.62</td><td></td></tr>
<tr><td>0.90</td><td>2.95</td><td></td></tr>
<tr><td>1.00</td><td>3.28</td><td></td><td></td></tr>
<tr><td>1.20</td><td>3.94</td><td></td><td></td></tr>
<tr><td>1.40</td><td>4.59</td><td></td><td></td></tr>
<tr><td>1.60</td><td>5.25</td><td></td><td></td></tr>
<tr><td>1.80</td><td>5.91</td><td></td><td></td></tr>
<tr><td>2.00</td><td>6.56</td><td></td><td></td></tr>
<tr><td>2.10</td><td>6.89</td><td></td><td></td></tr>
</table>

7. Run Simulations: Apply Storms and SLR to Model

With a complete model and generated storms, simulations could begin. To start, time series data for the 10-year storm was selected in SWMM. Following this, a fixed outfall height of 0.1 meters (0.33 feet) was determined, and a simulation was run. The simulation report was exported, and the fixed outfall height was increased to the next SLR estimate and another simulation was run and the report exported. This process continued until all SLR estimates had been simulated with the 10-year return storm, upon which the time series for the 25-year storm was selected and the process restarted. Once all combinations of storms and SLR had been simulated, the outfall was changed to “free” to

represent no restrictions or preexisting bodies of water at the outfall. In other words, this represented zero SLR present at the outfall. All storms were then simulated and their reports exported.

IV. Results

Determining Airfield Failure Indicators

When running simulations of combinations of storms and fixed outfalls, several characteristics were monitored. These characteristics included junction flooding volume, the duration in hours of junction flooding, the duration in hours of conduit capacity limitation, and the duration in hours of junction surcharge. Duration of conduit capacity limitation was chosen over conduit surcharge because this limitation indicates the conduit can no longer efficiently vector stormwater runoff. If a conduit is limited, it implies the conduit is surcharged, full at both ends, and runs above normal flow for some duration. A portion of a SWMM simulation report containing the Conduit Surcharge Summary illustrates this effect, Table 4. For example, Conduit 26 is present in the table because it experiences surcharge during the simulation. This conduit is full at both ends for 24.93 hours during the simulation, and the capacity is limited for 1.27 hours. Conduit 16 is full at both ends for 24.52 hours, but its capacity is limited for only 0.01 hours. Overall, capacity limited is a more descriptive and differentiating failure indicator than pure surcharge. Additionally, this table illustrates that conduits can experience a surcharge of longer than 24 hours in the simulations, reflecting that the conduit experiences surcharge from SLR prior to the beginning of the model storm.

Table 4: 100+30% Storm, 1.4m SLR Conduit Surcharge Summary

```
*************************
Conduit Surcharge Summary
*************************
```

Conduit	Hours Full Both Ends	Hours Full Upstream	Hours Full Dnstream	Hours Above Full Normal Flow	Hours Capacity Limited
C1	1.22	1.22	1.88	0.01	0.01
C2	1.88	1.88	2.22	0.01	0.02
C3	1.28	1.28	21.90	0.01	0.01
C4	2.22	2.22	2.98	0.01	0.01
C5	2.21	2.21	2.98	0.01	0.01
C6	2.98	2.98	5.00	0.01	0.01
C7	1.99	1.99	2.86	0.01	0.01
C8	5.00	5.00	8.08	0.01	0.01
C9	2.21	2.21	5.01	0.01	0.01
C10	5.01	5.01	7.08	0.01	0.01
C11	3.17	3.17	6.81	0.01	0.01
C12	8.32	8.32	16.79	0.01	0.01
C13	6.81	6.81	8.32	0.01	0.01
C14	8.07	8.07	14.11	0.01	0.01
C15	14.11	14.11	24.52	0.01	0.01
C16	24.52	24.52	24.80	0.01	0.01
C17	2.36	2.36	6.99	0.01	0.01
C18	6.99	6.99	24.54	0.01	0.01
C19	24.54	24.54	24.80	0.01	0.01
C20	1.70	1.70	2.99	0.01	0.01
C21	2.99	2.99	7.02	0.01	0.01
C23	7.02	7.02	24.54	0.01	0.01
C24	3.41	3.41	7.02	0.01	0.01
C25	24.80	24.80	24.93	1.34	1.26
C26	24.93	24.93	24.96	1.33	1.27
C27	24.96	24.96	25.00	6.90	6.70
C28	7.03	7.03	13.67	0.01	0.01
C29	13.67	13.67	24.54	0.01	0.01

SWMM simulation reports contain a plethora of data for nodes, conduits and subcatchments, with tabular results for subcatchment runoff, node depth, node inflow, node surcharge, node flooding, outfall loading, link flow, flow classification, and conduit surcharge. Once a simulation was completed, the simulation report was exported and used to first identify and record in a summary spreadsheet the conduits and junctions that experienced any degree of flooding or surcharge, through referencing the following SWMM simulation report tables: Node Surcharge Summary, Node Flooding Summary,

and Conduit Surcharge Summary. These summary tables were essential to helping identify system components that first begin to experience failure indicators as loading increases. Next, numeric values for the failure indicators of critical junctions and conduits were recorded for all design storms and SLR estimates. From the previously referenced SWMM simulation report tables, the duration in hours of surcharge in nodes, the duration in hours of flooding in nodes, the total flood volume in gallons, and the duration in hours of limited capacity in conduits was recorded. Each 24-hour storm from Table 2 was simulated using all SLR levels from Table 3, resulting in 153 combinations and 153 unique simulation reports. In each report, 11 critical component observations made, resulting in 1,683 total recorded numerical observations. A table summarizing the failure indicators, associated components, and SWMM simulation report table used for the indicators can be seen in Table 5. The locations of these components can be seen in Figure 13 and Figure 14.

Table 5: Results Breakdown

SWMM Simulation Report Table	**Failure Indicator from Table**	**Applicable Components (See Figs. 13-14)**
Node Surcharge Summary	Hours surcharged	N19, N27, N28
Node Flooding Summary	Hours flooded	N19, N27, N29
Node Flooding Summary	Total flood volume, 10^6 gallon	N19, N27, N30
Conduit Surcharge Summary	Hours capacity limited	C25, C26, C27

Determining Critical Components

These characteristics were tracked for several junctions and conduits identified as critical. These critical junctions and conduits were chosen based on several criteria,

including adjacency to airfield pavement and proximity to the system outfall. Additionally, these critical junctions and conduits were identified as surcharging, flooding, or becoming limited earliest as stronger combinations of storms and SLR were applied. Conduit 23 was initially identified as critical because it passes underneath Taxiway Golf, but after collection of the numerical results it was determined to have insignificant levels of surcharge and conduit capacity limitation compared to the other three critical conduits. The failure indicator values for this conduit were subsequently removed from consideration for interpretation. The final critical infrastructure points can be seen overlaid on a satellite image in Figure 13, and identified on the SWMM model in Figure 14.

Figure 13: Critical Nodes and Conduits (Satellite)

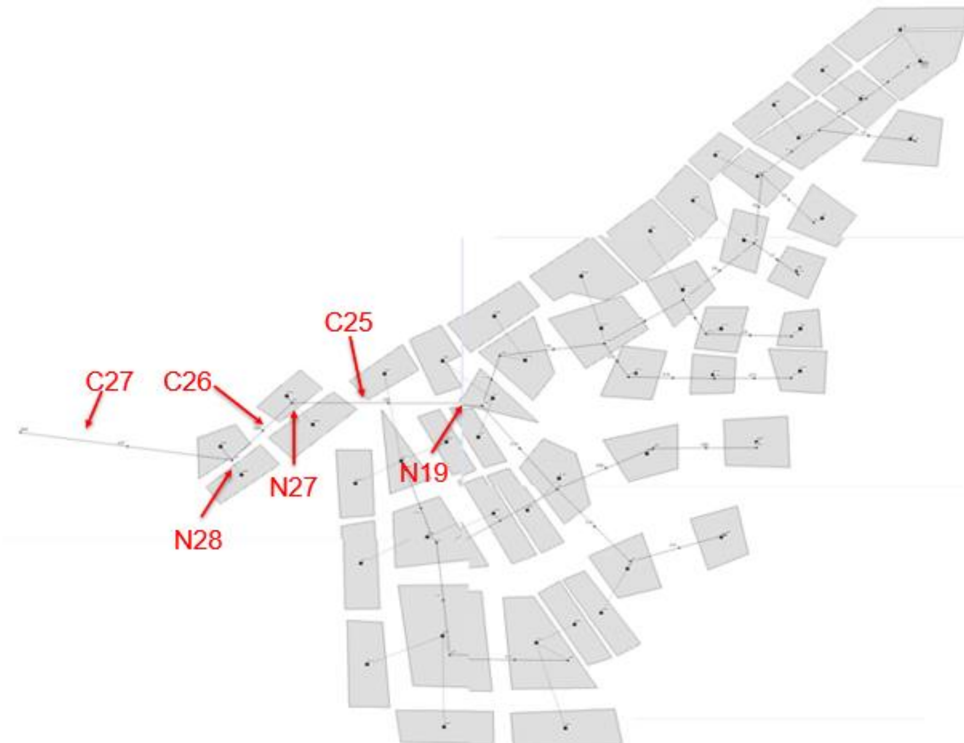

Figure 14: Critical Nodes and Conduits (SWMM)

Continuity Error

After successfully completing the simulation, continuity errors for runoff quantity and flow routing are reported. The SWMM manual describes the function of these percentages:

> "These errors represent the percent difference between initial storage + total inflow and final storage + total outflow for the entire drainage system. If they exceed some reasonable level, such as 10 percent, then the validity of the analysis results must be questioned." (Rossman 2015)

The average runoff quantity continuity error was -0.01744%, with a maximum deviation from zero of -0.022%. The mean flow routing continuity error was -0.2894%, with a maximum deviation from zero of -6.99%. The flow routing continuity errors were skewed right, as the median error was -0.001%. With all continuity errors under 10%, one can conclude that analysis results are acceptable. Notably, a fixed outfall height of 5.91 feet (1.8 meters) invariably produced the significantly highest flow routing continuity error across all storm intensities. The cause of this is unknown. A summary of these values can be seen in Table 6.

Table 6: Simulation Continuity Error

	Runoff Quantity Continuity Error, %	Flow Routing Continuity Error, %
Minimum	-0.0220	-6.9900
Maximum	-0.0160	0.5380
Mean	-0.0174	-0.2894
Median	-0.0170	-0.0010

Summary Spreadsheet Generation and Failure Indicator Results

As mentioned previously, 153 simulations were performed, applying every generated return-storm to every SLR level listed in Table 3. An example summary spreadsheet for 100-year storms across all SLR levels can be seen in Table 7.

Table 7: Summary Spreadsheet, 100-Year Return Storm

SLR (meters)	SLR (feet)	Node Flooding	Node Surcharge	Conduit Surcharge	Runoff Quantity Continuity Error	Flow Routing Continuity Error
0.1	0.33			27	-0.017	-0.019
0.2	0.66			27	-0.017	-0.001
0.3	0.98			27	-0.017	0.002
0.4	1.31			27	-0.017	0.002
0.5	1.64			27	-0.017	0.003
0.6	1.97			27	-0.017	0.003
0.7	2.30			27	-0.017	0.003
0.8	2.62			27	-0.017	0.003
0.9	2.95			27	-0.017	0.002
1	3.28		19, 27, 28	16, 19, 25, 26, 27	-0.017	-0.007
1.2	3.94	27	11, 14, 15, 16, 18, 19, 20, 21, 23, 27, 28, 29, 30	3, 8, 10-19, 21, 23-29	-0.017	0.002
1.4	4.59	27	3, 5, 6, 9, 11-30	2- 29	-0.017	-0.005
1.6	5.25	1, 9, 13, 17, 27, 28	ALL	ALL	-0.017	-0.781
1.8	5.91	1-4, 6, 10, 13, 16, 17, 22, 23, 27, 28	ALL	ALL	-0.017	-4.426
2	6.56	1, 4, 6, 10, 13, 16, 17, 22, 25, 26, 27, 28, 30	ALL	ALL	-0.017	-0.515
2.1	6.89	1, 4, 6, 10, 13, 16, 17, 22, 2, 27, 28, 30	ALL	ALL	-0.017	0.176

Analysis of summary spreadsheets reveal important information about the system's performance. As these spreadsheets were populated as simulations were completed, they help establish which components of the system are most susceptible to surcharging or flooding as fixed outfall heights rise. For example, one will notice that conduit 27 begins surcharging immediately, followed by a quickly increasing number of conduits as fixed

outfall heights rise. Node surcharge begins to occur at a fixed outfall height of 1.0 meters, while flooding from nodes begins at 1.2 meters. These observations helped identify the previously mentioned critical components listed in Table 5 and shown in Figure 13.

With summary spreadsheets complete and critical components identified, specific data could be recorded. As previously mentioned, 11 observations were made for each combination of SLR and return storm, for a total of 1,683 observations. The 11 observations for the combination of 100-year storm and 1.6 meters of SLR can be seen below in Table 8. The Value column, comprised of hours and volume of flooded runoff, provided the foundation for data analysis and visualization. The compilation of these observations into one spreadsheet was crucial for ease of data management in RStudio.

Table 8: Failure Indicator Results for 100-Year Storm, 1.6m SLR

SLR	Return Period	Failure Metric	Conduit/Node ID	Value
1.6	100	Hours Capacity Limited	23	0.01
1.6	100	Hours Capacity Limited	25	0.03
1.6	100	Hours Capacity Limited	26	0.01
1.6	100	Hours Capacity Limited	27	2.27
1.6	100	Hours Surcharged	19	24.84
1.6	100	Hours Surcharged	27	24.96
1.6	100	Hours Surcharged	28	24.97
1.6	100	Hours Flooded	27	0.01
1.6	100	Hours Flooded	28	0.01
1.6	100	Total Flood Volume (10^6 gal)	27	0.004
1.6	100	Total Flood Volume (10^6 gal)	28	0.003

Results Visualization

The failure indicator results were imported into RStudio and segregated by failure metric for visualization.

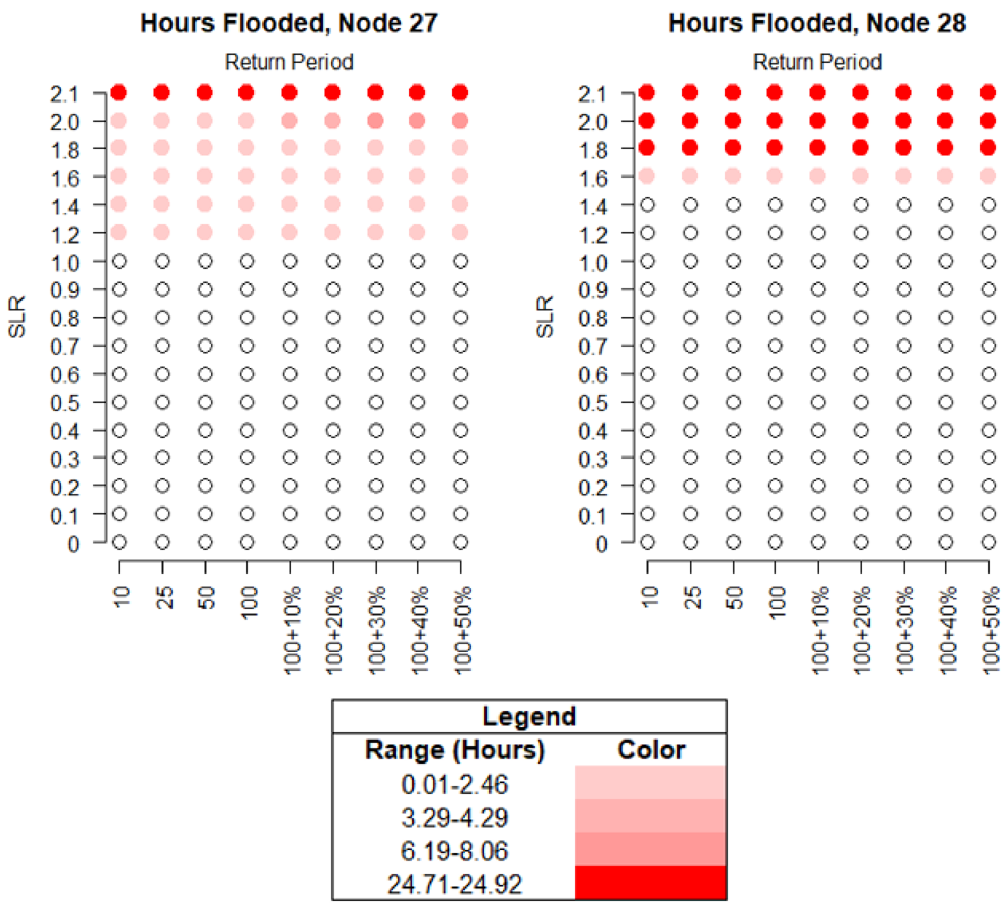

Figure 15: Hours Flooded, Critical Nodes

Figure 15 shows that flooding is avoided at the critical nodes until the water level at the outfall becomes 1.2 meters. Despite node 28's closer proximity to the system outfall, node 27 becomes flooded at lower levels of SLR. However, node 28 experiences much more severe durations of flooding at lower levels of SLR than node 27, with flooding durations of over 24 hours at 1.8 meters and higher of SLR. Additionally, the flooding duration at node 27 is predominantly 4.29 hours or lower, until 2.1 meters of SLR is applied and the duration of flooding surges over 24 hours.

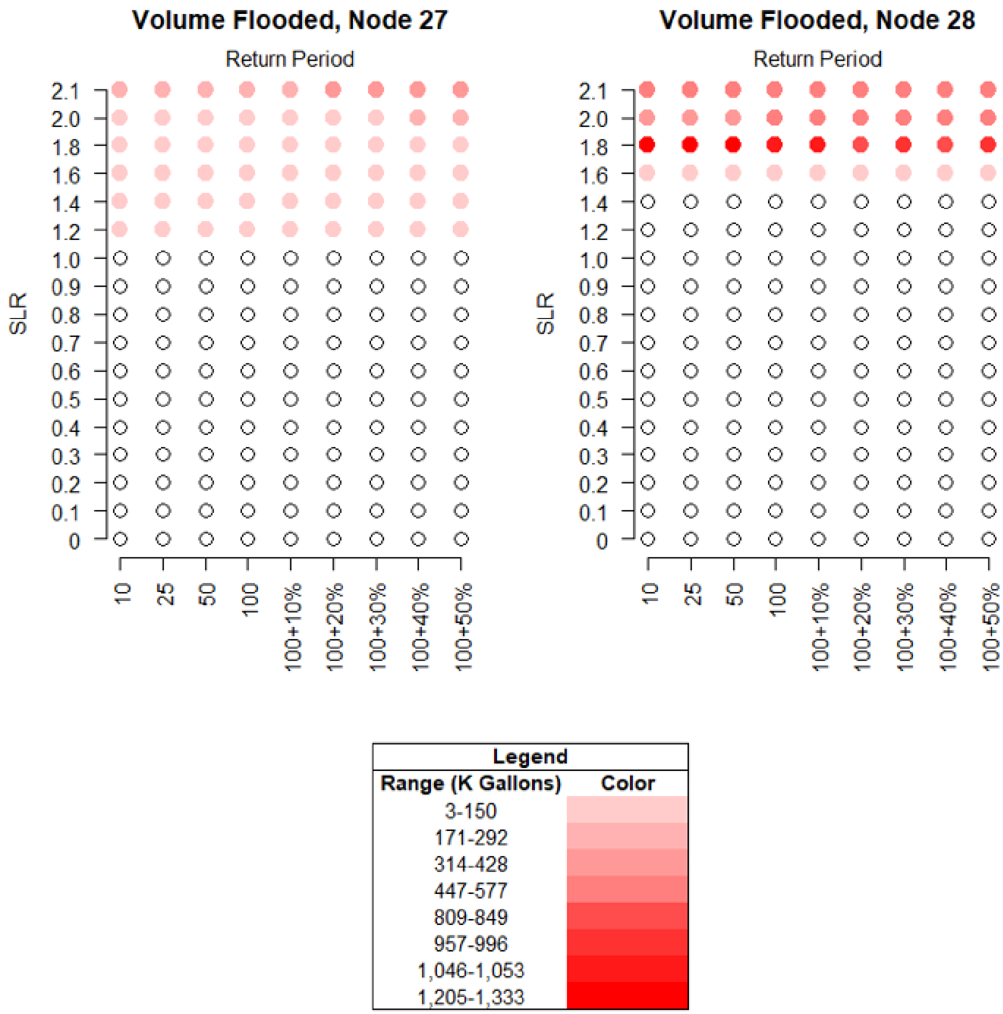

Figure 16: Volume of Water Flooded, Critical Nodes

Figure 16 visualizes the associated volume of water flooded from the critical nodes. Although node 27 floods first, its flooding is volumetrically much lower than the flooding at node 28. Flooding volumes at node 28 rise extremely quickly at the 1.8 meters mark, with a rough average of one million gallons flooded from the node over the simulation

period for all storms. One will notice that flooding volume is highest at node 28 at the 1.8 meters mark; it is assumed that the higher SLR at the outfall results in flooding further upstream in the stormwater system. Since these nodes are located roughly 100 feet away from the edge of taxiway Bravo, it is feasible that these high flooding volumes could impact airfield usage even in lower return storms.

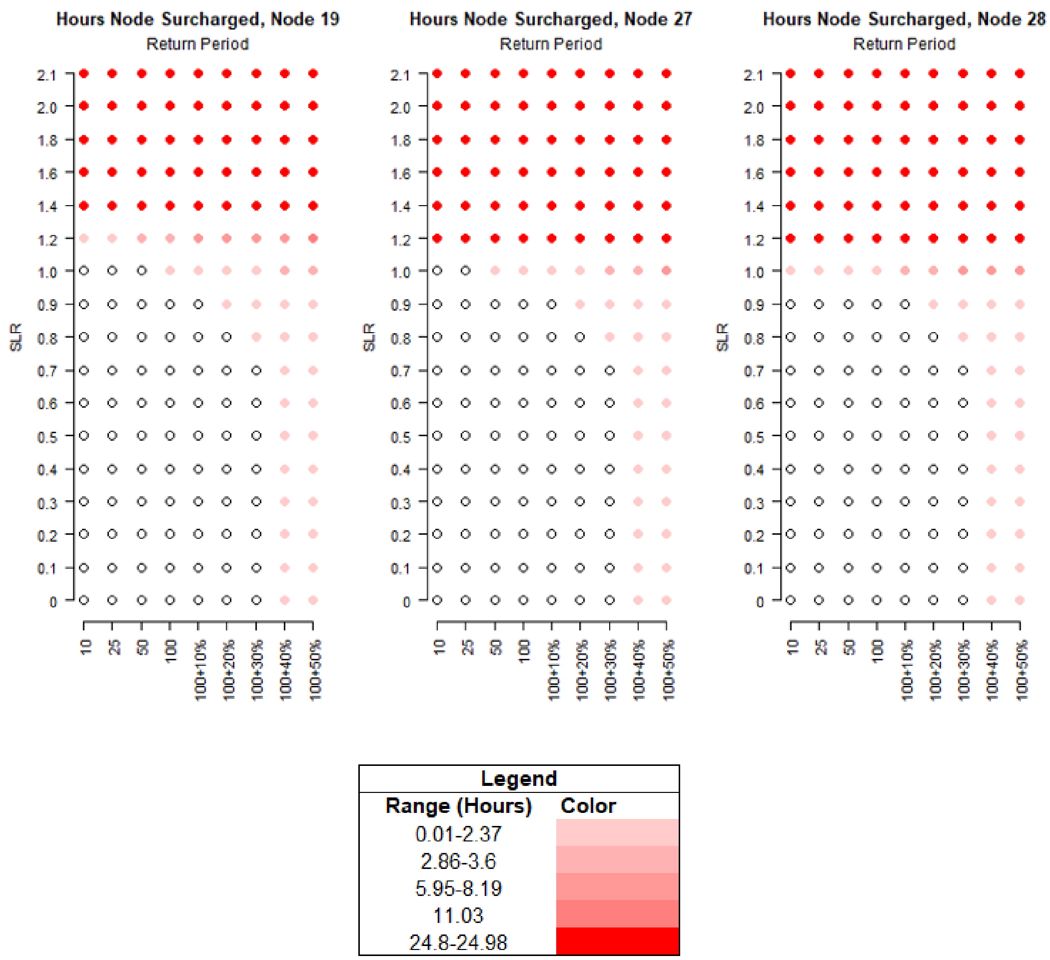

Figure 17: Hours Surcharged, Critical Nodes

Figure 17 illustrates that node 19 begins to surcharge at 100-year return storm scales of 40% and 50% at current conditions, with surcharge becoming more common at less strong storms as the applied SLR increases. The nodes become surcharged for virtually the entire duration of the simulation period at the 1.4 meters SLR scenario. Nodes 27 and 28, further downstream in the stormwater system, begin to surcharge at slightly lower levels of rainfall intensity and SLR. These junctions are surcharged for virtually the entire storm duration at the 1.2 meters SLR scenario. Proximity to the system outfall results in surcharging at lower SLR and storm levels. While surcharge is not as problematic for airfield operations as flooding, surcharge still places additional stress on the stormwater system.

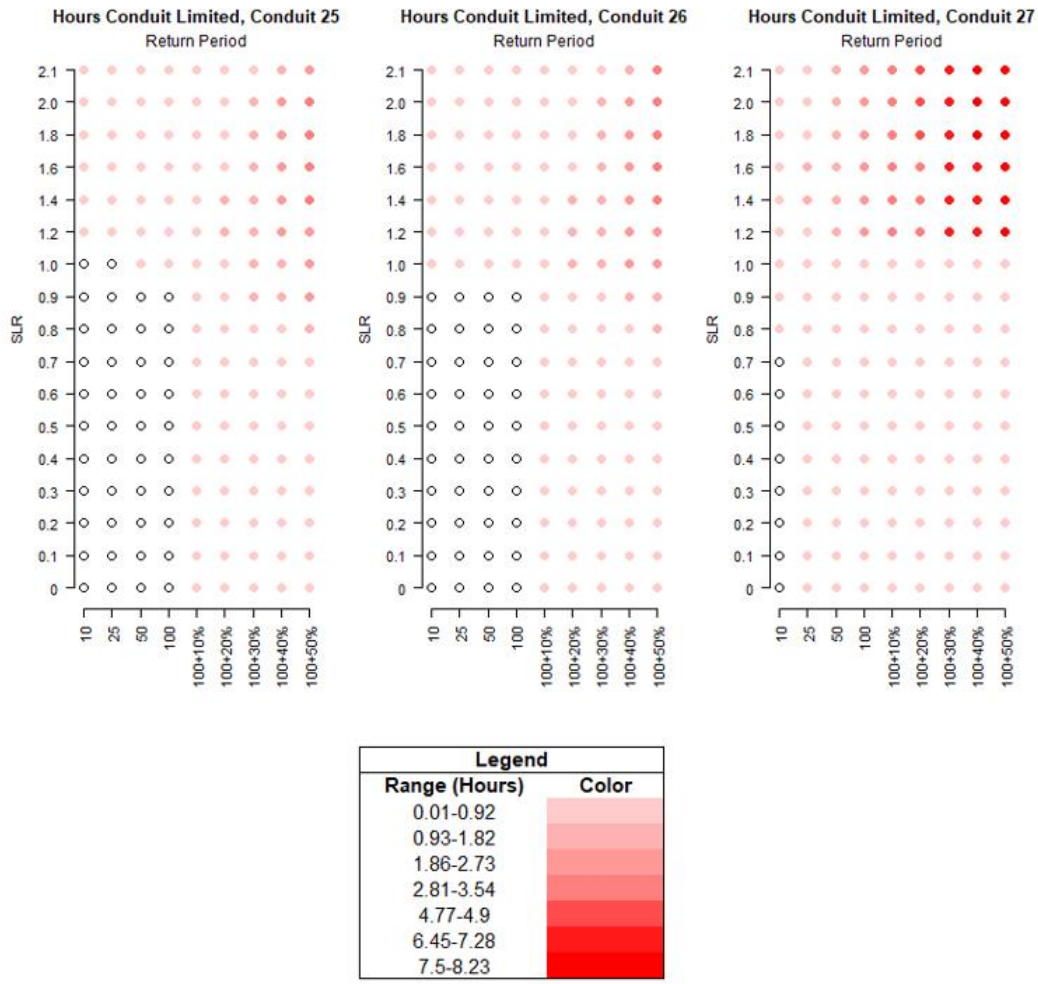

Figure 18: Hours Capacity Limited, Critical Conduits

Figure 18 Figure 18illustrates that the critical conduits experience capacity limitation under current conditions (no SLR at the outfall) under high return year storm conditions, with the exception of conduit 27 which experiences limitation beginning at the 25-year return storm. Conduit 25, which passes underneath the intersection of taxiways Bravo, Golf, and Delta first experiences limitation in the 1.2 meters of SLR scenario.

Downstream, conduit 26 first experiences limitation at all storm levels in the 1.0 meters of SLR scenario. Conduit 27, the terminal conduit in the stormwater system, is significantly stressed in nearly all storm and SLR scenarios, with limitation experienced in all but the 10-year return storm until SLR of 0.8 meters is reached. In all three conduits, duration of limitation is highest at both the strongest storms and most extreme sea levels, with a peak of 8.23 hours limited at conduit 27. This extensive surcharging places additional stress on these conduits.

V. Discussion

Interpretation of Results

Referencing Table 3, SLR projections by year can be used to predict when these failure indicators may begin to impact airfield operations. Overall, failure indicators began to become widespread at sea levels of 1.0 meters and higher. A sea level rise of 0.9 meters is currently expected at Tyndall AFB by 2065 under the highest emissions scenario, and a sea level rise of 0.9 meters is expected by 2100 under a medium emissions scenario, with higher rise under higher emissions scenarios. Therefore, Tyndall AFB could begin to see strong degradation in the performance of its airfield stormwater system from SLR in as soon as 2065 if global emissions continue to rise. If storms continue to intensify, limitation in conduits could be seen with increasing frequency. Even without SLR, the key components begin to surcharge under scaled storms. Furthermore, the significant stresses placed on the system by surcharging and the salinity of tidewater could prematurely degrade the system condition.

The interpretation of these results hinges crucially on an understanding of DoD stormwater design requirements. As discussed previously, the overall minimum design storm listed in the UFC for DoD airfields is two or five years, with requirements to avoid ponding during five and ten-year return storms. Analysis of the SWMM simulation report for a 10-year return storm with no SLR reveals no surcharge or flooding, indicating that the system, as modeled, can efficiently handle a storm of this magnitude. However, a 25-year storm will cause a slight limitation in capacity of the final conduit of the system, a

3’x6’ box culvert. In other words, with no SLR present at the outfall, the system begins to show signs of inefficiency during a 25-year storm. The rainfall amounts used in this study were accessed from FDOT IDF curves, which are based on NOAA rainfall data and do not take increase in rainfall from climate change into account. This highlights the need for updated, or projected, rainfall data for use in design, as intensified 10 and 25-year storms would exacerbate this inefficiency.

Paths Forward

The initial findings of this study indicate that a combination of high SLR and heavy precipitation can lead to rapid surcharging and flooding. In light of these challenges, Tyndall AFB could implement several infrastructure upgrades. Flap gates could be installed at stormwater system outfalls to lessen the impact of extreme water levels at the outfall. The installation could invest in pumps to ensure that stormwater is efficiently vectored off of the airfield and into the bay or ocean, similar to the system implemented by Langley AFB and discussed previously. Alternatively, the installation could physically increase the size of its stormwater systems to account for higher runoff amounts.

Limitations

There are several limitations in this study requiring discussion. As mentioned previously, SWMM models ideally need validation and calibration. Validation and calibration were not accomplished for this model, as rainfall data and associated stormwater system performance were not available. As such, the model was generated as close as possible to the available construction drawings. In the future, this model could be

validated and calibrated if storm data and system performance could be monitored. Notably, the day-to-day conditions in the drainage ditch and canal leading to the sea are unknown.

Additionally, for the purposes of this study, estimated sea levels were applied directly to the stormwater system outfall as a fixed water body height. Since the terminus of the stormwater system drains into a ditch, and then into a canal, these sea levels do not directly translate to the system outfall. Without further study, it is unknown how these sea levels will translate to the canal, the ditch, and ultimately the system outfall. The timeframes suggested above, 2065 under highest emissions and 2100 under medium emissions, may be pushed back to allow the SLR to encroach inland. This limitation is unequivocally the largest in this study and most recommended for further study.

Furthermore, it is possible that intricacies and details of the modeled stormwater system may be inadvertently modeled inaccurately. This could be due to errors in the construction drawings used or user adaptation to SWMM's learning curve. Without model validation and in-person survey of the system, it is unknown if there are errors in the model, and if so, how many.

Additionally, only parts of the modeled system deemed "most critical" were studied in higher detail and their data graphed visually. Nodes on the interior of the airfield do experience flooding, but nodes closer to the system terminus were chosen for data visualization. It is entirely possible that the flooding from interior nodes, while not as volumetrically high, could have a greater impact on airfield operations. With more time,

the failure indicator results for all components of the stormwater system could be interpreted, with more simulation characteristics used as potential failure indicators. Simulation results in SWMM are exported as .RPT files, which can be opened in Notepad. This format makes it extremely time-intensive to extract simulation data for visualization, as even copy/paste commands fail for moving the data into actual spreadsheets. Future study could explore options for automating this data extraction process.

Future Options and Applications

There are numerous ways this study can be furthered and enhanced. First, as mentioned previously, validation and calibration would result in a model that mirrors real-world performance of the system. The scope of study could be expanded by modeling all stormwater systems on the airfield in order to present a wider look at the airfield's risk from rising seas and intensified storms, or modeling stormwater systems servicing other portions of the base.

Future study could also incorporate elevation into the model in order to better visualize the results of flooding, and prevent flooded water from being "lost" from the system. This could be potentially accomplished with GIS. This combination could result in the most encompassing model for coastal flooding and intensified storms, as both the stormwater system performance and overland flow could be simulated.

In this study, only baseline SLR projections were used. However, the sea level rise scenarios tool created by SERDP and ESTCP also offers projections for extreme water levels, representing storm surge and tides. With these projections combined with base SLR

projections, a more complete risk profile could be created for the stormwater systems of study. Thus, the maximum possible extent of inundation could be modeled.

With additional study, fragility curves could be developed for the airfield. Fragility can be described as "the conditional probability of attaining or exceeding a specified standard of performance conditioned on different demand variables" (William et al. 2019). In terms of stormwater risk modeling, fragility can be defined the stormwater system failing to meet predetermined standards, such as having the capacity to convey stormwater without ponding. A fragility curve is a visual way of communicating the probability of failure of an asset as negative variables increase in intensity; in the case of stormwater, increasingly severe storms could be a negative variable. Fragility curves offer a wide range of benefits, including "customization, comparison, adaptation, evaluation, and communication" (William and Stillwell 2017). Application of fragility curves to this study would indicate what rainfall intensities and sea levels would be most likely to cause airfield failure.

VI. Conclusions

Through unvalidated modeling of a portion of Tyndall AFB's airfield stormwater system in SWMM and applying estimates of SLR and current and intensified storms, failure indicators for key parts of the stormwater system were analyzed. Overall, widespread system overload begins when roughly 1.0 meters of SLR are directly applied to the system outfall as a fixed water body. A meter of SLR is currently projected for 2065 under highest emissions levels and 2100 under medium or higher emissions levels. Without SLR present at the system outfall, key conduit inefficiency begins to appear at the 25-year return storm. However, additional study is needed in order to validate both the model and these initial findings. Of highest importance is the need to ensure the model closely mirrors actual performance of the stormwater system and translating SLR inland through a canal and drainage ditch to the system outfall.

With dozens of installations located on coasts or islands, the need for the DoD to begin evaluating the coupled threat of rain and SLR is immediate and critical. If SLR encroachment, rainfall, or combination of the two is intense enough to cause stormwater system inundation and resultant flooding, installations could face mission hindrance or stoppage. System inundation places additional stress on stormwater system components if the system runs full or above its design capacity, potentially leading to pre-mature system degradation or failure. Additionally, research has underlined the stormwater system component degradation that can occur from the salinity of encroaching sea water. In cases of recurrent flooding, the cost and personnel hours preparing for and recovering from

encroaching sea levels or intense rainfall events could sap financial resources and impede the maintenance of other installation infrastructure. DoD efforts have taken steps to project SLR and rainfall amounts at installations, but these factors and projections need to be combined to understand the total risk posed to coastal airfields.

There are several ways the DoD can incorporate projections of these climate change effects into efforts to protect infrastructure. First, the DoD needs to move away from stationary IDF data for stormwater planning. A change to UFCs to require updated, or projected, rainfall data could help prepare installation stormwater systems for both current and future storms. Additionally, the incorporation and combination of SLR, tides, and storm surge data into UFCs for stormwater planning can help installations prepare for and prevent high tailwater conditions at system outfalls. The importance of these changes into DoD-wide used regulations cannot be overstated. A Department-wide requirement would result in standardized stormwater planning for new construction and construction upgrades, and would prevent individual installations from over-or-under-planning for climate change effects in comparison to the established Department standard. Precedence exists in Florida for incorporating SLR into stormwater management; for example, the Florida Department of Transportation Drainage Manual requires the following in regard to SLR:

> "The design of coastal projects (including new construction, reconstruction, and projects rebuilding drainage systems) must incorporate sea level rise analysis to assess the vulnerability of flooding over the design life of the facility. Use the relative sea level trend

> data from historical tidal records gathered by the National Water Level Observation Network (NWLON) and managed by NOAA. NOAA manages tidal gage stations located around the state of Florida. Use the station nearest the site for analysis. Analysis must consist of straight-line extrapolation based on the design service life of the project. Consider existing system criticality/vulnerability and project costs when implementing this best practice analysis." (Florida Department of Transportation 2022)

This example from the FDOT offers a blueprint worth emulating in stormwater management-oriented UFCs for usage at coastal installations. Overall, this study reveals a threat to airfield operations by SLR and intensified rainfall. Despite its limitations and uncalibrated/unvalidated status, the findings nevertheless underline the need not only for increased evaluation of climate change effects and dissemination of projections, but also for the DoD to require the use of these projections in new construction.

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14. ABSTRACT
Climate change is resulting in rising sea levels and increased rainfall, posing new challenges to stormwater management, particularly along coastlines. The airfield stormwater systems of Tyndall Air Force Base discharge directly into an interior bay of the Gulf of Mexico through tidal canals and ditches, creating a risk of system inundation from high tidewater conditions from sea-level rise (SLR). This study explores the performance and consequences of an inundated stormwater system from SLR during rainfall events using the EPA's Stormwater Management Model (SWMM). One hundred and fifty-three combinations of SLR and return year storms were applied to a model of an independent stormwater system servicing the Bravo taxiway, and analysis of the results indicate that SLR projections associated with 2065 under high emissions and 2100 under medium emissions will result in widespread flooding, surcharging, and capacity limitation in stormwater inlets and conduits adjacent to airfield pavements and proximate to the system outfall. The results of this model warrant future study and validation, while indicating that the Department of Defense needs to account for the dual threat of SLR and intensified rainfall in stormwater planning.

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