Interdisciplinary approach to flood risk and the Consequence of Flooding

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Abstract. This paper describes an alternate approach to prioritizing pluvial flood risk intervention strategies, and quantifying Consequence of Flooding (CoF) by applying the methodology of Failure Mode and Effect Analysis (FMEA). The intent is to develop an integrated, efficient, and quantitative CoF assessment approach to support pre-event efforts and post-event mitigation for flooding. The CoF assessment is based on three elements: (1) probability of flooding occurrence, (2) severity of the event, and (3) damage impact control. Two case studies are presented, one with an established Federal Emergency Management Agency (FEMA) zoning label, and the second for an unincorporated area in South Florida, USA. The results are compared with published values for flooding risk, and the outcome of the proposed method agrees with flood risk zoning label determined by FEMA. With the proposed alternate method, communities without FEMA classification due to lack of zoning map or data, could propose to FEMA potential flood insurance credit for premium reduction. This study also identified other elements to be included in future modelling efforts, such as elevation, to improve model development.

1 Introduction

The objective of this study is to develop a method for communities to achieve credit for developing a flood risk strategy where there is no data or mapping available. Currently, the Federal Emergency Management Agency (FEMA) methodology, provided by FEMA.gov website, consists of the following steps: (1) define the base topography, (2) evaluate the flood water level and storm surge, (3) define the cross-shore transects and primary frontal dune, (4) evaluate the storm-induced erosion and shore protection structures, (5) model the wave hazard, and (6) map the coastal flood hazard, to finally generate a Flood Insurance Rate Map (FIRM) of the flood zone.

Currently, flood risk is defined as the contribution from two components: the probability of the event and the consequence of adverse effects caused by the event (Teegavarapu, 2012; Zhou, et al., 2012; Purvis, et al., 2008). A straightforward approach to estimate the Consequence of Flooding (CoF) is presented in this study for pluvial flooding in South Florida. It is based on the well-established Failure Mode and Effect Analysis method (FMEA) used extensively in the manufacturing and research industries to determine the risk of failure to products and industry processes, and even in the medical field (Cristaldi, et al., 2020; Gueorguiev, et al., 2020; Li, et al., 2020; Mascia, et al., 2020; Baynal, et al., 2018; Sellappan N. and K. Palanikumar, 2013; Rassiah, et al., 2020).

In this study the CoF contribution to flood risk, labelled as Risk Priority Number (RPN) in the FMEA

method, is obtained by using the FMEA's outcome of three elements: (1) occurrence of flooding, (2) severity of the event, and (3) damage control. Similar to FMEA, the three elements are subdivided into ten sectors, as a function of the probability of the element's influence into CoF. The sum of the outcome for the three element generates the CoF score, later to be used for flood intervention strategies.

The occurrence of flooding, or recurrence interval, is defined as the mean time between flooding from an ordinary 1-hour duration in 2-year recurrence interval to 3-day duration in 100-year recurrence interval. The flooding occurrence scale follows the FMEA format, which ranges from one to ten, where almost persistent flooding is ten, with an occurrence exceedance probability of 0.5, and extremely remote recurrence of flooding is one, with an occurrence exceedance probability of 0.01, per the American Society for Quality.org site on 2020.

The severity of the flooding is measured by property damage based on the depth of inundation, and it follows the FEMA Multi-hazard loss estimation methodology (Hazus®). The severity of flooding is evaluated on a scale from one to ten. One is assigned when there is no impact to the wellbeing of the community, and ten is assigned when the damage accumulated is detrimental to human life. The outcome of the assessment is used to calculate the CoF.

The third element, damage impact control, being damage reduction or damage avoidance, is estimated from temporal assessment of development pressures, such as, progressive population variation and decreased flood

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resilience due to impact area imperviousness. The damage scale also ranges from one to ten. One is assigned for an extremely low probability of flooding due to developmental pressures, and ten is assigned for a scenario that is almost certain to occur due to the anthropogenic effect by the community.

Lastly, the paper outlines a methodology to estimate the CoF from flooding events, and provides a prioritization risk-reduction strategy, targeting credit under the National Flood Insurance Program (NFIP) Community Rating System (CRS) classification process, which will eventually achieve flood insurance premium reduction. The method could be expanded to include the consequences of coastal surge generation and propagation, and fluvial flooding interaction with pluvial flooding, maximizing synergies for flood risk management (Tanaka, et al., 2020; Khanal, et al., 2019; Chen, et al., 2010).

2 Background

Climate change in the last 30 years has impacted the frequency of flooding events, and the mean time between flooding has become a dynamic variable for the risk of flooding analysis. Several studies have been conducted to prioritize and estimate the impact of a single flooding event for economics and health related issues (Bell, J., et al., 2017; Grames, et al., 2016; Jonkman, et al., 2008; Vrouwenvelder, 2007; Asselman and Jonkman, 2003). However the combination and interaction of elements has only recently been investigated (Frame, et al. 2020). For example, the severity of persistence of flooding over a particular impervious area and the interaction with the impact of anthropogenic activity in a rapid developing sector, has not been incorporated into the flood risk model.

Previous modelling efforts used optimization of socio-economic inputs and the uncertainty associated with the flood damage model to assess the CoF, and to mitigate a predicted failure into the flood risk analysis (Makwana and Thakkar, 2014; Bubeck et al., 2011). This study presents an approach used in the manufacturing industry, analogous to the Six Sigma risk management approach. However, instead of using the standard Six Sigma for quality strategy, this study modified the concept of Consequence of Failure from the manufacturing industry into the Consequence of Flooding (CoF). The forecasting model, based on probability theory, estimates the CoF into a given area as a function of probability of occurrence, the severity of the different scenarios, and the damage incurred by the flooding event.

The impact FEMA Community Rating System (CRS) have into public awareness and the insurance premiums is a function of flooding consequences. Previous studies to model public awareness of upcoming flooding was considered a crucial aspect in flood risk management (Kellens, et al. 2011; Bubeck, et al. 2016; Grahn 2017). Variables such as location, as well as personal and residential characteristics, were included in those models of perceived hazard from coastal flooding. This study includes a range of predictive variables that allows for objective prioritization of mitigation strategies.

A recently proposed flood risk calculation established the flood risk score as a function of the Likelihood of Failure (LoF) and Consequence of Failure (Scott and Smith, 2019; Alexander, et al., 2011). However, their risk score has subjective elements, based on the opinion of a committee of experts, following Delphi techniques, rather than a more objective probabilistic method as proposed in this study.

Other recent attempts to quantify flood risk to a range of socio-economic variables is in the development phase by the Southeastern University Research Association (Wright et al., 2020). They published a white paper recognizing how objective and quantifiable risk assessment is critical to prioritizing strategies and resource allocation in support of communities' resilience to climate hazards and storm impacts. In addition, a project at Florida Atlantic University (FAU), funded by the Florida Division of Emergency Management (FDEM), provides guidance to vulnerable regions on how best to concentrate resources for maximum mitigation benefit (Bloetscher et al., 2020; Meeroff and Bloetscher, 2020). The screening tool provides an initial risk assessment focused on the hydrologic response to a specified rainfall event given certain key features of the sub-watershed. This tool gives an overview of the driving factors and a pre-assessment where this study calculated CoF for flood risk assessment should converge. The modified FMEA, and calculated CoF provides a format to link projected challenges with the most cost-effective solutions, and deliver a strategy to prevent or mitigate flood risk.

Lastly, an attempt to re-label the occurrence of storm events has been proposed (Grisa, 2012) with lukewarm approval from the technical community. The logical approach was not tied to flooding, rather to rainfall event intensity, frequency and duration. The authors of this paper incorporated and expanded the methodology from Grisa (2012), and applied it to the National Oceanographic and Atmospheric Agency (NOAA) site number 08-0845 at Boca Raton, Florida, for reference. The calculated flood occurrence values used the 3-day, 100-year storm event as the base in this study.

The use of FMEA to assess potential problems and mitigation solutions is well known in the industry, however its application to calculate flooding consequences is a new application of this manufacturing methodology.

3 Discussion

In this research the authors used a modified FMEA method to calculate the CoF. This alternate CoF calculation was used in two case studies in Florida, to demonstrate the applicability of the proposed method.

3.1 Flooding occurrence

Flooding occurrence is defined as the mean time between flooding events, or recurrence, and is a function of storm event impact, soil saturation capacity, tide cycle, wave heights, storm angle, barometric pressure, bathymetry measurements, and storm surge reach. From those mentioned, the two factors used on this study to determine

the flood occurrence were the storm event impact, based on the intensity, duration, and frequency; and the soil capacity to absorb the water.

Maximum annual values from NOAA Atlas 14 Volume 9 Version 2.0 Precipitation Frequency Data Server at Site ID: 08-0845, latitude 26.3675° longitude -80.1108° Boca Raton, Florida, period of record 01/1942 to 12/2010, were used to generate the Occurrence Exceedance Probability (OEP) chart in Table 1 (Perica et al., 2013). NOAA's procedure for developing an Annual Maximum Series (AMS) included extracting only reasonable maxima, if a year was incomplete. Missing data occurred in some South Florida records where observations were not taken regularly. All annual maxima that resulted from missing data were highlighted and screened to ensure incomplete data did not biased the results.

The OEP value was obtained from the mean time between flooding (1/years), also called recurrence. For example, a frequency of 2-year recurrence equals 1/2 probability of occurrence exceedance. The format for Table 1 was previously derived by Grisa (2010) and modified to the FMEA format, where storm duration was considered from 1-hour to 3-days, and the recurrence intervals were defined from 2-years to the 100-year storm, which translate into an OEP from 50 percent to 1 percent.

Storm duration	Maximum Storm Intensity (inches)				
	OEP 50%	OEP 10%	OEP 4%	OEP 2%	OEP 1%
1-hr	2.35	3.56	4.26	4.81	5.37
2-hr	2.99	4.54	5.46	6.18	6.91
3-hr	3.36	5.16	6.26	7.13	8.04
6-hr	3.96	6.32	7.84	9.09	10.4
12-hr	4.52	7.61	9.7	11.5	13.3
24-hr	5.14	8.89	11.5	13.7	16.1
3-days	6.59	10.6	13.5	15.9	18.6

Table 1. Storm intensity, duration and frequency per OEP

The depth of the flooded area is directly correlated with the soil capacity to absorb the storm. This analysis involves the dominating soil type. Other variables, such as topography and slope have less impact in the South Florida flooding occurrence scheme. The Hydrologic Soil Groups (HSG) classification from the Natural Resource Conservation Services (NRCS) was used to determine the soil capacity ranking in South Florida. The standard classification was: HSG group A for soils with high infiltration rates, even when thoroughly wetted, low runoff potential, and a final infiltration rate of 0.30 to 0.50 inches/hour. HSG group B was given to soils with moderate infiltration rates when thoroughly wetted, slight runoff potential, and a final infiltration rate of 0.15 to 0.30 inches/hour. HSG group C was given to soils with slow infiltration rates when thoroughly wetted, moderate runoff potential, and final infiltration rate of 0.05 to 0.15

inches/hour. Lastly HSG group D was given to soils with very slow infiltration rates when thoroughly wetted, high runoff potential, and final infiltration rate of less than 0.05 inches/hour. The HSG factor was incorporated with the seven different soil orders in Florida, and a rating for flood occurrence was determined for the state (Table 2).

Approximately 45 percent of the soils in Florida are classified as HSG groups A and B, with 28 percent as HSG group C and 27 percent as HSG group D. The United States Department of Agriculture (USDA) soil texture classification for the first case study, where FAU is located, is mostly HSG group A: sandy soils, muck, or fine sandy-loams (Mylavarapu, R., et al., 2016; McCollum et al. 1974). Approximately 2 percent of the soils at Palm Beach County (PBC) are sandy clay loam, with a higher water retention capacity and lower infiltration rate when compared to the soils in the rest of Florida, however this type of soil is not at the current site location used for this study.

The soil texture at the locations investigated for this study were classified as mostly sandy and some sandy-loams, where permeability is rapid in the surface and subsurface layers, and moderate in the subsoil (McCollum et al. 1974). For this study an average percolation rate of 0.5 inch per hour and a maximum soil water content capacity of 15 percent were considered (O'Geen 2013). These values were used to calculate the flooding occurrence rating based on the infiltration rate for the maximum storm intensities in Table 1. Flooding occurrence rating for the PBC location falls between 1 and 3, when the rate of rainfall is greater than 1.0 inch per hour. The flooding occurrence rating will be used to determine the CoF later in the analysis.

Flooding Occurrence Rating	Infiltration Rate (inches per hour)
1	> 0.50
2	0.40 - 0.50
3	0.30 - 0.40
4	0.25 - 0.30
5	0.20 - 0.25
6	0.15 - 0.20
7	0.10 - 0.15
8	0.05 - 0.10
9	0.01 - 0.05
10	<0.01

Table 2. Flooding occurrence allocations per soil capacity and infiltration rate

3.2 Severity of the event

FMEA severity is defined as the effect of the failure impact to residents. To quantify severity of flooding, the depth of inundation was used. Severity was defined as percent loss from inundation level. Each structure or building has its own inundation damage function per FEMA Multi-hazard Loss Estimation Methodology Flood

Model (Hazus®) developed by the Department of Homeland Security. The Hazus® model is used by FEMA to estimate property losses, from one-story residences to multi-level buildings. For example, a single-story residence without basement, typical in the area covered by this study, would follow an inundation depth-damage function as depicted in Figure 1, where the most likely damage would be close to 18 percent the value of the residence for a 1-foot inundation, and for 5 feet of inundation, up to 40 percent the value of the property. However, it may withstand as high as 30 percent maximum damage for the same one foot of flooding water. A scale from one to ten assigns values based on the criteria defined above. Table 3 was specifically established for the case study considered later in this project. Similar approach could be used for other buildings and flooding scenarios. This ranking was used as a variable in the calculation of the CoF.

Figure 1. Example of FEMA Depth Damage Functions

Rating	Severity description
1	No property impact from flooding, nor to the well-being of the community
2	Temporary relocation, no damage to property
3	Relocate, property damage less than 1%
4	Minor effect, less than 5% property replace value
5	Moderate effect, less than 18% property replace value
6	Significant effect, 28% property replace value
7	Major effect, inundation that exceeds 40% property replace value
8	Extreme effect, inundation that exceeds 50% property replace value
9	Serious effect, total building replace value, and economic activity and community, parcel, or watershed disfunction
10	Hazardous effect, detrimental to human life

Table 3. Severity allocations per incurred property loss

3.3 Damage impact control

Flood damage impact control is the combination of damage reduction and damage avoidance. Damage reduction is based on resolution after flooding, while damage avoidance is preventive measure prior to a flooding event. Damage reduction, by resolution, are quality control challenges, such as, environmental and political water resources management, reservoir releases, spills, and equipment damages.

Conversely, damage avoidance is achieved by mitigating and implementing preventive measures. Damage avoidance uses projected anthropogenic impacts due to development pressures: land use, urbanization and population change, and planned percent impervious surface for development areas (new roads, parking lots, buildings, and other structures). The focus of this alternate method is to establish a model to prevent flooding, rather than resolution after flooding.

The Environmental Protection Agency, Report on the Environment (EPA-ROE, 2020) defined two indicators for impact to area utilization changes, and consequently, increased propensity to flooding: land use and urbanization and population change. The term land use describes the economic and population cultural activities at a location. Urbanization and population changes are related to the U.S. Census Bureau, annual population estimates, and data collected by the USDA Natural Resources Conservation Service's National Resources Inventory (NRI) to track developed land. The intent is to capture trends in overall population growth for both rural and urban populations, the amount of developed land relative to the amount of population change, and overall population density. Table 4 depicts the development growth in South Florida, using data from Pompano Beach, FL.

The last factor considered is the amount of impervious area defined for a parcel of land. The U.S. Department of the Interior and U.S Geological Survey established six classes of impervious cover, in order of impact to natural water flow: buildings, roads, parking lots, driveways, sidewalks, and other minor obstacles, such as pavers, large stones, and gravel. They used a digitized spatial resolution aerial imagery to quantify imperviousness (Tilley and Slonecker 2007). Their assessment was modified for this study, where the authors used the percent of impervious areas as it applied to South Florida (Table 5).

Census year	Population density (per square mile)	Imperviousness (%)
2010	4159.8	70
2000	3257.9	50
1980	2442.4	30

Table 4. South Florida land population density impact (Pompano Beach, FL)

Imperviousness (%)	Categorized	Description
> 40	Severe	Area covered with asphalt, self-standing dwelling and structures
25 - 40	Degraded/Non-supportive	High frequency of flooding
11 - 25	Impacted	Moderate frequency of flooding
2 - 10	Stressed/Sensitive	No frequency flooding
< 2	Undisturbed	Natural landscape

Table 5. South Florida soil imperviousness impact distribution

The relationship between the percent imperviousness and the population density, Figure 2, was used to develop the criteria to assess the probability of damage avoidance, that is probability of success, as shown in Table 6. Figure 2 shows a scale for population density up to 5000 people per square mile. With the exception of Miami, the rest of South Florida falls below the 5000 people per square mile limit. A scale from one to ten is used as a factor of pre-emptive damage control, per FMEA method. For example, an area with less than 10 percent imperviousness, and population density below 2500 people per square mile, is 98 to 100 percent prepared to mitigate the 100-year storm.

Figure 2. South Florida land development growth relation to area imperviousness

Rating	Flood damage control assessment
1	>97% probability of successfully avoid damage
2	93% probability of minimum flooding damage
3	88% probability of avoiding flooding damage
4	80% moderate probability of avoiding flooding damage
5-6	67% low probability of avoiding flooding damage
7-8	40% probability, slight possibility of avoiding damage
9	20% probability, remote possibility of avoiding damage
10	<1% probability, no control, damage unavoidable

Table 6. Damage allocations per flooding events

3.4 Consequence of Flooding

The Community Rating System (CRS) specifies in Section 410 Flood Hazard Mapping, the process of accurately mapping the flood-prone communities based on accumulated flood hazard data. An abridged list of FEMA Special Flood Hazard Areas (SFHA) and zones outside of the SFHA, with a brief description, is provided in Table 7. Flood zones identified by the letters A or V represent high-risk areas, and zones identified with the letter X represent areas with moderate or minimal flood hazard.

FEMA Zone	Description
A	SFHA where no base flood elevation is provided
AR	Temporary designation, base flood to be improved, part of SFHA
AE	SFHA where base flood elevations are provided.
AH	Shallow flooding SFHA. Base flood elevations related to national datum are provided.
D	Undetermined area, but possible flood hazard
V	SFHA subject to coastal high hazard flooding
X	Moderate or minimal flood hazard, less than one foot.

Table 7. FEMA flooding zone ranking

The calculated CoF range aligns with the FEMA zone ranking, providing a link to flood risk mitigation plans, and in some cases, providing a strategy to identify potential flooding challenges. The CoF is calculated by Equation (1).

$$CoF = (Occurrence) + (Severity) + (Impact) \quad (1)$$

The maximum possible value for CoF is 30, and the minimum is three. When the calculated CoF is below or equal to 6, no actions are required and the classification should be Zone X. When the CoF value is greater than or equal to 27, if the area is unincorporated or labelled Zone D, the recommendation is to change to Zone V and apply the mitigation measure against flooding. CoF values between 6 and 26 should be labelled Zone AR if mitigation is planned for the near future, and Zone A if there is no plan to mitigate within the next three years.

3.5 Case studies

The CRS indicates how FEMA will provide credit for developing flood risk management strategies when there is no data to support the Flood Insurance Rate Map (FIRM) activity. This is an opportunity to evaluate an alternate method to fill the flooding maps for insurance purposes. The objective of this study is to develop a method for communities to achieve this credit, particularly when there is no data or map from FEMA. To validate the alternate

method, two areas were selected. One case was conducted to demonstrate similar results to the official FEMA method, and a second case was conducted to predict the FEMA zone when none is provided.

The area selected for the first case study is a parcel at Florida Atlantic University (FAU), near the Boca Raton Water and Wastewater Treatment Facility (Figure 3). The area is located at latitude N26.3684° and longitude W80.1088°. Figure 4 depicts the Zone assignment per current FIRM.

Figure 3. Case 1 illustration of study area

Figure 4. FIRM depiction for case 1 area

Results for case study one, using the alternate flood risk assessment, are given in Table 8. The area is classified by FEMA CRS as AH, that is, shallow flooding SFHA with base flood elevations in relation to a national datum. The occurrence exceedance probability of six was assigned given the propensity of occasional flooding in the area, due to a mean elevation of 16 feet (Kanelidis 2020). Severity of event and damage control were assigned a value of two since the occasional flooding does not cause damage to the property, it is mostly an open area used for outside sport activities. A CoF of ten will identify this area for further investigation, and assign a temporary zone value of AR. The zone classification of AR precedes the AH assignment when the base flood elevations are included in the map.

Risk elements	Allocation	Explanation
OEP	6	Medium flooding frequency, elevation below 16 feet.
Severity	2	Minor severity, no damage cost due to open area usage
Damage	2	Preventive measures in place, drainage installed to prevent flooding
CoF	10	Zone AR. Assess for AE, if base flood elevations are available, or AH if shallow flooding and SFHA.

Table 8. Case 1 alternate method ranking results

The second test case was conducted in an unincorporated area in South Florida. FEMA uses Zone D for areas where there are undetermined flood hazards and risk of flooding, however no analysis of flood hazards has been conducted; or when a community incorporates portions of another community's area where no map has been prepared. Mandatory flood insurance does not apply, it is left to public awareness and property owner pro-action to buy coverage, which exposes the property owner to potential economic losses, especially while in the process of mapping the area.

Case two is an example of an unincorporated area in Palm Beach Gardens, FL surrounded by an area with detailed FIRM mapping and Zone AE (Figure 5). The data for this area was obtained from the Palm Beach Gardens Document Center depository. PBG population density is 986 people per square mile. The results for case two are summarized in Table 9. The CoF for the area aligns with the expected value, based on the surrounding FEMA FIRM allocations.

Figure 5. Illustration of unincorporated area of case 2

Risk elements	Allocation	Explanation
OEP	2	Remote, unlikely, with elevation above 16 feet.
Severity	3	No property damage, or <\$1000
Damage	1	Low population density (<1000/square mile)
CoF	6	Zone X, low flooding risk

Table 9. Case 2 alternate method ranking results

4 Conclusion

An alternate method to calculate the Consequence of Flooding (CoF) is proposed, and evaluated for two areas in South Florida. The proposed method was based on the Failure Mode and Effect Analysis (FMEA) process, an improvement over current CoF estimation using the Delphi technique. The CoF has three elements: (1) flooding occurrence, (2) severity of flooding, and (3) damage impact control, and each contributes to the total CoF value. This simplified approach is useful for unincorporated areas or areas labelled Zone D by FEMA, which are areas undetermined but with possible flood hazards.

The results from two case studies demonstrate the applicability of this method and address how to expeditiously evaluate undetermined areas with possible flood hazard, or newly incorporated areas in preparation to receive credit toward the CRS classification process, and eventually insurance premium reduction.

This interdisciplinary approach introduces the concept of Failure Mode and Effect Analysis to the flood risk field, and starts a baseline for future improvements to the alternate methodology. Growth of the methodology will evolve into a more probabilistic method, with the inclusion of additional variable, such as, elevation, slope, bathymetry measurements, and area topography.

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