Conflation Methodology Applied to Flood Recovery

E. L. Suarez, D. E. Meeroff, Y. Yong

Abstract**—**Current flooding risk modeling focuses on resilience, defined as the probability of recovery from a severe flooding event. However, the long-term damage to property and well-being by nuisance flooding and its long-term effects on communities are not typically included in risk assessments. An approach was developed to address the probability of recovering from a severe flooding event combined with the probability of community performance during a nuisance event. A consolidated model, namely the conflation flooding recovery (&FR) model, evaluates risk-coping mitigation strategies for communities based on the recovery time from catastrophic events, such as hurricanes or extreme surges, and from everyday nuisance flooding events. The &FR model assesses the variation contribution of each independent input and generates a weighted output that favors the distribution with minimum variation. This approach is especially useful if the input distributions have dissimilar variances. The &FR is defined as a single distribution resulting from the product of the individual probability density functions. The resulting conflated distribution resides between the parent distributions, and it infers the recovery time required by a community to return to basic functions, such as power, utilities, transportation, and civil order, after a flooding event. The &FR model is more accurate than averaging individual observations before calculating the mean and variance or averaging the probabilities evaluated at the input values, which assigns the same weighted variation to each input distribution. The main disadvantage of these traditional methods is that the resulting measure of central tendency is exactly equal to the average of the input distribution's means without the additional information provided by each individual distribution variance. When dealing with exponential distributions, such as resilience from severe flooding events and from nuisance flooding events, conflation results are equivalent to the weighted least squares method or best linear unbiased estimation. The combination of severe flooding risk with nuisance flooding improves flood risk management for highly populated coastal communities, such as in South Florida, USA, and provides a method to estimate community flood recovery time more accurately from two different sources, severe flooding events and nuisance flooding events.

Keywords**—**Community resilience, conflation, flood risk, nuisance flooding.

I. INTRODUCTION

FLOODING in coastal areas is becoming a greater challenge, with the complexity of climate change. United States (US) Federal Emergency Management Agency (FEMA) estimation of flood losses recognizes that 66-percent of dwelling losses are not compensated; $13 billion per year for homeowners [1]. Many coastal areas in southeastern United States do not require flood insurance by the federal government due to flood-zone designations. Current flood analysis identifies the recovery period from severe rainstorm events, such as hurricanes, river overflow, or reservoir discharge based on past long-term flooding events [2], [3]. The current methodology does not consider the recovery time from frequent low-grade localized nuisance rainstorm events causing flooding within a few blocks or neighborhood, usually overstressing the storm management system in the community.

Integrating the contribution of flood-risk from severe and nuisance flooding is an improvement in traditional modeling methods [4]. The common method to combine distributions is either averaging the individual recorded data values at each specific criterion before calculating the measure of central tendency and associated variance, or by averaging the input probabilities assigning the same weighted variation to each input distribution. The main disadvantage of these traditional methods is that the resulting measure of central tendency is exactly equal to the average of the input distribution's means without including the information provided by the independent and individual input distribution variance.

When combining two distributions, the variation of the resulting distribution is customarily assumed larger than that of the individual input distribution. A larger variation will generate additional uncertainty on the combined results, based on the prescribed assumption. The conflation method considers the contribution of each individual input probability variance into the calculation when generating the consolidated distribution. It gives more weight to input distributions with reduced variation, therefore smaller variance. Combining the recovery time from a high-impact catastrophic flooding event with the recovery time of a low-level nuisance flooding event, for a specific geographical area affected by hurricanes as well as frequent urban flooding, is a new concept not considered in current investigations of flood management, and represents a comprehensive flooding recovering framework for coastal areas. The independent probability distributions of recovery time from severe events and recovery time for nuisance events follows an exponential Poisson distribution. The Poisson distribution lambda (λ) identifies the recovery rate from the severe and the nuisance flooding events. To consolidate the recovery time of two events with different recovery time averages and dissimilar variances into one exponential distribution model, such as Poisson, the following assumptions are required: (1) there should be no identified correlation between measurements, regardless how they were determined, (2) individual variances must be independent before combining the variances for the conflated model, (3) the events are random and independent, that is, the probability of success from one

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does not affect the probability of success of the other, and (4) the resulting conflated probability is the product of the probability density functions [5]. Another advantage of the conflation method is that the resulting probability distribution follows the same distribution as the parent distribution, eliminating uncertainty from introducing a different probability in the resulting prediction model. Conflation is a common method used in the geomatics field to combine links in the geoprocessing mapping formation with the goal to improve the quality of the analysis [6]-[8]. The conflation concept is also used in the biology field, specifically molecular profiling with focus not only on the individual genes but also on their interrelationship [9].

The developed conflated flooding recovery time model (&FR) is derived from established mathematical methodology [10]. The symbol "&" is used to indicate conflation. &FR is defined as the distribution resulting from the product of the probability density functions for severe flooding events and those quotidian nuisance-causing flooding events.

When different analyses collect the same information, the &FR model estimates, with improved accuracy, the flood-risk for all events. The resulting conflated distribution resides between the parent distributions, favoring the one with smaller variance, as it is statistically more robust and more accurately estimated. As a result, the &FR summarizes the data in an unbiased rigorous mathematical method, consolidating the input distributions proportional to their variation.

II. Methodology

The method used to quantify &FR is based on probability density functions of individual distribution and the combination of those probabilities into a single metric. It has been presented in the literature with normal distributions, however, it was indicated that it will be useful with other types of distribution, such as exponential distribution where positive values have an independent probability of success [5].

In this study, the common variable "recovery time" is used to consolidate two distributions. A data-driven stochastic method is developed to determine the recovery time that a municipality will require to recuperate basic functions after both short-term catastrophic or severe flooding events and nuisance flooding events. The datum of 1.7 ft above Mean Higher High Waters (MHHW) is used as the arithmetic average flooding threshold for south Florida.

Short-term events are hurricanes and severe tropical storms resulting in 6.5 inches or more of rain per day and incurring flooding inside a single dwelling. The probability for a 1-day 100-yr severe event follows an exponential function shown in (1). The recovery time after a severe flooding storm, RS(t), is based on government reports and is measured by the completion of phases identified by the government hurricane center and recovery agency [11], [12]. The US government measures the time to recover to a satisfactory socioeconomic state from a severe flooding event as a function of: (1) the time it takes to restore critical services, (2) time to ensure accessibility to resources, (3) complete damage assessments, (4) debris clean-up, and (4) civility is restored, within a given time interval.

$$RS(t_i) = \alpha_i \left(exp^{-\lambda_{Severe\ event}{}^{*}t}\right)_i + \varepsilon_i, \text{¥}_i \tag{1}$$

where: α_i = coefficient adjustment; $\lambda_{\text{Severe event}}$ = flooding recovering rate for severe events; ε_i = error of estimation.

The probability of a less catastrophic event also follows an exponential function, RN(t) given in (2), and is defined as the recovery time for a community returning to social-economic functions after a nuisance event. Nuisance events are those of low intensity, however, highly frequent. They are torrential rain events with 6.5 inches or more causing a disturbance in the community for a limited time. RN(t) is a function of the community Flood Risk Index, and subsequently, the Consequence of Nuisance Flooding (CoNF) and the Probability of Nuisance Flooding (PoNF) [13]. RN(t) is a function of spatial and temporal conditions. In the spatial context, the propensity to have nuisance flooding events in a particular area is associated with distance from the coast. In the temporal context, community recovery over a given period is related to the amount of time impacting the community. Even as coastal communities are more sensitive to nuisance flooding, nuisance flooding for inland communities is impacted by torrential rainstorms generated from weather patterns, like the ones at the coast.

Estimation of the recovery time from nuisance flooding impacting transportation, acute health issues, and property damage in a coastal community has a wider range. It has been observed for coastal localized nuisance events of 6.5 inches or more, without repetition, that it takes a community from four-and-a half hours for transportation of emergency vehicles to be restored, up to five to six weeks for property damage repairs to be completed [14]. The highest end of the range occurs when a damp environment in dwellings causes mold growth and aggravate individual respiratory illnesses, forcing remediation before the homeowners could return to their house.

Nuisance flooding from torrential rainfall occurs unexpectedly at irregular intervals, however, usually clustered around a 3-month period. This pattern allows for a constant recovery rate, λ. The time-to-flooding follows a Poisson distribution and the recovery function is given in (2) [15]-[17]:

$$RN(t_j) = \alpha_j \left(exp^{-\lambda_{Nuisance\ event}{}^{*}t}\right)_j + \varepsilon_j, \text{¥}_j \tag{2}$$

where α_j = coefficient adjustment; $\lambda_{\text{Nuisance event}}$ = flooding recovering rate for nuisance events; ε_j = error of estimation.

When dealing with exponential distributions, such from severe flooding events and nuisance flooding events, conflation results are equivalent to the best linear unbiased estimation or the weighted least squares method. The combination of those models, &FR, completes the flood-risk analysis framework (3), with an estimated conflated recovery time $\lambda_{\&FR}$ per (4). The resulting &FR conflation model is the maximum likelihood estimator for central tendency, and it has the best unbiased estimate of the conflation variance [5]. The &FR model's input probabilities are independent and continuous between [0, ∞).

For exponential functions, the median is the best estimate of central tendency for skewed distribution, and the value is estimated using (5).

$$\&FR(t_{i,j}) = \alpha_i(e^{-\lambda_{\&FR} * t}) = \alpha_j\left(e^{(1-k_i\,[\,\alpha_i\,\mathrm{CoNF} * \alpha_j\,\mathrm{PoNF}\,] * t)}\right) * \alpha_k(e^{-\lambda_{Severe} * t}) + \varepsilon_{i,j}, \forall i, \forall j, \forall k \quad (3)$$

where α_i, α_j, α_k = coefficients adjustment; k_i = model adjustment; $\varepsilon_{i,j}$ = sample error; $\lambda_{\&FR}$ = flooding rate, combined number flooding per day.

$$\frac{1}{\lambda_{\&FR}} = \alpha_i\left[\frac{1}{(\lambda_{Severe\ event})}\right] + \alpha_j\left[\frac{1}{\lambda_{Nuisance\ event}}\right] - \alpha_{j-i}\left[\frac{1}{(\lambda_{Severe\ event}) + \lambda_{Nuisance\ event}}\right] + \varepsilon_{i,j}),\ \forall i, \forall j \quad (4)$$

where α_i, α_j = coefficients adjustment; $\varepsilon_{i,j}$ = sample error.

$$Median\ \&(FR)_{system} = log_e(2)/\ (\lambda_{\&FR}) \quad (5)$$

The general exponential distribution variance is given in (6):

$$Var(X) = E(X^2) - [E(X)]^2 \quad (6)$$

where $E(X^2) = 2\,/\,\lambda^2;\ E(X) = 1\,/\lambda$.

This study did not include the tidal element since high tide mitigation strategies, such as higher sea walls, elevated transportation systems, higher roads, or effective water channels, are dissimilar compared to sub-annual rainfall mitigations strategies. Sub-annual rainfall mitigation sub-systems, such as improved soil infiltration, open space and bio-diversity management, use of pavers for water percolation, or improved storm water management (pump systems, canals, swales, others) will alleviate the flooding impact for transportation and acute human health issues.

III. Results

The US Department of Energy has estimated that 90 days are required to restore basic services for individual standing houses and restore civil order after a devastating severe flooding event, and up to eight years for total reconstruction [18], [19]. Based on government reports it is estimated that recovery time from severe flooding events due to catastrophic hurricanes, $\lambda_{severe\ events}$ was 1/90, or 0.011 days^{-1}.

The integrity of the sample space is maintained by considering south Florida torrential rainfall data from January 2018 to June 2021, due to no-hurricane events during that period. To determine the recovery rate for nuisance flooding in coastal areas, an average of six days is used. Coastal community awareness is a factor for them to prepare for the consequence of frequent low-grade flooding, and mitigating actions are in place to prevent devastating flooding at their homes. The first line of action for the community, and of higher concern after a nuisance flooding event, is the transportation system to ensure the path is clear for emergency vehicle to reach the area. Based on records from news articles and local government reports, the average recovery time value for overall transportation to be restored after a single nuisance flooding event is equal to six days. This study uses a recovery rate lambda value ($\lambda_{Nuisance\ event}$) of 1/6 or 0.166 days^{-1}.

The probability of recovering from a severe flooding event and the probability of performing after a nuisance flooding event is consolidated into an &FR flooding model. The conflation flooding recovery rate, $\lambda_{\&FR}$, is estimated to be 0.051 days^{-1}. The coefficients adjustments α_i and α_j, 0.20 and 0.80 respectively, are stochastically obtained from rainfall events of 6.5 inches or higher in south Florida causing dwelling flooding in coastal communities [20].

Coastal communities may evaluate risk-coping mitigation strategies (Fig. 1) depending on their System Recovery Index (SRI). The higher the Recovery Index, the faster the municipality will recover from the flooding due to more damage avoidance and mitigation in place to resolve emergency issues. A community with SRI values greater the 0.60 indicates community preparedness capacity to manage flooding events within a week to 10 days from rain deposition greater the 6.5 inches per day.

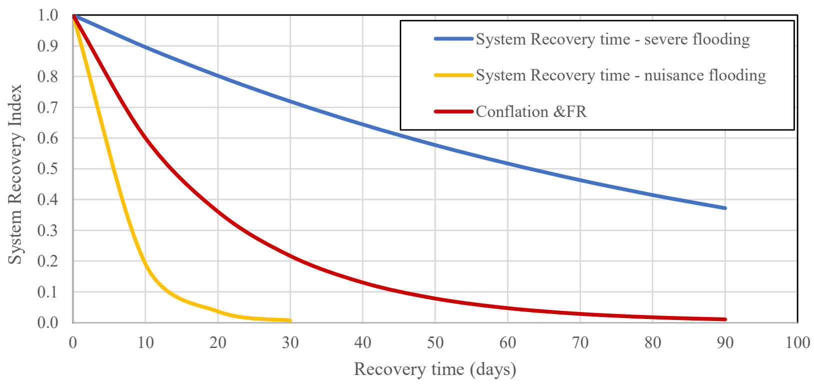

Fig. 1 Recovery time models for severe and nuisance flooding events and the conflation modeling result

Table I shows the resulting statistical measures from severe flooding storms, frequent nuisance flooding, and conflation model results for south Florida. The empirically generated mean of the distributions agrees with the government standard values; however, the median is a more appropriate measure of central tendency, which will indicate approximately 33% faster recovery.

The &FR variance is lower than the variance for severe flooding storms, and as expected, is higher than the variance for nuisance flooding events. When conflating two distributions, the variation contribution of each independent input distribution is weighted to favor the maximum likelihood distribution with minimum variation. The &FR model demonstrates that the system recovery time from the nuisance flooding curve with a smaller variance is the dominating function, a factor not considered in current governmental flood risk assessments.

TABLE I
DISTRIBUTION COMPARISON FOR SEVERE FLOODING, NUISANCE FLOODING, AND CONFLATION MODEL RESULTS

Measure	Severe storm distribution	Nuisance event distribution	&FR distribution
Mean (days)	90.91	6.17	18.08
Median (days)	63.01	4.27	12.63
Variance (days^2)	8264.46	38.03	326.85

IV. CONCLUSION

The recovery times from severe flooding and nuisance flooding are consolidated into a conflation (&FR) model, where the variation contributions of each independent input is weighted to favor the distribution with minimum variation. This comprehensive approach provides awareness to local municipalities on their flood-risk, highlight areas where attention to community's mitigation plans should be considered, and gives insight into flood management actions. The conflation recovery time model is essential to infer the amount of support required by a community after a flooding event to return to basic functions, such as transportation and civil order, regardless of the root cause of the flooding event.

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