Risk of Flooding due to Extensive Rainfall

Prashant Polampally1, Rohit Suresh2, Srikar Mutyala1, Srujana Kandukuri1

1Department of Industrial and Manufacturing Systems Engineering,

2Department of Aerospace Engineering

Abstract:

Table of Contents



[**Abstract: 1**](https://docs.google.com/document/d/1wkN0x775tgCYNj3lw1cBToxQud2-DCZIi21NkaFyF6Y/edit#heading=h.5l3617627tyc)

[**Table of Contents 2**](https://docs.google.com/document/d/1wkN0x775tgCYNj3lw1cBToxQud2-DCZIi21NkaFyF6Y/edit#heading=h.svtdvmbmz8wi)

[**1. Introduction: 3**](https://docs.google.com/document/d/1wkN0x775tgCYNj3lw1cBToxQud2-DCZIi21NkaFyF6Y/edit#heading=h.o6vd4h3bsx7r)

[**3. Model: 5**](https://docs.google.com/document/d/1wkN0x775tgCYNj3lw1cBToxQud2-DCZIi21NkaFyF6Y/edit#heading=h.1o8dw1ci28aj)

[Influence Diagram 6](https://docs.google.com/document/d/1wkN0x775tgCYNj3lw1cBToxQud2-DCZIi21NkaFyF6Y/edit#heading=h.pyi03jmu0rj1)

[Data Gathering and Data Generation  
  
City Modeling: 7](https://docs.google.com/document/d/1wkN0x775tgCYNj3lw1cBToxQud2-DCZIi21NkaFyF6Y/edit#heading=h.4w1ouk3w3180)

[Rainfall Modeling: 8](https://docs.google.com/document/d/1wkN0x775tgCYNj3lw1cBToxQud2-DCZIi21NkaFyF6Y/edit#heading=h.2ct9tvtfyffv)

[Flood Modeling: 8](https://docs.google.com/document/d/1wkN0x775tgCYNj3lw1cBToxQud2-DCZIi21NkaFyF6Y/edit#heading=h.agli4shxgb7n)

[Damage Modeling: 9](https://docs.google.com/document/d/1wkN0x775tgCYNj3lw1cBToxQud2-DCZIi21NkaFyF6Y/edit#heading=h.djdrv67d9ddr)

[**4. Results 9**](https://docs.google.com/document/d/1wkN0x775tgCYNj3lw1cBToxQud2-DCZIi21NkaFyF6Y/edit#heading=h.kbi494on7qka)

[**5. Applications and Discussion 9**](https://docs.google.com/document/d/1wkN0x775tgCYNj3lw1cBToxQud2-DCZIi21NkaFyF6Y/edit#heading=h.rrb5mgxvvsfl)

1. Introduction:

Floods are among the most serious disasters in the world and number one natural disaster in the United States. Annually, flooding affects about 520 million people and their livelihoods, claiming 25000 lives worldwide[1]. The annual cost of flooding and other flood-related disasters to world economy ranges between USD 50 and 60 billion (Teegavarapu, 2012). The cost of damage and economic impact resulting from floods in the lower North Island alone was estimated to be close to $300 million. (Fuller & Heerdegen 2005). In recent years, risks and consequences due to floods have become very critical. Floods can be a result of various factors such as heavy rains, river overflow, strong winds in the coastal area, dam breaking and Ice-snow melts. Of these factors, heavy downpours have become more frequent cause over the last 3 to 5 decades especially in the United States, and global warming is thought to have increased rainfall in some of the world’s driest regions (SOURCE: Journal of Geophysical Research: Atmospheres). Heavy rains can lead to significant flooding, contributing to flash floods, mudflows, or overtopping levees and dams. Heavy rains can happen throughout the year, putting property and lives at risk. The 1998 Bangladesh floods, caused primarily due to heavy rainfall, cost the country around $1 billion and over 1300 people were killed along with huge property damage.

Comment:

In order to reduce the damage to property and lives, we need to thoroughly analyse the impact\severity\effect a flood is going to have. This again depends on the intensity of the flood. Minor and moderate category floods will cause lesser property damage compared to major and severe type of floods [1].

Aim: Reducing the risk of property damage due to floods.

Assumptions:

Rainfall has been assumed to follow a normal distribution based on data from 50 urban areas.

Expansion upon this distribution has been provided in the appendix. Took mean and std of that data and distributed it normally in matlab.

Number of houses is population/4 . All structures follow normal distributions. Population follows exponential distribution. **Number of schools statistically is found to be 1 school for 10k people**

Inundation level is assumed to be constant throughout the city. The structures in the city are of three types: high rises, general concrete buildings and residential buildings. This model focuses on dealing with property damage. 4 types of flooding - minor, moderate, major and record. Cities with population only above 800000 have been considered. Distribution of number of buildings of each type are normally distributed based on data from 72 urban areas [wikipedia]. Rainfall stays constant throughout its duration.

For all urban areas avg daily rainfall was calculated and fitted to a normal dist. The normal dist was truncated to eliminate negative values. For each iteration, the program selects one value from the truncated distribution. Number of continuous  rainy days - uniform dist between 0 and 20. From here total rainfal is calculated as avg rain x total rainy days.

DRAIN FAILURE: Rain < 1 = drain failure 0.03.rain < or =1-4 - .15 chance of drain failure. 4-6 -45%.; above 6 - 75%;

Flood chance:

Drain working = 0 implies drain failed.

Depth = 3times tot rain.

Flood stage - when will city start taking action; normally distributed; changes with city:

In this paper, a method is proposed to compute the risk the property damage caused by flooding in a metropolitan location. This paper will address the case where the flooding is caused specifically due to intensive rainfall. The model will then go on to combine the flood probability with probabilities of structures failing to arrive at a projected cost incurred due to property damage. This method will address the cases wherein the flood is caused due to rainfall in the selected place. It will also address the cases where flash floods can take place due to excessive rainfall taking place at a place that lies upstream from the place around which the study is based.

This paper is arranged in the following way. The section “Literature Review” will acknowledge different research materials and other sources which have helped u The section “Case Study” will introduce the place that has been selected to be studied. The section “Model” will describe and illustrate the proposed model. This section will also list out methods using which the model can be populated. The section “Results” will discuss the performance of this model.The section “Applications and Discussion” will discuss the ways in which this model can be extended to a few other cases.

2. Literature Review:

The extent of damage to property caused by the flood are be estimated using vulnerability indices (cite 1) and their monetary values, based on the percentage of structural damage, are assumed to be deterministic for a given depth (cite 2).

The depth of inundation is estimated by populating the model with historical data. One important part of the model is the failure of the drainage system. The probability of this failure is calculated using a fault tree whose failure modes are the failure of the physical components of the drain system (cite 3).

*Unique feature:* Other than just the rainfall at the selected geographic location, this model also addresses flash floods caused due to heavy rainfall in an area that lies upstream.

\*more lit survey pending\*

3. Model:

The problem of quantifying the risk of rainfall in an urban location has been modeled as an influence diagram. Data to populate this influence diagram has been gathered through various sources. Data for factors for which data has been hard to come by has been generated through observations and inferences.

Influence Diagram

The influence diagram visually depicts the factors/uncertainties that have an *influence* on the risk of a flood event taking place. This influence diagram will specifically address the problem of risk of a flood occurring due to intensive rainfall.

Fig 1. Influence diagram depicting Flood Risk

The various uncertainties involved in this problem

By modelling of floods due to heavy rainfall, we are determining the risk path for property damage. This damage varies with varying intensities of floods, which is again influenced by various other parameters. This model addresses the floods caused mainly due to heavy rainfall. Various factors such as tropical storms, seasonal rainfall and hurricanes are the causes of heavy rainfall, which can potentially cause floods. Our model consists of an influence diagram, which shows the variables causing floods, the consequence node of which is the property damage caused by the same. This value will depend on probabilities of a flood due to rainfall and the probability of failure of structures.

As shown in the Fig 3.1, rainfall is influenced by factors such as season, tropical storms, hurricanes etc, which in turn will cause floods. Our model is not limited to any particular geographical area. It is a general model of a city with a river bank. Hence, additional factors such as levee failure, drainage system failure, flash floods etc which also influence the occurrence of floods have been considered. Sometimes, if there is heavy rainfall in the areas upstream of a river and due to various factors, such as less vegetation cover, if most of the water gets carried to downstream areas, this sudden surge in the level of river water might also cause floods. This case is also addressed in our influence diagram. The consequences of floods, failure of structures (or property damage) and fatalities, have been modeled as deterministic nodes. These nodes are then connected to a final value node, cost, which sums up the total cost involved in repairs, losses and maintenance due to floods. Fatalities has also been included in the value node ‘cost’ in the form of loss of productivity and income.

The uncertainty nodes will be then populated with numerical probabilities. These numerical probabilities will be calculated using historical data for some nodes and fault trees for a few other nodes.

Data Gathering and Data Generation  
  
City Modeling:

Important parameters of a metropolitan area like population and structures were modeled such that a wide range of cities was covered.

*Population*: Population data from 72 American metropolitan areas was collected and a histogram was plotted for this data. The population seemed to follow an exponential distribution. As such, for the simulation, population was chosen randomly from an exponential distribution that was fitted to the real population data. It must be noted that only cities with a population above 800,000 were considered for this model. Depending on the population, the city was classified into one of four tiers.

Since this model addresses cost incurred due to property damage, 3 types of structures(buildings) were chosen to populate the urban area:

1. Highrises - Concrete buildings with 10 floors and over.
2. General Concrete Structures - Concrete buildings with less than 10 floors.
3. Houses - Residential buildings with 1 or 2 floors(typically with wooden exterior).

*Highrises*: Based on population, the 72 cities were categorised. In each category for each city, data on number of highrises was gathered and distributed. It was found that the number of highrises mostly follows a normal distribution.  This variable in the simulation is generated from a truncated normal distribution.

*General Concrete Structures*: Data on number of general concrete structures could not be found owing to the fact that this category of buildings is by far the most diverse since it would include buildings like schools, restaurants, malls, smaller offices etc. In order to model this data, the number of schools in each city were found, and the number of general buildings was estimated to be 15 times the number of schools in this city. Like in the case of highrises, it was found that this data also follows a normal distribution. This variable in the simulation is generated from a truncated normal distribution.

*Houses*: Data on the number of houses was also hard to come by since it includes a variety of structures like apartment complexes, town houses etc. Hence, the number of houses in a given city was estimated to be a quarter of the population. This would be the same as saying that each house is occupied by 4 people. The mean and standard deviation of this data was calculated and a normal distribution was created using these values. The value for this variable is obtained from the above stated distribution.

Rainfall Modeling:

Measurements and duration of rainfall were modeled in order to cover a large range of geographical locations with varying rainfall. This type of modeling would also cover cases of storm induced rainfall since the distributions have substantial range.

*Average Daily Rainfall*:

Data on annual rainfall and wet days was collected from 50 American cities and using this data, daily rainfall for these cities was estimated. Using these estimates, average daily rainfall in inches for a city was modeled as a normal distribution. It must be noted that the value generated for average daily rainfall as assumed to remain unchanged throughout the duration of the rainfall. Distributing this data over a wide range helps account for storm induced rains which usually register high on a rain gauge.

*Rainy Days*:

The number of wet days(days with rain) was modeled as a uniform distribution between 0 and 20. It is important to note that the number of rainy days means the number of consecutive days on which it rains in the city. Using this model and distribution for wet days helps account for cases where there is not rainfall (0 rainy days). It also helps in accounting for storms of both short and long duration. This way, the analysis is much more closer to reality and not fundamentally skewed towards reporting an overestimated or an underestimated risk.

Flood Modeling:

*Total Rainfall*:

Total rainfall is the measurement in inches of the cumulative rainfall that the city has received duration the complete duration of the rainfall. It is the product of product of *Average Daily Rainfall* and *Rainy Days*. Total rainfall is important in order to calculate the chances of flooding and the value of water stage.

*Drain Failure Probability*:

This probability represents the chances of the city’s drainage system failing, leading to the city being flooded. It is determined by undertaking a fault tree analysis of the city’s sewer and drainage system. Depending on the total rainfall, this probability can take up four values in the simulation. Whether the drain system would fail or not is modeled as a binomial variable. This approach seeks to account for the rare cases wherein the drain system can fail during light rainfall.

The values that this probability can take on are:

|  |  |
| --- | --- |
| **Total Rain (TR) in inches** | **Probability of Drain Failure (%)** |
| TR < 1 in. | 3% |
| 1 in. < TR 4 in. | 15% |
| 4 in. < TR 6 in. | 45% |
| TR > 6 in. | 75% |

The probabilities may seem high but one must keep in mind that the drainage system is dealing with rainfall that is continuous, which mean that the system will have to function with no cooldown period.

*Depth/Water Stage*:

Water stage is the depth of water above ground after flooding. It is calculated as a function of the *Total Rainfall*. It is taken as a multiple of *Total Rainfall*. The factor with which it is multiplied will henceforth be referred to as *Inundation Factor.* It is assumed that the city has a perfectly flat terrain, which means that the water stage will be constant throughout the city.

Water stage will be used to determine the extent to which the buildings in the city are damaged.

*Inundation Factor*:

*Inundation factor* as defined before is the factor used to directly compute water stage. This makes *Inundation Factor* a very important parameter which should have a wide range so as to cover many different types of cities. Hence, this variable has been modeled as normally distributed. Normally distributing inundation factor over a wide range serves a very important purpose of accounting for the city’s altitude and soil type. Cities at higher altitudes (Ex: Denver) and with soil that is more absorbent (Ex. Oklahoma City) will tend to have lower inundation factors since a part of the rain water would flow downhill or get absorbed. Similarly, low lying cities(Miami) or ones with marshy soil (Washington DC), will have a higher inundation factor because water pooling or water not being absorbed.

*Flood Stage*:

Damage Modeling:

4. Results

Pending

5. Applications and Discussion

Pending

**References:**

[1] Damage and loss prediction model considering inundation level, flow velocity and     vulnerability of building types, <https://www.witpress.com/Secure/elibrary/papers/FRIAR12/FRIAR12005FU1.pdf>

[2] Catalog of Residential Depth-Damage Functions, <http://www.dtic.mil/dtic/tr/fulltext/u2/a255462.pdf>, 1988

[3] Fault tree analysis for urban flooding, *J.A.E. ten Veldhuis, F.H.L.R. Clemens, P.H.A.J.M. van Gelder,* 2008

[4]Managing Flood Water Before and After the Storm.

[5] Impacts of Flash Floods. Margaret S. Petersen

[1] Estimation uncertainty of direct monetary flood damage to buildings by B. Merz1, H. Kreibich1, A. Thieken1, and R. Schmidtke2.

[2] The Probability Distribution of Daily Rainfall in the United States by Lars S. Hanson1 and Richard Vogel2.

[3]http://www.skyscrapercenter.com/quick-lists#q=&page=1&type=building&status=COM&status=UCT&status=STO&status=UC&status=PRO&min\_year=1885&max\_year=9999&region=0&country=0&city=1641

Influence diagram

The influence diagram above shows the influence of factors on Flood.

**Drainage system**:  Flooding may happen in large amounts over an area in a short period of time or it can happen from a single heavy storm or hurricane. After these storms, one relies on the man made flood control system to drain excess water from the low, flat lands. These man-made structures are known as drainages. Drainages are the most important infrastructure when it comes to mitigation of flood effects. The drains keep cities from flooding.

Large and small structures, culverts, gates, weirs, pumps, and levees, even street grates are all components of drainage system. Water bodies such as ponds, lakes, and lagoons also play a role in water management. While they do provide a beautiful view, their real function is to hold excess rainwater or to carry it off to regional storage areas or to the ocean [4].

Increase in total rainfall and rainfall intensity will result in a greater load on the drainage and sewerage systems. Existing levels in surface waters and groundwater affect the ability of drainage systems to receive or store new rainfall. If surface waters such as canals, lakes and rivers are already full, they cannot receive or transport additional water. This causes the excess water to flow in the city neighbourhood resulting in floods.

**Levee Failure**:

A levee is a natural or artificial wall that blocks water from its course. Levees are generally used to increase available land for habitation or to divert a body of water so the fertile soil of a river or sea bed may be used for agriculture. They prevent rivers from flooding cities in a storm surge. But when a levee fails it can be disastrous. A levee breach is a situation where a levee fails or is intentionally breached, causing the previously contained water to flood the land behind the levee. There are various causes of levee failure.

Foundation Failure: Soil erosion beneath the levee can lead to gradual failure of the levee. This erosion is usually caused by action of wind and water. Trees in levee can be very risky because a tree can become unstable after the soil of the levee has become saturated with water. When the tree falls the root system will likely take a chunk of the saturated soil out of the levee.The shallow region formed due to this can erode and result in a breach. If the tree falls in the water and floats it can damage the levee further downstream.

Overtopping

Sometimes levee failures are caused when the water overtops the crest of the levee. Other forms of damage can be caused by ships or other large floating objects in the levee.

**Flash flood**:

Flash floods is a rapid flooding of areas especially the low lying areas. These are caused by heavy rains usually associated with hurricane, tropical storm or meltwater from ice.Flash floods most frequently occur on small headwater basins in association with short-duration convective, frontal, or orographic type storms with high-intensity rain cells. The economic, social, and environmental effects of flash floods are similar to impacts of “river floods” of other types; the major differences being that the effects of flash floods generally occur with little, if any, warning over a very short time period and are generally limited to relatively small areas [5].  These floods can occur within a few minutes or hours of excessive rainfall. Johnstown flood of 1889 [Wikipedia] was caused due to flash flood which was caused due to dam failure. Occasionally, water held back by the ice jam or debris dam can cause flooding upstream. Subsequent flash flooding can occur downstream if the obstruction breaks or melts down.

https://www.sfwmd.gov/sites/default/files/documents/bts\_before\_after\_storm.pdf