# Vulnerability Analysis methodology: The vulnerability prediction based on the expected number of heavy storms and flood in Rio de Janeiro city.

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**Abstract**

*The society's vulnerability to natural disasters are increasing since the environment, climate changing in the last 10 years. Nevertheless, the vulnerability perception of the society, including the public and private sector leaders is still low which can be realized based on the last catastrophic natural disaster events around the globe. Therefore, the first step in a direction to increase the authorities and leader vulnerability perception is to assess the expected number of future natural disasters as well as its consequences. In order to provide a methodology to approach this problem the paper proposes the prediction of the expected number of natural disasters based on the Crow AMSSA model as well as the final prediction of the vulnerability based on Bow tie analysis. The vulnerability criteria are also proposed as a baseline to support leader to take decision regarding the necessity to reduce their vulnerability face of natural disasters.*

*Keywords: Vulnerability, expected number of storms, mean time between storms, Acceptable vulnerability, Bow Tie model.*

## 1. Introduction

The Vulnerability is defined as a lack of protection or fragile that one system has and can be exploited by external forces. Such lack of protection or fragile are related to external events like nature catastrophes, security information and terrorism attacks or internal events like sabotage.

In case of Systems' infrastructure, vulnerability describes how a system faces problems to carry out its intended function when exposed to materialize threats (Hofmann, 2012). The vulnerability of critical infrastructures as shown in figure 1 can be divided into several dimensions to form a general framework for analysing vulnerability that is:

- Threat / hazard and unwanted event;
- Exposure;
- Susceptibility;
- Coping capacity;
- Criticality.

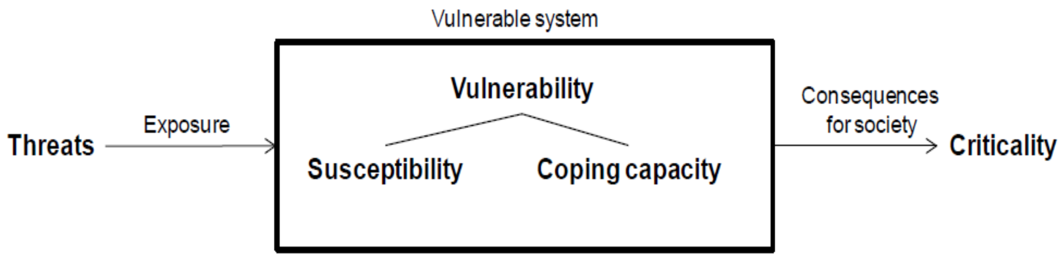



**Figure 1: General Vulnerability Framework**

**Source: Hofmann, 2012.**

Threat can be defined as any event with the potential to cause some damage to systems, society and environment. Threats can be categorized into nature/weather related threats, human threats and operational conditions threats. A threat may lead to an unwanted event, understood as a disruption of the system. The vulnerability regards threat susceptibility and loss of coping capacity. Concerning infrastructures, the susceptibility succeeds if a threat leads to a disruption in the system and is depending on, for instance the technical components, the working force and the organization.

On the system level, other factors like institutional and social factors also have an influence on the susceptibility. A system is susceptible towards a threat if the threat leads to an unwanted event in the system. The coping capacity describes the ability of the system itself to cope with an unwanted event, limit negative effects, and restore the function of the system to a normal state. The copy capacity can also be understood as resilience.

## 2. Natural disaster

Nature catastrophes are event triggered by nature forces like Tsunamis, Hurricanes, Tornados, volcanoes, Earthquakes, Thunderstorms and universe space treats (G. Woo et al 2006). Whenever such event occurs, industrial accident and public infrastructure rupture may take place which has extreme consequences for the whole society such as flooding area, transportation service disruption, environmental impact, health damages and death.

Throughout history, natural disasters have exacted a heavy toll of death and suffering and are increasing worldwide (Reyes, 2006). During the past 34 years, they have claimed about four million lives worldwide, adversely affected the lives of at least a billion more people, and resulted in property damage exceeding $50 billion (Guha-Sapir and Lechat 1986b).

In general terms, in case of disaster events (Natural catastrophes, Terrorism attacks, sabotage) we need to consider the application tools and our entities of interest to define impact and the most appropriated response to mitigate such disastrous effect. The figure 2 below summaries, issues that must to be considered in respect to the vulnerability of the system.

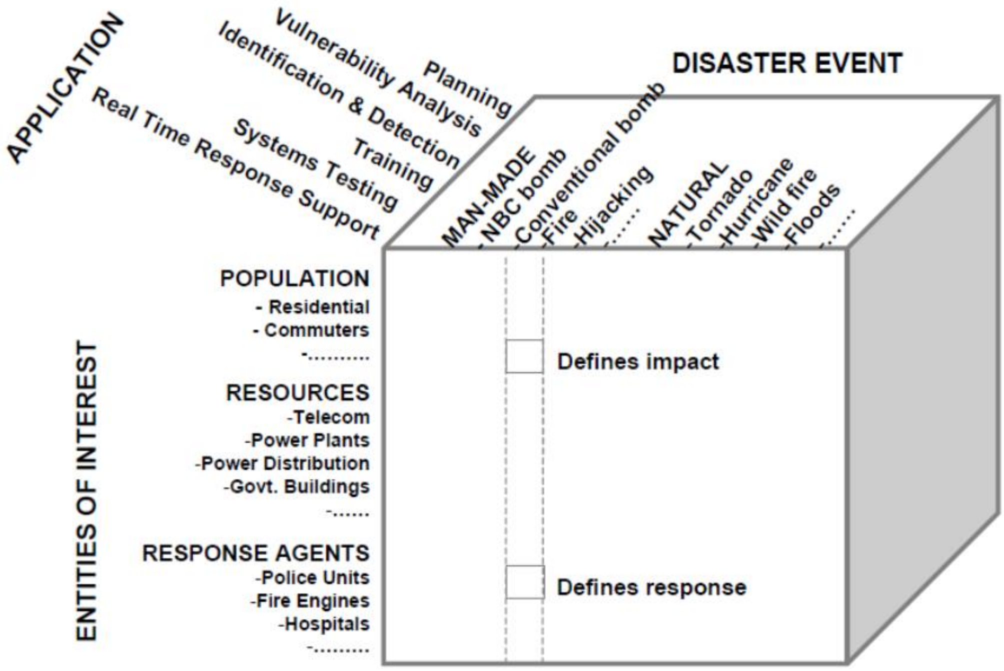



**Figure 2: Integrated Emergency Response Framework (IERF) proposed by NIST**

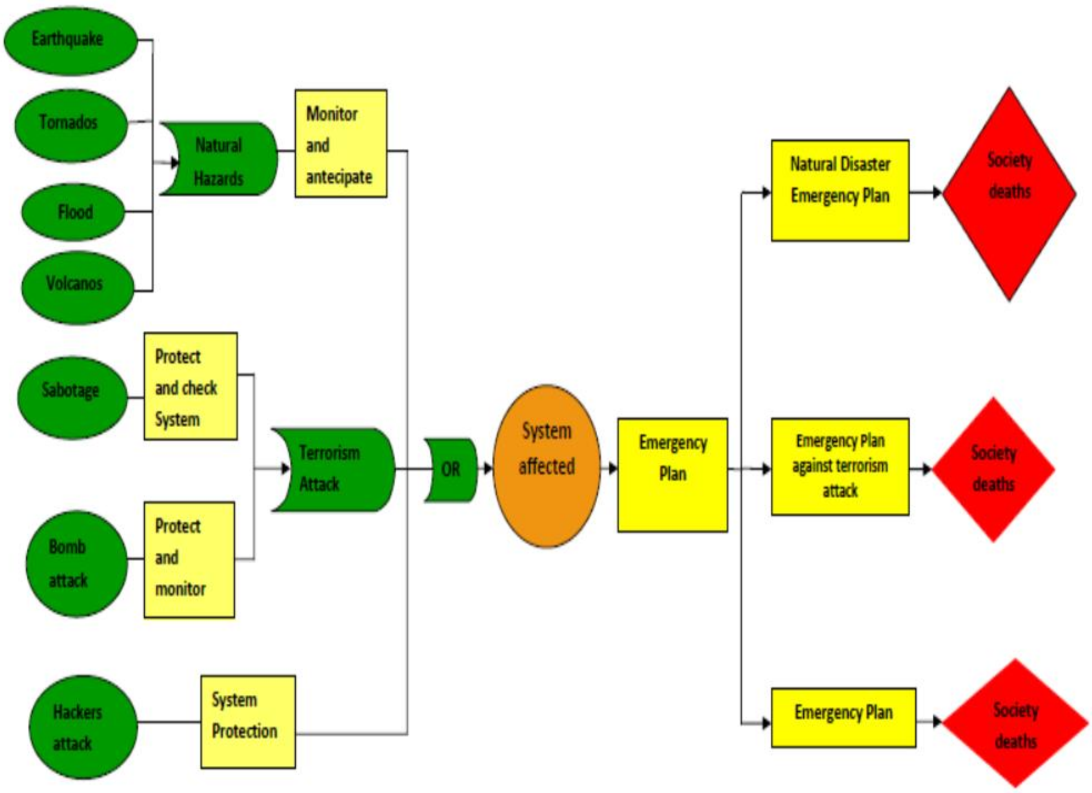
**Source: Jain and McLean, 2003.**

Considering that such threats really exist in the world, it is necessary to have a measure of system vulnerabilities to monitor and mitigate the susceptibility of the system and avoid the bad consequence for the whole society.

## 3. Vulnerability model

In order to consider all vulnerabilities such as the disaster event, entities of interest and it's impact it´s necessary to have a model. A Model is a representation of some reality in the real world which enable us an easier understand and predict. Therefore, to model the natural disaster vulnerability, the Bow Tie model is proposed as shows figure 3. The Bow Tie methodology is usually applied to a risk analysis which considers on the left diagram side the probable cause of the incident, the incident in the middle and the consequences on the right size. Among the causes and incident is the control measures and between incidence and consequences are the recovery measures.

In case of vulnerability analysis, the causes are threats like natural disasters, terrorism attack and hacker's attacks. The control measures are protecting, check, monitoring and anticipate actions. The incident is the susceptibility of threats and recover measures a copying capacity to mitigate threats' effects. The figure 3 shows a Bow tie Model which describes the vulnerability of generic systems like industrial plants, trains, commercial building and aircrafts.




Legend:

Potential Causes (threats)

Control Measures (Control Measures)

Loss of Control (susceptibility)

Recovery Measures (coping capacity)

Consequences

Figure 3: Bow Tie Vulnerability Analysis. Source: Calixto E, et al 2016.

The threats events can have multi effects on different systems on the same location, in other words, city state or country. Because of that, is necessary to have a complete Vulnerability analysis considering all systems affected because is necessary for prior which location requires support and which kind of support. Therefore, a Multi Bow Tie is a more appropriate model and allows accessing all threats' effects on different systems with different consequences. The figure 4 shows the Multi Bow Tie model to have a complete Vulnerability analysis.

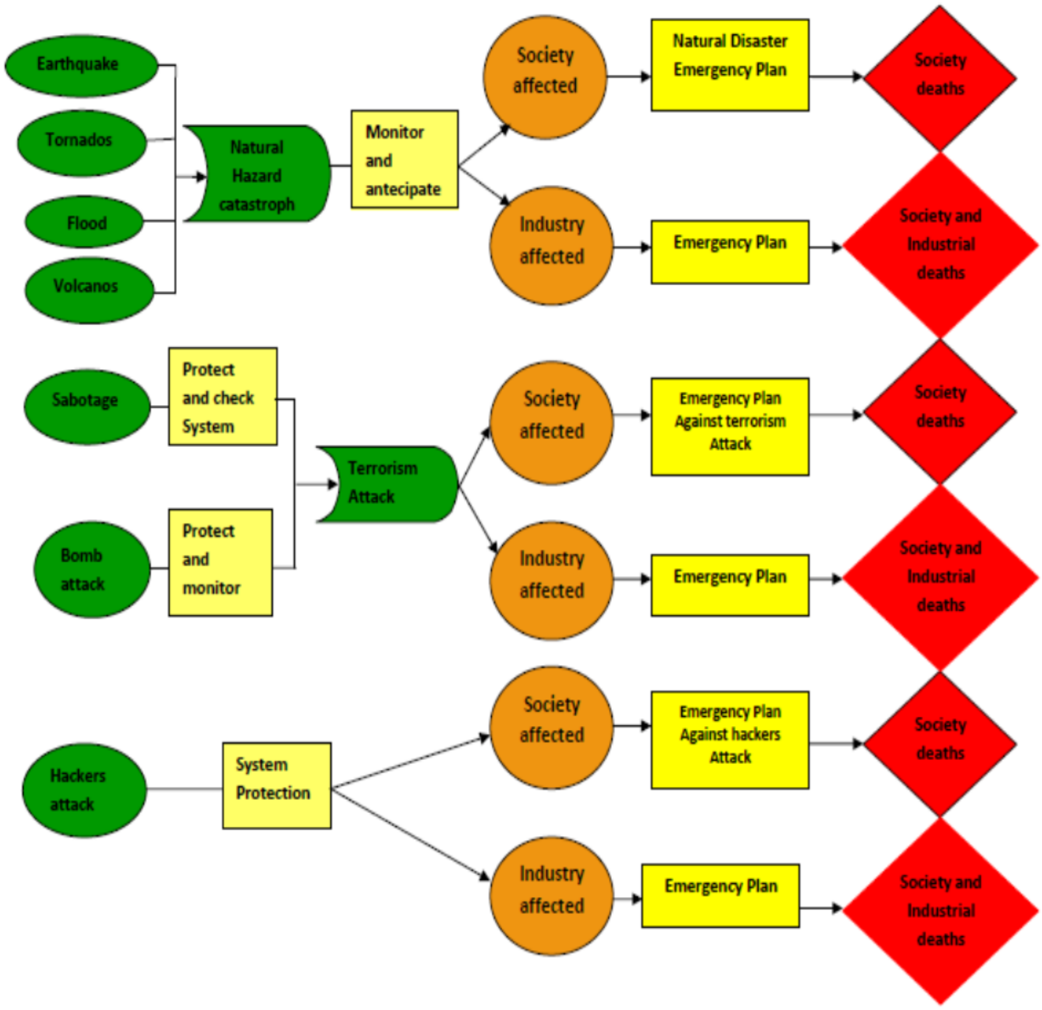



Figure 4: Multi Bow Tie Model for Vulnerability Analysis. Source: Calixto, et al 2016.

Considering that threats can affect system and society, it is necessary to consider different susceptibility for each threat group (Natural catastrophes, Terrorism Attack and Hackers Attacks). In addition, different emergency plans will be carried out depends on treat characteristics.

## 4. Vulnerability prediction

The vulnerability can be defined qualitatively as the capacity of a certain threat to be susceptible to a system or society and cause a negative impact in this system or society.
The system susceptibility can be described mathematically by the number of times that the threat tries to enter into the system and succeed during an interval of time t. Therefore, the susceptibility is a combination of treats number of success and control measures failure probabilities (copy failure probability). By this way, the System Susceptibility is defined in (1):

$$S_i = ENT_{t_i} \times CM_{i_j} \qquad (1)$$

$Where$:

i=0, 1,2... n

j=0, 1,2... m

$S_i = System\ suceptibiliy$

$ENT_{t_i} = Expected\ Number\ of\ threat\ at\ time\ t$

$CM_{i_j} =$ Threat control measure failure probability

Since the threat is susceptible to the system, which means the control measure failed, the copy capacity is the last layer of protection to avoid that such threat causes a damage to the system or society.

Therefore, the system or society's vulnerability is defined in (2):

$$V_{SO_i} = S_i \times CO_{i_k} \times END_i \qquad (2)$$

$Where$:
i=0, 1,2... n

k=0, 1,2... m

$V_{SO_i} = Society\ vulnerabiliy$

$S_i = System\ suceptibiliy$

$CO_{i_k} =$ Copy capacity failure probability

$END_i = Expected\ Number\ of\ deaths$

Depends on type of threat, it´s possible to mitigate the vulnerability by reducing the threat susceptibility success by increasing the control measure effectiveness or by increasing the coping capacity success. In case natural catastrophes, it´s hard to reduce the susceptibility success by reducing the frequency of natural disaster or by avoiding their effect on systems. In this case, the control measure are not so efficient to reduce the threat susceptibility but it´s possible to mitigate the society's vulnerability by increasing the copy capacity, such as an effective emergency alarms evacuation and emergency response, which will lead the population to a safe place with low number of casualties. Concerning the natural disaster, the most effective vulnerability mitigation is to avoid as much as possible the threat consequences by dislocating the population to a safe place before the threat susceptibility takes place.

By the other hands, others threat like terrorism attack and hacker attach, the more effective is to reduce the susceptibility by monitoring the threats and reduce the frequency that such threats penetrate into the system. Once such threat is susceptible is very hard to predict or avoid the intended damage to the system or society.

Considering that different threats like Natural disasters, terrorism attacks and hacker attacks can affect society or Industrial plants in the same interval of time, the Multi Bow Tie Model described in item 3, will consider such multi effect. Consequently, the Total vulnerability is the sum of all vulnerabilities as defined in (3).

$$V_{SO_i} = \sum_{i=0}^{n} S_i \times CO_{i_k} \times END_i \qquad (3)$$

After defining the vulnerability, is also important to estimate properly the expected number of susceptible threats to help emergency response and security teams have a target and keep such number as low as possible. By this way is possible to define the expected number of susceptibility in (4).

$$E(N_i) = \int_o^T \rho(t)dt \qquad (4)$$

The Crow AMSAA Model assumes that the intensity of the event is approximately Weibull event rate, thus intensity of event on time defined in (5):

$$\rho(t) = \frac{\beta}{\eta^\beta} T^{\beta-1} \qquad (5)$$

Considering the initial event rate as:

$$\lambda_i = \frac{1}{\eta^\beta} \qquad (6)$$

If we consider the event as a threat, the cumulative threat rate is approximately threat intensity we have:

$$\lambda_c = \beta \lambda_i T^{\beta-1} \qquad (7)$$

$$E(N) = \lambda_i T^{\beta} \quad (8)$$

When β=1,

(9)

Where:

$E(N_s)$=Expected Number of susceptible threats

$\lambda_C$ = Threat frequency

T=Accumulated time

The equation above describes the threat intensity and depends on β value its increase, decrease on keeping constant along time. Is very important to have in mind that β in Crow AMSSA Model describes threat intensity behaviour and have not relation with Weibull distribution shape parameter. In fact, β is a shape parameter of threat Intensity Function in Crow AMSSA Model. Thus, in this model when β>1 means higher threat because threat intensity is increasing, in other words, the frequency of threats increases and control measures and copy measures actions are not reducing the vulnerability. When β<1, threat intensity is decreasing along time, in other words, threats frequency is reduced or control measures and copy measures actions are reducing the vulnerability. When β=1, the threat intensity is not getting higher or lower.

To find the variable value in Crow AMSSA method, it is necessary to find the maximum value related to one parameter and that is achieved by performing partial derivation of the equation as follows:

$$\frac{\partial(\wedge)}{\partial(\theta_j)} = 0$$

$$j = 1,2,3,4...n$$

Applying the maximum likelihood method, we have:

$$f(t) = \frac{\beta}{\eta}\left(\frac{T_i}{\eta}\right)^{\beta-1} e^{-\lambda_i T_i^{\beta}} = \beta \frac{1}{\eta^{\beta}} T_i^{\beta-1} e^{-\lambda_i T_i^{\beta}} = \beta \lambda_i T_i^{\beta-1} e^{-\lambda_i T_i^{\beta}} \quad (10)$$

$$L = \prod_{i=0}^{N} f(t) = \prod_{i=0}^{N} \beta \lambda_i T_i^{\beta-1} e^{-\lambda_i T^{\beta}} = \beta^N \lambda_i^N e^{-\lambda_i T^{\beta}} (\beta - 1) \prod_{i=0}^{N} T_i$$

$$\Lambda = LnL$$

$$LnL = Ln\left(\beta^N \lambda_i^N e^{-\lambda_i T^{\beta}} (\beta - 1) \prod_{i=0}^{N} T_i\right)$$



$$\Lambda = NLn\beta + NLn\lambda_i - \lambda_i T^{\beta} + (\beta - 1)\sum_{i=0}^{N} LnT_i$$

$$\frac{\partial(\wedge)}{\partial(\lambda_i)} = 0$$

$$\frac{\partial(\wedge)}{\partial(\lambda_i)} = \frac{N}{\lambda_i} - T^{\beta} = 0$$

$$\lambda_i = \frac{N}{T^{\beta}}$$

$$\frac{\partial(\wedge)}{\partial(\beta)} = 0$$

$$\frac{\partial(\wedge)}{\partial(\beta)} = \frac{1}{\beta} - \lambda T^{\beta} LnT + \sum_{i=0}^{N} LnT_i = 0$$

$$\beta = \frac{N}{NLnT - \sum_{i=0}^{N} LnT_i}$$

This paper proposes that the expected number of catastrophic consequences in a cumulative time must be between 0 and 0.1 to be acceptable. The different qualitative vulnerability class is defined in the table 1. Therefore, we can consider low vulnerability for values between 0 and 0.1, moderate vulnerability value between 0.1 and 0.5, high vulnerability for values between 0.5 and 0.7, very high vulnerability for value between 0.7 and 1 and unacceptable vulnerability for values equal or higher than 1.

Even in case of low vulnerability, the threat monitoring and data updated must be continuous but is not necessary for mitigations actions implementations.

In case of high and very high vulnerability is necessary not only for monitoring the threats but also to improve the existing control measures or implement additional control measures as well as copy capacity improvement to achieve a low vulnerability level whenever is feasible. In case of high or very high vulnerability it is necessary to monitoring the threat and try to eliminate or block them whenever it´s possible, improve existing control measures and copy capacity as well as implement new ones when the mitigation actions are not enough.

In addition, to mitigate the system and the society threat effect is recommended to shut down or isolate systems and dislocate the possible affected society to a safer location as much as possible.

Table 1 - Vulnerability Indexes and classification

| Vulnerability Indexes | Vulnerability Class | Vulnerability consequence |
|---|---|---|
| ≥1 | Unacceptable | One or more deaths. |
| 0.7≤Vi<1 | Very High | Expected number of deaths very close to 1. |
| 0.5 ≤Vi<0.7 | High | Expected number of death close to 1. |
| 0.1≤Vi<0.5 | Moderate | Moderate expected number of deaths. |
| Vi<0.1 | Low | Very low expected number of deaths. |

In fact, if copy capacities are not able to eliminate threats, there will be consequences and society, industrial population or both will be affected. By this way, is also important to estimate the number of deaths, causalities and cost caused by threats to have complete consequence analysis of vulnerability effect. Thus, the vulnerability related to such threats can be measured by the combination of threat susceptibility with the expected number of deaths, causalities or cost. Concerning the number of deaths, it´s important to have a perception of the whole society's tolerance of such threats' effects. In fact, there's no any acceptance vulnerability criterion for events such as natural catastrophes, terrorism attack and hacker attacks. Nowadays and is a worldwide concept that as lower as possible better will be to the whole society.

## 4. Rio de Janeiro Flood natural disaster: Vulnerability methodology application

Once of the most frequent natural disaster which affect a large number of population every year around the globe is flood caused by heavy storms. In South America, it´s also a reality and especially in Rio de Janeiro, Brazil, this event has been intensified in the last ten years.

The first flood cause by heavy storms in Rio de Janeiro is dated in 1711 when no emergency response and neither report about such natural disaster was done. The two realities between the past 300 years and the last 10 years in Rio de Janeiro is the population density, which grew up specially in the last 50 years. As many of the main cities in South America such as Sao Paulo, Lima, Rio de Janeiro, Santiago, Caracás, Bogota e Buenos Aires, the high number of the population lives under bad social and economic conditions, which force a high percentage of such population to live in inappropriate and dangerous areas. In the case of Rio de Janeiro, huge part of the population, approximately 1.5 million people, around 24% of the population, live in favelas. Such reality is even worse in terms of vulnerability, because most of the favelas are on hills. Such areas have a high risk of landslides caused by heavy Storms which is facilitated by vegetation devastation which is motivated by houses construction as shows figure 5.

Figure 5: Rio de Janeiro Favela. Source: Calixto, et al 2016.

In order to define the natural disaster vulnerability, which in Rio de Janeiro city is a Heavy storm vulnerability, the last seventy years with the eleven worse heavy storms are summarized in table 2.

Table 2 – Heavy Storms in Rio de Janeiro effect (1966 – 2016)

| **Storm date** | **Concurrent Data** | **MTBE** | **Disaster description** | **Deaths** | **Injures** | **Families houses destroyed** | **Economy Losses** |
|---|---|---|---|---|---|---|---|
| 01/01/1966 | 255 | 0.00 | Heavy Storm and flood area | 250 | Not defined | 50 000 | Not defined |
| 01/01/1967 | 256 | 1.00 | Laranjeira Hill slides | 200 | 300 | Not defined | Not defined |
| 01/03/1982 | 271 | 15.00 | Pau da Bandeira Hill landslides | 6 | Not defined | 2 | Not defined |
| 20/03/1983 | 272 | 1.00 | Heavy Storm and flood area | 23 | Not defined | 150 | Not defined |
| 01/01/1987 | 276 | 4.00 | Serrana Hill Region landslides | 292 | Not defined | 20000 | Not defined |
| 01/02/1988 | 277 | 1.00 | Serrana Hill Region land slides | 289 | 734 | 18560 | Not defined |
| 01/01/1999 | 288 | 11.00 | Serrana Hill Region land slides | 41 | 72 | 180 | Not defined |
| 01/02/2003 | 292 | 4.00 | Serrana Hill Region land slides | 36 | 95 | 1693 | Not defined |
| 01/04/2010 | 299 | 7.00 | Bumba Hill landslides | 264 | Not defined | Not defined | Not defined |
| 14/01/2011 | 300 | 1.00 | Serrana Hill Region land slides | 1000 | Not defined | 14000 | $300.000.000 |
| 09/01/2016 | 305 | 5.00 | Heavy Storm and flood area | 250 | 1000 | 50000 | Not defined |

Based on table 2 description, is noticed that the intensity of heavy rains has been increasing in the last fifty years and unfortunately, the consequence of the society has been catastrophic with a huge number of deaths and injured population, population without houses and economic losses. The main concern now is when the next failure will go to happen, and to predict vulnerability, the first step is to calculate the time when the next heavy storms will occur. The table 3 shows the summarized calculation of the CROW AMSSA model parameters based on the methodology description on the item 4 and the information defined in table 2.

Table 3 – Expected Number of Heavy Storms in Rio de Janeiro prediction basis.

| N | T | b | λi | d | λc | N(t) | MTBFi |
|---|---|---|---|---|---|---|---|
| 1 | 16 | 2.7725887 | 0.12618 | 0.227874402 | 2.64E-02 | 1.089 | 7.925 |
| 2 | 17 | 2.8332133 | 0.13288 | -0.254969115 | 2.78E-02 | 1.219 | 7.526 |
| 3 | 21 | 3.0445224 | 0.15913 | -0.377184473 | 3.33E-02 | 1.803 | 6.284 |
| 4 | 22 | 3.0910425 | 0.16557 | -0.411144177 | 3.46E-02 | 1.966 | 6.040 |
| 5 | 33 | 3.4965076 | 0.23401 | -0.871608438 | 4.89E-02 | 4.167 | 4.273 |
| 6 | 37 | 3.6109179 | 0.25800 | -1.077460618 | 5.40E-02 | 5.151 | 3.876 |
| 7 | 44 | 3.7841896 | 0.29910 | -1.485437273 | 6.26E-02 | 7.102 | 3.343 |
| 8 | 45 | 3.8066625 | 0.30489 | -1.548606109 | 6.38E-02 | 7.404 | 3.280 |
| 9 | 50 | 3.912023 | 0.33357 | -1.882510643 | 6.98E-02 | 9.000 | 2.998 |

The Crow AMSAA parameters base on table 3 are:

$$\beta = \frac{N}{NLnT - \sum_{i=0}^{N} LnT_i} = 1{,}85$$

$$\lambda_i = \frac{N}{T^{\beta}} = 0{,}006394$$

The time to have the next heavy storm is defined by the equation (11).

$$E(N_s) = \lambda_i \mathrm{T}^{ß} \qquad (11)$$

$$T = \left(\frac{E(N_s)}{\lambda_i}\right)^{\frac{1}{\beta}} = \left(\frac{10}{0.006394}\right)^{\frac{1}{1.85}} = 52.9\ years \cong 53 \text{ years}$$

For the current time of 50 years (2016), we have nine failures. Therefore, in 3 years' time the next failure will happen as shows the figure 5.

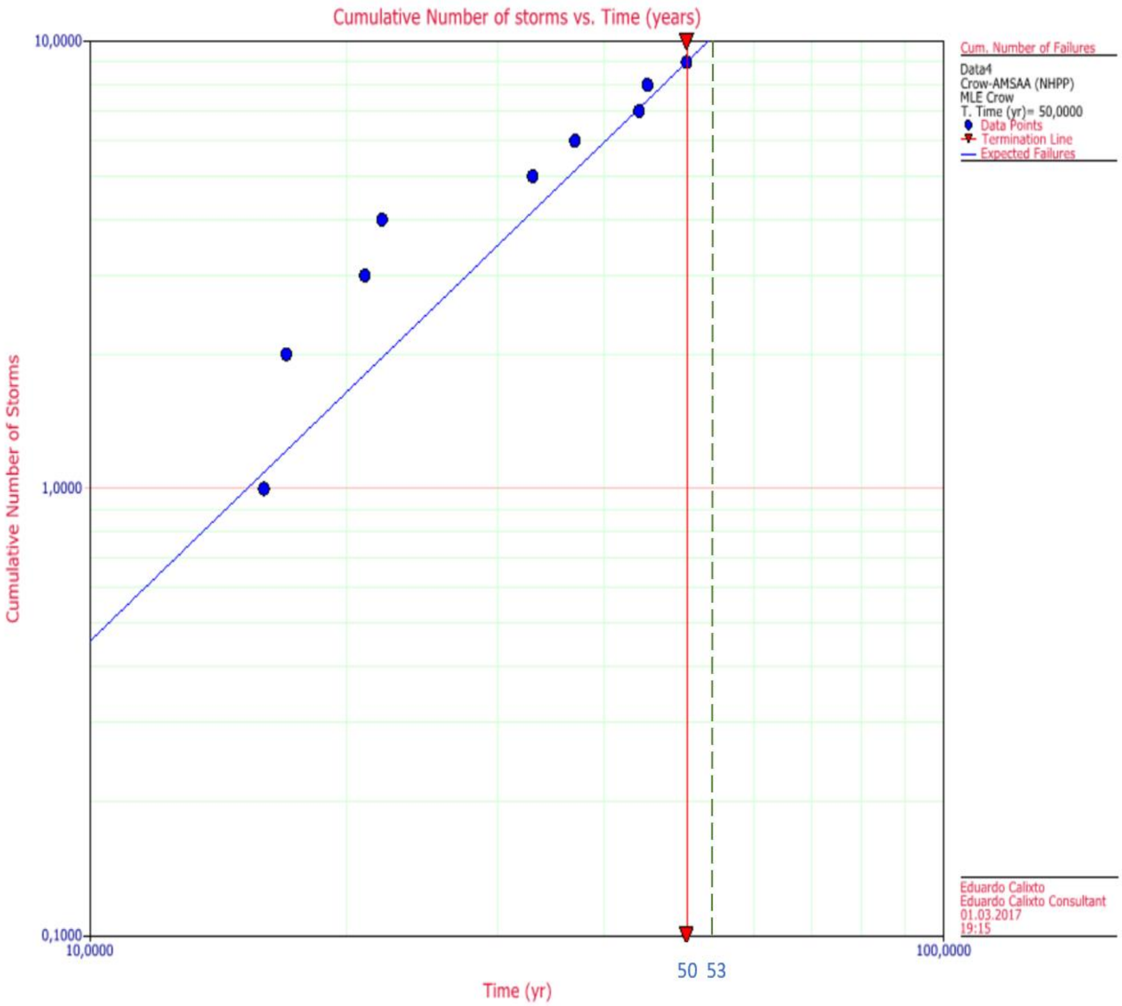



Figure 5: Cumulative number of Storms.

The confirmation of the increased number of heavy storms is demonstrated in the figure 6 which shows the decreasing interval between heavy storms (MTBS). Therefore, are expected 1 heavy storm for the next three years, which will lead to such catastrophic consequences for the Rio de Janeiro society. The vulnerability calculation considers also the mitigation event's probability. Therefore, the bow tie model is applied to define the vulnerability of heavy storms based on the following definition:

- Potential Causes (exposure): Heavy Storm
- Control Measures (Control Measures): Monitoring weather, emergency alert and population reallocation
- Loss of Control (susceptibility): Probability of heavy rain affects the Rio de Janeiro city
- Recovery Measures (coping capacity): Emergency response
- Consequences: Deaths

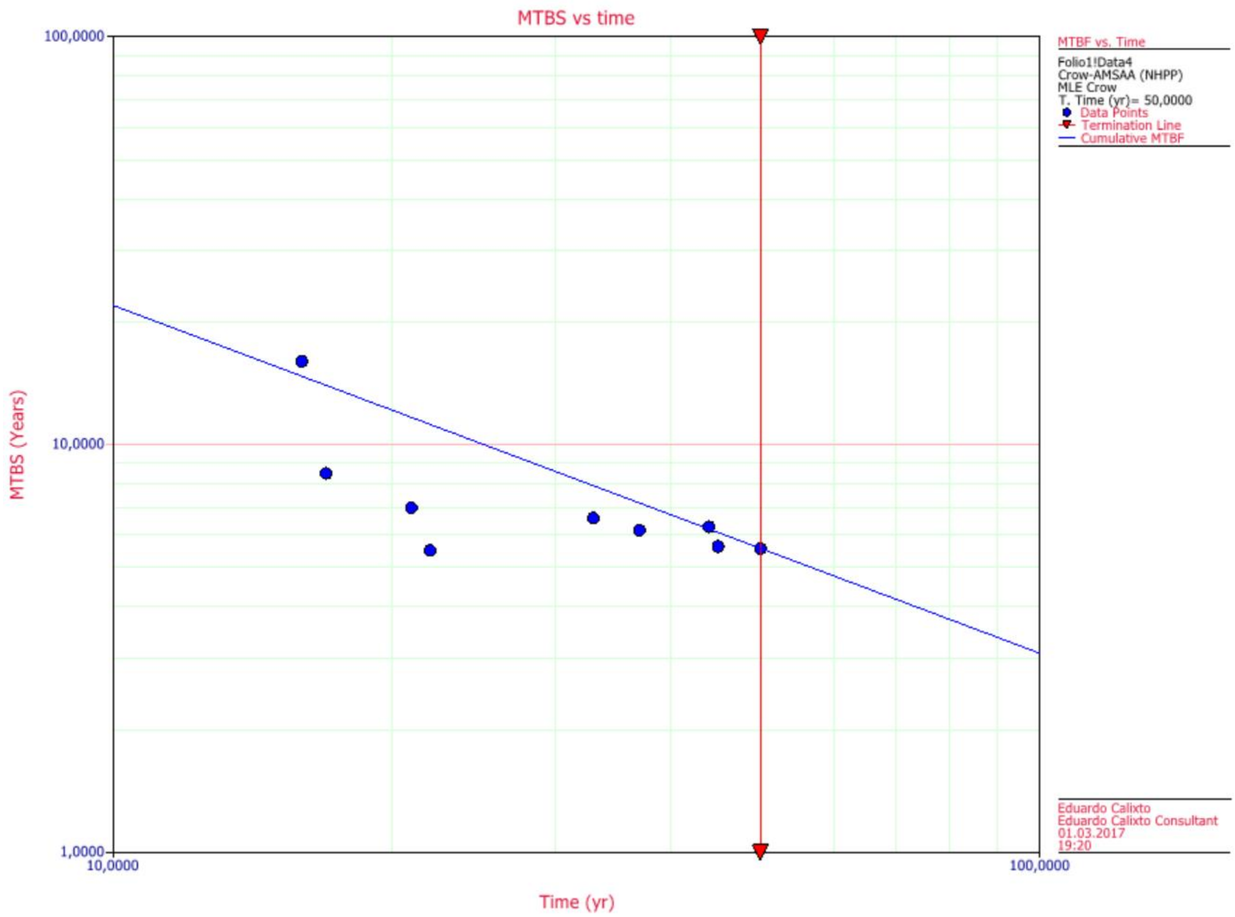



Figure 6: Mean Time Between Storms tendency.

Concerning the next five years, the expected number of heavy rain is 1.7, the following Bow tie elements which the probability of failures values is defined below as:

- Potential Causes (exposure): Heavy Storm = 1.0
- Control Measures 1(Control Measures): Weather Monitoring and Alert = 100%
- Control Measures 2(Control Measures): Population reallocation = 100%
- Loss of Control (susceptibility): Probability of heavy rain affects the Rio de Janeiro city =100%
- Recovery Measures (coping capacity): Emergency response = 100%
- Consequences: Deaths = at least 1

The figure 7 below shows the Bow Tie model for the heavy storm in Rio de Janeiro.

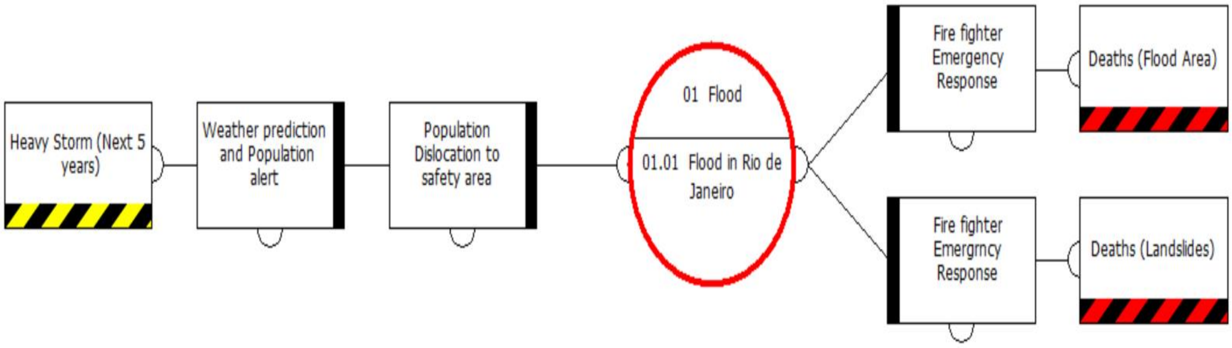



Figure 7: Heavy storm Vulnerability.

Vulnerability = ENHS x CM1 X CM2 X Co1x END

Where:
ENHS=expected number of heavy storms
CM1 = Probability of control measure 1 (weather prediction and alert) failure
CM2 = Probability of control measures 2 (Dislocation to safety area) failure
Co1=Probability of Copy capacity (Fire Fighters emergency response) failure
END=expected number of deaths

Vulnerability = 1,0 x 1 (100%) x1 (100%) x 1 (100%) x1= 1 death in the next three years

It´s important to understand why the control measures and the copy capacity has 100% of failure for the last 10 years. Concerning the weather prediction and alert, it has not been effective because the limited whether prediction technology in Rio de Janeiro state as well as the ineffectiveness of the population alert.
In case of heavy storm detection on time, it´s not possible to dislocate the population for a safe area because there´s no enough available are for the 1,5 million of people who lives in vulnerable areas in Favelas in the Rio de Janeiro state. The additional condition is that most of the population are afraid to leave their homes and after the natural disaster have no more permitted to return to their homes.
Regarding the copy capacity´s effectiveness, as we consider that only one death will bring the vulnerability level to an unacceptable level, despite the Rio de Janeiro fire fighters effectiveness during emergency response, they have not enough resource to avoid all deaths.
The expected number of deaths is very conservative when we look to the table 2 which show the lowest number of deaths (six) occurred on 01-03-1982. In this case that was done to show how vulnerable is the population based on the final vulnerability number. In other words, even considering the lowest possible number of deaths, the vulnerability is still unacceptable.

## 5. Conclusion

The vulnerability of heavy storms in Rio de Janeiro analysis faces 2 natural disasters for the next three years. In order to reduce such vulnerability and bring this number of acceptable level, which means Moderate class, it´s necessary that the population be dislocated to a safe area in Rio de Janeiro city as well as the emergency plan effectiveness improves to be able to set up the alarm in risk areas in case of heavy rains and dislocate as much as possible the remain population to a safe place. In this direction, it´s necessary in a short time frame to develop a National Disaster Emergency Plan, which enable to coordinate resources to the affected area as much as possible and involve government authorities and local companies which would supply resources during this natural disaster. In long time period, it's necessary to dislocate the whole population in a safe area. That is the most effective action to reduce the vulnerability. Nevertheless, that involves investment to build new popular houses in safe areas of Rio de Janeiro with all necessary infrastructure for the population. As much as such population is dislocate to safe areas lower will be the vulnerability of the population to heavy storms.

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