Critical Flood Risk Assessment, Priority Classification and Vulnerability Assessment Guidelines for PR Wastewater Treatment Plants

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Abstract — *Floods occurs in almost every part of the world because of extreme rainfall events. Around 7,000 people lose their lives and nearly 100 million people worldwide are adversely affected by floods each year. Flooding also cost billions of dollars each year in damages and repairments. Puerto Rico is not exempt to this problem. In this project, a risk assessment priority matrix was created to classify each wastewater treatment plants in Puerto Rico. The classification and prioritization of the plants will allow the owner to identify those with highest risks and perform specific vulnerability assessment. General guidelines for the specific vulnerability assessment were provided. The results of this project showed that 57% of the wastewater treatment plants are at high risk of flood damage.*

Key Terms — *Flood Assessment, Flood Resilience, Risk Assessment, Vulnerability*

INTRODUCTION

Flooding is a problem that affects many areas in Puerto Rico. These critical events have caused serious damages to private and public property, as well as agriculture and infrastructure, in addition to causing loss of life [1]. This problem also affects critical facilities that have an essential function in Puerto Rico. The Puerto Rico Aqueduct and Sewer Authority (PRASA) owns and operate 51 Wastewater Treatment Plants (WWTPs) that use primary, secondary, and advanced processes to treat an average monthly flow of 298.73 million of gallons of wastewater per day. WWTP's are essential facilities that protect the environment and, therefore, the public health. Many of these facilities are located near water bodies, either rivers or coasts, since must discharge their effluents to these bodies. The location of WWTPs creates a challenge to PRASA since makes them susceptible to flooding and storm surge events. This issue become more relevant due to climate change.

This project presents a risk assessment using a matrix with the purpose of establishing a critical floods priority value and risk classification to each WWTP. The elements used in the risk matrix were the Federal Emergency Management Agency (FEMA) flood zones, the discharge facility classification, and the categorization of the receiving waterbody according to the designated uses to be protected. A facility level vulnerability assessment guideline was also presented. San German WWTP was used as example since it was obtained the highest priority number in the west region of PRASA.

The results of this project provided an insight and roadmap to PRASA to make concerted efforts in those WWTP's with highest risk classification and to conduct a facility level vulnerability assessment. This project provided the basis to setting a Flood Risk Asset Database and a subsequent resilient mitigation flood plan.

LITERATURE REVIEW

A risk is a random event that may possibly occur and, if it did occur, would have a negative impact on the goals of the organization. Thus, a risk is composed of three elements: the scenario; its probability of occurrence; and the size of its impact if it did occur, either a fixed value or a distribution [2]. Risk analysis refers to techniques for identifying, characterizing, and evaluating hazards. The identification of risk, defined in Equation 1, and risk analysis found their way into many applications where they can add value in prioritization and management processes [3].

$$Risk = Probability\ x\ Consequences \qquad (1)$$

Risk analysis methodology is widely used in different professional disciplines. It is increasingly used in environmental and ecological issues. For the purposes of this project, a risk matrix method was developed and adapted to prioritize and classify the flood risks of multiple public facilities. Flood Risk is defined by the European Flood Directive as the combination of probabilities of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event [4].

Risk Matrix Method

Risk matrices provide a framework for an explicit examination of the frequency and consequences of hazards. The method may be used to rank the hazards of significance, screen out insignificant ones, or evaluate the need for risk reduction of each hazard. A risk matrix separates the dimensions of probability (POF) and consequence (COF) into typically three to six categories (A to E in Figure 1). There is little standardization in matters such as the size of the matrix or the labeling of the axes.

Risk matrices may use quantitative definitions of the frequency and consequence categories or some numerical indices of frequency and consequence (e.g., one to five) before adding the frequency and consequence pairs to rank the risks of each hazard or each box on the risk matrix. The strengths of the risk matrix approach are [5]:

- It is easy to apply and requires few special skills, and for this reason it is attractive to many project teams.
- It allows a consistent treatment of risks to people, property, environment, and business.
- It allows hazards to be ranked in order of priority for risk reduction effort.

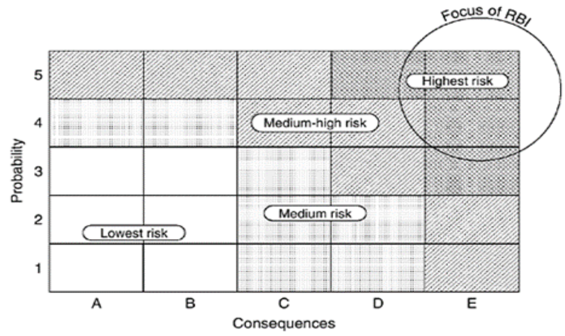

Figure 1

Example of Five per Five Matrix

Risk matrices have been widely praised and adopted as simple, effective approaches to risk management. This methodology provides a clear framework for the systematic review of individual risks. Also, can be applied to portfolios of risks. Provides convenient documentation for the rationale of risk ranking and priority setting. It is simple to use with attractively colored grids. Stakeholders can participate customizing category definitions and action levels. This collaboration offers an added value in educating on the concept of "risk culture" at different levels of detail, from simply positioning different hazards within a predefined matrix to helping thought leaders try to define risk categories and express preference for " risk appetite "-coding of cells. As many risk matrix practitioners and advocates have pointed out, constructing, using, and socializing risk matrices within and organization requires no special expertise in quantitative risk assessment methods or data analysis. Yet despite these advantages and their wide acceptance and use, there has been truly little rigorous empirical or theoretical study of how well risk matrices succeed in leading to improve risk management decisions [6].

METHODOLOGY

This project presents a risk analysis to establish a flood risk priority and classification system for active WWTP's, based on their exposure to the FEMA flood zones, the classification of facilities, and receiving waterbodies.

The first step in conducting this analysis was the data collection from each WWTP's. The information was obtained from three main sources: (1) Geographic Information Systems of the Puerto Rico Planning Board; (2) PRASA's Geographic Information Systems; and (3) National Pollutant Discharge Elimination System (NPEDS). These sources provided the information about the location, description, operation, and FEMA flood zones for each WWTP.

Risk Assessment Priority Matrix

A risk assessment priority matrix (RAPM) was created with the most relevant information. The RAPM consists of an arrangement of rows and columns, which allow the weighting of selected key elements. The key elements used in the matrix columns were the FEMA flood zones with their percentage coverage and the impact of the floodway on the WWTP property. The elements used in the rows of the matrix were the classification of the facility (major or minor) in combination with the classification of the receiving waterbody (SA, SB, SC, or SD). This matrix was organized in such a way that the upper left corner is the area with the highest risk, while the bottom right corner is the area with the lowest risk. In other words, the lower the priority value or the higher the risk; in the other hand, the higher priority value, or the lower risk.

Risk Columns Arrangement

FEMA flood zones were placed in columns, from left to right in the matrix, from highest risk to lowest risk of flooding. Each zone was divided into two parts. The first one is the flood zone covering between 50% and 100% of the property. The second one is the flood zone covering less than 50% of the property. It was also included as a weight factor for each zone whether the floodway affects the property. If the floodway affects the property or part of it, it is a more critical situation within the same flood zone. A risk factor was assigned to each of these columns. Table 1 presents a brief description of each FEMA flood zone used in this analysis.

Table 1

FEMA Flood Zones Definition

Zone	Description	Flood Risk
A	Special Flood Hazard Area, within 100 yr. floodplain, BFE not determined by FEMA.	High
AE	Special Flood Hazard Area, within 100 yr. floodplain, Detailed study by FEMA, BFE determined by FEMA.	High
VE	Coastal areas with a 1% or greater chance of flooding and an additional hazard associated with storm waves.	High
X (0.2 ACF)	Areas not in a Special Flood Hazard Area, within the 500 yr. floodplain.	Low
X	Areas not in a Special Flood Hazard Area, outside the 500 yr. floodplain.	Low

Matrix Rows Arrangement

The rows were organized according to the classification of the facilities and the categorization of the receiving waterbodies. Each facility is classified according to the Environmental Protection Agency (EPA) rating criteria. Facilities classified as major discharges include those with design flows greater than one million gallons per day (MGD) and facilities with approved industrial pretreatment programs. Facilities with design flows less than 1 MGD are classified as minor discharge facilities. This facility classification criteria were combined with the categorization of the receiving waterbody where the facility discharges it effluent. There are various classifications, but the most common are

SA, SB, SC, and SD. Table 2 shows a brief description of each classification according to the Puerto Rico Water Quality Standards Regulations of the Department of Natural and Environmental Resources (DNER).

The combination of both elements was used in the matrix to weigh the consequences or the severity if a disruption in the water treatment occur due to a critical flood event. Disruption in a major facility discharging into receiving waterbody class SA would have greater environmental effects than a minor facility with an effluent to a receiving waterbody class SD. Following this judgment, a severity factor was assigned according to the combination of both elements.

Table 2

Classification of the Waters of Puerto Rico According to the Designated Uses to be Protected

Class	Description
SA	Bioluminescent lagoons and bays and any other coastal or estuarine waters of exceptional quality or high ecological or recreational value.
SB	Coastal waters to be used for activities where the human body will be in direct contact with the water; and for propagation and maintenance of desirable species
SC	Coastal waters to be used for activities where the human body will be in indirect contact with the water; and for propagation and maintenance of desirable species.
SD	Surface waters to be used as a source for water supply and for propagation and maintenance of desirable species

RISK ASSESSMENTY PRIORITY MATRIX

RISK FACTOR			**1**	**2**	**3**	**4**	**8**	**12**	**13**	**16**	**20**	**40**	**60**	**70**	**100**	**200**	**210**	**215**
Category		FEMA Flood Zone	A - AE (50% - 100%)		A - AE (>0% - 50%)		VE (50% - 100%)		VE (>0% - 50%)		X 0.2 ACF (50%-		X 0.2 ACF (>0%-50%)		X (50% - 100%)		X (>0% - 50%)	
		Floodway	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No
SEVERITY FACTOR Facility Classification / Water Classification	**1**	**Major / SA**	1	2	3	4	8	12	13	16	20	40	60	70	100	200	210	215
	1	**Major / SB**	1	2	3	4	8	12	13	16	20	40	60	70	100	200	210	215
	2	**Major / SC**	2	4	6	8	16	24	26	32	40	80	120	140	200	400	420	430
	3	**Major / SD**	3	6	9	12	24	36	39	48	60	120	180	210	300	600	630	645
	4	**Minor / SA**	4	8	12	16	32	48	52	64	80	160	240	280	400	800	840	860
	5	**Minor / SB**	5	10	15	20	40	60	65	80	100	200	300	350	500	1000	1050	1075
	6	**Minor / SC**	6	12	18	24	48	72	78	96	120	240	360	420	600	1200	1260	1290
	6	**Minor / SD**	6	12	18	24	48	72	78	96	120	240	360	420	600	1200	1260	1290

Legend Very High High Medium Low Very Low

Figure 2

Risk Assessment Priority Matrix

Priority Value and Risk Classification

A risk factor (columns) and a severity factor (rows) were assigned to each WWTP according to the factors previously explained. In facilities where there are several flood zones, the lowest risk factor was used since is the most critical. The multiplication of these two factors (Equation 1) provide the priority value of each WWTP. A risk index was settled to provide a ranking for priority values. This Ranking Risk Index is presented in the Table 3.

Table 3

Ranking Risk Index

Priority Value	Risk / Vulnerability Classification
0 – 7	Very High Priority
8 – 16	High Priority
17 – 69	Medium Priority
70 – 209	Low Priority
210 o more	Very Low Priority

Results and Discussion

The objective of this project was to perform a risk analysis using a matrix to establish priority values and risk classification for each WWTP in Puerto Rico. Key results were obtained that can be useful for PRASA. 29 of the 51 active WWTP, or 57%, are at high risk of flood damage. Figure 3 shows the distribution of risk classifications island wide. The priority values ranged from 2 and 112. Priority values equal to 1 or greater than 112 were not obtained. This is because there was no combination of flood zones, facility classification, and receiving water-body classification that produced these values. For example, there are no WWTP discharging to receiving waters classified as SA (bioluminescent lagoons and bays). For this reason, there are no priority values equal to 1. Similarly, there are few plants with less than 50% in flood zones X that produce priority values greater than 112. The south region has the higher number of WWTP with high risk classification. Figure 4 shows the risk classifications by operational regions.

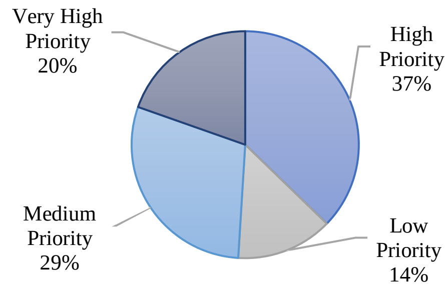

Figure 3

Risk Classification Results

The results of this project validated the assumption of the vulnerability to critical floods due to their proximity to water bodies. Flooding in WWTP's could produce disruption in water treatment, causing damage to the structures, mechanical and electrical equipment, among others. Possible damage to wastewater infrastructure would lead to environmental impacts on surrounding waters and therefore, on the public health.

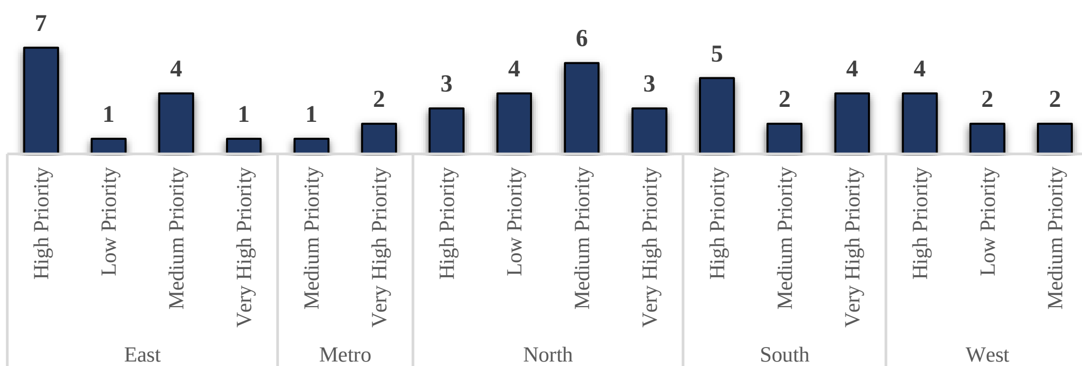

Figure 4

WWTP's Risk Classification by PRASA Operational Regions

Once established the priority and risk classification for each WWTP, a specific vulnerability assessment should be performed. Figure 5 shown a suggested approach for a specific vulnerability assessment. This vulnerability assessment must identify vulnerable assets according to the wastewater plant flood condition, identify consequences in the event of failure of these assets, and evaluation of resilient countermeasures as well as adaptation strategies considering the effects of climate change. Possible resilient countermeasures or adaptation strategies should include:

- Elevation of equipment above the critical flood elevation.
- Making pumps submersible.
- Enclosing electrical equipment in watertight casings.
- Construction of static barrier.
- Sealing structures with watertight windows and doors.
- Temporary sandbagging.
- Provide backup power generation.

These countermeasures and strategies aim to protect vulnerable assets and reduce the time to return to normal operation after a flood event. This project is an initial step in identifying the most vulnerable facilities and serves as starting point for conducting specific vulnerability assessment. The EPA published a Flood Resilience Basic Guide for Water and Wastewater Utilities that can be used for this purpose. It is recommended as first step the creation of a Flood Risk Asset Database that help PRASA for a subsequent development of a Comprehensive Flood Hazard Mitigation Program.

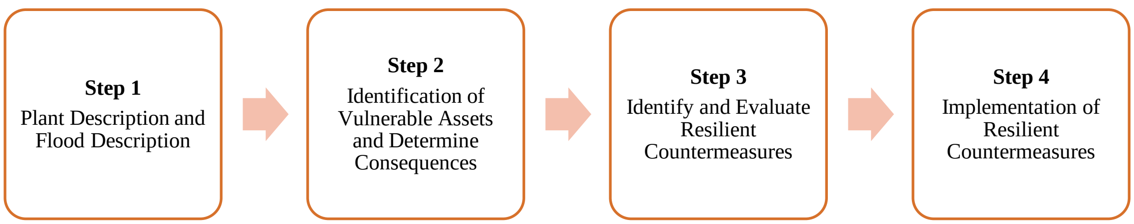

Figure 5

Approach to Specific Vulnerability Assessment [7]

Conclusion

This project applied a risk analysis technique using a matrix to create a priority value and a risk classification for each WWTP in Puerto Rico. The risk assessment priority matrix (RAPM) was created using the FEMA flood zones, facilities classification according to the EPA and classification of receiving waters according to DNER obtained from Geographic Information Systems (GIS) and NPDES. Table 4 shows a broad overview, grouped by risk classification and the priority values ordered from highest to lowest risk. The most susceptible WWTP's were identified and general guidelines for specific vulnerability assessments were recommended. The results indicated that 57% of the wastewater treatment plants are classified as high risk of critical floods. The calculated priority values allow to establish the order to perform the specific vulnerability analysis.

Recommendations

To better understand the implications of these results, it is recommended to start the specific vulnerability analysis of the WWTP's with very high-risk classification. This project was performed using wastewater facilities, but this analysis can be modified and applied to other types of infrastructure such as drinking water supply facilities or pump stations within PRASA. Likewise, it can be applied to critical infrastructure in the island such as hospitals, schools, police, and firefighters' stations, among others.

Future Research

Further research is needed to include other factors such as coastal erosion and sea level rise for those plants located on the coasts.

Table 4

Results of WWTP's Risk Classification and Priority Numbers

Very High Risk / Priority Value		**High Risk / Priority Value**		**Medium Risk / Priority Value**		**Low Risk / Priority Value**	
Dorado WWTP	2	Guayanilla WWTP	8	San Sebastián WWTP (Old)	24	Orocovis WWTP	112
Guánica WWTP	2	Toa Alta WWTP	8	Aguas Buenas WWTP	24	Barranquitas WWTP (New)	112
Carolina WWTP	3	Peñuelas WWTP	8	Naranjito WWTP	24	Culebra WWTP	112
Ciales WWTP	4	Patillas WWTP	8	Vieques WWTP	28	Las Marías WWTP	112
San Lorenzo WWTP	4	Yabucoa WWTP	8	Isabela WWTP	28	Maricao WWTP	112
Yauco WWTP	4	San Germán WWTP	8	Adjuntas WWTP	32	Unibon WWTP	112
Guayama WWTP	6	Comerío WWTP	8	Parcelas Borinquen WWTP	32	Alturas De Orocovis WWTP	112
Arecibo WWTP	6	Humacao WWTP	9	Jayuya WWTP (New)	32		
Puerto Nuevo WWTP	6	Ponce WWTP	9	Bayamón WWTP	36		
Santa Isabel WWTP	6	Barceloneta WWTP	9	Camuy WWTP	42		
		Fajardo WWTP	12	Cayey WWTP	56		
		Maunabo WWTP	12	Corozal WWTP	56		
		Aguadilla WWTP	12	Lajas WWTP	56		
		Mayagüez WWTP	12	Lares WWTP (New)	56		
		Rio Grande Estates WWTP	16	Morovis WWTP	56		
		Aibonito WWTP	16				
		San Sebastián WWTP (New)	16				
		Utuado WWTP	16				
		Caguas WWTP	16				

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