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DEVELOPING A LOCALIZED OPTIMAL FLOOD BARRIER IN THE PHILIPPINES

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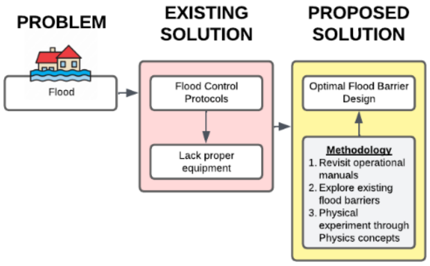

Abstract

In the Philippines, flood is a usual experience due to its geographical location near the equator. This calls for governmental units to establish flood control protocols that utilize equipment to effectively mitigate the impact of the floods. However, the existing protocols lack proper equipment integrated in their flood protocols that effectively handle flood occurrences. This research aims to improvise the current practices of the Philippine local government units in combating flood by proposing the optimal flood barrier design to be deployed for flood control and damage mitigation and investigate the optimal flood barrier for deployment. The methodology involves revisiting operational manuals of the target community of the Philippine governmental units and exploring existing flood barrier designs in literature and the market, whether in or out of the Philippines. Barriers designed in the literature and market were investigated, where there is a physical experiment conducted for the optimal design using physics concepts and past tests performed by studies. Results demonstrated the amount of force that can be resisted by the barriers, the amount of flood water until it floats, and the maximum velocity until barriers move. This is the first study to investigate the designs of flood barriers that are suitable for deployment and selects the optimal barrier for flood control for the Philippine setting while integrating it to the Philippine flood protocols. This research will be valuable to studies in regards with flood emergency disaster management planning.

Keywords: flood, flood disaster management, flood barrier, flood response, risk mitigation

1.0 INTRODUCTION

The Philippines is an archipelago that is near the equator, where the country experiences wet and dry seasons dictated by the monsoon winds (i.e. Southwest and Northern Monsoon). The country is also known to be flood-prone due to having an average of 20 tropical cyclones experienced by the Philippine Area of Responsibility yearly, where 8 out of 9 make a landfall (Department of Science and Technology, 2023).

The flood control protocols being implemented by local government units (LGUs) consists of four (4) main phases, which are preparedness, mitigation, response, and recovery (NDRRMC, n.d.). Most of the protocols are placed under the preparedness phase since it is important to be prepared for flood occurrences to mitigate its effects to the community. In partnership with Red Cross PH, the government has a funding initiative for anticipatory action, where a minimum of 5% of national and local budgets are allocated for risk management for disaster risk reduction and management (How local governments allocated funding for anticipatory action in the Philippines [Case Study], 2021).

Although existing protocols are being practiced in LGUs, there is still a problem on efficiency and level of impact on handling flood occurrences to mitigate their risks and impacts. There is a lack of designed equipment to aid in during-flood operations that is suitable in the Philippine setting and integrating it into the current systems. This study aims to introduce a more efficient equipment during-flood operations through an optimal flood barrier design for operational usage during flood protocols in the Philippines.

2.0 LITERATURE REVIEW

Flood barriers can be classified into three categories: (1) demountable, (2) permanent, and (3) temporary (Gupta et. al., 2020). Demountable barriers are structures in which a part of its design is permanently fixed on site, with another part that is also a movable structure to be socketed during flood. Meanwhile, permanent barriers are location-dependent protection structures that do not require any additional operation to put up the protection system. On the other hand, temporary barriers are location-independent structures, since these are removable and are solely installed during an event in which flood occurs. Further distinctions of flood barriers are described by Massolle et. al. (2018) as shown in Figure 2 below.

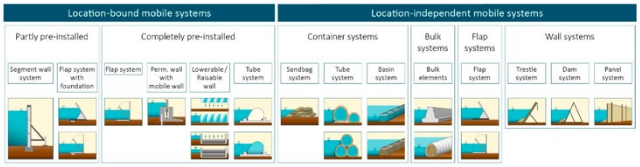

Figure 1 Categorization of Mobile Flood Protection Systems by Massolle et. al. (2018)

Among the protection systems, sandbags are often used to strengthen defense and prevent the flow of flood. Although the technical reliability of the sandbag system is acceptable, sandbag deployment largely depends on the human actors, proving a large disadvantage for placement time (Lendering et. al., 2014). With that, other alternatives can be used instead to shorten time of deployment with less difficulty involved. To combat storm surge near coastal areas, location-bound dike systems are deployed with increased height and strength (Marijnissen et. al., 2021). Meanwhile, others use large scale flap and wall systems such as the MOSE project in Venice (Cavallaro et. al., 2017) and movable barrier in Houston-Galveston Bay area and Saint Petersburg (Walraven et. al., 2022). Small scale pre-installed wall systems are also used to combat general high flood events. This includes the self-closing flood barriers often with the goal to safeguard an establishment (Mugesh et. al., 2015). Nevertheless, such protection systems may be expensive to implement on a wide scale.

Researchers in the academe have investigated designs to lower the cost of flood barriers. Marissen et. al. (2013) designed a flexible membrane barrier made of UHMWPE fibers and floating cables. The design of the barrier is such that the bottom part connects to a foundation, and the top part connects to floating cables. In case when a flood happens, the floater will rise due to buoyancy forces which form the shield against the flood. Guo et. al. (2022) designed an air-inflated rubber dam deployed at subway entrances. The rubber dam is made of a waterproof membrane with its end anchored on a vertical side of the wall. The inflation of the dam is to be performed by an operator in case of floods. Ianakiev & Greenwood (2013) designed a self-erecting low-cost (SELOC) flood barrier utilizing geosynthetic membrane. The SELOC barrier is designed where it has a cover and is restrained by a tie, connected to the membrane. Its design has an opening near the cover, also the wall, where it permits the water to flow in and use buoyancy to raise the wall.

There are also several types of barriers designed and sold in the market for pedestrian use. These include NoFloods inflatable barrier, Aquobex floodgate, Quick Dam bags, Water-Gate movable dam, FloodBlock, and Noaq boxwall. The difference between NoFloods inflatable barrier (NoFloods by Environment Solutions, 2023) and the designs made by researchers of academe is that this barrier is not specifically bound to a location. It can also extend to more than 1,000 meters through its junction functionality. On the other hand, the flood gate designed by Aquobex is intended for residential use (Aquobex, 2019). It is slipped in front of doors to obstruct the flow of water, mitigating the damage inside residential houses. Quick Dam bags function similarly to sandbags, except these are lightweight (until water absorption) and reusable (Paul, 2023). Water-Gate movable dam functions the same like the membrane barriers designed in the literature, however, these are movable roll-out barriers (Flood Protection Solutions, 2023). Both FloodBlock and Noaq boxwall utilize the same feature of using flood waters to stabilize itself. The main difference is that FloodBlock is a LEGO-like designed block with a hole that allows water going in (FloodBlock, n.d.), while Noaq boxwall is a thin freestanding barrier with a lengthened base for water to press the barrier down (Noaq, 2021). Aside from the inflatable and membrane designs, most barriers in the market have restrictions on the surface or surroundings. In essence, the goal of this study is to investigate available barrier designs made by researchers and available in the market to design a location-independent barrier that can be utilized by the LGUs during flood operations.

To simulate the effectiveness of barriers and designs, simulations and test facility setup were conducted by several researchers. Rappazzo and Aronica (2016) used a 2D hydrodynamic model to replicate Barcelona's "dry poofing" measures for floods. Results proved that flood barriers can mitigate the risks that come along with flooding. Šooš et. al. (2016) used a parametric simulation model to examine the most suitable shape of the barrier made from plastic. A triangular convention was utilized. Massolle et. al. (2018) set up a testing facility and evaluated the functional capability of existing sandbag replacement systems using life size models. Sandbag replacement systems all worked better than sandbag barriers. Srb et. al. (2017) conducted numerical analysis through Abaqus software, simulating the deformation of the barrier designed. They were more focused on the replicability of the real-life experiment on the Abaqus software by Coupled Eulerina Lagrangian (CEL). Guo et. al. (2022) performed both laboratory and simulation tests, using FLAC2D, investigating air pressure of inflation and anchor head of its inflated barrier design. Results indicate the air pressure has no evident output on the height of the barrier, however, it impacts the flood-fighting mechanism.

3.0 METHODOLOGY

The study is performed through topic selection, literature review, problem identification, flood barrier and experiment design, validation through experiments, analysis of results, and conclusion and recommendations. Figure 1 shows the flowchart of the methodology for the study.

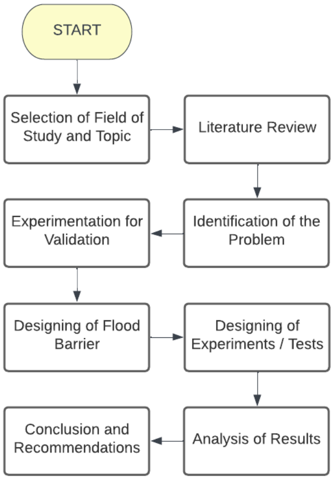

Figure 2 Methodology Flowchart

2.1. Designing of Flood Barrier

The operations for flood countermeasure are principally done by humans in the Philippines. In that regard, the designs for flood barriers took into consideration of human factors and ergonomics. Specifically, the configurations of the designs were made for them to be able to be deployed and used by even the 5th percentile of the Filipino female population, with hand fittings designed to be able to fit the 95th percentile of Filipino male population (Del Prado-Lu, 2012). By catering to the 5th percentile of the Filipino female population for the general design and the 95th percentile of the Filipino male population for the hand fittings, it will be able to accommodate majority of the population to use the product comfortably. The material to be used for the final design of the flood barrier was set to be recycled plastics as the strengths of recycled plastics have also already been proven (Lamba et. al., 2021). Additionally, this addresses the rising concern of plastic pollution in the bodies of water near the Philippines (Acot et. al., 2022). To design the flood barrier for adoption, multiple sources of inspiration for the design were considered. There are a total of four (4) designs made in this study, all of which have different sources of inspiration, where the aspect ratio of the dimensions of the designs are based on the inspirational designs for better comparison and reference.

Design 1 as shown in Figure 3 was inspired by the general structure of the rigid traffic barriers. Rigid traffic barriers are often made of concrete and are designed to dissipate the energy of impact through redirection of the angled lower base. In the case where water comes into contact with rigid traffic barriers, the water molecules are redirected upwards (run-up mechanism) which separate from the mixture and return to the flow, dissipating some of its energy (Fang et. al., 2022). Design 1 uses the standard configuration of rigid traffic barriers. Ribs are added to the design to increase the wall strength without increasing the thickness. The design also includes a flap that covers its entire structure and extends a little more on the lower base to place the structure on an even surface with the flap covering the uneven surface.

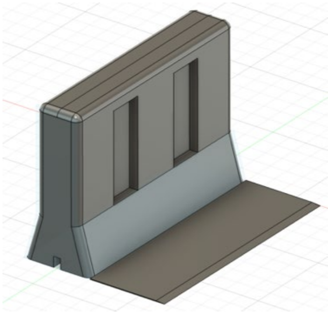

Figure 3 Flood Barrier Design 1

Design 2 as shown in Figure 4 was based on the design of the Noaq boxwall (Noaq, 2021). The design was modified by putting in place an angled lower base, decreasing ribs, increasing thickness, and changing the interlocking mechanism. The angled lower base was put in place to dissipate the energy during the flow of impact, like the rigid barrier. Curved base was used to further reduce the energy. With the increase of overall thickness, less ribs were designed. To guarantee the strength of the barrier, the height of the ribs was also increased. As the overall thickness of the barrier increased, the interlocking method was also altered, utilizing the thickness.

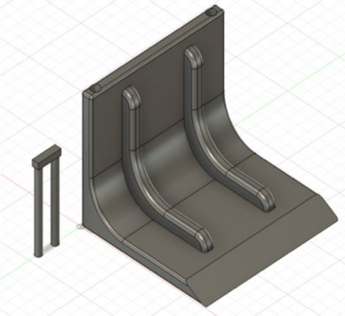

Figure 4 Flood Barrier Design 2

Design 3 as shown in Figure 5 was motivated by the design of the Water-Gate (Flood Protection Solutions, 2023). Nevertheless, the damming capacity, in terms of height, is inadequate in the Philippine context. With that, the height was extended by adding an extra wall. Figure 4 shows the third barrier design. As opposed to the Noaq boxwall with ribs, this design uses its Z-shaped structure to provide further stability much like the application of sign plate stands. This design, with less complexity on its injection molding process, is more cost-friendly in terms of production for wide pedestrian use.

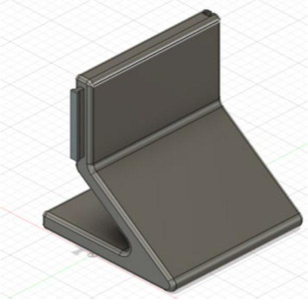

Figure 5 Flood Barrier Design 3

Design 4 as shown in Figure 6 was elicited from FloodBlock (n.d.) and Šooš et. al. (2016), where triangular configuration proved to be more stable. This design is also like the rigid flood barrier in design 1, with the interlocking mechanism and design look like LEGO blocks. The tradeoff of this design is that the curves and interlocking means add more complexity for production, which increases the cost.

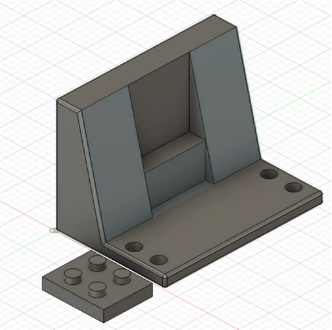

Figure 6 Flood Barrier Design 4

Prototyping is a valuable method in the design process, as it enables designers to evaluate their concepts in a tangible, realistic setting. This is particularly significant in the case of flood barriers, as it allows designers to assess the feasibility and effectiveness of their designs in a real-world context. By constructing a prototype at a reduced scale, designers can experiment with various designs and materials without incurring the substantial costs and time associated with building a full-scale barrier. This enables them to refine their design and make necessary modifications to ensure that the barrier is effective at preventing flooding. Furthermore, testing a prototype at a reduced scale allows designers to identify and possibly resolve any potential issues with the barrier at a smaller scale before it is constructed at full scale. This would allow the construction of a larger scale model to have reduced design issues and reduce potential additional costs.

A ⅛ scale prototype was 3D printed using ABS filament (Khabia & Jain, 2020), which is known for its strong mechanical properties. Each design was printed twice to observe the interlocking mechanism and observe the point of connection between two (2) barriers.

2.2. Designing of the Experiments/Tests

Each prototype will be evaluated to determine which design provides the most favorable results. The experiment aims to determine the maximum velocity each design can resist and to identify the maximum height of water it can take before overtopping. According to Kreibich et al. (2009), flow velocity serves as a significant influence on structural damage and that forecasts on structural damage should be based on this alone. If the chosen barrier can resist a high maximum velocity, then this can help mitigate the effects of flooding on infrastructure.

To calculate the velocity, the volumetric flow rate (mL/s) was first determined. This was performed by calculating the amount of time (seconds) it takes to fill up 500 mL of container at different intervals. A garden hose with a pressurized nozzle was used for this experiment. The garden hose was set at different strengths to determine the intervals for the volumetric flow rate. This serves as a limitation of the study as the water hose cannot be set to a specific flow rate to achieve definite flow rate intervals. The flow rate was then converted to the flow velocity using the formula in Eq. (1) taken from Environmental Protection Agency (n.d.).

$$\text{Volumetric Flow Rate}_{\text{pipe}} = A \times v \qquad (1)$$

Where, A = area of pipe (πr^2) and v = velocity of water (m/s)

Afterwards, the four prototypes were subjected to each flow velocity to observe at which velocity the barriers will start to move. To determine the maximum height each prototype can take before floating away, another experiment was conducted. This experiment involves creating a boxed container that is open on one end where the barrier will be placed, as shown in Figure 7. This container was made from recycled materials and has the dimension of 32.5 cm L x 24 cm W.

Figure 7 Boxed Container for Experimentation

After securing the barrier in place, a measuring tape was placed on the side of the inner wall to serve as a guide on the water height. The water is then poured into the container slowly, and the height when the barrier breaks free from the container is noted.

The maximum height the barrier can reach was determined to identify the hydrostatic force each barrier can handle. Hydrostatic force is the force exerted by a fluid at rest on an object. In the case of flood barriers, it is important to understand the hydrostatic force that water will exert on the barrier to design a barrier that can withstand the force of the water and prevent flooding. This is important in areas where flooding is a common occurrence, as the barrier needs to be strong to protect against the potentially damaging effects of flooding. The formula for hydrostatic force is shown in Eq. (2) taken from Klipalo et al. (2022):

$$F = pA \qquad (2)$$

Where F is the hydrostatic force, p is the pressure of the fluid, and A is the area on which the pressure is exerted.

The pressure of a fluid at a given point is determined by the depth of the fluid at that point, the density of the fluid, and the acceleration due to gravity. The formula for pressure is shown in Eq. (3) taken from Gupta et al. (2020):

$$P = \rho g h \qquad (3)$$

Where h is the depth of the fluid, ρ is the density of the fluid, and g is the acceleration due to gravity. Therefore, the hydrostatic force formula can be rewritten as:

$$F = (\rho g h)A \quad (4)$$

3.0 RESULTS AND DISCUSSION

3.1. Flood Barrier Design

Figures 8, 9, 10, and 11 present the prototype of the four (4) different flood barrier designs. They were printed in ⅛ scale using ABS filament.

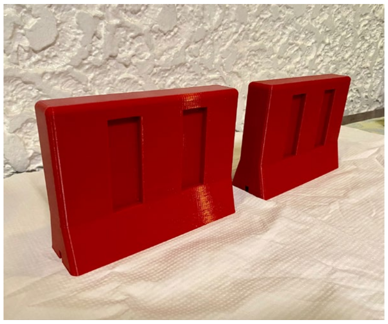
Figure 8 Flood Barrier Design 1 in 1/8 Scale Prototype


Figure 9 Flood Barrier Design 2 in 1/8 Scale Prototype


Figure 10 Flood Barrier Design 3 in 1/8 Scale Prototype

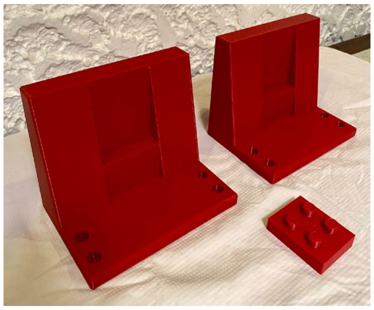
Figure 11 Flood Barrier Design 4 in 1/8 Scale Prototype

The weight of each design was also determined to evaluate the portability of the barrier. Design 4 has the heaviest weight, which can be attributed to its triangular shape. This is followed by Design 2, which features a thicker barrier design and a higher rib structure. Design 1 follows the standard configuration of rigid traffic barriers, but with less thickness due to the added ribbing. The lightest design is Design 3, which uses a Z-shaped structure to provide stability while using minimal materials. In addition, the recommended dimensions are added, which are based on the inspired designs. These are shown on Table 1.

Table 1 Dimensions and Weight of Each Design

Design #	Design Comparison	Recommended Actual Dimension (length x width x height, cm)	Prototype Dimension (length x width x height, cm)	Weight , g
1	Flood Gate	480 x 30 x 324	60 x 3.75 x 40.5	181.57
2	Water Filled Flood Tube	762 long and 182 high	95.25 long and 22.75 high	261.17
3	Alteau Mobile Flood Barrier	1,005 x 143 x 500	125.63 x 17.88 x 62.5	150.50
4	NAOQ Boxwall	1,199 x 992 x 1,060	149.88 x 124 x 132.5	329.00

The results of the first experiment as found in Table 2 indicated that Design 3 was able to withstand velocities up to 1.98 m/s, while Designs 1 and 4 were able to handle velocities of up to 4.66 m/s. Design 2, on the other hand, did not topple over even when subjected to a velocity of 5.52 m/s. However, the maximum velocity that Design 2 can withstand could not be determined in this experiment due to the use of a garden hose, which is not capable of producing velocities greater than 5.52 m/s. This limitation of the study highlights the importance of using appropriate equipment to accurately assess the performance of the designs.

Table 2 Maximum Fluid Velocity for Each Design

Observed Fluid Velocity (m/s)	Design 1	Design 2	Design 3	Design 4
1.34	/	/	/	/
1.98	/	/	/	/
2.91	/	/	X	/
3.42	/	/	X	/
4.66	/	/	X	/
5.04	X	/	X	X
5.52	X	/	X	X

For the next experiment, the maximum height of water the barrier can handle before floating away was determined. Three repetitions of this experiment were performed with the averages shown in Table 3. It can be observed that Design 4 has the highest maximum water height, showing that it can withstand higher flood waters. The barrier with the lowest maximum water height was from Design 2.

Table 3 Maximum Water Height

Trial	Design 1	Design 2	Design 3	Design 4
1	4.00 cm	2.50 cm	3.00 cm	4.80 cm
2	3.98 cm	2.60 cm	2.50 cm	5.00 cm
3	3.77 cm	2.20 cm	2.60 cm	4.50 cm
Average	3.92 cm	2.43 cm	2.70 cm	4.77 cm

The average value derived from Table 3 was utilized to calculate the hydrostatic pressure and hydrostatic force for each barrier, which indicates the maximum force that each barrier can withstand when submerged in water. Consistent with the results discussed previously, Design 4 demonstrated the greatest ability to withstand hydrostatic force, while Design 2 exhibited the lowest capacity in this regard, based on Table 4..

Table 4 Hydrostatic Pressure and Force

	Design 1	Design 2	Design 3	Design 4
Hydrostatic Pressure (Pa)	101,709	101,563	101,590	101,776
Hydrostatic Force (N)	1,274.73	790.87	877.74	1,498.15

During the experiments, it was observed that there was water seeping through the gap between the two interlocking barriers. This was determined to be a normal occurrence due to the uneven surfaces of the barriers. Therefore, a smaller seepage rate is ideal. In this experiment, the length of time it took for 1L of water to seep through the barriers was measured to determine the seepage flow rate, where a smaller value indicates better performance.

Based on Table 5, the results showed that Design 4 exhibited the slowest seepage flow rate, indicating that it can hold water for a longer period. This was closely followed by Designs 1 and 3. The fastest seepage flow rate was observed in Design 2, where the tapered portion on the bottom of the design was found to easily float in the water, allowing water to pass through.

Table 5 Seepage Flow Rate

	Design 1	Design 2	Design 3	Design 4
Observed Time (s)	355	218	316	415
Flow Rate (mL/s)	2.54	4.59	2.93	2.29

Lastly, the water volume held within the test box of each design were compared to each other. This is an important metric to assess to see how effective the flood barrier is able to hold the water from seeping through when floodwaters are rising. This is due to the main purpose of barriers blocking of water from seeping through the main residential areas and even touch the communities, which is why the amount of water held indicates the amount of water blocked. This was computed with the test box length and width and the maximum water height from Table 3 for the volume to be acquired. It shows that Design 4 can hold the most water within the barrier, indicating less seepage during rising floodwaters. With this, it implies that Design 4 is most effective in blocking off water and performing its duty as a flood barrier. The water volume of each design is enumerated in Table 6.

Table 6 Comparison of Water Volume held in the Flood Barriers

	Design 1	Design 2	Design 3	Design 4
Water Volume (cm^3)	3,057.6	1,895.4	2,106	3,720.6

After conducting the experiments, it was determined that each design has its own advantages and disadvantages. Design 4 demonstrated better resistance to hydrostatic force and can withstand higher flood depths, but its heavy weight makes it less portable. It can handle a maximum fluid velocity of 4.66 m/s and has the smallest seepage flow rate. Design 3 has the lightest weight, making it more portable, but its low weight also limits its ability to handle fluid velocities of up to 1.98 m/s. In terms of its resistance to hydrostatic pressure, it scored the third lowest among the designs, indicating that it can only accommodate shallow depths before being floated away. It also ranked third in terms of seepage flow rate. Design 2 is the second heaviest design and can handle the highest velocity of 5.52 m/s. However, it showed the worst performance in terms of maximum water height, resistance to hydrostatic pressure, and water seepage. Moreover, Design 1 is the second lightest in terms of weight, and can withstand fluid velocities of up to 4.66 m/s. It also performed well in the other experiments, showing high resistance to hydrostatic force and the second lowest seepage rate. In terms of the water volume held, Design 4 shows to be the most effective in blocking off floodwaters.

Given that Design 4 inspired from the Noaq Boxwall is identified as the optimal flood barrier design amongst the designs, the dimension proposed for it is similar to that of the Noaq Boxwall. With this, the proposed dimensions based on length x width x height is 992 x 1,199 x 1,060 cm with an effective length of 90 cm (Aquasafe, n.d.).

3.2. Integration of the Optimal Flood Barrier to Philippine LGU Protocols

The optimal flood barrier selected based on the results is integrated into the current Philippine flood protocols. Based on literature review, the current Philippine Local Governmental Unit (LGU) flood protocol is compiled in Figure 12.

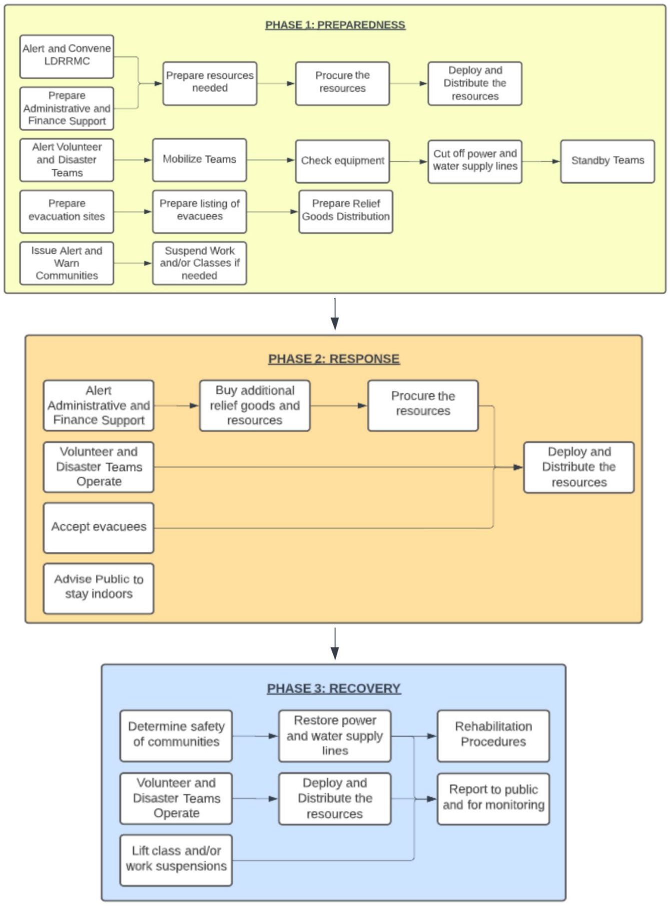

Figure 12 Compiled Flowchart of Existing LGU Protocol System

Based on the current LGU protocol system, this is analyzed to integrate the identified optimal flood barrier as the proposed LGU protocol system flowchart. A proposed LGU protocol system is developed, where the red boxes indicate added protocols. The added steps are for the checking and setting up of the flood barrier in strategic locations where flood occurs the most and in high impacts. The packing up of the flood barrier is also integrated into the flowchart in Figure 13.

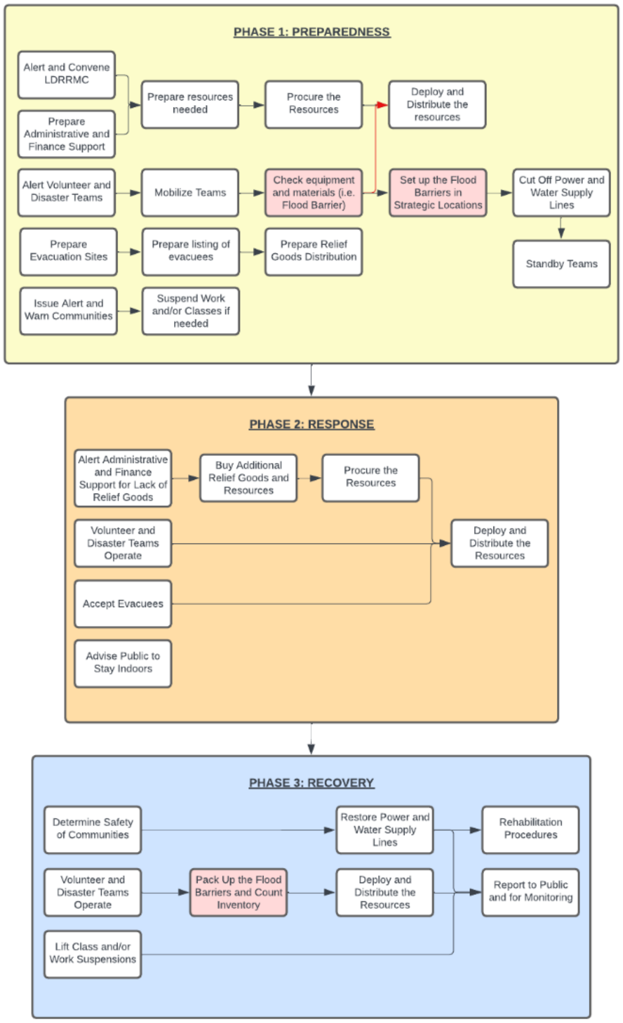

Figure 13 Compiled Flowchart of Proposed LGU Protocol System

4.0 CONCLUSION

During flooding catastrophes, it is essential for affected areas and individuals to be provided with adequate information and assistance across all stages from mitigation, preparation, response, and recovery to minimize property damage and casualty and maximize the resources. Along this line, this paper seeks to proposing an optimal flood barrier to be deployed for flood control and damage mitigation and investigating the optimal flood barrier for use. In addition, this is applied into the current Philippine LGU flood protocols that would integrate the optimal flood barrier for use. Aside from this insight, certain metrics for flood disaster management have also been demonstrated such as the amount of force that can be resisted by the barriers, amount of flood water until the barrier floats, and the duration of the barrier's capacity to hold up flood.

In terms of novelty, this paper is the first to lay out designs of flood barriers that are deemed suitable for deployment which also serves as optimal barriers for flood control. Future research includes quantitative support tools, approaches to measure the effectiveness and to verify its fitness for implementation, and determining an in-depth study on the strategic locations for the flood barrier placements.

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