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Flood Vulnerability Index for Critical Infrastructure Towards Flood Risk Management

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In the recent years, the impacts of floods have gained importance because of the increasing number of people who are affected by its adverse effects. Flood destroyed critical infrastructures that are needed as shelter and also emergency relief for victim. In order to provide a better understanding of flood risk management, a review of current practice in flood risk management and flood vulnerability index was carried out.

Keywords: Critical Infrastructure, Flood, Flood Vulnerability Index, Flood Risk Management, Vulnerability

I. INTRODUCTION

Flooding is the most costly hazard worldwide. It has catastrophic impacts on people, economy and environment. Over the last three decades, it was reported that the number of flood events have increased crucially around the world (Kourgialas *et al.*, 2011). Although flood events in certain low lying coast areas occur annually, the flood magnitudes are unpredictable. It is a big problem if the flood magnitude is bigger than expected, as it demolished houses due to rush of water flow. Hence, it causes loss of homes for population in the affected areas. In some cases, flood event of bigger than expected magnitude also engulfs large cultivation areas and wreck public services which makes the life of survivors difficult.

It was reported by Espon (2013) that flood event on 2007 had affected a disproportionate number of poorer people living in flood-prone areas in United Kingdom (UK). There were also deaths caused by flooding events reported in Romania and other Eastern European countries that occurred particularly in rural areas. This might due to the fact these areas have lack of flood control and sufficient defences against big magnitude flooding, thus causing damage to infrastructure in the areas.

Nevertheless, flood affect people, buildings and infrastructures everywhere even in urban area too such as the city of Santiago (Muller *et al.*, 2011). While in the rural areas have lack of flood control and defence, the flood hazard in

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urban area are caused by dramatic development process. Flood hazard increases as city development attracted rising number of population and infrastructure, even to the flood-prone areas.

The amount and sort of damage affected elements within these hazard zones suffer, are heterogeneous and unfortunately not recorded in any inventory. Therefore, the extent of damage depends on the vulnerability of the affected people and infrastructure. People rely on the safety and integrity of infrastructure on daily basis, moreover during natural disaster as shelter and emergency relief. Damage to the infrastructures would cause greater misery for the flood-affected population. A small increase in extreme events and climate variability can result in a great damage to infrastructure (Freeman *et al.*, 2001). Therefore, there is a need to decrease the flood vulnerability for infrastructure towards floods.

This paper presents the review of some flood vulnerability indices that have been used in the world towards the flood risk management. This paper also present the definition of risk terminology which helps to understand more about the risk and can helps in reducing it.

II. RISK TERMINOLOGY

Risk is defined as the expected losses of lives, persons injured, property damaged and disruption of economic activity due to certain hazard for a given area and reference period (Marfai *et al.*, 2002). Based on the risk triangle as shown in Figure 1 below, risk is the probability of a loss that depends on three elements; hazard, vulnerability and exposure (Crichton, 1999).

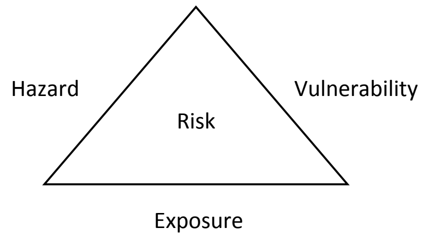

Figure 1: The Risk Triangle (Crichton, 1999)

If any one of these factors increases, the risk increases. As risk can be recognized as function of these three elements, understanding of major drivers for flood risk and reduction of flood risk can generally help in establishing flood vulnerability assessment.

Firstly, “hazard” refers to the probability of a particular flood event occurring while “exposure” is described as patterns and processes that estimate its intensity and duration (Balica *et al.*, 2012). Hazard can be understood by way of the values that present at the situation where floods can occur. Exposure is among the anthropogenic factors that contribute to flood risk and is usually represented by the population and properties located in risky zones (Barredo *et al.*, 2010). Lastly, the concept of “vulnerability” varies over the last 20 years and it is emphasized to be considered meaningful with reference to a specific vulnerable situation (Brooks, 2003; Hinkel *et al.*, 2007), which in this case is the flood event. Flood vulnerability can then be defined as the susceptibility of the exposed structures when in contact with water (Barredo *et al.*, 2010), the extent to which the subject matter could be affected by the hazard.

Balica *et al.* (2009) in defending against the risk such as flood, three factors played important role in increasing's vulnerability against the flood, which are exposure, susceptibility and resilience. Previously, Smit *et al.* (2006) had concluded that vulnerability of any scale is a function of the exposure and susceptibility of the system to hazardous conditions and the resilience of a system to recover from the effects of those conditions. Exposure can be described as the measure of susceptible elements within a region threatened by a hazard (Fekete, 2009) and defined as the estimated value of the infrastructure that are present in the areas potentially threatened by flooding (Remo *et al.*, 2016). Susceptibility is defined as the probability of the human population affected and associated building stock damages within the floodplain during a flood of a particular scale (Balica *et al.*, 2009). Susceptibility also can be defined as the extent to which elements at risk (Messner *et al.*, 2006) within the system are exposed, which influences the chance of being harmed at times of hazardous flood. Resilience can be explained by the ability of a system to preserve its basic roles and structures in a time of misery and disturbance.

III. FLOOD VULNERABILITY INDEX (FVI)

As discussed earlier, vulnerability is an essential component in assessing risk. Therefore, flood vulnerability is an important element in flood risk assessment and damage evaluation (Nasiri *et al.*, 2013) as vulnerability is understood as the origin cause of disaster. As the flood vulnerability in an area relies on some environmental, economic, social and even political factors is difficult to measure vulnerability. Many methods to assess flood vulnerability have been developed by researchers (Nahiduzzaman *et al.*, 2015).

Flood Vulnerability Index (FVI) enables the assessment of vulnerability to flood disaster at basin level (Connor, 2009) where is produces a relationship between the theoretical perceptions of flood vulnerability and the daily management process (Nasiri *et al.*, 2013). The vulnerability index determines which areas most exposed to flooding that should be considered in the future redevelopments.

FVI is an important tool for raising public awareness, guiding the international organizations in direction of involvement and assisting governments in priority setting. This is because there are several factors influencing vulnerability including human settlements conditions, infrastructure, authority's policy and abilities, social imbalances, economic patterns and more. Therefore, flood vulnerability index is different for people in different condition. This index can also be used in action plans in managing flood and can improve local decision-making practices with appropriate measures to reduce vulnerability in different spatial levels (Balica *et al*, 2012).

In assessing the total flood vulnerability index, it is essential to determine the vulnerability (exposure, susceptibility and resilience) relevant to the local study context first. The general formula for FVI is calculated by categorizing the indicators to the factors (Exposure (E), Susceptibility (S), and Resilience (R)) (Cendrero *et al.*, 1997). Indicators showing resilience are flood insurance, amount of investment, dikes and levees, storage capacities, etc. (Remo *et al.*, 2016).

$$FVI = (E*S)/R \quad (1)$$

Urban areas are compactly populated, which makes them vulnerable to flood impacts. The areas are vulnerable to flood because of the three important main factors (Exposure, Susceptibility and Resilience). Balica *et al.* (2012) stated that understanding each concept and considering certain indicators may air to characterize the vulnerability of different systems, by which actions can be identified to decrease it. Every vulnerability factor represents a set of constituent indicators based on the characteristics of a system, which can help to better understand the response of a city to flood. Development of FVI involves the understanding different relational situations and characteristics of a system exposed to flood risks, a logical approach to identify the best possible indicators has been used, based on existing principles and the conceptual framework of vulnerability. The vulnerability indicators in urban area that used in vulnerability index are tabulated in Table 1 below

Table 1: FVI system components (Balica, 2012)

Factors	Indicator Exposure	Acronym	Susceptibility	Acronym	Resilience	Acronym
Social	Population Density	P_D	Child Morality	C_M	Warming System	W_S
	Disable People	% disable			Evacuation on Roads	E_R
	Cultural Heritage	C_H			Emergency Services	E_S
	Population Growth	P_G			Shelters	S
					Past Experience	P_E
					Awareness & Preparedness	A_P
Economic	Closeness to River	C_R	Unemployment	U_M	Amount of Investment	Am_{Inv}
	Industries	I_{ND}	Urban Growth	U_G	Flood Insurance	F_I
	River Discharge	R_D	Human Development Index	H_{DI}	Dams Storage Capacity	D - SC
Environmental	Rainfall	$R_{ainfall}$				
	Evaporate Rate	E_V				
	Land Use	L_U				
	Contact with River	C_R			Storage over yearly runoff	S_c/V_{year}
	Topography	T			Dikes-Levees	D – L
	Evaporate Rate Rainfall	E_V				
Physical		$R_{ainfall}$				

By using the indicators above, flood vulnerability can be determined by Equation 2 to 5 based on different factors (Balica *et al.*, 2012).

$$FVI_{social} = \frac{P_D * C_H * P_G \% disables * C_M}{P_E * {}^{A}/_{P} * S * W_S * E_R * E_S} \quad (2)$$

$$FVI_{economic} = \frac{I_{ND} * C_R * U_M * U_G * H_{DI} * R_D}{F_I * Am_{Inv} * D - S_C * D} \quad (3)$$

$$FVI_{environment} = \frac{U_G * R_{ainfall}}{E_V * L_U} \quad (4)$$

$$FVI_{physical} = \frac{C_R * T}{{}^{E_V}/_{R_{ainfall}} * {}^{S_C}/_{V_{year}} * D - L} \quad (5)$$

Total FVI of each urban area (Equation 6) is average of FVI of four factors (Equation 2-5). The value obtained can be interpreted as shown in Table 2. The index gives value of 1 and below, by decrement of 0.25 for each flood vulnerability description, signifying low or high urban flood vulnerability and shows which urban areas need detailed investigation for selecting more effective measures. This shows that FVI provides a reliable source for wide overview of flood vulnerability to take appropriate strategies.

$$Total\ FVI = F\ \square_{Hydro-geological} + FVI_{Social} + FVI_{economic} + FVI_{politico-administrative} \quad (6)$$

Table 2: Flood vulnerability interpretation (Balica, 2012)

Index Value	Description
< 0.01	Very small vulnerable to floods
0.01 – 0.25	Small vulnerable to floods
0.25 – 0.50	Vulnerable to floods
0.50 – 0.75	High Vulnerable to floods
0.75 – 1.00	Very high vulnerable to floods

Balica *et al.* (2012) has developed a Coastal City Flood Vulnerability Index which is also based on exposure, susceptibility and resilience to coastal flooding. The index was applied to the nine cities around the world with each different kinds of exposure and the result indicated that this index was able to provide a means of gaining a general idea of flood vulnerability and the effect of possible adaption options.

The procedure for calculating the Coastal City Flood Vulnerability Index Starts by converting each identified indicator as shown in Table 3, 4 and 5 into a normalized (on scale from 0 to 1), dimensionless number using predefined minimum and maximum values from the spatial elements under consideration. By using generalized approach of FVI (refer Equation 1), it is acknowledged that each system has its own vulnerability to floods, so a variable cannot be considered as zero. The benchmark is to gather a list of proxies using the following criterion: suitability, definitions or the theoretical structure, availability of data, usefulness and ease of recollection.

Table 3: Indicators information of hydro-geological component

Indicators	Abb.	Factor	Unit	Definition	Functional Relationship with Vulnerability
Sea-level rise	SLR.	Exposure	mm/ year	How much the level of the sea is increasing in 1 year.	Higher SLR, higher vulnerability
Storm Surge	SS		cm	A storm surge is the rapid rise in the water level surface produced by onshore hurricane winds and falling barometric pressure.	Bigger increase in WL, higher vulnerability
# of cyclones	#Cyc		#	Number of cyclones in the last 10 years.	Higher # of cyclones, higher vulnerability
River Discharge	RD		m^3/s	Maximum discharge in record of the last 10 years m^3/s.	Higher RD, higher vulnerability
Foreshore Slope	FS		%	Foreshore slope and depth of the sea near the coast, can change a lot and often. Average lope of the foreshore beach.	Lower slope, higher vulnerability
Soil Subsidence	Soil		m^2	How much the area is decreasing?	Higher areas, higher vulnerability
Coastline	CL		km	Kilometers of coastline along the city.	Longer CL, higher vulnerability

Table 4: Indicators for the politico-administrative component

Indicators	Abb.	Factor	Unit	Definition	Functional relationship with vulnerability
Flood Hazard Maps	FRP	Susceptibility	-	Flood hazard mapping is a vital component for appropriate land use planning in flood-prone areas	Existence of those measures, low vulnerability
Institutional Organizations	IO	Resilience	#	Existence of IO	Higher #, lower vulnerability
Uncontrolled Planning Zone	UP	Exposure	%	% of the surrounding coastal area (10km from the shoreline) is uncontrolled	Higher %, higher vulnerability
Flood Protection	FP	Resilience	-	The existence of structural measures that physically prevent floods from entering into the city (storage capacity)	If yes, lower vulnerability

Table 5: Indicators information of socio-economic component

Indicators	Abb.	Factor	Unit	Definition	Functional relationship with vulnerability
Cultural heritage	CH	Exposure	#	Number of historical buildings, museums, etc., in danger when coastal flood occurs	Higher # of CH, higher vulnerability
Population close to coastline	PCL	Exposure	People	Number of people explosed to coastal hazard	Higher number of people, higher vulnerability
Growing coastal population	GCP	Exposure	%	% of growth of population in urban areas in the last 10 years	Fast GCP, higher vulnerability, hypothesis is made that fast population growth may create pressing on land subsidence
Shelters	S	Resilience	#	Number of shelters per km2, including hospitals	Bigger # of S, lower vulnerability
% of disabled ppersons (<12 and >65)	%Disabled	Susceptibility	%	% of population with any kind of disabilities, also people less 12 and more than 65 years	Higher %, higher vulnerability
Awareness and preparedne ss	A/P	Resilience		Are the coastal people aware and prepare for floods? Did they experience any floods in the last 10 years?	Higher amount of time, higher vulnerability
Recovery time	RT	Resilience	days	Amount of time needed by the city to recover to a functional operation after coastal flood events	Higher km, low vulnerability
km of drainage	Drain	Resilience	km	km of canalisation in the city	Higher km, low vulnerability

The Coastal City FVI of each coastal component (hydro-geological, social, economic and politico-administrative) where Equation 7 is expressed as Coastal FVI for hydro-geological component, Equation 8 and 9 for social and economic component and Equation 10 for politico-administrative component.

$$FVI_{Hydro-geological} = f\{SLR, SS, \#Cyc, FS, RD, Soil, CL\} \quad (7)$$

$$FVI_{Social} = f\,\frac{CH, PCL, \%Disable}{A/_{P}, S} \quad (8)$$

$$FVI_{economic} = f\,\frac{GCP}{RT, Drainage} \quad (9)$$

$$FVI_{politico-administrative} = f\,\frac{FHM, UP}{IO, FP} \quad (10)$$

Therefore, total Coastal City FVI can be determined by calculation as shown in Equation 11 below.

$$Total\ FVI = FVI_{Hydro-geological} + FVI_{Social} + FVI_{economic} + FVI_{politico-administrative} \quad (11)$$

The integrated Coast al City FVI is a method to combine multiple aspects of a system into one number. The results will be presented in values between 0 and 1where 1 being the highest vulnerability and 0 the lowest vulnerability. All data for the indicators must be derived from reliable sources in order not to ruin the accuracy of the data on which it is based. This approach allows for relative comparisons to be made between urban areas irrespective of uncertainties. Thus, proposed measures can be prioritised for urban areas that are at greatest risk. Uncertainty is not removed but is included into the assessment. While a level of uncertainty is included in CCFVI, its use in operational flood risk management is useful for policy and decision-makers in terms of prioritising investments and formulating adaptation plans. CCFVI is a flexible tool, it can be used to create different "scenarios" by changing one or more indicators and can be tailored on different situations and areas, since the principle "one size fits all" cannot be applied to vulnerabilities present in complex and dynamic realities (Balica, 2012).

These FVI has been included all the measures for 9 different coastal cities around the world but there are countries that are still developing and there are no research about FVI for rural area. The current practice of FVI has been applied on different river basins scale, sub-catchments scale and urban areas scale. Different indicators for different scales were taken into the account, which is the hydro-geological, social, economic and politico-administrative components. There are numerous studies which attempt to quantify the vulnerability into a more sensible form, however, to the investigators' knowledge, almost no study has been done so far to assess the vulnerability of critical infrastructures to flood by using FVI. Therefore, the FVI towards critical infrastructures can be formed by modifying approached made by Balica *et al.* (2009), which by modifying the physical components of the vulnerability indicator to be implemented on the existing critical infrastructures. It should be noted that determination of critical infrastructures in the area of interest is important in order to evaluate the damages to selected infrastructures and what type of flood proofing measures were taken to lower the effects of flooding.

IV. CRITICAL INFRASTRUCTURE

Infrastructure is the basic physical and organizational structures and facilities need for the operation of a society. This is the very reason why infrastructure plays important role

in the daily living people. However, most infrastructure is usually designed using codes and standards based on the historic climate data which is no longer adequate for climate loads experienced by the infrastructure today (Bowering *et al.*, 2013). In extreme climate event
such as flood, climate impact required adaptation of strategies, particularly in urban areas (Walsh *et al.*, 2011).

Critical infrastructures play an important role in functioning of industries and communities and also responding against natural disaster to reduce their impacts *(Oh et al.*, 2010). It can be defined as the infrastructural facilities that can provide essential or emergency services which includes hospital, emergency services, fire stations, police stations, and schools (Bowering *et al.*, 2013). These service are important during flood event and thus, it is studied separately from the other types of infrastructure. They experience similar structural impacts as regular buildings but they are more costly to build and repair, as well as containing other expensive equipment and contents.

Vulnerability of critical infrastructures is an indicator of infrastructure vulnerability. Critical infrastructures include institutions which play an integral role in public safety, health, and provision of aid (Peck *et al.*, 2007). The critical infrastructures also considered include schools, fire stations and hospitals. While infrastructure vulnerability includes road networks, railway and road bridges. Infrastructure components are important to the movement of a population, communication and safety. If the infrastructure is affected by the flooding event then the population is affected as well.

V. FLOOD RISK MANAGEMENT

Risk management has been well known with defined procedure for managing risks that caused by natural disasters, especially flood. Flood risk management has been discussed in many studies previously that gave different meanings to the term (Plate, 2002).

Kourgialas *et al.* (2011) presented a viable approach for flood management strategy in river basin based on European Floods Directive. These researchers for Koiliaris river basin in Chania, Greece have established a reliable flood management plan, with two components; a proper flood management strategy and the determination of flood hazard areas in the region of interest. The first component includes three strategy: (i) pre-flood measures which provide the natural, institutional and social infrastructure for the viable management of flood risk. This includes technical measures and regulatory, economic and communication measures, (ii) flood forecasting which includes the planning of a network of telemetric station for recording rainfall, meteorological parameters and river flow from The Flood Forecasting-Warning

System, and (iii) post-flood measures which promote the fast re-establishment of the affected regions and include measure of alleviation, damaged infrastructure and the revision of the effectiveness of the flood-prevention system. The second component is an inherent part of the flood management strategy. The need of estimation of hazardous areas and exposure of a region to various phenomena and to natural disasters in particular, emerged long before the application of computers and the development of specialized software for cartography. The estimation of hazardous areas is a fundamental non-structural measure to address the management of the territory along the river channel. The produced map of flood-hazard areas by using Geographic Information System (GIS) software such as ArcMap identifies the areas and settlements at high risk flooding.

Tingsanchali (2012) found that integrated urban flood disaster and risk management for developing countries, particularly in Thailand are mostly in terms of reactive response in prevailing disaster situation (emergency response and recovery). Reactive response should be changed to proactive response to increase effectiveness of management and reduce losses of life and properties. Flood disaster management followed strategic framework of management cycle such as preparation before flood impacts, readiness upon flood arrival, emergency responses during flood and recovery and rehabilitation after the flood. The flood risk management, on the other hand, was based on a conceptual framework for urban area by Associated Programme on Flood Management (APFM) as shown in Figure 2. This conceptual framework consisted of; (a) Integrated Flood Management (IFM) which is based on the following principles (APFM, 2009): i) Employ a basin approach; ii) Treat floods as part of the water cycle; iii) Integrate land and water management; iv) Adopt a mix of strategies based on risk management approaches; enable cooperation between different agencies and ensure a participatory approach, (b) Total Water Cycle Management (TWCM) which applied in order to stress the linkages between storm water management on one hand and water supply and sanitation on the other and (c) Land-use Planning (APFM, 2009) which leads to calls for a closer integration or coordination between flood management plans and land use plans. The regulations and by-laws concerned with land use planning should consider the flood risks and local disaster management authorities (APFM, 2008). All its principles and at the same time incorporates risk management principles are embraced by Integrated Water Resources Management (IWRM). It integrates land and water resources development in a river basin and aims at combining the efficient use of flood plains and the reduction of loss of life due to flooding.

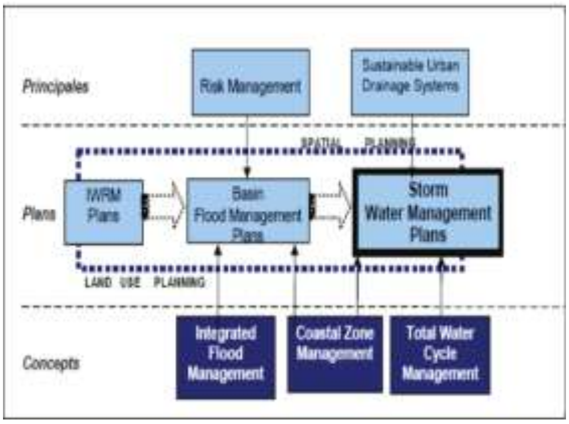

Figure 2: Conceptual framework of urban flood risk management (APFM, 2008) (APFM, 2009)

Kourgiales *et al.* (2011) took all measures, which are pre-flood, flood forecasting and post-flood measures into the flood risk management. While Tingsanchali (2012) used the conceptual framework for urban are for the flood risk management, the fore-casting measure is not included in the framework but Total Water Cycle Management (TWCM) is included which to plan water management activities to counterpart each other and provide optimal outcomes for the victims and the environment. Lastly, by taking references from these past studies, it is possible combine both of the ideas from these past researchers. By taking all measures that are needed, to establish a flood risk management plan in determining flood hazard area using GIS software and then integrating the conceptual framework.

VI. CONCLUSION

This review provides a brief understanding of risk triangle, especially vulnerability concepts and review of assessing flood vulnerability approaches as part of flood risk management and concerning on FVI methodology from past researchers. The FVI can be used in combination with other decision making tools and specifically include participatory methods with the people of areas as identified as vulnerable.

VII. ACKNOWLEDGEMENTS

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