SETTING UP OF INDICES TO MEASURE VULNERABILITY OF STRUCTURES DURING A FLOOD

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Abstract

Computation of flood extents and identification of vulnerable elements help to take mitigatory measures effectively and efficiently during a disaster. This is a baseline study carried out to examine how effectively the vulnerability of a small administrative division that depend on the type and facilities of existing structures can be assessed. In this study the flood extent of upper reaches of Kalu-Ganga River in Sri Lanka for a rainfall of 100 year return period was derived using HEC-HMS and HEC-RAS software. Building vulnerability within the administrative divisions affected by floods were derived using census data. Subsequently, flood risk maps with respect to structures due to 100 year return period rainfall were developed based on vulnerability derived from census data and the developed flood hazard maps. This approach could be used to identify high risk administrative divisions during a disastrous flood event to organize relief aids. It further helps in taking post disaster mitigatory measures according to the vulnerability levels of the buildings in each administrative division. Identification of crucial factors that influence vulnerability helps to reduce vulnerability and to mitigate the risks involved in future flood events.

Keywords: *structural vulnerability; flood vulnerability; flood hazard; flood risk maps; flood modeling;*

1. Introduction

Most disasters are characterized by short reaction/response times, and present a significant strain on the resources of the affected communities. Therefore, responding effectively to post-disaster events requires a rapid and coordinated response to save lives and enables communities to get back on their feet. Most often, this response is predicated on access to good information (Lembo et al., 2008). Recent studies have indicated that the need for information in post-disaster response for first responders, command and control managers, public information managers, and eventually, recovery workers (Gunes & Kovel, 2000).

The concept of vulnerability has been a powerful analytical tool for describing states of susceptibility to harm, powerlessness, and marginality of both physical and social systems, and for guiding normative analysis of actions to enhance well-being through reduction of risk (Adger, 2006). Knowingly or unknowingly new houses are built in areas at risk from flooding making more people are being placed at risk by moving into these ‘unsafe’ areas.

Before any study on the social distribution of risk can be made, the areas at risk need to be defined. In this research the flood plain maps for 100 year return for flood was used to identify area at risk.

Kalu-Ganga river basin in Sri Lanka was selected as the study area since flooding in this river basin is the most frequent natural hazard in the country. Due to its geographical location the Kalu-Ganga river basin receives a large amount of rainfall during monsoon seasons. This causes flooding almost every year in the Kalutara and Ratnapura districts. As stated by (Churchill & Hutchinson, 1984) relief and aid programmes have been essentially the only collective adjustment to flooding in Sri Lanka, which is still in practice. Increase in human population and migration to cities has made the flood risk management an inevitable step that should be taken to reduce the vulnerability of human population to frequently occurring floods in Sri Lanka.

2. Materials and Method

2.1 Study Area

Kalu-Ganga river catchment covers 2658 km^2 and is dominant by forest, residential and agricultural cropland land use types. It experiences an average annual rainfall of 4000 mm, which varies from

2800 mm in lower reaches to 5300 mm in higher elevations. Geographically the catchment lies between 6.32°N and 6.90°N latitude and 79.90°E and 80.75°E longitude as per WGS84 coordinate system and the river flows from a height of about 2,250 m MSL (Figure 1).

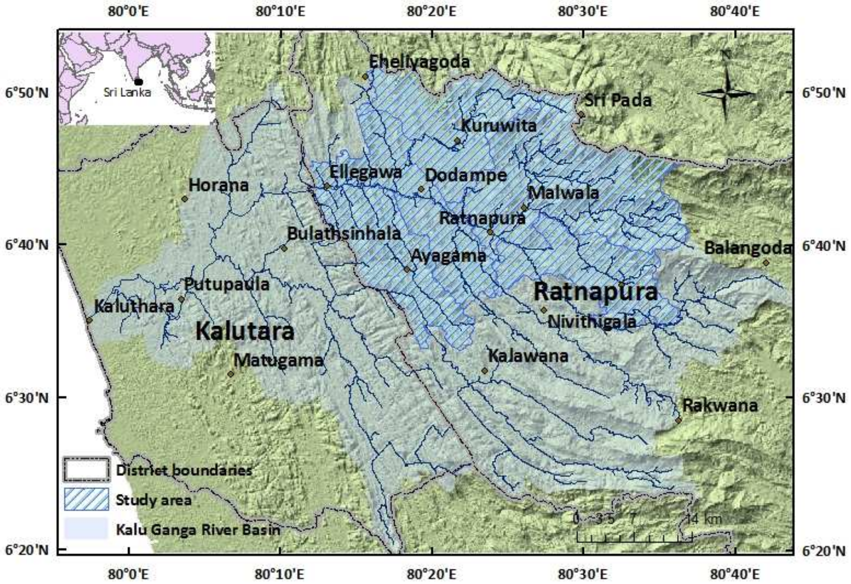

Figure 7. The Kalu-Ganga catchment and the area under investigation

The Kalu-Ganga river passes through two administrative districts, Ratnapura and Kalutara, as shown in Figure 2. This paper focuses on analyzing floods in upper reaches of the Kalu-Ganga river in the Ratnapura District. In Sri Lanka administrative divisions within a district are named as Divisional Secretariat (DS) divisions while as the lowest administrative division a DS division is divided into several Grama Niladhari (GN) divisions. In the study six DS divisions in the Ratnapura district namely, Kiriella, Kuruwita, Ratnapura, Pelmadulla, Elapatha and Ayagama were considered and the GN divisions were taken for unit-wise risk assessment.

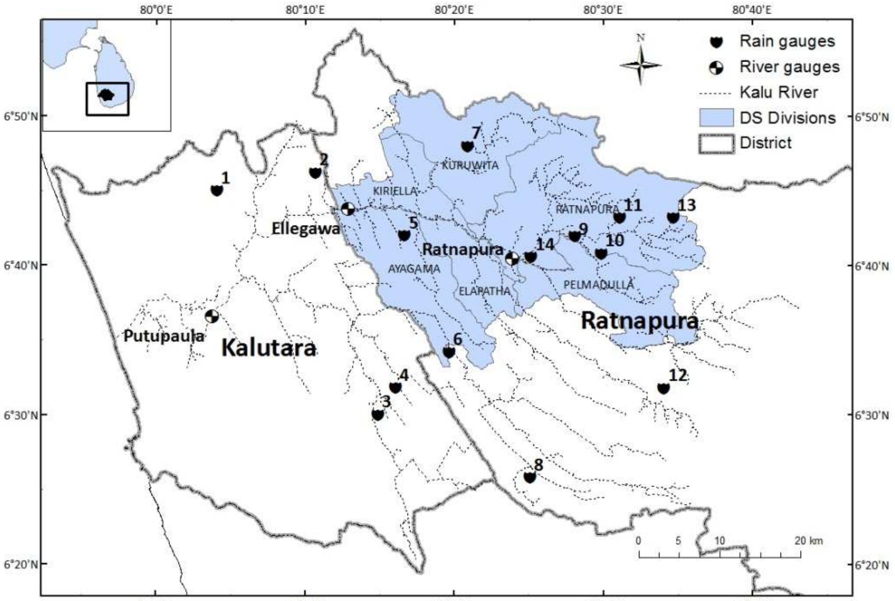

Figure 8. Hydrological gauging stations

2.2 Methodology

Risk-oriented methods and risk analyses are gaining more and more attention in the fields of flood design and flood risk management since they allow us to evaluate the cost effectiveness of mitigation measures and thus to optimize investments. The most common approach to define flood risk is the definition of risk as the product of hazard, i.e. the physical and statistical aspects of the actual flooding (e.g. return period of the flood, extent and depth of inundation), and the vulnerability, i.e. the exposure of people and assets to floods and the susceptibility of the elements at risk to suffer from flood damage (Apel et al., 2009).

Hazard analyses give an estimation of the extent and intensity of flood scenarios and associate an exceedance probability to it. The usual procedure is to apply a flood/rainfall frequency analysis to a given record of discharge/rainfall data and to transform the discharge associated to defined return periods, e.g. the 100-year event into inundation extent and depths. Vulnerability analyses are normally restricted to the estimation of detrimental effects caused by the floodwater like fatalities, business interruption or financial/economic losses.

To determine the peak discharge due to a rainfall of 100 year return period Hydrologic Engineering Center's Hydrologic Modelling System (HEC-HMS) developed by US Army corps of Engineers (USACE, 2009a) was used. To obtain the flood extent HEC-GeoRAS (USACE, 2009b) and Hydrologic Engineering Center's River Analysis System (HEC-RAS) (USACE, 2010) software were used.

Cutter et al. (2003) found that eleven composite factors that differentiated U.S. counties according to their relative level of social vulnerability. Out of them they found that eleven percent of the variation in counties was captured by density of the built environment. Dominey-Howes & Papathoma (2006) identified 'attributes' (indicators) that are reported to affect the degree of damage from, or protection to, tsunami flooding for individual buildings and structures. (Dall'Osso & Dominey-Howes, 2009) had selected seven factors to assess the vulnerability of buildings to a tsunami flood namely; number of stories, building material and technique of construction, ground floor hydrodynamics, foundations, shape and orientation of the building footprint, movable objects and preservation condition.

Flood water can damage residential property in at least four ways: building materials and contents are damaged by immersion; mud, sediments and other contaminants in the flood water can cause corrosion or other decay; Dampness promotes the growth of mildew; the physical force of the water and objects swept along in the flow may damage the building structure. While the depth of overfloor inundation is usually seen as the most important control on residential damage, other factors may also be important – for example, duration of inundation, sediment content, water velocity, building materials, interior construction, building age, content location, and warning time ((N'Jai et al., 1990) as cited in (NHRC, 2000)).

Vulnerability of built in environment within the administrative divisions affected by floods were derived using census data. Due to the limited data availability building material used for construction of walls and floor and density of buildings per GN division were used to assess the vulnerability.

Subsequently, flood risk maps due to 100 year return period rainfall were developed based on vulnerability derived from census data and the developed flood hazard maps at GN division level based on built envioronment.

3. Theory/calculation

3.1 Flood-hazard assessment

Flood hazard assessment is the estimation of overall adverse effects of flooding for a particular area. It depends on many parameters such as depth of flooding, duration of flooding, flood wave velocity and rate of rise of water level. One or more parameters can be considered in the hazard assessment depending on the characteristics of study area and floods (Tingsanchali and Karim, 2005). Considering the characteristics of the study area, two major parameters, namely depth of flooding and percentage area of flooding, were considered for the assessment of hazard of land units considered.

A hazard index, HI, was introduced to represent degree of hazard corresponding to different flood depths. As recommended in past studies (e.g. Chowdhury and Karim, 1997), four hazard categories were used and each category was represented by a hazard index. To devise a scale for HI, flooding areas were divided into four depth categories based on three critical flood depths 0.6, 1.0 and 3.5 m. Based on these three critical values of flood depth (D), hazards were classified as low ($D \leq 0.6$ m), medium (0.6 m < D ≤ 1.0 m), high (1.0 m < D ≤ 3.50 m) and very high (3.50 m < D) as presented in Table 2.

Table 3. *Hazard index for depth of flooding*

Depth (D) of flooding (m)	Hazard category	Hazard Index (HI)
0 < D ≤ 0.6	Low	1
0.6 < D ≤ 1.0	Medium	2
1.0 < D ≤ 3.5	High	3
3.5 < D	Very High	4

For the practical application of predicted results, the hazard was estimated for a land unit and represented by a number, hazard factor *(HF)*. The *HF* for a land unit was taken to represent hazards due to flood depth (HF_D) and inundated area (HF_A). A land unit here is the lowest administrative division, while a piece of land of 200 m × 200 m is the computational grid cell. The DEM of 200 m × 200 m grid cells was generated from the 1:10000 contour maps (contour interval of 5 m). A land unit is several times larger than a computational grid cell and therefore, flooding of more than one depth category may occur in the same land unit. Exposure of a land unit to the flood hazard is taken as 1 assuming that all land units are equally exposed to it.

The hazard factor HF_D for flood depth of each land unit was computed based on the fraction area under each depth category and the corresponding hazard index using equation 1.

$$HF_D(i) = \frac{\left(\sum_{j=1}^{N_d} A(i,j) HI_i(j)\right)}{\sum_{j=1}^{N_d} A(i,j)} \qquad (1)$$

Where, *i* is the land unit identification number and j represents the depth category; N_d is the total number of depth categories; $HI_i(j)$ is the hazard index for the area under depth category *j* in land unit *i* and *A(i,j)* is the area under depth category *j* in land unit *i*.

The hazard factor HF_A for flood area of each land unit was computed as the percentage area under flood irrespective of depth using equation 2.

$$HF_A(i) = \frac{Arae\ under\ flood\ in\ land\ unit\ i}{Total\ area\ of\ land unit\ i} \times 100 \qquad (2)$$

As each of the above hazard factors were measured on a different scale, they were standardized as an index using equation 3.

$$HF_K^s(i) = \frac{HF_K(i)}{(HF_K)_{max}}; \quad (K = D\ or\ A) \qquad (3)$$

Where, $HF_K^s(i)$ is the standardized hazard factor of the land unit, HF_K (*i*) is the original hazard factor for land unit and $(HF_K)_{max}$ is the maximum *HF* in the range. Finally giving the same weight for both of these factors, average value was taken as the hazard factor of the land unit as in equation 4.

$$HF(i) = (HF_D^s(i) + HF_A^s(i))/2 \qquad (4)$$

3.2 Flood-vulnerability assessment

Vulnerability is a measure of the intrinsic susceptibility of an element at risk exposed to potentially damaging natural phenomena. The vulnerability is expressed on a scale from 0 (no damage) to 1 (total damage). The vulnerability factor (*VF*) of each land unit was assessed using the parameters, type of material used for floor and walls and density of the buildings per land unit. Thus the vulnerability indices with respect to type of material used for floor (VI_F), walls (VI_W) and density of the buildings (VI_D) are;

Vulnerability indices of land units (GN divisions) were calculated using the census data. Vulnerability rankings were assigned to each building category based on the material type used for construction of walls and floor as illustrates in Table 2 and 3, respectively.

Table 4. *Assignment of ranks according to construction materials used in walls*

Category	Construction Material of walls	Ranking [*R*(*i*)]
1	Brick	1
2	Kabok	3
3	Cement Blocks/ Stones	2
4	Pressed Soil Blocks	4
5	Mud	6
6	Cadjan / Palmyrah	7
7	Planks/Metal Sheets	5

Table 5. *Assignment of ranks according to construction materials used for floor*

Category	Construction Material of floor	Ranking [*R*(*i*)]
1	Cement/Tiles/Terrazzo	1
2	Clay/Wood/Sand	2

Therefore, vulnerability index of a land unit *j* with respect to construction materials of wall of a housing unit ($VI_W(j)$) was calculated as;

$$VI_W(j) = \sum_{i=1}^{n} F_W(i)R_W(i)/n \tag{5}$$

Where, $F_W(i)$ is the fraction of the buildings of a category from the total number of houses in the land unit *i* and $R_W(i)$ is the ranking assign to that vulnerability category based on construction material used for the walls.

Vulnerability index of a land unit *j* with respect to construction materials of floor of a housing unit ($VI_F(j)$) was calculated as;

$$VI_F(j) = \sum_{i=1}^{n} F_F(i)R_F(i)/n \tag{6}$$

Where, $F_F(i)$ is the fraction of the buildings of a category from the total number of houses in the land unit *i* and $R_F(i)$ is the ranking assign to that vulnerability category based on construction material used for the floor.

Vulnerability index of a land unit *j* with respect to density of housing units ($VI_D(j)$) was calculated as;

$$VI_D(j) = \frac{Total\ number of\ housing\ units\ in the\ land\ unit\ j}{Area\ of\ the\ land\ unit\ j} \tag{7}$$

However, scale of this VI_D differs from above two vulnerability indexes, therefore this vulnerability index was standardised using the flowing equation for summing up the vulnerability of buildings of a particular land unit.

$$VI_{DS}(j) = \frac{(VI_D(j)) - Min(VI_D(j))}{Max(VI_D(j)) - Min(VI_D(j))} \tag{8}$$

Finally, vulnerability factor of the land unit *j (VF(j))* with respect to built environment was calculated using;

$$VF(j) = \frac{VI_{DS}(j) + (VI_W(j) + VI_F(j))/2}{2} \tag{9}$$

3.3 Flood Risk Assessment

In general, risk as a concept that incorporates the concepts of hazard and vulnerability. It is customary to express risk (R) as a functional relationship of hazard and vulnerability. The magnitude of risk for a land unit was estimated by a risk factor, *RF*(*i*), which was computed as the product of the hazard factor and the vulnerability factor as in equation 10.

$$RF(j) = HF(j) \times VF(j) \tag{10}$$

4. Results

4.1 Flood Flow Simulation

A frequency analysis was performed using the Gumbel distribution for all fourteen rainfall gauging stations. Average value of the rainfall with 100 year return period was selected as the rainfall to be used in the generation of river flows. This rainfall was used in the calibrated HEC-HMS based model for the basin to generate river discharges that are required for the hydrodynamic model to obtain flood. Using the HEC-RAS based model the inundation extents with corresponding depths for a flood expected to occur due to a rainfall of return period 100 years were developed. Figure 3 depicts the inundation area.

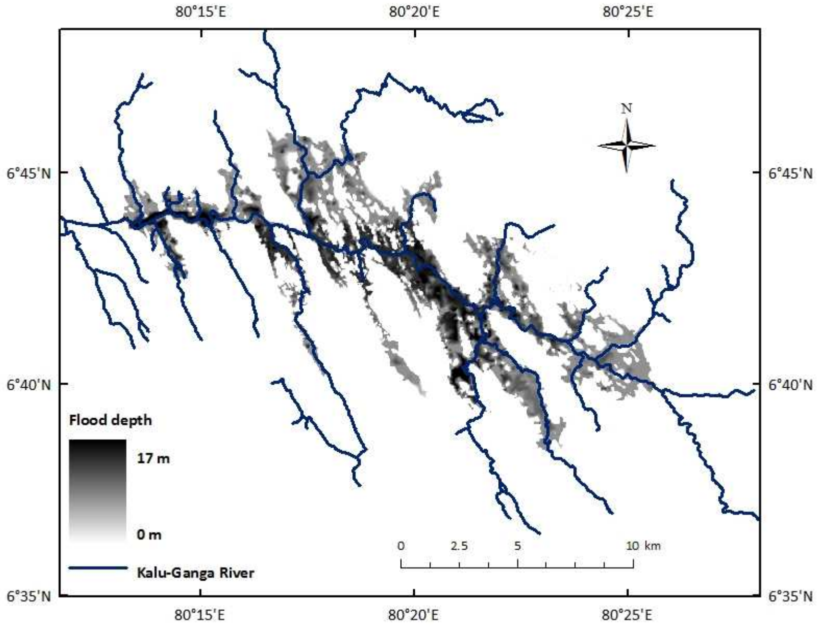

Figure 9. *Flood Inundation area along the Kalu-Ganga river*

4.2 Risk Assessment

Risk due to flooding was computed at GN division level. The inundation areas and depths obtained from the hydrodynamic model provide exposure that needed for the calculation of risk.

Sixty seven GN divisions were identified within the 100 year return period floodplain area as shown in Figures 3. The numbers appear in the figure are the identification numbers given for the GN divisions within the Ratnapura district by the administration. These GN divisions were categorized into five risk zones based on scores of five equal intervals. The risk areas were named as very low-risk zone for $0.001 < RF \leq 0.1$, low risk zone for $0.1 < RF \leq 0.2$, medium risk zone for $0.2 < RF \leq 0.3$, high risk zone for $0.3 < RF \leq 0.4$ and very high risk zone for $0.4 < RF \leq 1.0$. According to this analysis 37 GN divisions were rated as very low risk, 21 GN divisions as low risk, 6 GN divisions as medium risk, 2 GN divisions as high risk and 1 GN division (Ratnapura, No.284) as very high risk divisions . Figure 4 presents the spatial distribution of risk levels of the sixty seven GN divisions.

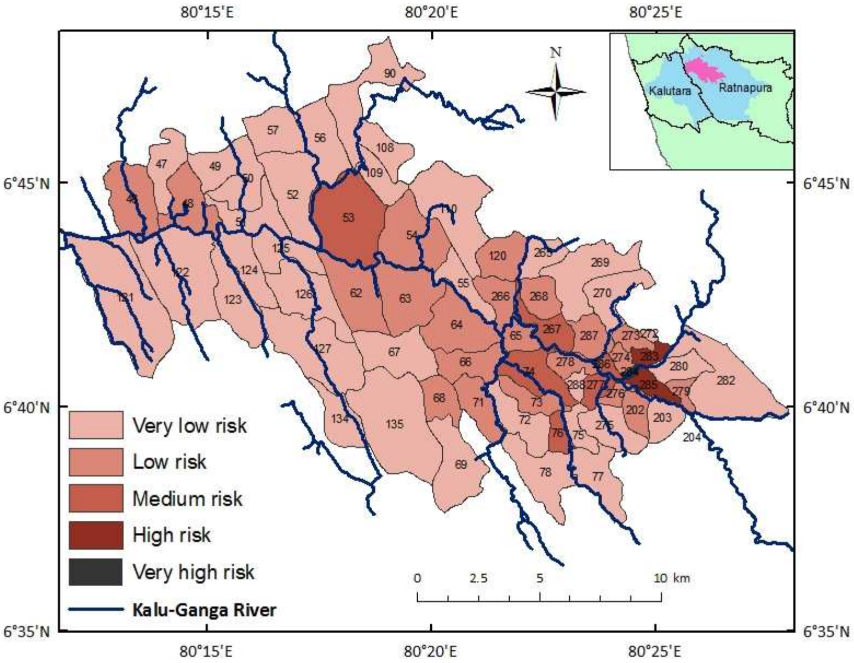

Figure 10. *Flood risk map based on built environment*

5. Discussion and conclusions

A flood risk analysis of a flood prone area immensely supports the decision makers to take correct decision at the right time. It helps in all phases of a flood related disaster i.e., pre, post, and during the disaster. In Sri Lanka, during a disaster, all relief activities are carried out always at GN division level and therefore, flood risk analysis taking the land units as GN divisions is the most suitable. The HEC-HMS and HEC-RAS based models were found to be very suitable in the derivation of flood inundation area in the Kalu-Ganga river basin.

Among the different hydraulic parameters that determine hazard due to a flood, the flood depth and inundation are found to be two major parameters that can be used to determine hazard level sufficiently.

Vulnerability of an area always depends upon the population of that area and also the type of built environment of the area. There are many studies related to the study of damages due floods on structures. However, very little emphasis has been given for the studies related to the flood risk based on built environment. Vulnerability factors based on type of material used for floor and walls and density of the buildings per land unit, were found to be effective in the determination of risk in the area.

Flood risk analysis conducted based on census data found to be effective in taking decisions during pre and post disaster due to floods. However, if GIS data on built environment were available enabling explicit consideration of building vulnerability, mitigating measures to be taken with regard to built environment such as flood proof techniques to buildings would be very easy.

GIS data of buildings (building foot prints) including all necessary secondary data is not available in Sri Lanka at present. Building such a data base would facilitate disaster mitigation immensely.

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