JOURNAL OF WATER AND LAND DEVELOPMENT
e-ISSN 2083-4535

Polish Academy of Sciences (PAN), Committee on Agronomic Sciences
Section of Land Reclamation and Environmental Engineering in Agriculture
Institute of Technology and Life Sciences (ITP)

JOURNAL OF WATER AND LAND DEVELOPMENT
2020, No. 46 (VII–IX): 20–28
https://doi.org/10.24425/jwld.2020.134194

Available (PDF): http://www.itp.edu.pl/wydawnictwo/journal; http://journals.pan.pl/jwld

Received 16.10.2019
Reviewed 10.04.2020
Accepted 06.05.2020

Physical vulnerability to flood inundation: As the mitigation strategies design

Azmeri AZMERI [1] ✉, Halida YUNITA [1], Safrida SAFRIDA [2], Indra SATRIA [3], Faris Z. JEMI [4]

[1] Syiah Kuala University, Engineering Faculty, Civil Engineering Department, Merpati Street No. 24, Keuramat village, Banda Aceh, Aceh, 23123, Indonesia
[2] Syiah Kuala University, Agriculture Faculty, Agribusiness Department, Banda Aceh, Indonesia
[3] Office of Public Work, Meulaboh, Aceh Barat Regency, Indonesia
[4] Syiah Kuala University, Engineering Faculty, Electrical Engineering Department, Banda Aceh, Indonesia

For citation: Azmeri A., Yunita H., Safrida S., Satria I., Jemi F.Z. 2020. Physical vulnerability to flood inundation: As the mitigation strategies design. Journal of Water and Land Development. No. 46 (VII–IX) p. 20–28. DOI: 10.24425/jwld.2020.134194.

Abstract

Flood with intense rainfall and inadequate drainage system leads to flood inundation in residential areas, which in turn damages the housing components and causes a loss. The different level of flood inundation at various affected locations caused varying degrees of losses. This study aimed to identify the damage conditions and analysed the physical loss of the residential building components. The physical vulnerability level is influenced by two damage qualification: the structural and architectural damages. The third-order polynomial function approach produces the best model for both qualifications, yielding the smallest average of errors (*RMSE*) of 0.0187 for the structural quality and 0.0672 for the architectural quality. The amount of losses related to the architectural elements of the house is smaller compared to the structural one as it is not its main component. This approach is useful as a guide in determining the post-flood handling rehabilitation cost of both structural and architectural elements that will be more appropriate for future conditions. This information is essential as effective management to design flood disaster mitigation strategies and may serve as a basis for flood risk management.

Key words: *architectural damage, flood, physical vulnerability, structural damage*

INTRODUCTION

Hydrometeorological disasters such as flood, drought, and storm occur due to unstable hydrometeorological parameters. Such disasters have been prominent around the world and more than 95% of the disaster trends in Indonesia are hydrometeorological. It is also predicted that the flood will be more severe and frequent due to climate change [RIEUX *et al*. 2012]. Consequently, many parts of the world face severe threats of flood hazards. Unplanned urbanization, rapid conversion of land use, and poor flood management are some of the factors contributing to the impacts of flood and increasing the risks for the population [NASIRI *et al*. 2016].

Generally, the flood risk affects the people living in the cities, especially in developing countries, as the locations are usually in urban areas with unique spatial characteristics of informal settlement [BAKER 2012]. The informal settlements are the residential areas where the residents do not have access to essential services, ownership security, and are non-compliance with UN-Habitat building regulations [UN-Habitat 2011]. Most residents of these settlements are vulnerable to various hazards due to their living conditions, as indicated by poor essential services and infrastructure as well as the proximity to hazardous zones, such as floodplains and rivers [BAKER 2012].

According to risk management, three main aspects cause the flood risk of urban systems, namely hazard exposure, vulnerability, and resilience. Hazard is an extreme natural event including its frequency; exposure refers to the society, environment and the property affected by flood; and resilience refers to the vulnerability of the society and the property to flood [KRON 2009]. Meanwhile, regional resilience reflects the recovery conditions from the flood impacts [ROBERTS *et al*. 2009; SMIT, WANDEL 2006]. In flood management to reduce the effects of the flood, vulnerability evaluation is a crucial element [AHMAD, SIMONOVIC 2013; TOTSCHNIG, FUCHS 2013].

An understanding of vulnerability is vital for developing programs to assess the vulnerability of urban settlements [SALAMI *et al*. 2017]. The definition of 'vulnerability' is multi-dimensional [BIRKMANN 2006; VOGEL, O'BRIEN 2004], and there has been no comprehensive explanation to represent its best conceptualization [KASPERSON, ARCHER 2005]. The vulnerability has been widely defined in different contexts, for example, in the context of environmental hazards [ZENTEL, GLADE 2013], the vulnerability to natural and human-caused hazards in Indonesia is related to climate change [FIRMAN *et al*. 2011].

Vulnerability usually applies to a series of conditions that occur from physical, social, economic, and environmental conditions [WILSON 2012; ZENTEL, GLADE 2013]. Many researchers examined vulnerability in the context of variation in hazard exposure, while others assessed it in term of the difference in the human capacity to overcome the hazards. Several other researchers also examined the flood vulnerability, an essential element of urban flood management, using various methods. The development of an evaluation method is due to the need to improve decision making, for example, to obtain the best solution related to economic or infrastructure investment in cities. Therefore, an index to evaluate the vulnerability and to identify more vulnerable zones is introduced; followed by relevant comparisons to obtain more useful insights [NASIRI *et al*. 2018].

The flood vulnerability index is a method for examining the flood vulnerability based on the river areas, subwatershed, and scale of the urban regions. The categories rely on various components affecting the vulnerability of the people living in flood-prone areas [BALICA 2007]. The flood vulnerability index is a quantitative variable enabling the comparison of disaster risk and its impacts between various regions affected by the flood [BIRKMANN 2007]. First, each index is formulated by identifying the most suitable types of data for calculating the vulnerability, followed by recognizing the available data on the spatial scale [MCLAUGHLIN, COOPER 2010]. The index assessment serves as a guide for vulnerability reduction strategies [BALICA 2007].

Similarly, in the case of Aceh Barat Regency, specifically in Johan Pahlawan district (Sumatra, Ind. Sumatera – Indonesia), the flood often occurs in several residential areas. Based on the data from the Regional Disaster Management Agency (Ind. Badan Penanggulangan Bencana Daerah, BPBD) of Aceh Barat Regency, Leuhan and Blang Beurandang villages experienced a repeated flood. The flood in 2016 affected nine sub-districts, and Johan Pahlawan district was the most severely affected. This condition led to thousands of residents in Aceh Barat to evacuate, and thousands of houses were submerged. The flood damaged the main structural components of the building, such as the foundation, columns, and the sloof of the houses. It also ruined the architectural elements of the building, such as ceramic floors, wall plastering, wall paint, doors, and windows. The damages resulted in the flood losses and the magnitude of losses varied depending on the water depth and the physical conditions of the residential buildings. After considering the threat of repeated flood and the losses, this study aimed to conduct the physical vulnerability assessment due to flood. This information is critical for providing quick and accurate risk assessments of a given area. By highlighting the vulnerability factors, emergency management can effectively devise mitigation strategies.

STUDY AREA AND METHODS

STUDY AREA

The study was conducted in Johan Pahlawan district, Aceh Barat Regency, Aceh Province, Sumatra, Indonesia. It is located between 04°08' N and 96°07' E, and covers an area of approximately 44.91 km^2 (Fig. 1). Based on the previous research [AZMERI *et al*. 2020], the flood inundation map informed by the key informants were analysed using a contour map and processed by the ArcGIS program. To verify the map, field observation was conducted to record the height or traces of the inundation at residents' houses and other public facilities affected by the flood (Fig. 2).

METHODS

The literature review undertaken revealed that the most appropriate vulnerability indicator method is to use the available field data. This method provides a logical image of the location to the value of vulnerability. It is widely used in flood vulnerability studies and is preferred by policymakers due to the clear vulnerability image. The illustration clarity aims to measure the priorities and plan the risk responses in the study area [NASIRI *et al*. 2016]. The flow chart of the research method is presented in Figure 3.

The relationship between the damage ratio and the process intensity is defined as the vulnerability based on the engineering approach [FUCHS *et al*. 2007]. In this study, the buildings were evaluated based on the monetary value of each exposed element [KEILER *et al*. 2006]. Therefore, information concerning the exposed and at-risk elements of the affected area was necessary. The monetary value of each exposed element gathered for each building was associated with each process intensity (in this study, the water depth of flood inundation). This data was analysed by employing a regression approach to inform a vulnerability function as the structural and architectural obstacles of buildings related to the flood. The vulnerability curve links the data related to the losses and the process intensity.

The characteristics of the exposed buildings were compiled by employing empirical data collection conducted between September and November 2018 based on a door-to-door survey. The survey was carried out by investigating the exposed elements, with a total of 40 exposed houses in Johan Pahlawan district. The characteristics were the area, type of building, and the building materials used.

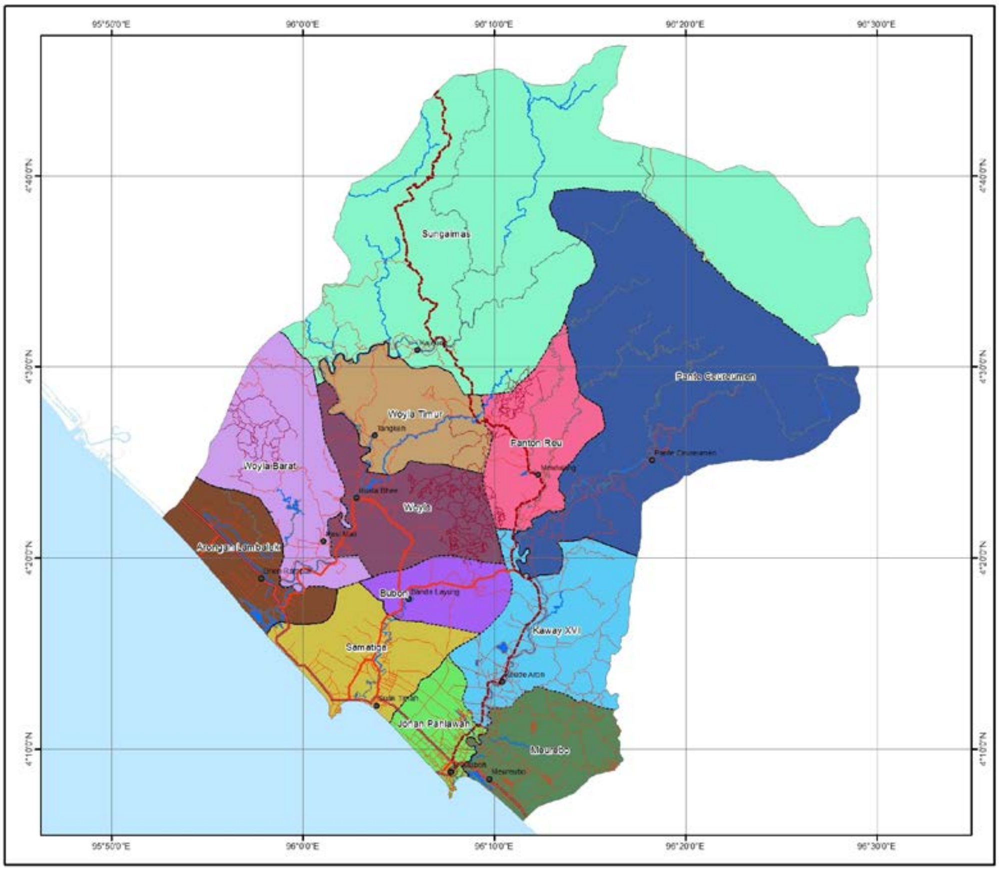

Fig. 1. The study area in Aceh Barat Regency; source: Government of West Aceh Regency [2019]

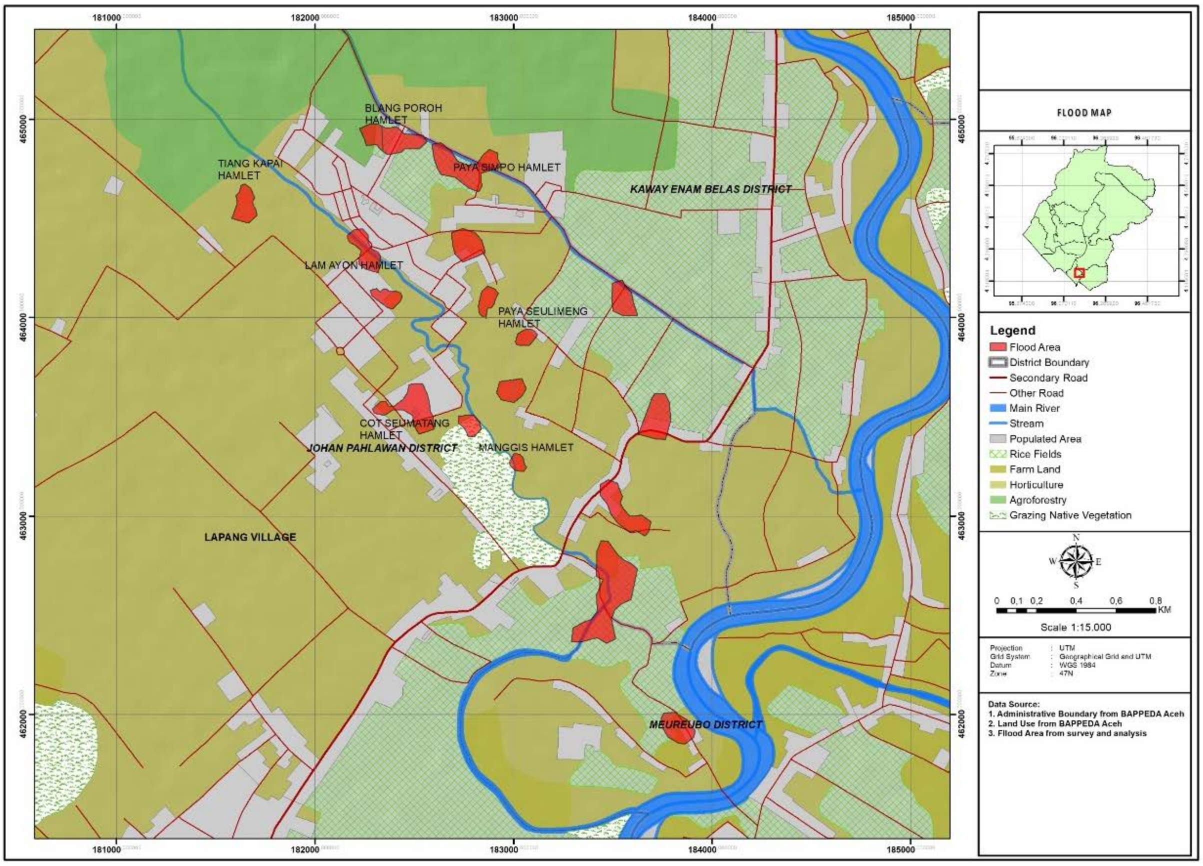

Fig. 2. The flood inundation map; source: AZMERI, SATRIA [2020]

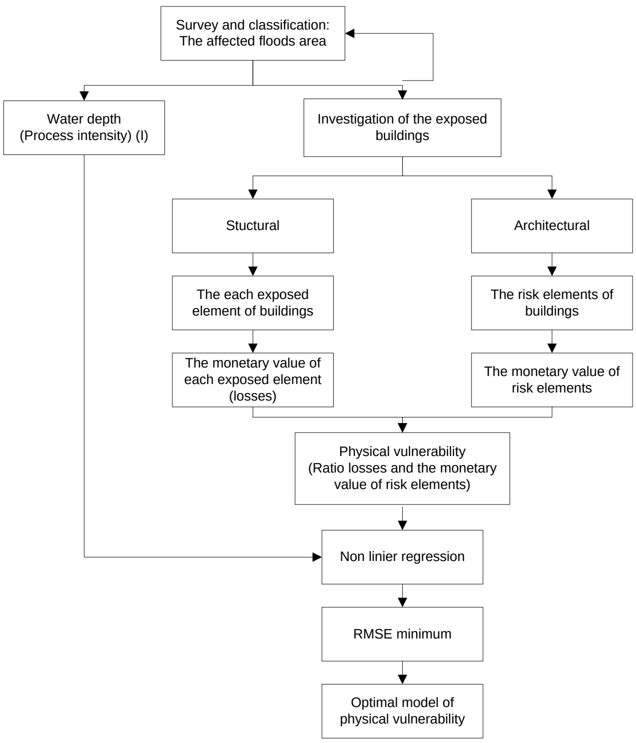

Fig. 3. The flow chart of research method

Details analysis of the unit price for each component of the residential building was conducted by analysing the unit price of the public sector works established by the Minister of Public Works and People Housing (Ind. Peraturan Menteri Pekerjaan Umum dan Perumahan Rakyat No. 28 PRT/M/2016. The wage and prices of materials refer to Keputusan Gubernur Provinsi Aceh Number 028/782/2016 concerning the Standards Goods Price for Aceh Barat Regency Government, the Fiscal Year 2018 (Tab. 1).

The damage ratio was employed to calculate the vulnerability. The method adopted an economic approach by establishing the ratio between the losses due to flood and the value of each element at risk [HAUSMANN 1992]. In the second set of calculations, the value of each building is related to the magnitude of the process intensity of the last flood condition (2018). The magnitude of the process intensity is the water depth of each house. Relating this data to the object level generated scatter plots. The vulnerability function was then created using a non-linear regression approach. This function represented the relationship between degree of loss (DoL) and the magnitude of process intensity (*I*) due to flood in the study area (Eq. 1) [AZMERI, ISA 2018; KARAGIORGOS *et al*. 2016].

Table 1. Prices of repair works and the respective housing assistance

Repair work	Unit of measurement	Cost (IDR)
Red brick walls installation (5×11×22 cm), the thickness of one stone mixture is 1PC : 4S	m^2	319,691
Mixed stucco installation of 1PC : 4S with 15 mm thickness	m^2	72,080
Ceramic floor tiles installation (30×30 cm)	m^2	277,668
Production and installation of door and window frames made of class II or III wood	m^3	10,138,113
Production and installation of panel door leafs made of class I or II wood	m^2	806,035
New wall painting (1 plamuur coat, 1 base coat, 2 finished coat)	m^2	35,676
New wood painting (1 plamuur coat, 1 base coat, 2 finished coat)	m^2	61,434

Explanations: IDR = Indonesian rupiah (1000 IDR = 0.068 USD in 10th August, 2020), PC = Portland cement, S = sand.
Source: own elaboration.

$$\text{DoL} = f\,(I) \tag{1}$$

The targeted function should fulfil three requirements. First, the value of the vulnerability should be between zero and one (f: $I \rightarrow [0, 1]$). Second, the vulnerability function should exceed its original value ($f(I = 0) = 0$). And third, the vulnerability function shows a substantial increase ($I_1 \leq I_2 \rightarrow f(I_1) \leq f(I_2)$). Two functions were used in this study that reflected the vulnerability behaviour (Tab. 2).When the value of the process intensity is relatively low, DoL increases slowly [AZMERI, ISA 2018; PAPATHOMA-KOHLE *et al*. 2015; TOTSCHNIG *et al*. [2011]. The moderate value of process intensity increases DoL almost linearly, and when it is high, DoL asymptotes with one. Due to these behaviours, the linear function is inappropriate to be used for flood vulnerability. The presented function was modified to reflect the three requirements previously outlined [TOTSCHNIG *et al*. 2011]. The vulnerability parameters of the model presented were determined by employing the root-mean-squared error (*RMSE*), as illustrated in Equation (2).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}} \tag{2}$$

Where: y_i and $\hat{y}_i$ are the values surveyed and modelled at time *i*, where *n* is the total number of residential buildings exposed [MONTESARCHIO *et al*. 2009].

Table 2. Functions applied for vulnerability analysis

Model structural	Model architectural	Function	Formula	Parameters (θ)
M_1	M_3	the second-order polynomial	$ah^2 + bh$	*a*, *b*
M_2	M_4	the third-order polynomial	$ah^3 + bh^3 + ch$	*a*, *b*, *c*

Explanations: *a*, *b*, *c* = parameters in function, *h* = water depth.
Source: own elaboration.

The best model selection (M*) is undertaken by comparing the average *RMSE* for all models, and M* is based on the smallest *RMSE*.

RESULTS

THE DAMAGES AND LOSSES OF RESIDENTIAL BUILDINGS

The flood inundation in Aceh Barat Regency submerged the residential area. Based on the survey data, there were 40 units of houses impacted by the flood in Leuhan Village (17 units) and Blang Beurandang Village (23 units). Of the 17 units in Leuhan Village, nine were in Raja

Aceh Hamlet, and eight were in Cot Seumatang Hamlet. Of 23 units in Blang Beurandang Village, three were in Raja Hamlet, four in Paya Simpo Hamlet, five were in Paya Seulimeng Hamlet, two were in Manggis Hamlet, and nine were in Lam Ayon Hamlet.

Of the residential areas exposed to flood, nine houses suffered structural damage, while 31 houses were damaged in term of the architecture. The damage conditions of the residential areas exposed to flood were varied, such as dropped foundation, damaged column and sloof structures, damaged floor tiles, cracked plaster walls, and peeled wall paint, as well as damaged doors and windows. The survey identified the damages by noting the information concerning the condition of the housing damages, classifying them into good condition (GC), slightly damage (SR), moderately damage (MS) and severely damage (SB). The data concerning the damages of each house impacted by the flood was indexed using the damage magnitude adopted from WURYANTI [2002]. The scores for slightly damage (SR), moderately damage (MS) and severely damage (SB) were 10%, 25%, and 50%, respectively. Then, the prices of the exposed building elements were multiplied by the score to generate the total loss.

The analysis of residential buildings losses impacted by the flood was undertaken by establishing the price of the public works unit, using a list of wage and material prices to create the unit price of structural elements of the houses. The unit price of work was then multiplied by the magnitude of damage generating the value of the losses. The value of losses for each house impacted by floods varies, ranging from the smallest to the biggest losses with different levels of water depth. The damages occurred to the houses, including the structural and architectural elements.

THE PHYSICAL VULNERABILITY ANALYSIS OF THE BUILDINGS DUE TO INUNDATION FLOODS

The flood risk is the potential damage and losses in the future due to damaged residential housing. The calculation of the risk value is based on the damage after the flood and the possibility of future damage and losses. The risk value of the structural quality of the houses is based on the assumptions concerning the damage of each element to the total damage/destruction, whereas the risk value for the architectural quality of the houses is also based on the assumption related to the damage of each element to the severely damaged condition.

THE STRUCTURAL QUALITY OF THE HOUSES

The degree of loss concerning the structural quality of the house is a ratio between the value of losses for each element of the exposed house and the risk value. The structural risk value was calculated based on the assumption of potential damage and losses related to the damage of the main structural components of the house. Table 3 presents the structural loss value. Scatter-plots were generated by associating the water depth and the value of losses for each house. Furthermore, the vulnerability function was acquired by employing a non-linear regression approach.

Table 3. The degree of structural loss to water depth

House No.	Water depth (h) (m)	Degree of loss (–)
1	1.00	0.053
2	1.00	0.075
3	2.00	0.196
4	2.00	0.259
5	1.00	0.058
6	0.90	0.039
7	1.50	0.067
8	1.50	0.082
9	1.30	0.077

Source: own study.

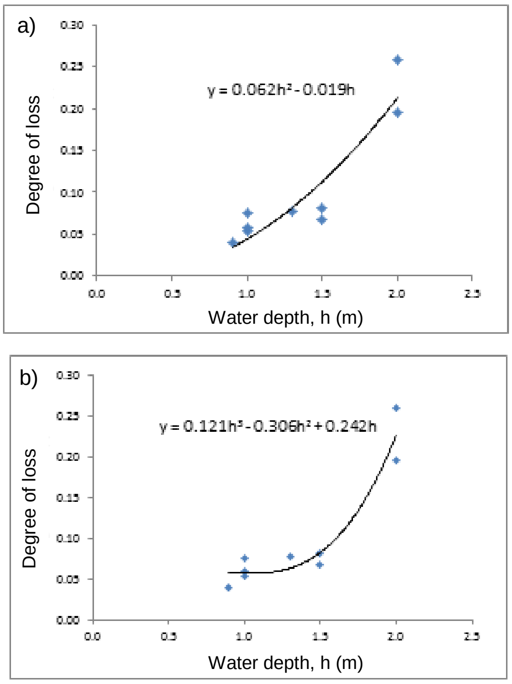

Fig. 4. Relationship between water depth and degree of loss acc. to the two different models: a) the second-order polynomial model (M_1), b) the third-order polynomial model (M_2); source: own study

Next, the second-order (a) and the third-order polynomial (b) regression analyses using the index from the previous equation were run to create the right model (Fig. 4).

Table 4 shows that the magnitude of losses in the usual process for nine houses at risk is 1.36 m, ranging from 0.90 to 2.00 m, with a median of 1.30 m. The average damage per unit is 1,491,888.88 IDR, ranging from 582,000.00 to 3,832,000.00 IDR, with an average of 1,116,000.00 IDR.

Table 4. Summary statistics for the analysis of data set concerning the value of structural loss of the houses (number of observations = 9)

Statistic	Symbol	Process intensity (m)	Loss (IDR)	DoL (a)	DoL (b)
Minimal	$h_{(1:9)}$	0.90	582,000.00	0.0338	0.0568
Mean		1.36	1,491,888.88	0.0996	0.1010
Median	$h_{(9:9)}$	1.30	1,116,000.00	0.0813	0.0629
Maximum		2.00	3,832,000.00	0.2124	0.2266

Explanations: a = the second-order polynomial, b = the third-order polynomial, h = water depth.
Source: own study.

The following are the comparison results of the two models: the second-order polynomial (a) resulting in the mean DoL of 0.0996, ranging from 0.0338 to 0.2124, with a median of 0.0813; and the third-order polynomial (b) generating the mean DoL of 0.101, ranging from 0.0568 to 0.2266, with a median of 0.0629.

The detail differences between M_1 and M_2 models are presented in boxplots in Figure 5. The results of root mean square error (*RMSE*) for structural parts of the houses presented in Table 5.

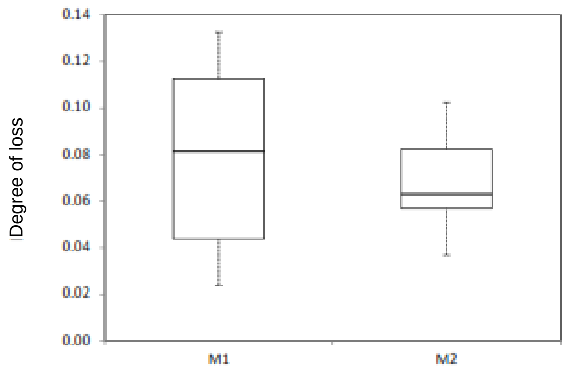

Fig. 5. Box plots highlighting the ranges in the degree of loss (DoL) for the M_1 and M_2 models; sours: own study

Table 5. The results of root mean square error (*RMSE*) for structural parts of the houses

Model (M)	Function	Mean *RMSE*
M_1	second-order polynomial	0.0275
M_2	third-order polynomial	0.0187

Source: own study.

Table 5 shows that the M_2 model has a lower *RMSE* (0.0187) compared to the M_1 model (0.0275). Therefore, the third-order polynomial function is considered as M*. The statistics results generate the vulnerability index of the structural elements of the house and the calculation of the vulnerability function based on the water depth.

Finally, the model was adjusted to the overall data set (nine points) for the structural conditions of the houses, resulting in Equation 3.

$$\text{DoL} = 0.121h^3 - 0.306h^2 + 0.242h \qquad (3)$$

THE ARCHITECTURAL QUALITY OF THE HOUSES

In line with the structural construction of the houses, the degree of architectural loss of the house is the ratio between the value of losses for each architectural element of the exposed house and the risk value. The risk value is based on the assumption regarding the potential damage and architectural losses of the house, as previously mentioned. The magnitude of the risk value differs between houses. The second-order polynomial (a) and the third-order polynomial (b) regression analyses were undertaken using the resulting index to create the best model. The results of the analysis can be seen in Table 6. Next, the second-order (a) and the third-order polynomial (b) regression analyses using the index from the previous equation were run to create the right model (Fig. 6).

Table 6. The degree of architectural loss to water depth

House No.	Water depth *h* (m)	Degree of loss (–)	House No.	Water depth *h* (m)	Degree of loss (–)
1	1.00	0.288	17	1.00	0.103
2	1.00	0.284	18	1.00	0.288
3	1.00	0.284	19	0.80	0.185
4	1.00	0.273	20	0.70	0.179
5	1.00	0.273	21	0.70	0.185
6	1.80	0.710	22	1.00	0.355
7	1.80	0.658	23	1.00	0.189
8	1.20	0.366	24	1.00	0.271
9	1.20	0.190	25	1.00	0.278
10	1.00	0.201	26	1.00	0.201
11	1.20	0.273	27	1.00	0.284
12	1.20	0.125	28	1.50	0.377
13	1.20	0.253	29	1.00	0.179
14	1.20	0.260	30	1.00	0.355
15	1.00	0.293	31	1.00	0.364
16	1.00	0.151			

Source: own study.

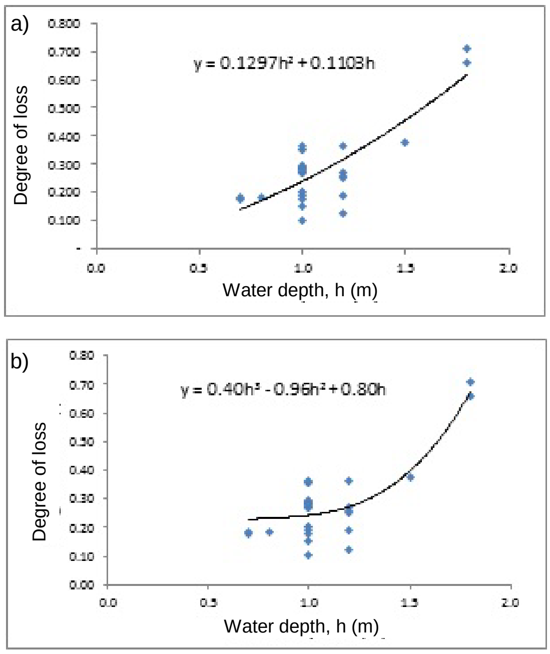

Fig. 6. Relationship between water depth and degree of loss acc. to the two different models: a) the second-order polynomial model (M_3), b) the third-order polynomial model (M_4); source: own study

Table 7 indicates that the magnitude of the losses in the usual process is 1.081 m for 31 houses at risk, ranging from 0.70 to 1.80 m, with a median of 1.00 m. The average damage is 209,129.03 IDR per unit, ranging from 89,000.00 to 518,000.00 IDR, with an average of 203,000.00 IDR. Comparing the two models, the second-order polynomial (a) generates the mean DoL of 0.2781, ranging from 0.1408 to 0.6188, with a median of 0.2400; while the third-order polynomial (b) generates the mean DoL of 0.2800, ranging from 0.2284 to 0.6734 with a median of 0.2427.

Table 8 presents the average *RMSE*, and Figure 7 illustrates in more details the differences between M3 and M4 models, as shown by the boxplots.

Table 7. Summary statistics of data set concerning the value of architectural loss of the houses (number of observations = 31)

Statistic	Symbol	Process intensity (m)	Loss (IDR)	DoL (a)	DoL (b)
Minimal	$h_{(1;31)}$	0.700	89,000.00	0.1408	0.2284
Mean		1.081	209,129.03	0.2781	0.2800
Median		1.000	203,000.00	0.2400	0.2427
Maximum	$h_{(31;31)}$	1.800	518,000.00	0.6188	0.6734

Explanations: a = the second-order polynomial, b = the third-order polynomial, h = water depth.
Source: own study.

Table 8. The results of root mean square error (*RMSE*) for architectural parts of the houses

Model (M)	Function	Mean *RMSE*
M_3	second-order polynomial	0.0766
M_4	third-order polynomial	0.0672

Source: own study.

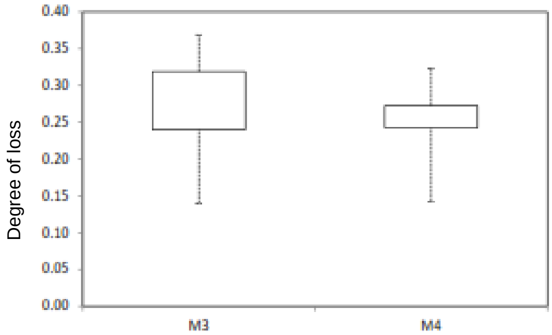

Fig. 7. Boxplots highlighting the ranges in the degree of loss (DoL) for the M_3 and M_4 models

Table 8 shows that the M4 model has lower *RMSE* (0.0672) compared to the M3 model. Therefore, the third-order polynomial function is referred to as M*.

The boxplots presented in Figure 7 indicates that the architectural model has no box-lower because the lower quartile value is equal to the median of the data. Most of the architectural damage occurred at the same water depth (between 0.70 and 1.20 m). Finally, the model was adjusted to the overall data set (31 points) for the architectural condition of the houses, creating Equation 4.

$$\text{DoL} = 0.40\, h^3 - 0.96\, h^2 + 0.80\, h \tag{4}$$

DISCUSSION

The structural condition of the second-order polynomial model (M_1) shows an overestimate prediction of DoL for the water depth greater than 1 m. On the contrary, the third-order polynomial model (M_2) represents the trend in the data more appropriately and shows no systematic bias. M_2 model shows the same trend for its data distribution pattern, as shown in Figure 4. The overestimate characteristic of M_1 model leads to the higher *RMSE* and variance distribution, as illustrated in Table 5. The final model represents the definition of the vulnerability index to water depth; the vulnerability increases significantly. The process intensity from 0.90 to 1.00 m is relatively equal, indicating relatively similar vulnerability. When the process intensity is >1.00 m, vulnerability and DoL rapidly increase. The highest DoL is 0.227 for a water depth of 2.00 m.

The architectural condition of the house has a similar trend to the structural one, the architectural condition of the second-order polynomial model (M3) showed that estimated DoL is overestimated for the water depth greater than 1 m. Conversely, the third-order polynomial model (M4) represents the trend in the data more appropriately and does not show any bias; instead, it shows similar behavior concerning the data distribution pattern. The overestimate nature of the M3 model results in a higher *RMSE* distribution and variation. The less severe flood can significantly increase the DoL of the architectural components of the house compared to the structural ones. The final model is generated, representing the definition of the vulnerability index to water depth, and the vulnerability increased significantly. For the process intensity between 0.70 and 1.00 m, the increase of DoL is very small. DoL begins to increase gradually when the process intensity ranges from 1.00 to 1.20 m, indicating that vulnerability is slowly increasing. Both vulnerability and DoL increase extremely when the process intensity is >1.20 m, with the highest DoL of 0.673 for a water depth 1.80 m.

The amount of losses related to the architectural elements of the house is smaller compared to the structural one as it is not its main component. The magnitude of losses experienced by residential housing in the study location for the structural and architectural elements of the houses indicates the necessity to focus on the vulnerability assessments due to a flood disaster. Therefore, the establishment of the post-flood rehabilitation expenses for the structural and architectural elements is more suitable for future conditions. The focal points of this information are critical to serving as effective management to design flood disaster mitigation strategies and may serve as a basis for flood risk management [BORGA *et al.* 2014; DE MARCHI, SCOLOBIG 2012; KARAGIORGOS *et al.* 2016]. The points are as follows:

- the accurate physical vulnerability formulation can better reduce the loss of lives and property;
- the conformity of the housing construction location and the level of physical vulnerability;
- the conformity of the type of housing materials and the level of physical vulnerability;
- the conformity of the housing rehabilitation cost budgeted and the level of physical vulnerability;
- determining the people prioritized for housing rehabilitation aid.

CONCLUSIONS

The results of this study inform that the third-order polynomial functions indicate the best relationship between the magnitude of the water depth and the degree of loss for structural and architectural conditions. *RMSE* estimates the accuracy of the model, and it indicates reliable results. As established in the distribution requirements, the vulnerability significantly increases as the process intensity increasing. The buildings analyzed have been damaged by the water depth (≤ 2.00 m for structural and ≤1.80 m for architecture); thus, it is impossible to modify the model with a higher process intensity. This is the limitation of this study compared to previous studies including the losses due to higher process intensity [TOTSCHNIG, FUCHS 2013]. The shape of the curve generated is in line with the results reported by Karagiorgos, et al. (2016) for the exposed residential buildings.

The amount of losses experienced by residential housing in the study location for the structural and architectural elements of the houses indicates the necessity to focus on the vulnerability assessments due to a flood disaster. Meanwhile, the amount of losses related to the architectural elements of the house is smaller compared to the structural one as it is not its main component. Therefore, the establishment of the post-flood rehabilitation expenses for the structural and architectural elements is more suitable for future conditions. The focal point of this information is critical to serving as effective management to design flood disaster mitigation strategies.

ACKNOWLEDGMENTS

The authors would like to thank Syiah Kuala University and the Ministry of Education and Culture of the Republic of Indonesia for all the funding provided for this research.

REFERENCES

AHMAD S.S., SIMONOVIC S.P. 2013. Spatial and temporal analysis of urban flood risk assessment. Urban Water Journal. Vol. 10. Iss. 1 p. 1–24. DOI 10.1080/1573062X.2012.690437.

AZMERI, ISA A.H. 2018. An analysis of physical vulnerability to flash floods in the small mountainous of Aceh Besar Regency, Aceh province, Indonesia. Jàmbá: Journal of Disaster Risk Studies. Vol. 10. Iss. 1 p. 1–6. DOI 10.4102/jamba.v10i1.550.

AZMERI, SATRIA I. 2020. An urban flood inundation and damage assessment for disaster risk reduction in Johan Pahlawan subdistrict, West Aceh Regency. Proceeding of AIWEST. Bristol, UK. IOP Publishing [In press].

BAKER J.L. 2012. Climate change, disaster risk, and the urban poor: Cities building resilience for a changing world. Washington, DC. World Bank Publications. ISBN 978-0-8213-8845-7 pp. 132.

BALICA S.F. 2007. Development and application of flood vulnerability indices for various spatial scales. MSc Thesis. Delft. Unesco-IHE pp. 25.

BIRKMANN J. 2006. Measuring vulnerability to promote disaster-resilient societies: Conceptual frameworks and definitions. In: Measuring vulnerability to natural hazards: Towards disaster resilient societies. Ed. J. Birkmann. Tokyo. United Nations University Press p. 9–54.

BORGA M., STOFFEL M., MARCHI L., MARRA F., JAKOB M. 2014. Hydrogeomorphic response to extreme rainfall in headwater systems: flash floods and debris flows. Journal of Hydrology. Vol. 518 p. 194–205. DOI 10.1016/j.jhydrol.2014.05.022.

DE MARCHI B., SCOLOBIG A. 2012. The views of experts and residents on social vulnerability to flash floods in an Alpine region of Italy. Disasters. Vol. 36. Iss. 2 p. 316–337. DOI 10.1111/j.1467-7717.2011.01252.x.

FIRMAN T., SURBAKTI I.M., IDROES I.C., SIMARMATA H.A. 2011. Potential climate-change related vulnerabilities in Jakarta: Challenges and current status. Habitat International. Vol. 35(2) p. 372–378. DOI 10.1016/j.habitatint.2010.11.011.

FUCHS S., HEISS K., HUEBL J. 2007. Towards an empirical vulnerability function for use in debris flow risk assessment. Natural Hazards and Earth System Sciences. Vol. 7. Iss. 5 p. 495–506. DOI 10.5194/nhess-7-495-2007.

Government of West Aceh Regency 2019. Administrative area map.

HAUSMANN P. 1992. Die Schadenempfindlichkeit, ein Teilaspekt bei der Abschätzung des Schadenpotentials von Überschwemmungen. In: Forschungsgesellschaft für vorbeugende Hochwasserbekämpfung [Damage sensitivity, part of the assessment of potential flood damage. In: Research company for preventive flood control]. Internationales Symposion Interpraevent. Vol. 3. Klagenfurt. Internationale Forschungsgesellschaft Interpraevent p. 147–158.

KARAGIORGOS K., HEISER M., THAHER T., HUBL, J., FUCHS S. 2016. Micro-sized enterprises: Vulnerability to flash floods. Natural Hazards. Vol. 84 p. 1091–1107. DOI 10.1007/s11069-016-2476-9.

KASPERSON R.E., ARCHER E.R. 2005. Vulnerable peoples and places, in ecosystems and human well-being: Current state and trends: Findings of the condition and trends working group 1. Island Press. Washington. ISBN 978-0-415-64157-9 pp. 143.

KEILER M., ZISCHG A., FUCHS S. 2006. Methoden zur GIS-basierten Erhebung des Schadenpotenzials fűr naturgefahren-induzierte Risiken. In: GIS und Sicherheitsmanagement. Eds. J. Strobl, C. Roth. Heidelberg. Wichmann p. 118–128.

Keputusan Gubernur Aceh Nomor 028/782/2016 Tentang penetapan standar satuan harga barang bahan bangunan dan jasa permerintah Aceh tahun 2017 [The governor of Aceh Decree No. 028/782/2016 regarding the material unit price for public works and services] [online]. Banda Aceh, Indonesia [Access 12.09.2017]. Available at: https://bpka.acehprov.go.id/index.php/hukum/read/114/standar-satuan-harga-bahan-bangunan-dan-jasa-kebutuhan-tahun-2016.html

KRON W. 2009. Flood insurance: From clients to global financial markets. Journal of Flood Risk Management. Vol. 2(1) p. 68–75. DOI 10.1111/j.1753-318X.2008.01015.x.

MCLAUGHLIN S., COOPER A. 2010. A Multi-scale coastal vulnerability index: A tool for coastal managers. Environmental Hazards. Vol. 9. Iss. 3 p. 233–248. DOI 10.3763/ehaz.2010.0052.

MOEL H.D., VAN ALPHEN J., AERTS J.C.J.H. 2009. Flood maps in Europe – methods, availability and use. Natural Hazards and Earth System Sciences. Vol. 9 p. 289–301. DOI 10.5194/nhess-9-289-2009.

MONTESARCHIO V., LOMBARDO F., NAPOLITANO F. 2009. Rainfall thresholds and flood warning: An operative case study. Natural Hazards and Earth System Sciences. Vol. 9. Iss. 1 p. 135–144. DOI 10.5194/nhess-9-135-2009.

NASIRI H., YUSOF M.J.M., ALI T.A.M. 2016. An overview to flood vulnerability assessment methods. Sustainable Water Resources Management. Vol. 2(3) p. 331–336. DOI 10.1007/s40899-016-0051-x.

NASIRI H., YUSOF M.J.M., ALI T.A.M., HUSSEIN M.K.B. 2018. District flood vulnerability index: Urban decision making tool. International Journal of Environmental Science and Technology. Vol. 16 p. 2249–2258. DOI 10.1007/s13762-018-1797-5.

PAPATHOMA-KÖHLE M., ZISCHG A., FUCHS S., GLADE T., KEILER M. 2015. Loss estimation for landslides in mountain areas-an integrated toolbox for vulnerability assessment and damage documentation. Environmental Modeling and Software. Vol. 63 p. 156–169. DOI 10.1016/j.envsoft.2014.10.003.

Peraturan Menteri Pekerjaan Umum dan Perumahan Rakyat Republik Indonesia Nomor 28/PRT/M/2016 tentang pedoman analisis harga satuan pekerjaan bidang pekerjaan umum [Regulation of the Minister of Public Works and People Housing of the Republic of Indonesia Number

28/PRT/M/2016 concerning guidelines for the analysis of the unit price of work in the field of public works] [online]. Jakarta, Indonesia. [Access 15.09.2017]. Available at: http://ciptakarya.pu.go.id/bangkim/rp2kpkp/files/Permen%20PUPR%20No%2028%202016.pdf

RIEUX K.S., GAILLARD J.C., SHARMA S., DUBOIS J., JABOYEDOFF M. 2012. Floods, landslides, and adapting to climate change in Nepal: What role for climate change models? Chapt. 7. Climate change modeling for local adaptation in the Hindu Kush-Himalayan Region. Eds. A. Lamadrid, I. Kelman. Community, Environment and Disaster Risk Management. Vol. 11. Bingley, Emerald Group Publishing Limited p. 119–140. DOI 10.1108/S2040-7262(2012)0000011013.

ROBERTS N.J., NADIM F., KALSNES B. 2009. Quantification of vulnerability to natural hazards. Georisk. Vol. 3. Iss. 3 p. 164–173. DOI 10.1080/17499510902788850.

SALAMI R.O., VON MEDING J.K., GIGGINS H. 2017. Urban settlements vulnerability to flood risks in African cities: A conceptual framework. Jàmbá – Journal of Disaster Risk Studies. Vol. 9. Iss. 1 p. 1–9. DOI 10.4102/jamba.v9i1.370.

SMIT B., WANDEL J. 2006. Adaptation, adaptive capacity and vulnerability. Global Environmental Change. Vol. 16. Iss. 3 p. 282–292. DOI 10.1016/j.gloenvcha.2006.03.008.

TOTSCHNIG R., FUCHS S. 2013. Mountain torrents: Quantifying vulnerability and assessing uncertainties. Engineering Geology. Vol. 155 p. 31–44. DOI 10.1016/j.enggeo.2012. 12.019.

TOTSCHNIG R., SEDLACEK W., FUCHS S. 2011. A quantitative vulnerability function for fluvial sediment transport. Natural Hazards. Vol. 58. Iss. 2 p. 681–703. DOI 10.1007/s11069-010-9623-5.

UN-Habitat 2011. Cities and climate change: Global report on human settlements 2011. London–Washington, DC. United Nations Human Settlement Programme (UN-Habitat). ISBN 978-92-1-132296-5 pp. 128.

VOGEL C., O'BRIEN K. 2004. Vulnerability and global environmental change: Rhetoric and reality. Aviso. Vol. 13 p. 1–8.

WILSON G. 2012. Community resilience and environmental transitions. Routledge. London. eISBN 9780203144916 pp. 272. DOI 10.4324/9780203144916.

WURYANTI 2002. Mitigasi Kawasan Rawan Banjir Rob di Kawasan Pantai Utara Surabaya. Journal of Pomits Engineering. Vol. 3(2) p. C160–C165.

ZENTEL KO., GLADE T. 2013. International strategies for disaster reduction (IDNDR and ISDR). In: Encyclopedia of Natural Hazards. Encyclopedia of Earth Sciences Series. Ed. P.T. Bobrowsky. Dordrecht. Springer. DOI 10.1007/978-1-4020-4399-4_199.