

Responses to Reviewer 1

The authors develop a flood vulnerability method for the assessment of traditional residential buildings in Kuala Lumpur. The study includes a survey of 163 buildings using different building-level vulnerability parameters. This is a very interesting topic that contributes to the recent increase in studies looking at flood vulnerability, damages and mitigation measures at a building level, and it fits very well within the scope of NHESS. In my view, the paper would benefit from an improved explanation of the methods, mainly the parameter selection and valuation, and the findings regarding the vulnerability index (as discussed in more detail below).

We thank the reviewer for the thorough reading of the paper and the request for clarifications which have resulted in substantial changes to the manuscript. As a result we believe that the clarity of the manuscript is much improved.

Broad comments

–L. 185: what is the proportion and how was it determined?

Response: We thank the reviewer for highlighting this statement. At the outset of flood map development, we intended to remove an appropriate portion of gross rainfall to account for the volume of water that storm drains could accommodate. After researching what an appropriate proportion should be, we discovered that there is no clear design standard of drainage in use across the city. We also discovered several media reports stating that urban drainage in the city was ineffective. As a result, we made the decision to use the gross rainfall estimates, without adjusting them, rather than calculating a net rainfall amount to use in the modelling. We have adjusted the manuscript to correct the method description.

- Section 2.4: I miss a link between (some of) the parameters mentioned in table 2 and the way they impact a building's flood vulnerability. For example, I understand how footprint influences damages, but how does it link to vulnerability of a building? How does the surface condition link to the vulnerability of a building? The surface condition (permeability / infiltration rate) is commonly perceived as part of the hazard rather than vulnerability (e.g. Liu et al(2014))? It would be good to explain how each of the selected parameters contribute to vulnerability and how you differentiate the extent to which they contribute to vulnerability for each of these parameters.

Response: In this study, the vulnerability assessment consider the building characteristics and its surrounding environment as a system.

The surrounding environment, such as surface condition and drainage system, are closely related to the local permeability and runoff, and impact on the height of water. These parameters were further considered as current flood models are using general land use, but they do not consider the immediate surrounding, at the scale of the building, hence do not include local difference of surfacing and permeability for instance. Text has been edited to include a comprehensive description of the reason for inclusion of the various parameters

- Section 2.5 (Table 3): many flood building studies differentiate between 1 storey and 2 storeys (e.g Deniz et al. (2016); Englhardt et al. (2019)). Is it realistic to differentiate between an

inundation depth up to 3 storeys and 4 storeys or more? Especially because you state that “the maximum inundation depth due to flash flood for a 100-year return period is around 0.2m”.

Response: We agree that the difference between 1 storey and 2 storeys is more significant in terms of the damage to content. However building with more storeys impose higher pressure on ground and are more susceptible to post-flood subsidence. The flood hazard does not consider only flash flood but also riverine floods. The text has been changed to better explain how the parameter number of storeys is considered in this study.

- Section 3.1 could be improved by expanding the analysis of the index. E.g. L. 415 states that a normal distribution can be observed from fig 7a. This is not clear and needs to be elaborated on in the text as well as in the figure and its caption. L. 417 states that the total VRi follows a lognormal distribution, while in fig 8 it follows a normal distribution. Next, the caption of 7 mentions “VI”, should this then be “VR”?

Response: The vulnerability ratings of each parameter follows a normal (or quasi-normal) distribution. However the density probability function (or cumulative distribution) of VI follows a LogNormal distribution as shown in figure 7b. This portion of the paper has been redrafted to clarify these and other aspects of the description of the index.

- I think it is very important to emphasize that you are calculating the relative vulnerability. I was initially expecting the vulnerability classes to be categories within the range of 110 (the overall possible minimum) to 1100 (the overall possible maximum). Please elaborate in paragraph at L.320 why this decision was made.

Response: The categories in the manuscript were derived from the actual range of the samples. This was made to emphasize the differences within the sample as the range close to the two extreme values are not attained. Nonetheless to show the generic value of the approach, we have recast the results within the full theoretical values, i.e. 110 to 1100 for 11 factors, to re-categorise the vulnerability classes. This will make it possible to carry out future comparison with other studies using the same approach. The text and table 4 and subsequent diagrams have been changed accordingly.

- The percentages of the sample column of Table 4 do not add up to 100%.

Response: In accordance with the previous comment, we have changed Table 4, and rechecked the numbers. Thanks.

- The abstracts states that: “The paper discusses these in relation to a scenario event of 0.1% Annual Exceedance Probability (AEP), based on hydrological and hydraulic models developed for the Disaster Resilient Cities Project.” However, I can’t find a mention of this in the body of the manuscript.

Response: the abstracts has been redrafted to shorten it and the relation to the project is explained in the introduction L107 to 110

Minor things:

- L. 48 “control”: not clear what is meant here.
- L52 “...political negotiation”: these statements look stronger when backed-up with (a) reference(s).
- L. 54 maybe include some examples of “Non-structural measures” that provide “faster flood mitigation”.

Response: This and the above sentences have been redrafted to provide more explanation and references.

L. 63 “UNDRR”, write the actual name when using the acronym for the first time.

Response: Full name has been added.

- L. 81-83: please add page number(s) of the direct quote (or paraphrase).

Response: Page number has been added.

- L. 89: it would be good to add a reference for the definition of vulnerability.

Response: the definition also refers to Rehman et al 2019

- Figure 2: maybe crop the high rises from 2b so the focus is on the vernacular house. - It may be nice to add a map (or add it to fig 2a) showing the locations of the gauges.

Response: Modified.

- L. 207: along river network of the study area -> the river network

Response: Modified.

- L. 262 (“...by building type”): it would be good to include some references to support this statement.

Response: Reference added

- L. 352 “2415 to 4105 RM (525 to 890 C” -> it would be very useful to add the euro value to each mention of an RM value.

Response: Thanks. Good suggestion.

- L. 364: typically ranges

Response: Modified.

- L. 408: number of storey -> number of storeys

Response: Modified.

- Fig 7a and L. 415: it is unclear from figure 7a which of the variables represents the roof height. In general, this figure deserves a little bit more explanation and probably best to update the labels with the wording used elsewhere for each of the parameters (same holds for other figures such as fig 10).

Response: Thank you for pointing out the inconsistency. The roof height was not used in this analysis and it has been removed from figure 5, as it was misleading. Attention has been paid to use the same name and same order for all the parameters in all figures and tables.

- L. 424. “and smallest” -> and the smallest

Response: Modified.

- L. 424 “The largest VR is 852.5, and smallest is 477.5.” Refer to table 4.

Response: Modified.

- L. 461 “3 different scenarios” -> three different scenarios

Response: Modified.

- L. 474 “total number of building” -> buildings

Response: Modified.

- L. 475. “the total building” -> total number of buildings

Response: Modified.

- Fig 11b caption: SAMRT -> SMART

Response: Modified.

- L. 478: the -> The

Response: Modified.

- L. 483 “without SMART Major losses”->major

Response: Modified.

-L.483“concentrate”->concentrated

Response: Modified.

-L.487“was assessed to have” ->was found to have

Response: Modified.

-Fig12. The doubley-axisis fine, but may be adjust the colours to improve legibility (e.g. in 12a, the number of flash-flooded buildings and the cumulative graph are around a water depth of 0.1- 0.3 are difficult to decipher).

Response: Modified.

- L. 499. Flood has become a major hazard worldwide. -> better to add a reference for this statement.

Response: Modified.

- L. 501. The word “dearth” is a bit archaic, maybe better to use “lack of” or “limited”

Response: Modified.

L. 533 “varying the % of run off” -> percentage of run off

Response: Modified. Thanks for all the suggestions.

Responses to Reviewer 2

I have now read the paper titled: "Flood Vulnerability Assessment of Urban Traditional Buildings in Kuala Lumpur, Malaysia". The paper focuses on the vulnerability of buildings to flooding in Malaysia by developing a vulnerability index for each building based on a number of parameters and by actually taking a step beyond and calculate also the economic loss under different flood scenarios. The paper presents an interesting approach to vulnerability assessment however it demonstrates also a number of significant weaknesses.

We thank reviewer for the critical observations relating to the methodology of the paper and the request to expand on the impact and possible use of the study in the community. We believe the reviewer's query were most stimulating and hopefully the answers are equally satisfactory. The manuscript has been amended to reflect these observations and discussion.

In more detail:

Title: The title indicates that the main focus of the paper is the vulnerability assessment of buildings, however, the paper goes beyond that: a hazard map for different scenarios is produced and the possible economic loss under different scenarios is assessed. The title should probably change in order to include all that. Moreover, according to the title the focus is on traditional buildings, whereas in the abstract the buildings are referred to as urban heritage buildings which indicates something else and elsewhere in the text as residential buildings (page 3, line 101). This should be also considered in rethinking the title of the paper.

Response: We thank the reviewer for the consideration of the relevance of the title to the content of the paper. It is true that we do not only assess vulnerability but we have tried to determine the risks posed to these buildings by 3 hazards scenarios. The emphasis of the paper remains on the multi-scale vulnerability, which is novel, rather than on the risk, which is assessed in a more conventional way. For what concerns the buildings, these are indeed traditional, considered as a whole and in this particular setting, they represent an important heritage, within an area which is considered a protected area for minority settlement, and the specific buildings are residential. So all the above terms apply. We have changed the title and some of the introduction to reflect the reviewer's observation.

Abstract: the abstract is rather long and gives too much detail (e.g. field surveys with Google street view) but also it does not refer to additional aspects that the paper covers such as the economic loss calculation.

Response: The abstract has been updated to reflect the whole content of the paper and shorten it.

Introduction: in the introduction but also elsewhere in the text the authors refer to nonstructural measures but they never connect them to the results of their study or their aims. Also in the introduction, they refer to floods but they do not explain what kind of floods they are looking at. Later on in the manuscript, the authors shed light on that matter but it would be better if this would be done earlier on.

Response: By non-structural measure in this paper we mean adaptive measures at local levels, spatial planning (flood risk adapted land use), building regulation and improvement of building flood resistance (wet-proofing and dry-proofing), flood action plans at a local scale, rather than financial measures such as insurance. Currently there is no sufficient evidence to prove that insurance is an effective measure to mitigate flood risk in Malaysia, to our knowledge. This is why reference to insurance is not made. We have clarified this in the Introduction (lines 52 to 59). We have added a reference to the type of flood analysed in the Introduction. See line 107-110.

SMART: What is the relationship to the authors with the SMART project? Is SMART part of what they are doing or do they just use readymade results from this project? It is not very clear. More clarification is also needed in the description of the SMART defense scenario. What does this include? What kind of defense measures? Where?

Response: SMART (Stormwater Management and Road Tunnel) project is a very well-known major structural flood control intervention, implemented in Kuala Lumpur in the first decade of the 21st century, a first worldwide. The relevant reference is included in the manuscript (Abdullah 2004). It is not within the scope of this manuscript to describe the SMART project in greater details than already included at lines 75 to 78, lines 190 to 193 and Table 1 in the revised manuscript, which clearly explain the operations of the SMART infrastructure and its effect on flooding controls in Kampung Baru area.

Figure 4: The authors estimate the time of peak at all ungauged locations within the study area. Why is this information relevant to the vulnerability assessment of buildings?

Response: This has been explained in the text. Lines 236-238.

Vulnerability index: Why do attributes vary between 3 and 5? Please clarify.

Response: Qualitative parameters have 3 attributes, (e.g. Low, medium, high,) while quantitative parameters have 4 to 5 attributes to ensure capture of important quantities which represent thresholds in vulnerability. A sentence has been added to explain this. Lines 336-338.

Vulnerability parameters: How do parameters 1 to 6 relate to the expected intensity? I guess 8 and this also has to be clarified) that in e.g. parameter 4. With the height of stilts between 0 and 0,5m(?) there is 55 VR. But if the height of the flood is 2m this specific building will be highly vulnerable.

Response: In most risk models, hazard and vulnerability are independent variables of the problem. The vulnerability is the propensity of the asset to be damaged given its own

characteristics, independently of the magnitude of the hazard. So in this case the vulnerability indicators are independent of the specific intensity of a particular flood with a particular return period in this area, as they are applicable to any other urban context. Therefore in the case of the stilts, the mean value for 0.5 refers to typical values or most probable values of stilts in urban contexts, with direct reference to construction practice. Lower values of the stilt will increase the vulnerability and higher values correspond to lower vulnerability. A building with stilts will still be less vulnerable than a building without. The differential between the flood height and the stilts height is accounted in the damage function as explained in section 3.3. Similarly for other parameters.

Weighting and classification: the authors do not refer to the weighting of the parameters or the classification of the final VRs. These are two important issues that should be considered when working with indices. A reference to the following paper which deals with these issues is considered in my opinion necessary: Papathoma-Köhle M., Schlögl, M., Fuchs, S. 2019. Vulnerability indicators for natural hazards: an innovative selection and weighting approach. Scientific reports.

Response: It is stated in the manuscript (section 2.5) that all parameters are summed to the VI unweighted as there is not sufficient historical recorded evidence or insurance payment to correlate specific vulnerability indicator to actual damage or losses so that a classification (ranking) or weighting of any of the parameters would have statistical significance. For this reason, this strategy is not pursued as already explained also in Stephenson, D' Ayala 2014. Also in fluvial flooding indicators relevance is less polarized than in torrential flooding. A reference to the paper above is included in the text.

Flood depth-damage ration function: page 14, lines 375-376: does the window height play a role?

Response: The window sill height has a role, as it can be seen by the steep slope in the region of 0.5 to 1 m. of the damage-flood depth function.

Figure 6: The authors create a vulnerability curve based on the mean values of several damage functions in the literature. Why is it expected that the buildings in Malaysia correspond to an average value of the existing models? The depth damage ration functions used in the paper are from different countries (Japan, Ethiopia, and global generic functions). Clarifications are needed at this point. What are the points in the figure? The building used in the present study. Please clarify.

Response: The curve in Figure 6 is not a vulnerability curve is a damage function. Historically researchers have been using heuristic damage functions derived from historic USA data and recently recast in FEMA MH documents. In recent years other damage functions from other part of the world are emerging, but these depend on available empirical field data. However in most cases such function are obtained as averaged value of insurance claims over grid cells, so the relevance to specific building type or urban conditions is rendered negligible by the averaging. Credible values of flood insurance claim for Malaysia to derive a robust damage function are not available currently. The reason for using several functions, some global, some local is to eliminate biases of any particular function, by averaging the expected damage ratio for the same flood depth. The high determination coefficient obtained shows and the relatively

modest std for each average point, shows that the process is acceptable, give the lack of more accurate data. A sentence to explain this is added in the text. A statement has been added to clarify that the damage function has been validated against other damage functions derived on the basis of historical damage. The vulnerability is taken care for each individual building as a multiplier of the damage function in equation 5.

Figure 7 and 8: The authors present some descriptive statistics of the index. Why is this information relevant? How and by who can it be used?

Response: The descriptive statistic is used to validate the empirical model both in terms of the choice of the parameters and the choice of the sample of buildings. For the parameters is seen that they are all differently distributed within the sample, hence they are uncorrelated, which then verify their necessity and sufficiency for inclusion in the vulnerability index model. The cumulative distribution of the VI_i shows that the distribution obtained is well represented by a lognormal regression, which again provide confidence in the sample choice to represent the occurrence of different vulnerability level in the district. The descriptive statistics also justify the division of the sample in vulnerability classes (table 4). These are chosen to divide the total vulnerability rating in equal ranges, while identifying threshold values which are critical to the likely response of the building to flood.

In terms of who should use this analysis: The vulnerability cumulative function can be used at the level of the single building owner, to determine the level of vulnerability of their property and identify features that can be improved to reduce such vulnerability. At the level of the district and with reference to the map as well as to the classes it can be seen that buildings belonging to the same class are clustered, meaning that there are local intervention at the scale of few compounds, (such as drainage, surfacing, slope) which can be address to reduce such vulnerability. At the municipal level, if this exercise is repeated for different neighbors then a ranking of them in relation to the mean and dispersion of the VI function can provide support to decision making in terms of nonstructural flood defenses at neighbor scale. Text has been added to explain this at lines 610-620.

Table 4: the classification of the vulnerability classes has to be justified.

Response: The categories in the manuscript were derived from the actual range of the samples. To make our results more generic, we use the theoretical values, i.e. 110 to 1100 for 11 factors, to re-categorise the vulnerability classes. This makes our methodology and results more comparable with studies conducted in other areas.

Interpretation of results: The results are described but not interpreted or used to demonstrate the importance of the approach for specific end-users. For example, (page 17, lines 432-433) "the buildings in the eastern part of the area have higher vulnerability". Why is that (e.g. older part of town?) How can this information be used?

Response: please see new discussion and addition of two examples case which explain the meaning of the results for an individual building owner. At lines 527 to 544.

Page 18, lines 454-455: This needs to be discussed more There are two issues here: 1. Why is the number of floors a parameter of flood vulnerability anyway? Is a building with more floors more or less vulnerable to flooding and why? It can offer vertical evacuation to residents but apart from that does the number of floors contribute to the reduction or not of the physical vulnerability? And 2. The high number of floors means high building value which reduces the degree of loss. Some discussion on this kind of drawbacks of the approach is also needed.

Response: The text has been changed to better explain how the parameter number of storeys is treated in this study. See line 309-313

Estimation of replacement cost due to different flood scenarios: In my opinion the scenarios should also be reflected in the VR 8 see previous comment about vulnerability parameters.

Response: As we already mentioned the vulnerability in this study, as in most other literature on the subject, is independent of the hazard scenario.

Type of hazard addressed (page 20, line 485): this information comes too late. The authors focus on flash floods and river floods and they combine "the total flood risk". What is the difference between these two processes as far as their impact on the building is concerned? Why do the authors suddenly start talking about risk? Is this what they assess?

Response: This comment is related to two earlier comment from this reviewer. We have addressed both the type of flooding and the computation of risk in the title and in the introduction. We do not combine the flood type to compute a total risk. The risk associated to each of the 3 scenarios produced is evaluated separately and compared to the others.

Discussion: Some vital information is missing. what were their assumptions and uncertainties? How can this study be improved and further developed in the future? How can the results (e.g. the vulnerability maps) be used by end-users?

Response: This has been extensively addressed in the conclusions. Line 661-726

Conclusions: the conclusions should be stronger and show what the authors have really achieved with the specific study. Instead there are some repetitions (e.g. lines 564-576) without having a strong message at the end.

Response: This has been extensively addressed in the conclusions. Line 661-726

1 *Revised manuscript with track change*

2 **Flood Vulnerability and Risk Assessment of Urban Traditional Buildings in a Heritage**
3 **District of Kuala Lumpur, Malaysia**

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12

13 **Abstract:** Flood hazard is increasing in frequency and magnitude in Southeast Asia major metropolitan
14 areas due to fast urban development and changes in climate, threatening people's properties and life.
15 Typically, flood management actions are mostly focused on large scale defenses, such as river
16 embankments or discharge channels or tunnels. However, these are difficult to implement in town
17 centres without affecting the value of their heritage districts, and might not provide sufficient mitigation.
18 Therefore, urban heritage buildings may become vulnerable to flood events, even when they were
19 originally designed and built with intrinsic resilient measures, based on the local knowledge of the
20 natural environment and its threats at the time. Their aesthetic, cultural and economic values, means
21 that they can represent a proportionally high contribution to losses in any event. Hence it is worth to
22 investigate more localised, tailored, mitigation measures. Vulnerability assessment studies are
23 essential to inform the feasibility and development of such strategies. In the present paper we propose
24 a multi-level methodology to assess the flood vulnerability and risk of residential buildings in an area
25 of Kuala Lumpur, Malaysia, characterised by traditional timber housing. The multi-scale flood
26 vulnerability model is based on a wide range of parameters, covering building specific parameters,
27 neighbourhood conditions and catchment area condition. The obtained vulnerability index shows ability
28 to reflect different exposure by different building types and their relative locations. The vulnerability
29 model is combined with high resolution fluvial and pluvial flood maps providing scenario events with
30 0.1% Annual Exceedance Probability (AEP). A damage function of generic applicability is developed
31 to compute the economic losses at individual building and sample level. The study provides evidence
32 that results obtained for a small district can be scaled up at city level, to inform both generic and specific
33 protection strategies.

34 1. Introduction

35 The Sendai Framework 2015- 2030 identifies clearly both climate change and rapid urbanisation as
36 disaster risk drivers (UNISDR, 2015). Temperature rise and global warming are strictly correlated to
37 increased rainfall (Min et al 2011, Wang et al. 2017) and in turn with the increased frequency and extent
38 of droughts and floods (Pall et al 2011; IPCC, 2013, 2014; Mysiak et al. 2016). Flood risk however is
39 compounded not only by intensified hazard, but very importantly by increased exposure due to
40 increased urbanisation along coastlines, river basins and flood plains (Neumann et al. 2015, Kundzewicz
41 et al., 2013). Such flood risk becomes even more challenging in South and Southeast Asia, as observed
42 (Najibi and Devineni, 2018) and projected (Harabayashi et al 2013) flood frequency show dramatic
43 increasing trends.

44 Following studies on the increased flood risk caused by the increasing rate of impervious surface to
45 drainage capacity in urban areas, (e.g. Ashley et al. (2005), Jacobson (2011), Jha et al (2012), Liao
46 (2012)), the shift from control to adaptation in urban flood resilience is increasingly advocated by
47 governmental agencies, experts and developers alike. Structural mitigation measures have the objective
48 of reducing the hazard, i.e. the runoff, by diverting it and channelling it. However, structural measures
49 are mostly planned at large scale, require substantial investments, long implementation periods,
50 extensive socio-political negotiation. As a consequence of this long timeframe, they might turn out to
51 be inadequate, postponed or irreversible (Aerts et al 2014), and in many cases they prove to be
52 unsuitable for developing countries on economic and financial grounds (Inaoka et al 2019). **Non-**
53 **structural measures, such as measures at the building scale or small-scale urban rehabilitation measures,**
54 **however, can provide faster flood risk mitigation, yielding improved adaptability, (Andjelkovic, 2001;**
55 **Kang et al 2009), more distributed benefits and, as a result, better governance (Tullos, 2018). Such**
56 **measures are now widely advocated by governmental and non-governmental agencies in many**
57 **countries, as specifically suitable to heritage centres (Howard et al 2017). Other non-structural**
58 **measures, such as financial incentive and insurance are not investigated in this study, as there is**
59 **insufficient evidence of their implementation in the study area (Roslan et al 2019).**

60 Studies specific to Malaysia have shown that rapidly increasing flood events in recent decades are due
61 to unrestrained occupation of rivers by human activities, destruction of forest and extreme weather
62 events caused by climate change (Aliagha et al., 2013). Statistics show an average of 143 floods per

63 year since 2001, of which more than 90% are flash floods (Anip and Osman 2017). Such frequently
64 occurring floods cause a high level of threat to Malaysian citizens' personal safety and property, thereby,
65 inflicting considerable damage to the country's infrastructure (Nasiri & Shahmohammadi-Kalalagh,
66 2013). Data from the **United Nations Office for Disaster Risk Reduction (UNDRR)'s** Country Disaster
67 and Risk Profile ([Preventionweb](#) 2019) show for Malaysia that floods account for 98% of average
68 annual loss in the period 1990 to 2014. A report from the Malaysian Department of Irrigation and
69 Drainage (2003), identified an average of 29,000 sq.km or 9% of the country's total land area and more
70 than 4.82 million people (22% of the population) as affected by flooding every year. The annual losses
71 were evaluated at RM915 million (DID, 2003, accessed online 2019). At the beginning of the
72 millennium an integrated flood management strategy was launched, whereby the Malaysian government
73 invested in some major structural measures, along with non-structural measures and community
74 participation. (DID, 2003, accessed online 2019). In terms of urban flood mitigation, among the
75 **structural measures, the most conspicuous intervention is certainly the SMART (Stormwater**
76 **Management and Road Tunnel) project, aimed at alleviating the flooding problem in the city centre of**
77 **Kuala Lumpur caused by the Klang River, as well as reducing traffic congestion (Abdullah, 2004). The**
78 **SMART project is a flood diversion measure, realised as a tunnel bypass, diverting catchment discharge**
79 **from the Klang Basin.** Among the non-structural measures the government has also invested in flood
80 detection and warning systems, awareness campaigns and flood proofing guidelines for buildings with
81 basement (DID 2006; 2010). The effect of the SMART tunnel on the flood risk of the studied area is
82 analysed in this study (See sections 2.2 and 3.3).

83 Notwithstanding this proactive approach, the "Malaysia Disaster Management Reference Handbook
84 2019" states that: "Annually, floods account for the most frequent and significant damage, with 38
85 damaging events in the last 20 years, and are responsible for a significant number of humans lives lost,
86 disease epidemics, property and crop damage, and other losses". The Handbook also points out that risk
87 of floods has increased due to climate change, stating that "Malaysia had the highest percentage of the
88 population (67%) exposed to floods among ASEAN (Association of Southeast Asian Nations) member
89 states between July 2012 and January 2019" (**see CFE-DMHA, 2019, p 22**). With six major events in
90 the last five years, flooding remains a major source of risk and losses in Malaysia, with a dramatic three-
91 fold increase of population exposure in two decades. While the Malaysian government has officially
92 adopted a holistic approach to flood risk reduction from preparedness to post event relief, its

93 implementation has received critical reviews by several researchers (Shafiai and Khalid, 2016).
94 Flood vulnerability, refers to the susceptibility of goods and people in any region to suffer damage and
95 losses. An accurate assessment of such vulnerabilities is essential to devise effective flood risk
96 management (Rehman et al 2019). Vulnerability assessment studies, focusing on different scales
97 (Kundzewics et al 2019) and different dimensions (Rehman et al 2019), have demonstrated the
98 capability of predicting socio-economic damage and risk by floods. In an urban context, flood
99 vulnerability assessment of individual buildings, and the management of the associated risk, has also
100 proven to be an effective way to increase the flood resilience of the whole city (Stephenson & D' Ayala,
101 2014; Aerts et al 2014). Two approaches are common in flood vulnerability assessment, the physical
102 approach and empirical approach (Balica et al 2013). Physical approaches use hydrological models to
103 estimate the flood hazard and compute economic consequences for a particular event or area on the
104 basis of a damage index relating a measure of intensity of the flood to the associated economic loss.
105 Parametric approaches use a set of quantitative or qualitative indicators to rate the vulnerability of a
106 building or area, with no particular reference to the hazard intensity.

107 The present study is part of the 'Disaster Resilient Cities: Forecasting Local Level Climate Extremes
108 and Physical Hazards for Kuala Lumpur', an interdisciplinary 3 years project developed through a
109 partnership of UK and Malaysian academia, industry and local government institutions, supported by
110 UKRI and the Malaysian Industry-Government Group for High Technology (MIGHT). The flood risk
111 to traditional heritage houses in Kuala Lumpur, identified as one of the major contributors to disaster
112 losses in Malaysia (Bhuiyan et al 2018), is studied by adopting a hybrid approach using a hydrological
113 model to determine the flood hazard and a set of indicators to determine the vulnerability of individual
114 buildings. However, the present model does not compute the mechanical response of the building
115 envelop to water pressure (Custer and Nishijima, 2015).

116 Two different types of flooding are considered, pluvial flash flooding, caused by thunderstorms
117 characterised by localised rainfall of very high intensity and short duration, and fluvial flooding, caused
118 by monsoonal type long duration and low intensity rainfall over large area of the catchment. For both
119 types of flood, the expected depths are computed for a reference 0.1% Annual Exceedance Probability
120 (AEP). To determine the actual risk the present study uses a multi-scale approach to assess the
121 vulnerability of traditional houses in Kampung Baru (Figure 1), thus providing evidence to suggest
122 appropriate mitigation strategies at individual building, local compound and district scale. The empirical

123 vulnerability model used is particularly suitable for studies at the micro to meso scale levels, aiming at
124 identifying effective non-structural mitigation measures. It relies on a number of quantifiable and
125 qualitative parameters which allow to identify a number of construction typologies typical of the district,
126 with diverse vulnerability level. The local elevation around the building footprint and its position with
127 respect to any river courses are also recorded. By conducting on site and virtual surveys the
128 parameters that influence vulnerability can be determined and quantified, and the economic losses due
129 to flood hazards can be estimated, allowing to produce mappings which identify a ranking of risk at the
130 building and district scale, for a given hazard type. The hazard magnitude used is water depth, calculated
131 by developing 2D hydrodynamic models to simulate the behaviour of water conveyed by overland flow
132 and river systems in response to rainfall events of different frequencies and intensities. A damage
133 function of generic applicability is developed to compute the economic losses at individual building
134 and at sample level, considering both envelop and content damage and the loss of value associated with
135 the heritage character.



136
137 Figure 1: Pluvial Flood in Kampung Baru, 1st October 2019. Due to poor drainage, water depth of 1 meter was
138 reached after 2 hours of rain. (BERNAMA, 2019)
139

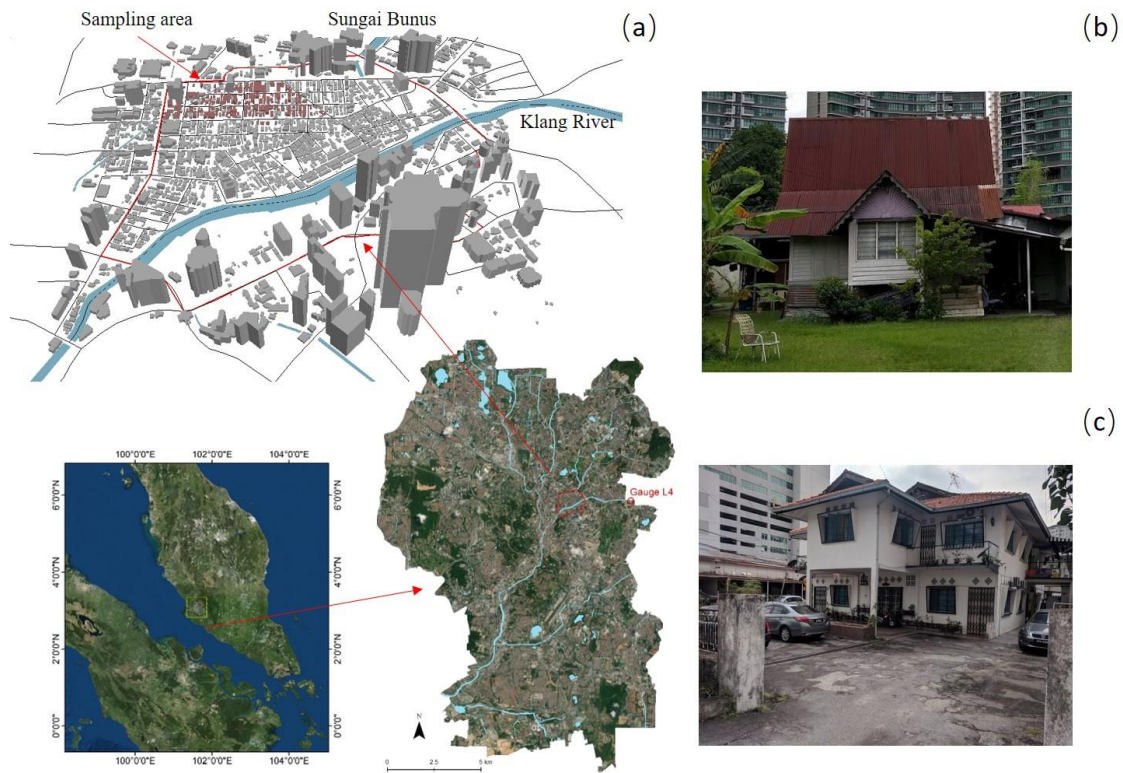
140 2. Data and Methods

141 2.1 Study Area

142 The Kampung Baru district is located in the central area of Kuala Lumpur enclosed between the Klang
143 River on the south east and the Sungai Bonus on the north-west (Figure 2(a)). Kampung Baru is an
144 historic Malay Agricultural Settlement dating back more than 100 years, spread over 100 hectares and
145 home to approximately 19,000 residents. While having witnessed the development of the city, and being

146 currently under pressure of redevelopment, this area, which has protected status, still contains a unique
147 building style, retaining the characteristics of both Malay traditional architecture and the ethnic Malay
148 lifestyle. Given its setting and local topography, Kampung Baru is prone to both river flooding and flash
149 floods, partly due to the poor drainage system (Menon, 2009; Bernama 2019) (see Figure 2).
150 Seo et al. (2012) recorded 121 traditional vernacular Malay houses, still inhabited by Malay people, in
151 Kampung Baru area. These represent an important cultural and architectural heritage as well as being a
152 touristic attraction and hence representing an important economic resource to the Malay Corporation.
153 Although these houses might have been altered in time, in terms of materials and form, they still
154 maintain two substantial characteristics related to the local environmental conditions: steep sloping roof
155 and floor raised on stilts (Figure 2(b)). These two iconic design features protect the space within from
156 high intensity precipitation and frequent flooding, rendering these houses intrinsically resilient to Malay
157 climate.

158 Examples of building on stilts in the area of study are shown in Figure 3. Earlier constructions are
159 characterised by buildings on short timber stilts (3a). In some cases, the space below is enclosed by
160 timber grids (3b). In wealthier construction, the stilts might have been made of stone (3c) and in modern
161 construction the stilts have been transformed in ground floor soft storey (3d) to accommodate
162 carparking, endorsed by the Department for Irrigation and Drainage Malaysia as a non-structural flood
163 mitigation measure.



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Figure 2: (a) Location of Kampung Baru in the centre of Kuala Lumpur (ESRI ArcGIS® Base Map); (b) traditional Vernacular House; (c) Modern Vernacular House.



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Figure 3: Typical buildings with stilts, (a) and (b) are more traditional buildings while (c) and (d) are modernized

2.2 Flood hazard mapping

172 Hazard maps showing flood extent and water depth associated with different types of flooding across
173 Kuala Lumpur were developed within the project for a range of return periods. The maps provide water
174 depth for pluvial flooding (also known as flash flood) and for fluvial (riverine) flooding. For fluvial
175 flooding, two scenarios are mapped: an undefended scenario where no mitigation measures (river flood
176 defences) are accounted for, and a scenario where the flood protection offered by SMART (see section 1)
177 is incorporated.

178 The maps were developed by analysing time series data from a selection of rain and river gauges across
179 the Klang Basin to calculate intensity rainfall hyetographs and river hydrographs for return periods of
180 20, 50, 100 and 200-years. The intensity rainfall and river flows were used as input for 2D hydraulic
181 modelling using JBA's proprietary JFlow® software (Lamb et al, 2009) to provide estimated depths of
182 inundation. The methods used to calculate the rainfall hyetographs and river hydrographs are described
183 in section 2.2.1. An important input to the flood mapping process is a digital terrain model (DTM). For
184 this study, a 0.5m resolution bare-earth DTM was provided by the Civil Engineering and Urban
185 Transportation Department, KL City Hall and City Planning Department, resampled to 5m resolution.
186 JFlow can be run in different configurations for different purposes. For large rivers, a fluvial model
187 configuration is used to apply hydrographs to the model at regularly spaced inflow points along the
188 drainage network. The volume of water that can be held within the river channel is estimated and
189 removed from the flood simulation. A JFlow simulation is run for each return period using a solver
190 based upon the two-dimensional Shallow Water Equations. For the SMART scenario a discharge-
191 limited directional culvert is constructed in the JFlow model, to represent the diversion and storage of
192 flood water between Kampung Berembang and the Desa Lake at Salak South, and is adjusted for each
193 of the four SMART operational modes as explained in Table 1.

194 For small rivers and pluvial flooding, a direct-rainfall configuration is used. This approach applies the
195 relevant hyetographs to each cell of the DTM. Different runoff and drainage rates are applied to reflect
196 spatial variations in soil type and land cover. Urban drainage systems can be accounted for by removing
197 a proportion of the total rainfall volume prior to running the JFlow simulation. But, in this study, no
198 such adjustments were made as there was insufficient evidence to support quantification of urban
199 drainage capacity across the city. Water depth in metres is calculated for each flood type (pluvial, fluvial,
200 and fluvial with SMART defence) and return period (20, 50, 100-year) and recorded in a set of GeoTIFF
201 raster files for use in Geographical Information Systems (GIS). In this study, flood maps of three flood

202 types for the 100-year return period are used in the estimation of flood hazard and risk, as this is a
 203 widely used return period in communication and decision making in flood risk prevention and
 204 management.

205 Table 1: Parameters of four SMART operational modes

| SMART Mode | Weather condition | Flow at stream gauge L4* | Flow diversion method | Road tunnel status | JBA return period map representing this scenario |
|------------|----------------------|---|---|--------------------|--|
| 1 | Fair | < 70m ³ /s | N/a | Open to traffic | RP20-RP200 undefended |
| 2 | Moderate rainfall | 70-150m ³ /s | Via lower drains only | Open to traffic | RP20 defended and RP50 defended |
| 3 | Major storm | >150m ³ /s | Via lower drains and possibly road tunnel | Closed to traffic | N/a |
| 4 | Prolonged heavy rain | >150m ³ /s and Mode 3 in operation for over 1 hour | Via lower drains and road tunnel | Closed to traffic | RP100 defended and RP200 defended |

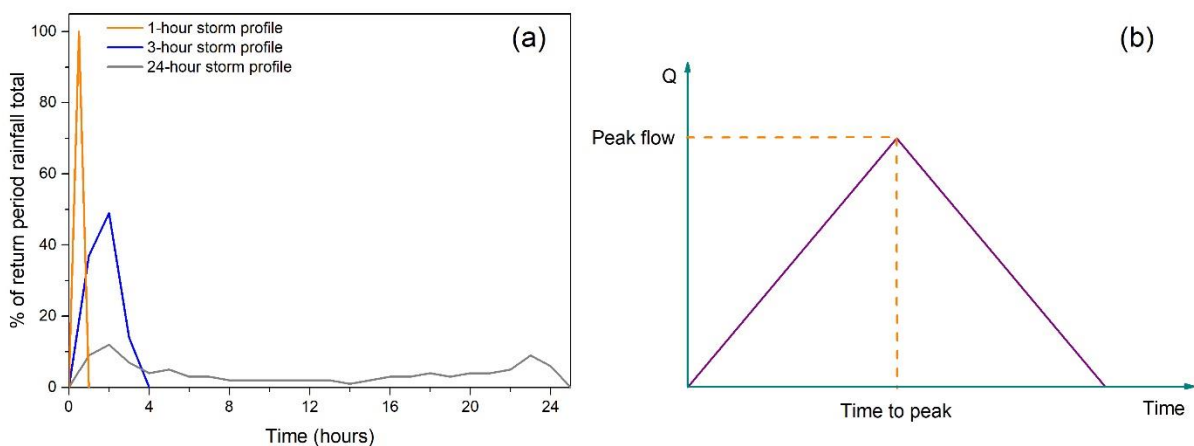
206 *L4 gauge is situated at confluence of Upper Klang and Ampang rivers.

207 2.2.1 Calculation of rainfall hyetographs and river hydrographs

208 Rainfall totals (in mm) were calculated at 11 rain gauge stations within a 6km radius of the centre of
 209 Kuala Lumpur. This was done by extracting peak-over-threshold values from the hourly rainfall record
 210 at each gauge and fitting them to a Generalised Pareto Distribution, to enable return period rainfall totals
 211 to be estimated for each gauge. This was done separately for the 1-hour, 3-hour and 24-hour storm
 212 durations. Spatial interpolation was then used to convert the estimates at the gauge stations into a set of
 213 continuous rainfall surface rasters across the entire study area, providing a rainfall total (mm) for each
 214 return period and storm duration on a 110m x 110m grid. Each gridded rainfall total was converted into
 215 a hyetograph to describe the temporal distribution of the rainfall for each of the three storm durations.
 216 Normalised rainfall profiles were developed by analysing hourly rainfall data for 20 events between

217 1997 and 2016 and calculating a mean 3-hr storm profile and a mean 24-hour storm profile across all
218 stations. Due to the lack of sub-hourly rainfall data, the 1-hour storm profile was assumed to be a simple
219 triangular shape. The storm profiles are illustrated in Figure 4(a) below.

220 River hydrographs were calculated at 2km intervals along the river network of the study area. Each
221 hydrograph was constructed using a linear function, defined by peak flow and time to peak estimates.
222 More advanced methods for deriving the shape of hydrographs are available, but in all but exceptionally
223 flat topographies peak flow can be considered the key variable in hydrograph shape, so for this study a
224 generalised triangular profile was considered appropriate. Firstly, peak flow was calculated at 10
225 streamflow gauges within the Klang River basin, using non-stationary flood frequency analysis. These
226 values were then regionalised using a linear regression equation for each return period, enabling peak
227 flow to be estimated at all ungauged locations within the study area, based on their catchment area (in
228 km^2).



229 Figure 4: (a) Storm profiles used in current flood modelling (b) Schematic diagram of the river
230 hydrograph shape
231

232 The time to peak at each gauge was calculated by extracting the median time to peak from all discrete
233 flood events recorded at the 7 streamflow gauges with hourly flow records available. A linear regression
234 equation was used to estimate time to peak at all ungauged locations within the study area, which
235 correlated time to peak (hours) to catchment area (km^2). Figure 4(b) shows a schematic diagram of the
236 river hydrograph shape. Although the time to peak isn't directly relevant to the vulnerability assessment
237 of buildings, it is a necessary step in constructing hydrographs which are needed to generate the hazard
238 maps for different return periods.

239

240 2.3 Data Collection

241 Given the multiscale approach adopted for the assessment of the flood risk in Kampung Baru, data is
242 obtained from multiple sources. A 3D building dataset and 0.5-meter resolution DEM dataset were
243 provided by UKM Southeast Asia Disaster Prevention Research Initiative (based on the 2013 LiDAR
244 dataset from the KL City Hall). These have been visualised in ArcMap 10.3 and manipulated to extract
245 data on building's position, footprint, position of the building's base relative to the road. This
246 information is essential to determine the depth of water at a particular building perimeter, given a flood
247 depth at the site. Other data were collected from a field survey and Google Street View. A preliminary
248 overview of all buildings in the targeted area of Kampung Baru was completed on Google Street View
249 (GSV), to identify the most interesting sector in the district and proceed to an initial screening of the
250 buildings' typologies present and the identification of critical parameter to best target the field survey.
251 The field survey of Kampung Baru, was conducted in July 2018, to gather specific data relative to
252 individual buildings. Critical parameters, difficult to identify from the GSV, such as the location and
253 dimensions of the drainage system, were typologically classified and measured on site, along with other
254 geometric parameters. A thorough photographic survey was also conducted at this stage, taking shots
255 for all visible and accessible elevations of sample buildings, as well as larger overview shots of the
256 whole study area. Specific features aimed at mitigating flood damage were also observed and recorded
257 during the field survey.

258 After detailed data was taken on a small sample of buildings during the field survey which also allowed
259 for identification of buildings' typologies, a further survey based on Google Street View (GSV) was
260 undertaken to gather additional data and cover a sample of buildings in excess of 160. This procedure
261 was successfully used by one of the authors to survey buildings to determine vulnerability and damage
262 in post-earthquake reconnaissance (Stone et al., 2017; Stone et al. 2018), and it is increasingly used to
263 produce exposure databases in an expedient and economic manner (Pittore et al. 2018). In GSV, a
264 continuous series of 360-degree panoramas, created by sewing multiple overlapping photos together to
265 display the real portrayal of a specific location (Street View, 2018), were observed according to the
266 location and the time when the photos were captured. In Kampung Baru images were collated in three
267 different years of survey, 2013, 2015 and 2017. In this study the latest version was chosen, and a full
268 front sight of a target building could be accessed online through the observation points allocated on

269 each street. During the survey, the qualitative parameters were collected visually, replicating the field
270 survey procedure. For quantification of other parameters, such as height of door threshold and window
271 sills, measured samples from the field survey were used as a reference to apply a measure of scale.

272 **2.4 Vulnerability Model**

273 Research on flood vulnerability and risk assessment encompasses a wide range of methods and focuses
274 (Rehman et al 2019). In an urban context a substantial component of losses is ascribable to physical
275 damage to vulnerable buildings and their contents (Chen et al 2016). Current flood risk assessment
276 study and damage models use either an empirical approach, relying on post event damage data
277 collection to determine vulnerability functions, or synthetic approaches, whereby the vulnerability
278 functions are based on expert opinion. Empirical methods are basin or catchment specific (Merz et al
279 2010), hence of limited transferability and applicability to other locations without substantial calibration.
280 Synthetic models are more adaptable spatially and temporally; however, they are often based on a single
281 variable relating flood depth to economic loss, possibly mediated by building type (e.g. HAZUS-MH,
282 FEMA 2013). Dottori et al (2016) present one of the few synthetic flood damage models based on a
283 component-by-component analysis of direct damage, correlating each damage component to different
284 flood actions and specific building characteristics. The damage functions are designed using an expert-
285 based approach validated on loss adjustment studies, and damage surveys carried out for past flood
286 events.

287 Historic data on flood damage and insured losses is not available for Kuala Lumpur or Kampung Baru.
288 It is increasingly recognised that models need to account for multiscale, from single asset to full
289 catchment area, and be able to consider many variables, in terms of both hazard intensity and asset
290 response (Amadio, 2019). Such models may rely on sophisticated physical modelling of the flood event,
291 while hazard-damage correlations are then determined using artificial neural networks or random forests
292 analysis of past damage data (e.g. Merz et al., 2013; Carisi et al., 2018), or Bayesian networks (Vogel
293 et al., 2013). For the majority of these models, however, while hazard and exposure are treated to a high
294 level of resolution, the individual building's vulnerability descriptors are limited in number and often
295 of a qualitative nature. Papatoma et al (2019) suggest a method for the vulnerability indicators
296 selection, which relies on data from systematically documented torrential events to select and weigh
297 critical indicators using an algorithm based on random forest. Although Kelman and Spence (2003),

298 Custer and Nishijima (2015), Hebert et al. (2018), and Milanesi et al. (2018) have used mechanical
299 approaches to determine the structural capacity of individual masonry walls to water pressure and derive
300 vulnerability functions which correlate physical damage to depth of water, such physical models have
301 not so far found direct application at urban scale

302 In the present study, a vulnerability index approach is applied to determine the relative vulnerability of
303 individual buildings. The building and its immediate curtilage are here defined as the system exposed
304 to the flood hazard. Therefore, the vulnerability index is obtained by identifying a number of parameters
305 which are considered all equally critical to the response of the system, ranging from its characteristics
306 to its surrounding conditions. The parameters used in the present study for characterising the building
307 vulnerability are adapted from studies conducted by one of the authors on historic buildings in UK
308 (Stephenson and D'Ayala, 2014) and the Philippines (D'Ayala et al. 2016). Parameters such as number
309 of storeys and footprint, provide indications on the volume of the building, its content and the bearing
310 pressure on the ground. This has implication on soil failure and subsidence following floods, which
311 could write off the building, hence outweighing the lower proportion of exposure of the total volume of
312 the building, usually assumed for multi-storey buildings. This is particularly relevant for the long term
313 flooding scenarios. Other descriptors such as height of the base, the stilts, the door threshold and
314 windows' sill, allow to estimate vulnerability to water breach in relation to flood depth. Finally,
315 building's fabrics and building's condition, provide a measure of the permeability of the building
316 construction materials and their likelihood to deteriorate when exposed to water. Besides these
317 building-specific parameters a classification of drainage systems in the immediate setting of the
318 buildings, of the surface condition surrounding the building and of any local flood prevention measure,
319 are also included as vulnerability indicators. This is because typically flood hazard models, although
320 take account of these parameters at urban scale, by assuming certain land uses and generic drainage
321 rates, they do not capture the local differences at the building scale. In this specific case study, as there
322 is no sufficient knowledge of the drainage system at the city scale, such data becomes a critical indicator
323 of vulnerability at the local scale, and one that can be directly surveyed on site. The full list of
324 parameters is illustrated in Figure 5 and Table 2. The attributes for each parameter and the rating scheme
325 adopted are further described in the next section.

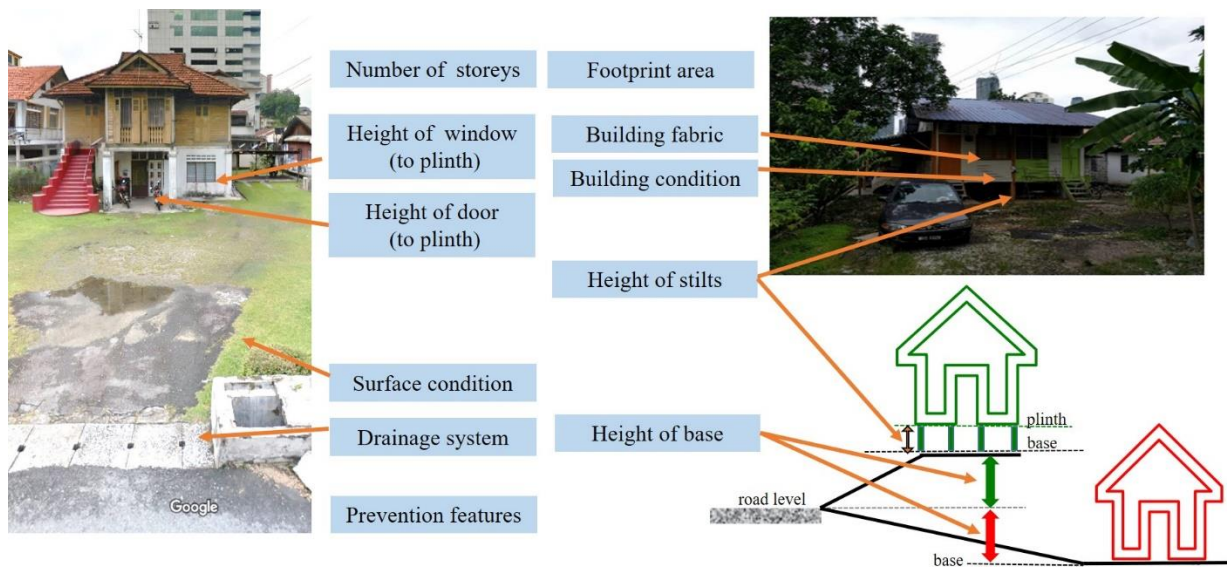


Figure 5: Example of traditional buildings in Kampong Baru and indication of the vulnerability index parameters

Table 2: Flood Vulnerability Index parameters.

| PARAMETER | DESCRIPTION | UNITS |
|-------------------------|--|----------------|
| 1. Number of storeys | Maximum number of storeys of the building | - |
| 2. Footprint | Building Footprint area at ground floor | m ² |
| 3. Height of base | Height of the base relative to the road | m |
| 4. Height of Stilts | Stilt height over building base and position of plinth | m |
| 5. Height of door | Height of door threshold to the plinth | m |
| 6. Height of window | Height of window sill to the plinth | m |
| 7. Building fabric | Structure and cladding material | - |
| 8. Building condition | The level of maintenance and building quality | - |
| 9. Drainage system | The level of drainage system around the building | - |
| 10. Surface condition | Type of surface around the building, surface cover, inclination and permeability | - |
| 11. Prevention features | The measures of flood prevention for the target building | - |

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333 **2.5 Vulnerability Ratings**

334 For each parameter a range of attributes varying between 3 and 5 is determined through logical
 335 derivation of the maximum possible number of responses and these are assigned a vulnerability rating
 336 (VR) on a scale from 10 to 100. Qualitative parameters have 3 attributes and quantitative parameters
 337 have 4 or 5 attributes to ensure important measurement thresholds, affecting the building's vulnerability
 338 are captured. The scale is divided into equal, unweighted parts according to the number of attributes,
 339 with the attribute indicating lowest vulnerability assigned the value 10, and the one indicating the
 340 highest assigned the value 100, as shown in Table 2, following the PARNASSUS V.1 procedure
 341 (Stephenson and D'Ayala, 2014). For instance, the parameter 'drainage system' has three possible
 342 outcomes: 'good', 'poor' and 'no', so that the numerical rating among these three outcomes can be
 343 assigned as 10, 55 and 100, to represent the increase in vulnerability. Table 3 summarise each parameter
 344 range of attributes and its conversion into vulnerability rating. The surface condition consists of three
 345 sub-parameters and the building fabric consists of two sub-parameters. In both cases, the vulnerability
 346 rating is calculated as the average ratings of the sub-parameters.

347 Table 3: Description of each parameter and the vulnerability value allocated for each possible outcome.

| Parameter | Sub-parameter | possible outcome | VR | Parameter | Sub-parameter | Possible outcome | VR | |
|-----------------------------|------------------------|------------------|------|-----------------------------|------------------------------|------------------|---------|-----|
| 1. number of storeys | | ≥ 4 | 100 | 7. Building fabric | frame material | timber | 100 | |
| | | 3 | 70 | | | masonry | 55 | |
| | | 2 | 40 | | | concrete | 10 | |
| | | 1 | 10 | | | wall material | timber | 100 |
| 2. Footprint | | > 500 | 100 | | masonry | | 55 | |
| | | $[400, 500)$ | 77.5 | | concrete | | 10 | |
| | | $[300, 400)$ | 55 | | 8. Building condition | | poor | 100 |
| | | $[200, 300)$ | 32.5 | | | good | 55 | |
| < 200 | 10 | excellent | 10 | | | | | |
| 3. Base | Height of base to road | < -1 | 100 | 9. Surface condition | | vegetation | no | 100 |
| | | $[-1, 0)$ | 77.5 | | poor | | 55 | |
| | | 0 | 55 | | good | | 10 | |
| | | $(0, 1]$ | 32.5 | | inclination | | concave | 100 |
| | | > 1 | 10 | | | | flat | 55 |

| | | | | | | | |
|--------------------------|------------------|------------|-----|----------------------------|--------------------------------------|-----|-----|
| 4. Stilt | Height of stilts | 0 | 100 | 10. Drainage system | convex | 10 | |
| | | (0, 0.5) | 55 | | permeability | no | 100 |
| | | >0.5 | 10 | | poor | 55 | |
| 5. Door threshold | door to plinth | 0 | 100 | | good | 10 | |
| | | (0, 0.1] | 70 | | no | 100 | |
| | | (0.1, 0.5] | 40 | | poor | 55 | |
| 6. Window sill | window to plinth | >0.5 | 10 | | good | 10 | |
| | | 0 | 100 | | 11. Flood-prevention features | no | 100 |
| | | (0, 0.5] | 70 | | yes | 10 | |
| | | (0.5, 1] | 40 | | *12. traditional construction | no | |
| | | >1 | 10 | | yes | | |

348 * factor used in equation (6)

349 Hence for each building and for each parameter a vulnerability rating VR_{ij} , can be defined, whereby
350 i , ranging from 1 to 163, denotes the building ID, and j , ranging from 1 to 11, denotes the parameter
351 under consideration. The vulnerability index VI_i for each building is therefore computed by summation
352 of the vulnerability rating for each parameter:

$$353 \quad VI_i = \sum_j VR_{ij} \quad (1)$$

354 The vulnerability index for each building can range from a minimum of 110 for lowest vulnerability to
355 a maximum of 1100 for the highest vulnerability. To compare the cumulative frequency of each
356 parameter and its relevance to the VI_i , a normalised vulnerability rating of each parameter nVR_{ij} and
357 the total vulnerability index nVI_i are calculated based on Eq (2) and (3).

$$358 \quad nVR_{ij} = \frac{VR_{ij}}{(VR_{ij_{max}} + VR_{ij_{min}})/2} \quad (2)$$

$$359 \quad nVI_i = \frac{VI_i}{(VI_{i_{max}} + VI_{i_{min}})/2} \quad (3)$$

360 where the normalisation is with respect to the mean value of the scoring range $\overline{VR_{ij}}$ and $\overline{VI_i}$. This
361 normalisation also allows comparison among different samples of buildings in different sites.

362 To further analyse the data, buildings are grouped in four classes by dividing the vulnerability range in
363 4 equal parts: Very Low vulnerability ($0.1, 0.325 * VI_{max}$), Low vulnerability ($0.325 * VI_{max}, 0.55 * VI_{max}$),
364 High ($0.55 * VI_{max}, 0.775 * VI_{max}$) and Very high ($0.775 * VI_{max}, VI_{max}$).

365 In this study, the VI of the surveyed buildings are concentrated in the middle two categories. To
 366 distinguish the vulnerability in this area, the low vulnerability and high vulnerability categories are
 367 further divided into two equal parts: Low ($0.325 * VI_{max}$, $0.4375 * VI_{max}$), Medium Low($0.4375 * VI_{max}$,
 368 $0.55 * VI_{max}$); Medium High ($0.55 * VI_{max}$, $0.6625 * VI_{max}$), and High ($0.6625 * VI_{max}$,
 369 $0.75 * VI_{max}$).

370 To determine the relative contribution of each parameter to the highest and lowest vulnerability index
 371 scores rVR_j was calculated based on Eq(4):

$$372 \quad rVR_j = \frac{\sum_k VR_{kj}/k}{\sum_i VR_{ij}/i} \quad (4)$$

373 where j denotes the parameter considered, k denotes the number of buildings in a given
 374 vulnerability class and i is the total number of buildings surveyed.

375

376 2.6 Economic loss

377 The vulnerability index VI_i derived in the previous section is a suitable measure to provide a scale of
 378 criticalities for particular properties in need of attention to improve their flood resilience. However,
 379 interventions and investments, whether at the individual property-owner level or at the level of the
 380 council or district authorities, are usually justified on the basis of cost-benefit analysis. Typically, this
 381 is expressed in terms of a replacement cost function which quantify the damage in monetary values and
 382 relates it to a measure of the flood intensity, such as flood depth. (Pistrika, 2014) The computation of
 383 the economic losses caused by flood events includes different components, that can be classified as
 384 tangible costs, including the physical damage to the building and contents, interruption of work etc.,
 385 and other intangible costs, such as loss or damage to objects with sentimental or cultural value, difficult
 386 to quantify (Kreibich et al 2014). The economic loss model proposed in this study considers the physical
 387 damage to each building and its content as it can be estimated on the basis of its specific vulnerability
 388 (see section 2.5) and a normalised damage factor $D(h_i)$ expressed as a function of the flood depth.
 389 Two different damage factors $D_b(h_i)$ and $D_c(h_i)$, for the building and contents, respectively, are used in
 390 the present study.

391 The physical damage to individual buildings can be calculated as the total replacement cost E_i

$$392 \quad E_i = C(i) * D(h_i) * F_{VR}(VI_i) * A_{Ti} \quad (5)$$

393 where i indicates the building identifier, C , D , F_{VR} and A_T are the construction cost per unit area of
 394 building, the Damage factor, the Vulnerability factor and the surface area of the building directly
 395 affected by the flood, respectively. They are derived as follows.

396 Building cost:

397 The replacement cost of buildings $C(i)$ includes two parts, the replacement cost of the building $C_B(i)$
398 and the replacement cost of contents $C_C(i)$.

$$399 \quad C_B(i) = F_B(i) * F_H(i) * C_0(i) \quad (6)$$

400 where $C_0(i)$ is the estimated construction cost in the study area depending on building type and
401 materials, $F_B(i)$ is a value factor depending on the perceived value of the building, $F_H(i)$ is a value
402 depending on the historic and cultural status of the building. The value factor F_B can be used to account
403 for the depreciated cost, i.e. the current remaining value, rather than the replacement value (Huizinga
404 et al 2017). However, as several of the buildings in the study area are either historic or traditionally
405 built, neither the depreciated cost or replacement cost might be appropriate to account for their cultural
406 value. Arcadis (2019) uses a range from 2415 to 4105 RM (525 to 890 €) per square meter to compute
407 the basic construction cost $C_0(i)$ of a detached house in Kuala Lumpur. This value includes the
408 construction and services (electrics, hydraulics and mechanical) costs. In this study the building fabric
409 material (timber, masonry, concrete) is used to determine the low, medium and high cost range, while
410 the building condition (poor, good and excellent) is used to determine the values of the adjustment factor
411 $F_B = (0.4, 0.7, 1)$, respectively. If the building is among the ones identified as of traditional construction
412 by Seo et al. (2012), or listed as of historic value in this study survey, a factor of $F_H(i) = 1.3$ is applied
413 to account for the additional cultural value as a touristic attraction.

414 Replacement cost for damage suffered by contents is also a non-negligible component of the total loss
415 suffered by building affected by floods. Huizinga et al. (2017) and FEMA (2013) assume that the
416 replacement cost of content typically ranges between 40 and 60% of the building cost for residential
417 properties. However, studies at the microscale (Appelbaum, 1985; Olivieri and Santoro 2000) show that
418 the proportion of content cost to structure cost also depends on type and quality of construction, level
419 of household income, etc. with a range from 15 to 60 %. Therefore, the content cost can be expressed
420 as:

$$421 \quad C_C(i) = C_B(i) * k_c \quad (7)$$

422 where k_c assumes values in the range (0.15 – 0.60), which is also determined according to the
423 building condition in this study.

424 Finally, combining the building replacement cost $C_B(i)$ and the content replacement cost $C_C(i)$
425 provides the total replacement cost for each building.

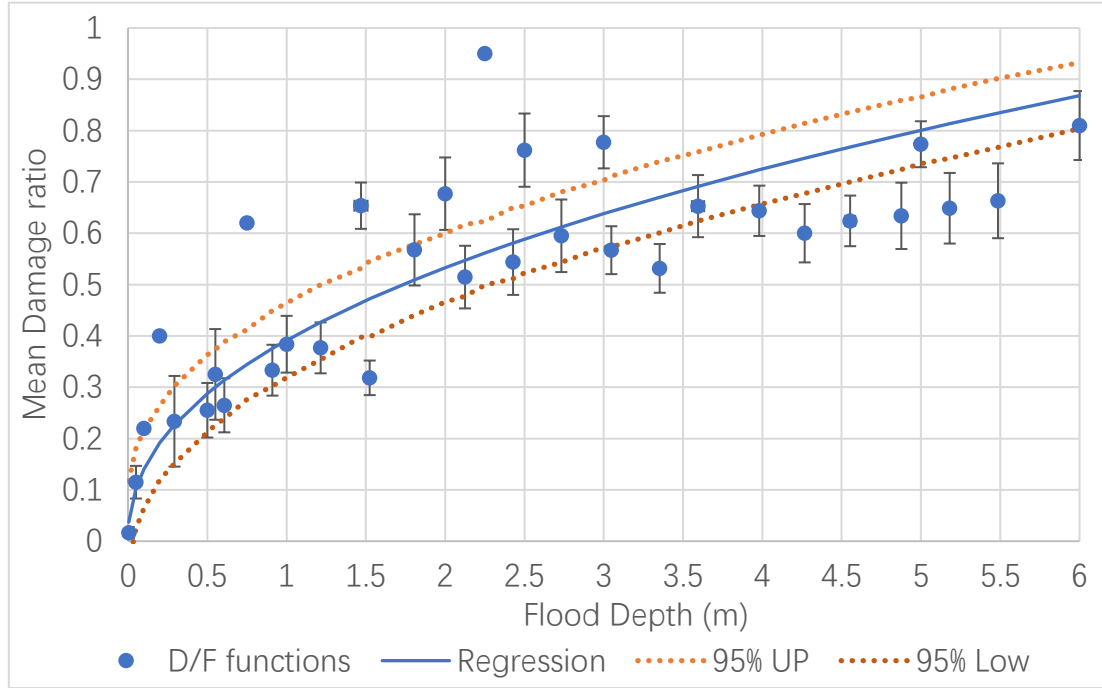
$$426 \quad C(i) = C_B(i) + C_C(i) \quad (8)$$

427 The Flood depth-damage ratio function $D(h_i)$, is a function of the water depth h_i , which in this study
428 is computed as the differential at each building site between the inundation depth FD_i computed by
429 the flood hazard model and the elevation of the building plinth above ground, i.e. the height of the stilts

430 (or other structure raising the plinth) HS_i .

431 $h_i = FD_i - HS_i$ (9)

432 Depth-damage ratio functions specific for Malaysia or Kuala Lumpur do not exist in literature, as data
433 on losses from past events has not been systematically collected and analysed to date, notwithstanding
434 the frequency of these, even just in the last decade (Romali et al ,2018). The derivation of synthetic
435 depth-damage functions relies on appropriate exposure databases, ad-hoc surveys, or heuristic
436 information on losses. When conducting studies at micro scale, as the present one, it is important that
437 the depth-damage ratio function used reflects the damage to single buildings, rather than aggregation at
438 grid cell level or larger, and also reflect the actual response of each single construction to flood. A
439 systematic review of several depth-damage ratio functions produced in literature (Appelbaum, 1985;
440 Lekuthai & Vongvisessomjai, 2001; Dutta et al 2003; Huizinga et al. 2017; MLIT, 2005; Pistrika et al.
441 2014; Enghardt, 2019) show the relevance of parameters such as construction material and quality,
442 number of storeys, conditions, etc, in determining the depth-damage function, leading to a non-
443 negligible variance among the available functions. However, as the proposed vulnerability model
444 discussed in section 2 accounts for these characteristics explicitly in the computation of the vulnerability
445 index VR_i for each building, it is appropriate to derive a mean damage ratio function, only dependent on
446 water depth, while the variance due to the building characteristics are accounted by the Vulnerability
447 Factor F_{VR} (VR_i) in equation (5). Figure 6 shows the damage ratio function obtained as regression from
448 the mean values of several damage functions available in literature, the associated variance for each
449 point in the series, and the 95% confidence bound. The regression damage function, with a coefficient
450 of determination $R^2 = 0.846$ (significant at 0.01 level), shows very good correlation with damage
451 functions produced on the basis of actual damage databases, such as the ones proposed by Pretenthaler
452 et al. (2010).



453

454 **Figure 6: Mean damage ratio as function of flood depth with point by point standard deviation**

455

456 Vulnerability factor F_{VR} .

$$457 \quad F_{VR}(VI_i) = \frac{VI_i}{VI_{median}} \quad (10)$$

458 The vulnerability factor $F_{VR}(VI_i)$ for each building is computed based on the vulnerability index
 459 calculated with equation (1) divided by the median value of the distribution of vulnerability indexes in
 460 the sample of interest. In this way the replacement cost function is calibrated directly on the local
 461 building stock of the study area, while remaining non-dimensional and of generic validity.

462 Total flooded area of each building A_{Ti} ,

$$463 \quad A_{Ti} = A_{fi} * n_{fi} \quad (11)$$

464 The total flooded area of each building A_{Ti} equals to the foot print of the buildings A_{if} times the
 465 **number of storeys** affected by the flood n_{if} , which is computed as

$$466 \quad n_{if} = \text{integer} \left(\frac{d_f}{h_s} \right) + 1. \quad (12)$$

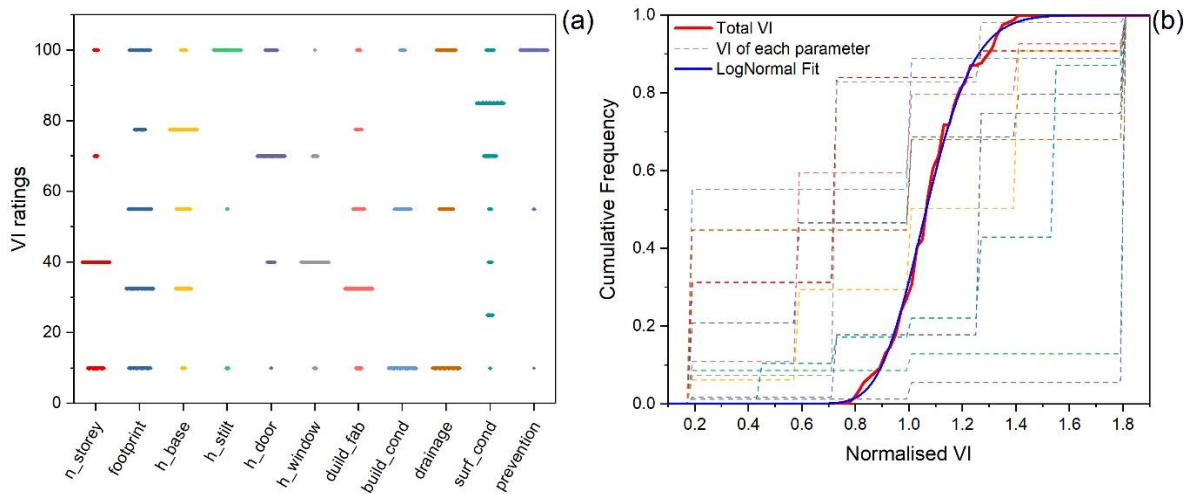
467

468 **3. Results**

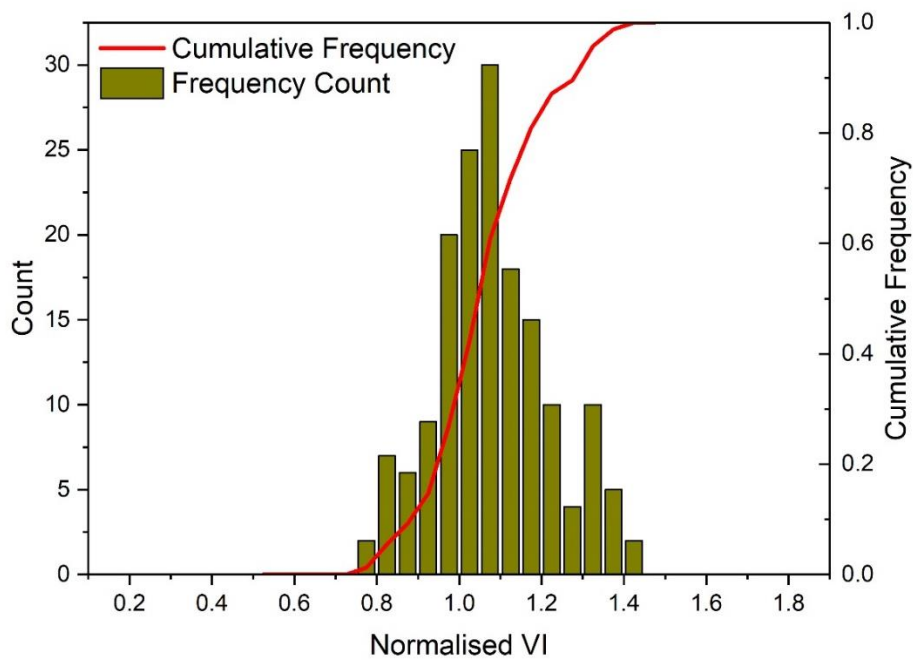
469 **3.1 Vulnerability Index of selected buildings**

470 **Based on the empirical model described above, the vulnerability rating VR_j for each parameter were**
 471 **attributed to each building and the total VI_i computed. Notwithstanding the relatively small size of the**

472 district considered, and the consequent uniformity of building height (mainly 2 storey) and footprint,
 473 Figure 7(a) and 7(b) show that the occurrence of each VR_j parameter attributes and each VR_j cumulative
 474 distribution, respectively, are all different, indicating that there is no direct correlation among the
 475 parameters chosen to represent the vulnerability of these buildings. Nonetheless, the VI_i cumulative
 476 distribution shows good agreement with a lognormal function (Figure 7b), with a coefficient of
 477 determination 0.997 (significant at 0.01 level).



478
 479 Figure 7: a) Scatter plot of the VR of each parameter b) The cumulative frequency of each parameter and the
 480 total VI for the classified sample of buildings.



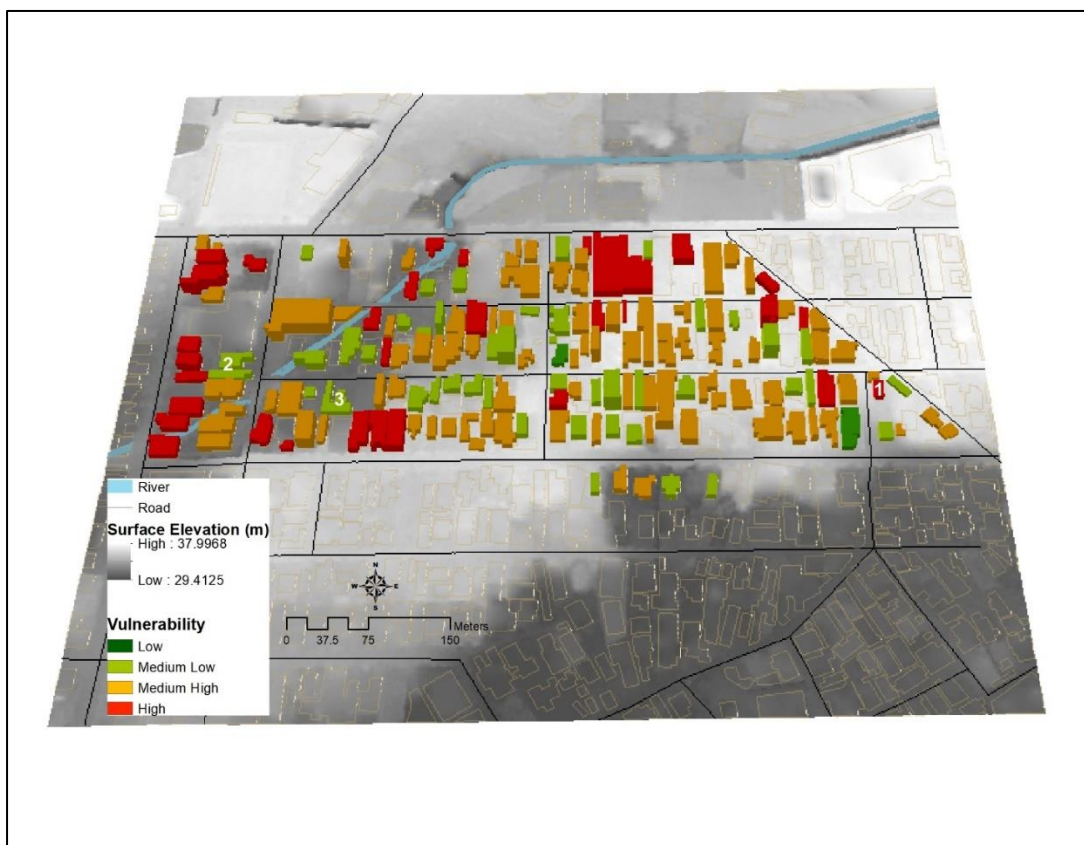
481
 482 Figure 8: Distribution of normalised vulnerability index VI_i

483
484
485

Table 4 Vulnerability Categories and number of buildings in each category

| Vulnerability Categories | | Quartile range VI | Percentage of value range | Occurrence in sample | Percentage in sample |
|--------------------------|-------------|-------------------|---------------------------|----------------------|----------------------|
| Very Low | Very Low | 110-357.5 | 10%-32.5% | 0 | 0 |
| Low | Low | 357.5-481.25 | 32.5%-43.75% | 2 | 1.2 |
| | Medium Low | 481.25-605 | 43.75%-55% | 45 | 27.6 |
| High | Medium High | 605-728.75 | 55%-66.25% | 85 | 52.1 |
| | High | 728.75-852.5 | 66.25%-77.5% | 31 | 19.0 |
| Very High | Very High | 852.5-1100 | 77.5%-100% | 0 | 0 |

486



487
488
489

Figure 9: Spatial distribution of VR of each building. Buildings marked 1, 2 and 3 are the cases described in section 3.2

490 **The largest VI_i value in the sample is 852.5, and the smallest is 477.5 (Table 4).** The distribution of the
491 values normalised with respect to the median is shown in Figure 8, together with the cumulative

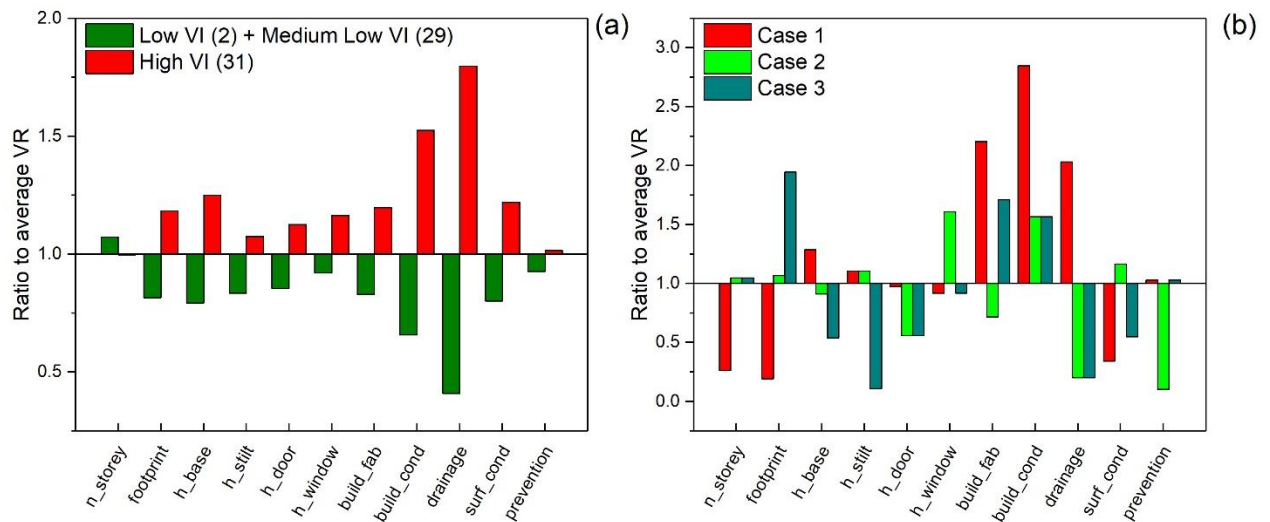
492 distribution. The full normalised range of the VI is divided in four equal intervals, which determine 4
493 classes of vulnerability: very low, low, high, and very high, as already explained in section 2.5 and
494 shown in Table 4. The classes low and high are further subdivided in low and medium-low, and medium-
495 high and high, respectively. There are no buildings falling in the extreme classes of very low or very
496 high vulnerability. Buildings with medium low and medium high vulnerability constitute the largest
497 portion of the sample. The low vulnerability class includes 1.2% and the high vulnerability class
498 includes 19% of the buildings. The spatial distribution of the vulnerability index shows a relatively
499 random pattern, without particular alignment to the roads' grid or the relative distance from the river.
500 (Figure 9). This confirms the lack of uniformity of the urban pattern of this district and the importance
501 of assessing the flood vulnerability at the scale of the individual building. As mentioned earlier, the
502 number of storeys and footprint are relatively uniform, hence the curtilage setting and the construction
503 details are really what characterise the variance in vulnerability. This is further explained in the next
504 section.

505

506 3.2 Relevance of factors contributing to vulnerability

507 Given the apparent random spatial distribution of buildings in the high and low vulnerability categories,
508 it is worth examining the relevance of the different parameters contributing to the VI_i of each building,
509 so that the adverse attributes can be mitigated to reduce risk to flood hazards. For buildings in the bottom
510 and top quintile of the distribution, as per eq. 4, the average scoring of each parameter in that category
511 is divided by the average scoring of the same parameter over the whole sample, hence highlighting the
512 parameters that most contribute to the tails of the distribution. This is graphically shown in Figure 10,
513 where 1 is the normalised value of the mean for each parameter over the whole sample. As there are
514 only 2 building in low VI category, another 29 buildings in the lower part of medium low VI , were
515 selected to compare with the 31 high VI buildings. It is shown that for the high vulnerability class, poor
516 drainage system, and building's condition, both have a value about 50% larger than the average score,
517 representing the most substantial contribution to high values of VI_i . The height of the base also
518 contributes to the higher VI_i , in accordance with the observation that often houses are built below the
519 road level at a distance from the drainage system and hence are located in concave, undrained settings.
520 This condition is particularly vulnerable in the case of high intensity- short duration pluvial floods.
521 Conversely, good drainage system, presence of stilts on the ground to elevate the plinth height, as well

522 as good building conditions, are key parameters in low vulnerability scoring.
 523 Further three specific buildings are selected, one located in the eastern part of the district, falling in the
 524 high class of VI_i ; the other two located in the western region of the district, characterised by a low value
 525 of VI_i (Figure 9). For the first case, the parameters that determine the high vulnerability are the lack of
 526 stilts, the poor building condition and permeable building materials, the lack of proper drainage and
 527 prevention measure, the setting of the building below the road level, although the curtilage of the
 528 building is characterised by a permeable and absorbent surface conditions. Topographically however,
 529 the building is set in the highest terrain of the district, and hence might be exposed to lesser hazard than
 530 other buildings. On the contrary, for the two low VI cases, although located in the portion of the district
 531 at lower topographical elevation and near the river, hence being characterised by high exposure, they
 532 are set at the same or higher level as the road or well above, both have door threshold set above average,
 533 both have good drainage, and finally they either have stilts or good prevention measures, to be overall
 534 less vulnerable, or better, more resilient to the flood hazard



535
 536 Figure 10: Relative values to the average VI for each parameter, (a) for the lower and upper quintile of the
 537 sample; (b) three selected cases as located in Figure 9

538
 539 This is a relevant finding, as commonly, for studies at mesoscale, it is assumed that parameters such as
 540 drainage and surface conditions can be assumed as uniform over an urban block, for instance. In relation
 541 to Kampung Baru the spatial distribution of the results demonstrates that the provision for drainage and
 542 permeable ground surfaces, might be rather fragmented, even along the same street, in parts owing to

543 plots redevelopments at different times. This further highlights the significance of local scale prevention
544 to reduce the flood vulnerability and risk.

545

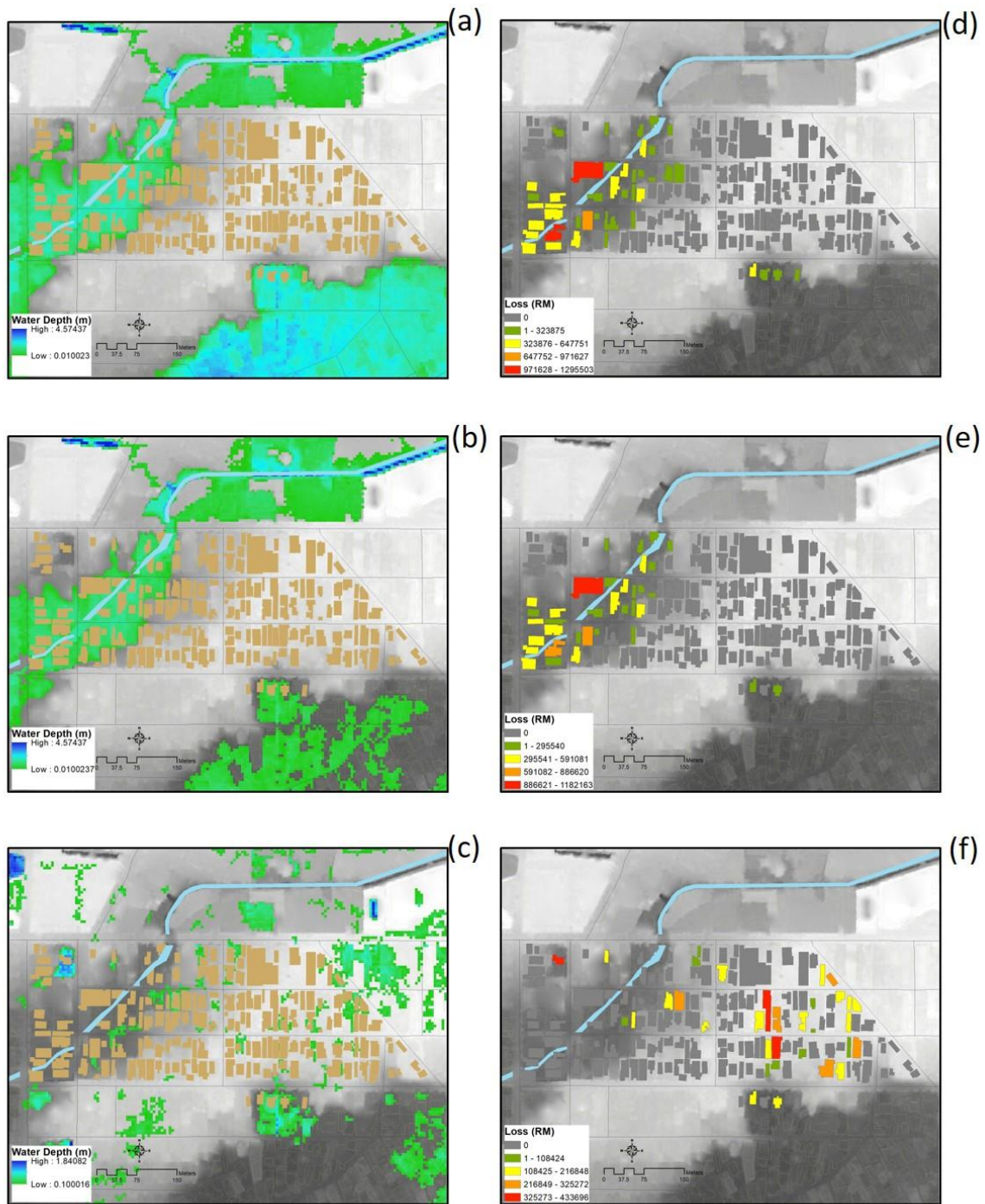
546 3.3 Estimation of replacement cost due to different flood scenarios

547 To estimate the flood damage to buildings, as introduced in section 2.2, three different scenarios are
548 considered: a pluvial flood, a fluvial flood without structural defences and a fluvial flood considering
549 the effect of the SMART tunnel defence (Abdullah 2004). For all scenarios the reference rainfall for
550 with 10% probability of exceedance in 100 years is considered here and the extent of flood water for
551 each scenario is presented in Figure 11 a)-c), together with the total losses (risk map) associated to d)
552 fluvial flood without SMART system in operation, e) fluvial flood with SMART system in operation, f)
553 pluvial flood. The number of buildings flooded and economic loss as a function of water depth at each
554 building are reported in Figure 12 where the water depth is defined as the difference between height of
555 plinth above ground and inundation depth, which provides a direct measure of the water depth entering
556 the buildings (Equation 9).

557 For fluvial flood, the flooded buildings are mostly located in the west part of the study area which is
558 close to the Sungai Bonus river. The maximum water depth is around 1.4 m, reducing to around 1m
559 with the action of SMART. The SMART has limited effect to flooding extent in the specific area of
560 study, as it mainly operates on the larger Klang river. For the pluvial flood, most buildings are flooded
561 to less than 0.2 meter, and have a scattered distribution across the study area. Notwithstanding the
562 differences in depth and spatial distribution of the three scenarios the total number of buildings affected
563 varies little, between 20% and 24% of the total number of buildings surveyed in the study area (Figure
564 12a). Note that buildings on the south-east portion of the map, close to the Klang river, are also suffering
565 fluvial flood; however, these buildings are outside the area of the present study.

566 The total replacement cost is calculated based on section 2.6. This amounts to around 5M RM ($\approx 1M \text{ €}$)
567 for pluvial flood for the 163 buildings. For river floods, the total cost is considerably higher, around
568 15M RM ($\approx 3M \text{ €}$) without defence and 10M RM ($\approx 2M \text{ €}$) with SMART in operation. The percentage
569 of cost to the total replacement cost are around 1.6%, 4.7%, and 3.1% for pluvial flood, river flood and
570 river flood with SMART respectively. The majority of economic losses for pluvial flood are
571 concentrated around 0.2m water depth; for fluvial flood without SMART the majority of losses are
572 concentrated in the range between 0.5 to 1.4 m; finally for fluvial floods with SMART, losses are

573 distributed mainly around 0.5m to 0.7 m with a maximum of 1.1.m. Figure 12a also shows a number
574 of building with negative water depth: these are buildings with stilts, where the flood depth is lower
575 than the position of the plinth above ground, meaning that although the buildings curtilage gets flooded,
576 this does not affect the building itself. This corresponds to 6% of the present sample. To emphasise the
577 relevance of the accurate elevation of the point of first breach in the building, i.e. the vertical position
578 of the door threshold with respect to the ground, Figure 12c shows the difference in total losses for each
579 of the 3 scenarios considered. The reduction in total losses ranges from a minimum of 13% for the
580 fluvial flooding with the SMART activated scenario, to a maximum of 20% for the pluvial flooding
581 scenario. Figure 12c also shows the range of variability of the total losses when the 95% confidence
582 bounds of the damage ratio function are considered.

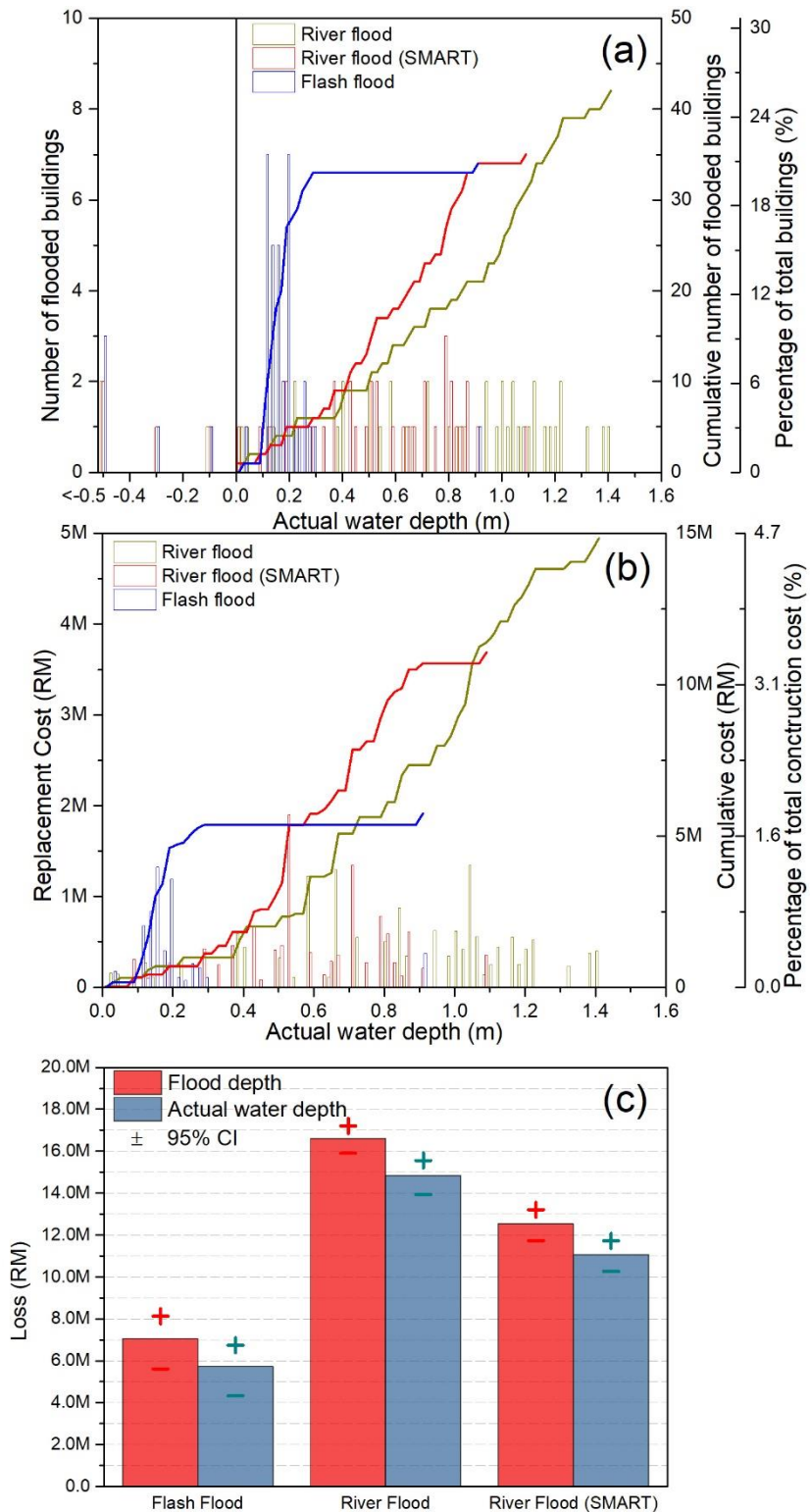


583

584 **Figure 11: Flood Maps of different scenarios (a) River flood without SMART (b) River flood with**

585 **SMART (c) Flash flood, and the estimated total replacement cost due to river flood without SMART**

586 **(d), with SMART (e) and flash flood (f). All under 100 year return period.**



587

588

589

590

591

Figure 12: Number of flooded buildings (a) and total replacement cost (b) for different flood scenarios. Some buildings with stilts get flooded but have no damage, hence are reported as having negative actual water depth. (c) The calculated difference in the loss between flood depth and actual water depth.

592 4. Discussion

593 While major improvements in modelling flood hazard and exposure have been achieved, there is still a
594 lack of compelling evidence on spatio-temporal patterns in vulnerability of societies around the world
595 (Jongman et al 2015). The Southeast Asian region is more vulnerable due to the higher population
596 density and higher frequency of rainfall. This study focusses on flood vulnerability of the buildings
597 in a small heritage community, Kampung Baru, in the city centre of Kuala Lumpur, Malaysia. This city
598 has experienced an increasing number of flood events due to the combined effects of observed
599 increasing extreme rainfall referred to as Wet Wetter Dry Drier pattern (Allan 2008, 2010) as well as an
600 increase of urban population, nearly doubled from 1980 to the current 1.8 million . As the trends for
601 these two variables are not slowing or reversing, it should be expected in the future that both flood
602 hazard and exposure in this city will continue to increase.

603 Buildings, being the primary shelter for people, the reduction of their vulnerability is critical in reducing
604 the risk to flood faced by population. By determining and quantifying the value of vulnerability and risk
605 for each building exposed to specific flooding scenarios, these can be visualised on thematic maps, thus
606 providing evidence to suggest appropriate design or protection strategies specific to each building in
607 the area of study. The present study has identified that higher vulnerability is related to absence or poor
608 drainage system, poor building's conditions and poor overall surrounding surface conditions. The
609 buildings with lowest vulnerability show a combination of good drainage systems and surface condition
610 and/or stilts at the ground floor or other forms of protection. The lognormal vulnerability cumulative
611 function obtained has generic validity and it is a synthetic representation of the vulnerability of the
612 district which can be used at different levels. For building owners, V_i can be used to determine the level
613 of vulnerability of their property and identify features that can be improved to reduce such vulnerability.
614 At the level of the district and with reference to the map as well as to the division in vulnerability classes,
615 it can be seen that buildings belonging to the same class are clustered, meaning that there are local
616 intervention at the scale of few compounds, (such as drainage, surfacing, slope) which can be address
617 to reduce such vulnerability. At the municipal level, if this exercise is repeated for different neighbours
618 and districts then a ranking of them in relation to the mean and dispersion of the V_i function can provide
619 support to decision making in terms of non-structural flood defences at neighbourhood scale. Thus,
620 several possible solutions can be provided to improve the flood vulnerability of building in Kampung
621 Baru or similar districts, among which some feasible strategies are:

622 1. Increasing the ground floor base elevation by either adding pillars or stilts at ground level in new
623 design . The raising floor on stilts is a traditional design of Malaysian vernacular buildings, common of
624 many surveyed cases in Kampong Baru, and such design is being modernised by introduction of open
625 car park at the bottom of high-rise building in Kuala Lumpur. This is considered as a soft measure in
626 the Malaysian national flood prevention programme (DID 2006). Moreover, as the maximum
627 inundation depth due to flash flood for a 100-year return period is around 0.2m, which is less than the
628 height of most traditional stilts, the stilts are also an effective way to prevent damage from pluvial flood.
629 The present study shows that such strategy can effectively reduce the flood vulnerability and hence risk
630 for individual buildings. For traditional buildings, which have been altered through time, this feature
631 can be reinstated to restore the traditional character and reduce vulnerability. However, this solution
632 without proper surface treatment and drainage systems may impact adversely neighbouring buildings.

633 2. Improving drainage system and surface condition. Residential buildings which have proper
634 drainage system or vegetation or permeable surrounding ground surfaces or alternatively, set on a higher
635 ground than the road, ensuring a downward slope from the façade to it, were assessed to be in the low
636 vulnerability class. These conditions are also reflected in the hazard model by varying the percentage
637 of run off in each grid, at a 5 m resolution. Improved drainage systems are recognised as an efficient
638 way to improve the flood resilience of residential buildings without altering their traditional or heritage
639 status. As mentioned above, good drainage is essential for the flood resilience to extend from the single
640 building scale to the urban block to the district.

641 3. Effectiveness of structural measures. The results obtained highlight that, although the operation of
642 the SMART tunnel can only marginally reduce the spatial extent of the flood and the number of
643 buildings affected, according to the simulation produced in this study, a reduction of about 27% can
644 be observed in the value of the maximum water depth and of about 50% in the cumulative value of
645 losses.

646 Hence a combination of non structural measures, e.g. use of stilts and proper surface treatment and local
647 drainage, and structural measures, e.g. SMART, appears to be the most effective strategy to increase
648 flood resilience from building scale to urban scale.

649 Large major cities in Malaysia, such as Kuala Lumpur, Penang, Petaling Jaya and Shah Alam among
650 others, have been established on floodplains and are increasingly prone to floods and flash-floods as
651 they grow in density and extension (Chan 2011). The use of structural measures is currently under

652 consideration to address the issue of flooding associated with further urban development. The findings
653 from the present study offer decision-makers an option of increasing building scale resilience, to make
654 structural measures more effective. This is particularly relevant in historical cities such as Penang,
655 where traditional Malay buildings are prevalent. The combination of structural and non-structural
656 measures is also in line with the aspirations of civil society groups that seek urban resilience within
657 ecological systems (Connolly 2019) and in line with national and international guidelines on flood
658 prevention damage for historic and traditional buildings.

659

660 5. Conclusions

661 In this study, a local empirical vulnerability model has been built to evaluate the flood risk to residential
662 buildings in Kampung Baru, Kuala Lumpur. Combining a field survey, Google street view and DEM
663 information, the data of 11 different parameters composing a building level vulnerability model, have
664 been collected and scored to rate the flood vulnerability of a sample of 163 buildings. A new economic
665 loss model is developed to quantify the flood risk in terms of replacement cost, considering both specific
666 vulnerability and a normalised depth-damage ratio function. The flood damage and economic loss were
667 then estimated based on the economic loss model under the flood hazards from 3 different scenarios.

668 In determining a risk model, a fundamental issue is the level of uncertainty associated to it. In relation
669 to the flood hazard modelling, uncertainty can be identified in the input and the simulation itself. In
670 terms of input, accuracy of water routing is dependent on the DTM accuracy. In the present study a high
671 resolution DTM (0.5m resolution LIDAR) is employed, and checks with aerial imagery and adjustment
672 are made to identify unrealistic flow pathways and amend them. Moreover river locations are defined
673 by analysing the DTM. As a result, the river network may contain false positives, i.e. rivers (and
674 therefore fluvial flood hazard) may be represented in areas where, in reality, there are no streams or
675 watercourses. A second source of input uncertainty is the hydrological input itself, and this is minimised
676 by including in the analysis only gauge data with long and complete records, however it is recognised
677 that gauge data availability in Kuala Lumpur and surrounding areas is poor. Uncertainties in the
678 modelling process arise from two orders of issues: the representation of the flow and the amount of
679 drainage in the model. In relation to the first issue, as each river section is modelled independently,
680 backwater effects at confluences are not represented; furthermore, current individual simulations
681 assumes boundary conditions whereby water can exit the model at the downstream boundary, while in

682 reality if the downstream is also in flood stage, this assumption is not correct. This is an intrinsic
683 limitation of the current fluvial JFlow model and no mitigation has been implemented for this study. In
684 relation to the overall catchment drainage a fundamental epistemic uncertainty is the location of culverts
685 in Kuala Lumpur, which have not been represented in the model. This is not necessarily a conservative
686 assumption as a blocked culvert may locally exacerbate flooding beyond the level expected in an
687 undefended (no culvert) scenario. Finally, the capacity of natural or artificial drainage systems across
688 the study area is represented at a broad scale and does not fully account for site-specific storm drains or
689 other localised features. A detailed land use dataset was combined with soil information and slope to
690 calculate variable percentage runoff rates on a 30m resolution grid. This resolution is appropriate for
691 the level of detail of the input (land use, soil and slope) information, but means that property-level
692 drainage systems cannot be accounted for.

693 From the perspective of determining the vulnerability, although increasingly the need for micro level
694 studies is recognised, most published work on flood risk analysis refers to generic building typologies
695 and their incidence on grid-cells containing several buildings, to characterise the exposure. In this
696 respect the vulnerability model proposed here has two advantages: identifies the vulnerability of each
697 specific assets on the basis of its geometry, material characteristic and level of maintenance, but also in
698 terms of its setting and hydraulic characteristic of its curtilage. This partly compensate the lack of
699 knowledge on drainage feature at the urban scale, from the modelling point of view, but most
700 importantly identifies deficiencies that can be mitigated at the scale of the single property. In
701 developing countries this can become an important tool for communication to stakeholders and
702 community involvement in mitigation strategies, through the mapping and visualization of the
703 vulnerability indicators. The sample used is relatively small, and although the robustness of the rating
704 process has been verified by cross correlating the scoring results of different surveyors, uncertainties
705 on the single buildings are related to the validity of the Google street map photo and the accuracy with
706 which measurements can be extracted from such pictures. In order to ensure applicability of the
707 methodology to other locations and to properly calibrate the single parameter's ratings and overall
708 vulnerability classes, larger samples should be studied..

709 A fundamental source of uncertainties in modelling losses, is the choice of an appropriate
710 damage/depth function, and its conversion in monetary terms. The first is usually mitigated by
711 calibrating any model on damage data for historic floods in the area or region and the second by

712 calibrating the replacement cost on insurance claim data. In the present study, both historic damage
713 and insurance claim datasets are not readily available in a format that can be used at this scale and in
714 this context. Therefore, rather than using a single arbitrary damage depth function, a large number of
715 functions derived for building types similar to the ones analysed have been used to obtain a mean
716 damage ratio function by regression. This was then validated by comparison with functions derived by
717 other studies on reach damage datasets. The fact that the damage function is independent of the specific
718 building typology or local exposure model, which are accounted for in the vulnerability model, renders
719 it of generic value and makes it applicable to other situations in Malaysia and worldwide. The
720 economic loss function considers the loss from both the physical damage to each building and its content.
721 The additional cultural value as a touristic attraction was rather crudely accommodated by an arbitrary
722 factor. There is an extensive, but also so far rather inconclusive debate in literature, as to how to compute
723 and quantify the increase in loss associated with the historic value of a property, both as it pertains to
724 its direct and indirect losses. This is an area that should be tackled in future by looking in detail at the
725 additional repairing costs and the loss in revenue from touristic business. The intangible aspects of
726 course deserves a different approach.

727

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732 Dept of Space & Climate Physics, Faculty of Maths & Physical Sciences) for providing normalised
733 rainfall profiles and gridded rainfall return levels for the Kuala Lumpur study area, used by JBA to
734 determine the hyetographs for the flood hazard simulations.

735 **Data availability**

736 Building data were collected from a field survey and Google Street View
737 (<https://www.google.com/maps/>). Primary data are strictly used within the project “Disaster Resilient
738 Cities: Forecasting Local Level Climate Extremes and Physical Hazards for Kuala Lumpur”. The data
739 of the research findings are the available from the corresponding author (DDA) on reasonable request.

740 **Author contributions**

741 DDA designed the research and analysed the results; KW and YY collected the data, analysed the results

742 and produced the visualisation; HS, AM and VP conducted the flood modelling; JJP discussed and
743 extended the findings. All authors discussed the results and drafted the final manuscript.

744 **Competing interests**

745 The authors declare that they have no competing interests.

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