



Flood shelter identification using a mechanics-based approach and triangular fuzzy analytical hierarchy process[☆]

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ABSTRACT

Flood events continue to cause substantial damage to people, infrastructure and communities. Effective evacuation planning is essential, and the identification of safe shelters is a key element in protecting people and property. Shelter selection depends on a reliable flood risk assessment that considers building characteristics, environmental conditions and occupant safety. This study proposes a three-stage framework for assessing and identifying shelter risks under flood disasters. The framework considers 3 criteria, namely hazard, exposure and vulnerability, and 14 subcriteria. These criteria and sub-criteria were evaluated using a hydrodynamic model, topographical data and an innovative application of a mechanics-based method (MBM) that assesses flood hazard from modelled water depth and velocity data. The relative importance of the criteria and sub-criteria was estimated with the Analytical Hierarchy Process (AHP) and Triangular Fuzzy Number-based AHP (TFN-AHP) approaches. Furthermore, the Geographical Detector Model (GDM) was employed to investigate the driving forces behind the contributing factors. The frameworks have successfully assessed 27 candidate shelters in Pontypridd, UK. The results showed that the MBM method was scientific for the hazard assessment, and TFN-AHP was more stable than the AHP method, effectively reducing the uncertainty of the assessment. Among the 27 candidate shelters, these frameworks have successfully recommended 5 candidate shelters with lower risk in the city centre and Treforest areas and identify 6 potential shelters to have higher risks and deemed unsuitable. The proposed framework supports safer shelter planning and contributes to improved people safety, better environmental risk management and stronger urban flood resilience.

1. Introduction

People evacuation management concerns the systematic organisation of how occupants move between buildings to achieve safe egress under hazardous environmental conditions (Remegio et al., 2026; Teoh et al., 2026; Ternero et al., 2024). A central element of this process is the identification of structurally and environmentally safe refuge buildings, which form the essential foundation upon which subsequent coordination, routing, and resource allocation decisions depend (Gong et al., 2024; Aghapour et al., 2019). The urgency of defining such shelters has intensified in recent years, as floods, which are characterised by their high frequency, severe environmental disruption, and substantial human and economic impacts, continue to escalate worldwide (IPCC,

2023; UNDRR, 2022; WEF, 2022). In flood-prone urban areas, where flooding is frequent and highly disruptive, the safety performance of evacuation shelters has become increasingly important for reducing casualties and enhancing urban resilience (Platt et al., 2021; Hasegawa et al., 2015).

London Resilience Team (2022) classifies evacuation shelters into temporary, short-term, and long-term categories, reflecting different levels of building robustness, environmental exposure, and safety provision. The standard procedure for identifying safe shelters involves gathering potential buildings, screening them based on flood-related environmental risk, and designating those that satisfy structural and safety criteria (Alam et al., 2021; Lee et al., 2020). In practice, schools, universities, community centres, places of worship, hospitals, and other

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houses that are structurally safe would usually be set as candidate shelters, because they can withstand a certain degree of flooding, are stocked with appropriate resources and have certain medical facilities (Qiu et al., 2024; Chen et al., 2016; Kar & Hodgson, 2008). Rahman et al. (2021) evaluated a set of 21 buildings using flood sensitivity maps, though without integrating dynamic flood simulations. Coles et al. (2017) conducted a shelter risk assessment in York, UK, using modelled water depths and flow velocities, yet did not account for additional environmental or building-level safety factors.

The safety of flood shelters depends not only on the severity of flood hazards, but also on the degree to which the surrounding environment is exposed to flood impacts and the ability of the surrounding community and supporting infrastructure to cope with such impacts (Salah et al., 2025; Lipatov et al., 2023; Shubham M. Jibhakate et al., 2023). Accordingly, hazard, exposure and vulnerability represent three complementary dimensions of risk and in turn shelter safety. Hazard denotes the severity of the disaster itself, for example, the water depth of a flood at a particular location (Wang et al., 2024; Edirisinghe et al., 2021). Exposure characterises the susceptibility of the physical environment surrounding shelters to flood impacts, such as those located in low-lying areas or adjacent to rivers (Yuan et al., 2021; Voskamp & Van de Ven, 2015). Vulnerability reflects the capacity of the surrounding community and supporting infrastructure to withstand and respond to flood events, including the susceptibility of people, land use, and buildings to damage or disruption (Roy et al., 2023; Alam et al., 2021). Considering only one or two of these dimensions may result in the selection of shelters that are either physically safe but poorly accessible, or capable of accommodating evacuees but located in areas highly susceptible to flooding. Therefore, reliable flood shelter assessment requires the integrated evaluation of hazard, exposure and vulnerability, together with the scientific weighting of these three components.

Substantial progress has been made in quantifying flood hazard, including methods based on rainfall intensity, simulated water depths, and hydrodynamic flow velocities (Quagliarini et al., 2023; Postacchini et al., 2021). Notably, Musolino et al. (2020b) extensively compared several hazard assessment methods and found that the Mechanics-Based Method (MBM) provided higher assessment accuracy. As it is founded on physical principles rather than expert judgement, MBM offers a more objective approach to flood hazard assessment. However, MBM has not yet been incorporated into an integrated flood shelter assessment framework that simultaneously considers hazard, exposure and vulnerability. This limitation highlights the need for a integrated framework to support more reliable flood shelter selection.

Risk assessment for buildings under hazardous environmental conditions frequently relies on multiple-criteria decision-making (MCDM) techniques, among which the Analytic Hierarchy Process (AHP) is one of the most widely applied methods (Chakraborty & Biswas, 2025; Theilig et al., 2025; Saaty, 2008). AHP constructs a risk assessment framework and uses the weights of the hazard, exposure, and vulnerability criteria to assess the risk level, which has no limitation on the type of disasters (Sadeghi et al., 2022; Guo & Kapucu, 2020). Wang et al. (2024) applied an improved AHP method to the evacuation of buildings during fires. Chakraborty and Biswas (2025) conducted a comprehensive assessment of flood risks in the lower Teesta River basin using the AHP method. However, AHP is subjective because the weights are determined from expert experience. To mitigate such subjectivity and increase objectivity, the Triangular Fuzzy Number-based AHP (TFN-AHP) has been proposed (Sadeghi et al., 2022). The TFN-AHP allows expert opinions to be expressed as fuzzy intervals that capture minimum, maximum, and most-likely values, thereby offering a more realistic representation of uncertainty (Liu et al., 2020; Chang, 1996). GIS is important in processing the basic site information, e.g. topography, land use data, for both AHP and TFN-AHP analysis (Malik et al., 2021). Given its reduced subjectivity and improved handling of uncertainty, TFN-AHP offers a more robust basis for assessing flood risk at potential shelter buildings,

but it has seldom been applied to the safety evaluation and selection of evacuation shelters in flood disasters.

Shelter risk assessment is a multidisciplinary process that must consider building characteristics, environmental conditions, and human safety, particularly under hazards such as floods or fires. However, existing studies often lack an integrated approach that accounts for hydrodynamic processes, mechanic stability, and uncertainties in expert judgement. This limitation highlights the necessity of establishing a more scientific and practical evaluation framework.

To address this gap, this study develops an integrated three-stage framework for evaluating and identifying safe evacuation shelters under flood conditions. The framework combines the DIVAST-TVD hydrodynamic model, a mechanics-based instability method (MBM), triangular fuzzy number-analytic hierarchy process (TFN-AHP), and Geographical Detector Model (GDM). The framework is implemented in Pontypridd, UK, to assess flood-related risks affecting potential evacuation shelters and to examine their spatial distribution. The proposed framework provides a systematic basis for evidence-based shelter assessment and selection, supporting safety-informed planning for flood-prone urban environments.

2. Research design and methods

The three-stage methodological framework for identifying suitable evacuation shelters in flood scenarios is shown in Fig. 1. In the first stage, a list of candidate shelters is established through an extensive literature review and expert consultation. The second stage involves conducting a flood risk assessment for both the study area and the candidate shelters. At this stage, a comprehensive examination of papers was carried out to identify three primary indicators, hazard, exposure, and vulnerability, alongside fourteen associated subcriteria. This indicator system was subsequently submitted to experts for review to ensure the scientific validity and effectiveness of the selected criteria. Meanwhile, the AHP and TFN-AHP were employed to collect, synthesise, and structure expert judgements, thereby establishing the relative weights of the indicators. For the hazard indicator in particular, this study introduces an innovative mechanics-based method, which considers pedestrians as the primary subjects of analysis, thereby capturing hazard perception with greater sensitivity. In the third stage, the spatial distribution of flood risk for all candidate shelters is analysed, and shelters located within low-risk zones are identified to produce the final list of suggested evacuation shelters.

2.1. Study area

Pontypridd is located in Wales, UK, to the north of Cardiff, as shown in Fig. 2. The town is situated at the confluence of the Rhondda and Taff Rivers. According to the 2021 Census, the population of the Pontypridd area is approximately 33,209.

On February 15 and 16, 2020, the UK experienced an extreme rainfall event caused by Storm Dennis. The rainfall triggered a surge in river levels, with the Taff River increasing to four times its normal level, reaching a maximum of 5.32 m. The resulting flood inundated 158 properties in Pontypridd, affecting residential buildings, transport infrastructure, the town centre, and key community facilities (Fig. 2). Natural Resources Wales (NRW) classified Storm Dennis as a 200-year event. The exceptional rainfall and water levels exceeded the design capacity of drainage infrastructure across Rhondda Cynon Taf, leading to the most severe damage to buildings, local environments, and critical infrastructure seen in a generation.

This study uses Pontypridd, UK, as a case study to apply evacuation shelter risk assessment, identify suitable locations for relief shelters and provide recommendations to enhance safety and reduce the impacts of future flood events.

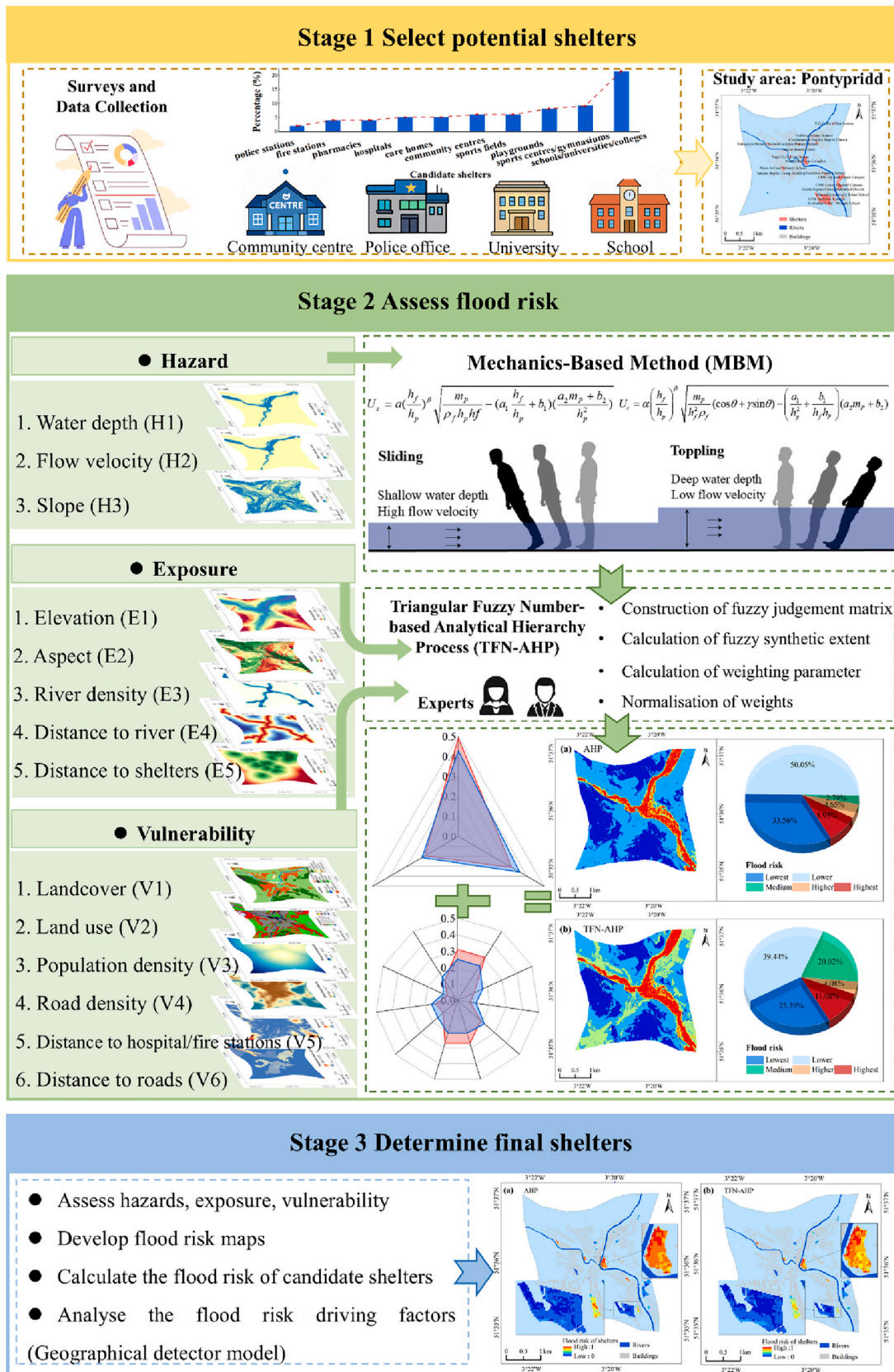


Fig. 1. The framework of shelter flood risk assessment.

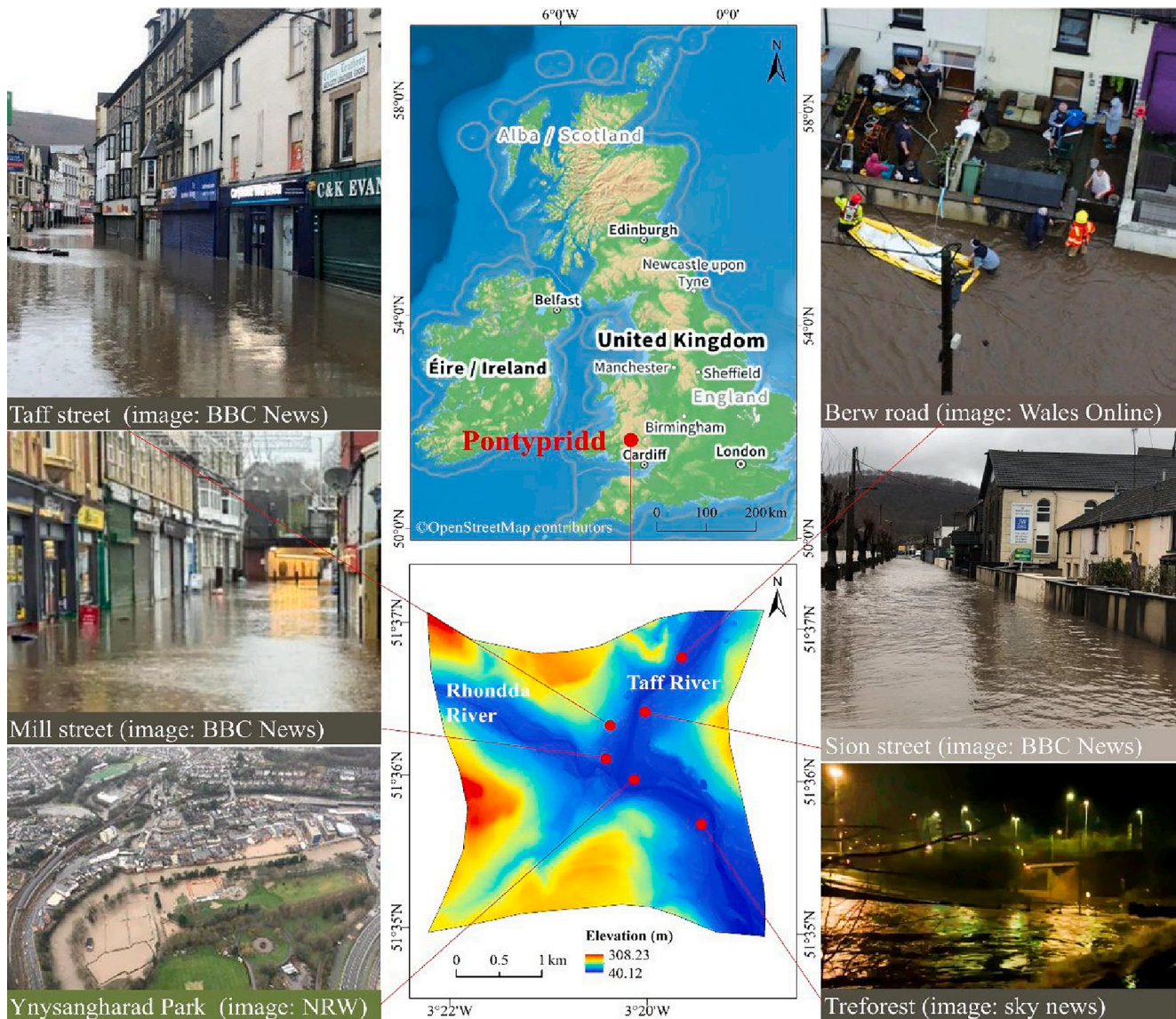


Fig. 2. Location and topography of the study area in Pontypridd, UK and image of the inundated scene during Storm Dennis.

2.2. Data

Based on an extensive literature review, we have selected criteria and subcriteria for assessing flood risk (Al-Juaidi, 2025; Sarkar et al., 2024; Malik et al., 2021). Specific criteria and subcriteria are described in the following methodology section 2.4. Additionally, we have reviewed relevant research papers to recognise appropriate information needs and then gather relevant data from credible sources. Pontypridd research data were obtained from publicly available data. DIVAST-TVD, which has been widely applied in the literature for flood modelling (Ahmadian et al., 2015; Liang et al., 2010; Liang et al., 2006a,b), was used to obtain hydrodynamic data. Model development and validation data were 15 min-interval water level, flow velocity obtained from the Natural Resources Environment Agency (NRW) (<https://rivers-and-seas.naturalresources.wales/>) and the National River Flow Archive (NRFA) website (<https://nrfa.ceh.ac.uk/>) and the topographic data with a spatial resolution of 1 m obtained from the Welsh Government LiDAR data (<https://datamap.gov.wales/maps>). River distribution, road network distribution, Points of Interest (POIs) such as existing hospitals, fire stations, etc., and land use data were obtained from the OpenStreetMap website (<https://download.geofabrik.de/europe/united-kin>

[gdom.html](https://download.geofabrik.de/europe/united-kin)). Land cover data were obtained from the UK Centre for Ecology Hydrology (<https://www.ceh.ac.uk/data/ukceh-land-cover-maps>). Population density data were obtained from the UK Welsh Government website (<https://datamap.gov.wales/layers/geonode:population-density-wales>). All spatial datasets were projected to the British National Grid and processed within a common spatial extent prior to analysis. Continuous variables were normalised before weighting to ensure comparability among indicators. Preliminary quality checks were conducted to verify the completeness and consistency of all input datasets before the subsequent analyses.

2.3. Candidate shelter buildings

Shelters are areas designated for temporary accommodation for people affected by floods and require robust buildings, essential supplies and basic medical facilities (Yazdani et al., 2022). They are often located in city centres to facilitate emergency rescue operations (Coles et al., 2017). However, pre-established shelters often cannot accommodate the vast number of evacuees during major flood events. Therefore, many studies have suggested using schools, universities, community centres, places of worship, sports centres, and similar facilities as temporary

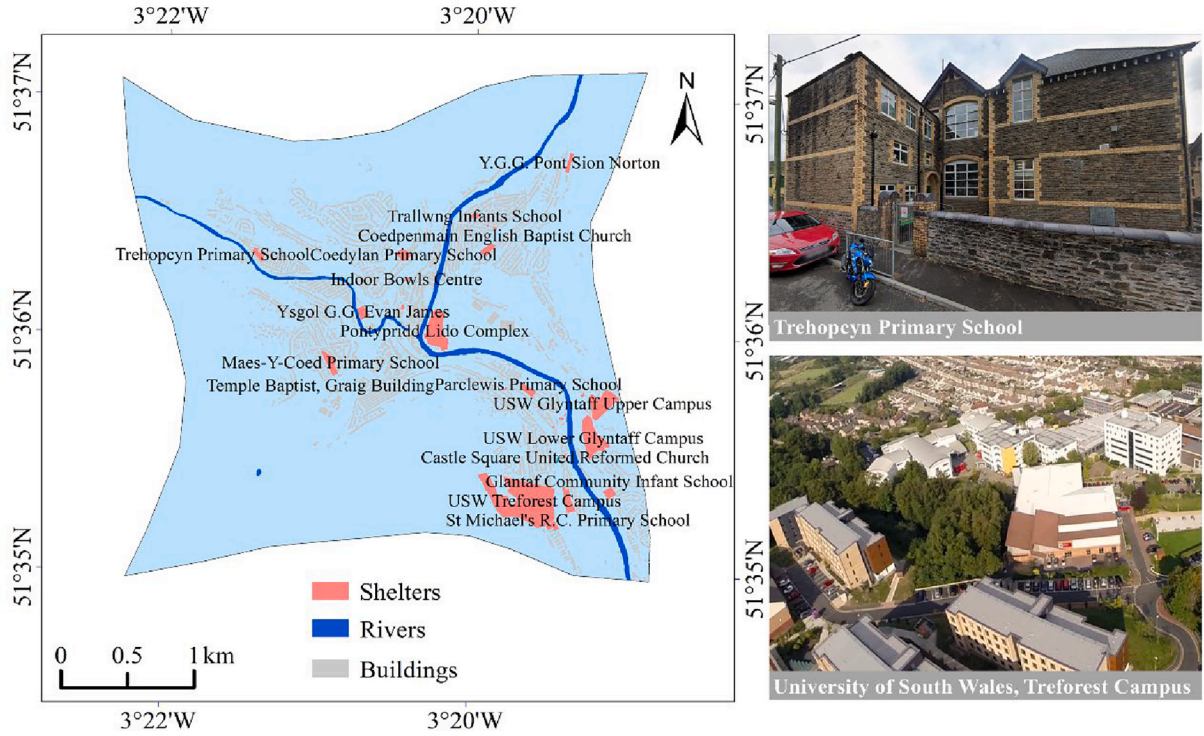


Fig. 3. Map of shelter building in the Pontypridd area.

shelters, as they are generally structurally suitable and can serve dual functions in both routine and emergency contexts (Esposito Amideo et al., 2019; Kar & Hodgson, 2008). Candidate shelters in this study were identified from these building categories following recommendations. Accordingly, the structural safety of candidate shelters is treated as a prerequisite. Where detailed structural information is available, structural safety should be incorporated into shelter selection and assessment. In this study, it is assumed that the selected public buildings have undergone the necessary structural inspections and satisfy the basic structural safety requirements for continued operation. The subsequent assessment therefore focuses on evaluating shelter suitability from the perspectives of flood hazard, environmental exposure and social vulnerability, rather than the structural vulnerability of individual buildings. Hospitals and fire stations were excluded as candidate shelters because their primary role during flood emergencies is to provide essential medical and emergency response services.

Following the above selection step, public buildings belonging to these categories were extracted from the building database of the study area, resulting in 27 candidate shelters within the Pontypridd area, the majority of which are schools. Their names and spatial distribution are shown in Fig. 3. These structures are primarily located along both banks of the River Taff within densely populated neighbourhoods. Recommendations regarding their suitability as evacuation shelters are developed based on the spatial pattern of flood risk.

2.4. Indicator selection for flood shelters

Unlike regional flood risk assessment, which evaluates the overall exposure and vulnerability of a geographical area, this study assesses these components specifically from the perspective of flood shelter suitability. Accordingly, the selected indicators describe the physical environment surrounding each shelter and the capacity of the surrounding community and supporting infrastructure to support safe evacuation and emergency response.

2.4.1. Hazard criteria

Hazard is quantified by flood water depth or rainfall depth in hydrological studies (Lyu et al., 2020). It posed to humans is affected by multiple factors (Wade et al., 2006). Xia et al. (2014) extended conventional assessments based on flood water depth and flow velocity by additionally incorporating ground slope, and proposed a Mechanics-Based Method (MBM) for assessing flood hazard. In this study, the pedestrian-based instability formulation of the Mechanics-Based Method (MBM) was adopted to quantify flood hazard from the perspective of pedestrian safety during evacuation. The relevant equations and parameter definitions are presented in Eq. (1) ~ (3).

Sliding formula:

$$U_c = \alpha \left(\frac{h_f}{h_p} \right)^\beta \sqrt{\frac{m_p}{\rho_f h_p h_f} - \left(a_1 \frac{h_f}{h_p} + b_1 \right) \left(\frac{a_2 m_p + b_2}{h_p^2} \right)} \quad (1)$$

where U_c = the incipient flow velocity; h_f = the water depth; h_p = the height of a human body; m_p = the weight of a body; ρ_f = the density of water; α and β = empirical coefficients; a_1, b_1, a_2, b_2 = coefficients describing the feature of a human body (Dong et al., 2022; Musolino et al., 2020a; Xia et al., 2014).

Toppling formula:

$$U_c = \alpha \left(\frac{h_f}{h_p} \right)^\beta \sqrt{\frac{m_p}{h_f^2 \rho_f} (\cos \theta + \gamma \sin \theta) - \left(\frac{a_1}{h_p^2} + \frac{b_1}{h_f h_p} \right) (a_2 m_p + b_2)} \quad (2)$$

where U_c , h_f , h_p , m_p , ρ_f , α , β , a_1 , b_1 , a_2 , b_2 defined above, θ = angle of the sloping ground and γ = a correction constant (Chen et al., 2019).

After calculating the critical velocity based on the stability formula for sliding and toppling, the flood hazard was assessed by comparing the modelled flood flow velocity and the critical velocity, as shown in Eq. (3).

$$\text{Hazard} = \min \left(1, \frac{U}{U_c} \right) \quad (3)$$

where $Hazard$ = flood hazard rating value, U = flow velocity, and U_c = incipient velocity, which is the minimum between $U_{toppling}$ and $U_{sliding}$ (Musolino et al., 2022).

As indicated in Eq. (1) (~ 3), it can be observed that the hazard considered 3 subcriteria of water depth, flow velocity and slope. Water depth and flow velocity data in the area were obtained by simulating the flood process using the DIVAST-TVD flood model, and these data are shown in Appendix Fig. A.1(a ~ c). The simulation results show that the inundation of areas such as Berw roads, Sion Street, Taff Street, Mill Street, Ynysangharad Park, and the Treforest area is severe, and the variation of water levels and the extent of inundation match the actual situation. As this study aims to suggest the assessment methodology and results, the detailed validation of the flood model is not further discussed.

2.4.2. Exposure criteria

Exposure is the extent of the study area's exposure to external disasters. The subcriteria of exposure include: (1) Elevation (E1), (2) Aspect (E2), (3) River density (E3), (4) Distance to river (E4), and (5) Distance to shelter (E5) (Guan et al., 2024; Lyu et al., 2020; Wade et al., 2006). Areas with a lower altitude have higher exposure to flood, and the elevation and aspect of a particular area are calculated from the Digital Elevation Model (DEM) using the Spatial Analyst tool in GIS. Aspect was included as slope orientation influences surface runoff patterns and the persistence of floodwater, thereby affecting the flood exposure of the surrounding environment. The river density and distance to rivers reflect the distribution characteristics of the river network, and higher river density and shorter distance to rivers indicate higher flood exposure. River density values were computed from the Line Density tool in GIS. Distance to river and distance to shelter were generated from the Euclidean Distance tool. Distance to shelter was included as it reflects the spatial accessibility of potential shelters, with shorter distances generally facilitating evacuation and reducing travel exposure during flood events. The results of exposure for the five subcriteria for the modelled flood event are shown in Fig. A.2(a ~ e).

2.4.3. Vulnerability criteria

Vulnerability is the inability of people and socio-economic systems to withstand and respond to disaster events. The vulnerability subcriteria include: (1) Land cover (V1), (2) Land use (V2), (3) Distance to hospitals/fire stations, etc (V3), (4) Road density (V4), (5) Distance to road network (V5), and (6) Population density (V6) (Ha-Mim et al., 2022; Uddin & Matin, 2021). Land cover and land use were included as they influence surface permeability, flood propagation and the distribution of exposed people and assets, thereby affecting the vulnerability of the surrounding environment. Different land use types and land cover types have different inundation risks. Distance to hospitals and fire stations was selected as these facilities provide essential emergency medical treatment and rescue services during flood events, and greater distances generally reduce the effectiveness of emergency response. The further away from infrastructure points such as hospitals and fire stations, the higher the vulnerability. Road density and distance to the road network can reflect the ability to escape from the affected area in time. The lower the road density and the longer distance to the road network, the higher the vulnerability. Areas with high population densities have a higher risk of flooding. The results for the six subcriteria of vulnerability for the modelled flood event are shown in Fig. A.3(a ~ f).

2.5. Risk assessment

Criteria and subcriteria for flood risk have different levels of importance and are assigned different weights as shown in the combined flood risk in Eq. (4). This study involved five experts from relevant academic and research institutions, all of whom hold PhD degrees and possess extensive expertise in flood-related research. The expert panel

Table 1

The fundamental scale of absolute numbers and corresponding triangular fuzzy numbers.

AHP		TFN-AHP	
Definition	Intensity of Importance	Triangular fuzzy number	Reciprocal triangular fuzzy number
Equal Importance	1	(1,1,1)	(1,1,1)
Weak or slight	2	(1,2,4)	(1/4,1/2,1)
Moderate importance	3	(1,3,5)	(1/5,1/3,1)
Moderate plus	4	(2,4,6)	(1/6,1/4,1/2)
Strong importance	5	(3,5,7)	(1/7,1/5,1/3)
Strong plus	6	(4,6,8)	(1/8,1/6,1/4)
Very strong or demonstrated importance	7	(5,7,9)	(1/9,1/7,1/5)
Very, very strong	8	(6,8,10)	(1/10,1/8,1/6)
Extreme importance	9	(7,9,11)	(1/11,1/9,1/7)

comprised two specialists in hydraulic engineering, two in urban flood modelling, and one in urban emergency planning. Their judgements were synthesised using both the AHP and TFN-AHP, through which indicator weights were systematically derived.

$$FR = w_H H + w_E E + w_V V$$

$$= w_H \left(\sum_{i=1}^n w_i H_i \right)_{Hazard} + w_E \left(\sum_{j=1}^n w_j E_j \right)_{Exposure} + w_V \left(\sum_{k=1}^n w_k V_k \right)_{Vulnerability} \quad (4)$$

where FR is the flood risk value, H, E, V are hazard, exposure and vulnerability criteria, w_H, w_E, w_V are the weights of H, E, V respectively; H_i, E_i, V_i are the subcriteria of H, E, V , w_i, w_j, w_k are the weights of H_i, E_i, V_i , respectively, and $\sum_{i=1}^n w_i = \sum_{j=1}^n w_j = \sum_{k=1}^n w_k = 1$.

To facilitate data overlay, both the criteria and sub-criteria are subjected to linear normalisation as defined in Eq. (5).

$$u_i = \begin{cases} \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} & (\text{positive indicator}) \\ \frac{x_{\max} - x_i}{x_{\max} - x_{\min}} & (\text{negative indicator}) \end{cases} \quad (5)$$

where u_i is the normalised value of the x_i , $x_{\max}$ corresponding to the maximum value of x_i , $x_{\min}$ corresponding to the minimum value of x_i .

2.5.1. AHP weight

The Analytical Hierarchy Process (AHP) is a common method for determining weights, which breaks down a complex objective into multiple criteria and subcriteria, and a method of weighting them and ranking them based on expert experience. Pairwise comparisons are applied to criteria and subcriteria, and numbers 1 through 9 and their reciprocals are used to indicate the relative importance of the assessment criteria to the risk. For example, if the importance of criterion 1 is far greater than that of criterion 2, the relative importance of criterion 1 to criterion 2 is represented by the number 9, and conversely, the relative importance of criterion 2 to criterion 1 is represented by 1/9, as shown in Table 1. The consistency judgement matrix is developed from the relative importance of the criteria to obtain their weights of the hazard, exposure and vulnerability criteria. Then the quality of the weights is evaluated by the consistency test as shown in Eq. (6 ~ 7). The parameter RI is the random index and its value for a given number of criteria n is shown in Table 2 (Ha-Mim et al., 2022; Lyu et al., 2020; Saaty, 2008). High quality weights require $CR < 0.1$. All expert surveys passed the CR test.

$$\text{Consistency Index CI} = \frac{\lambda_{\max} - n}{n - 1} \quad (6)$$

Table 2
RI values for the corresponding number of criteria.

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.52	1.54	1.56	1.57	1.59

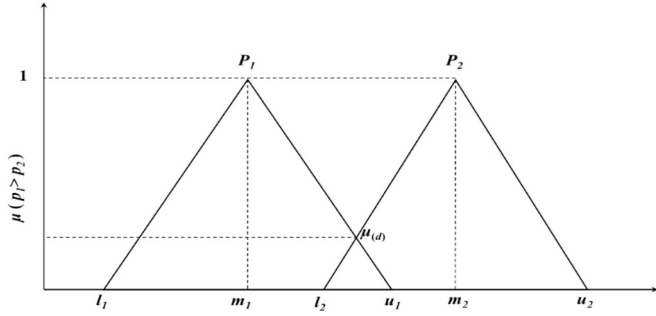


Fig. 4. Diagram of the calculation of the parameter μ in the TFN-AHP method.

$$\text{Consistency Ratio} CR = \frac{CI}{RI} \quad (7)$$

where n is the order of the judgement matrix and λ_{max} is the largest eigenvalue.

2.5.2. TFN-AHP weight

The Triangular Fuzzy Number-based AHP (TFN-AHP) is an improved analytical hierarchy process method, which introduces the triangular fuzzy number. The triangular fuzzy number is defined as $P = (l, m, u)$ ($l \leq m \leq u$), where the parameters l and u are the minimum and maximum values respectively, and m is the mean risk value. Similar to AHP, the weights of each criterion were calculated by the triangular fuzzy judgement matrix and triangular affiliation rule. The following illustrates the four steps for calculating weights under the TFN-AHP method for three criteria, involving Eq. (8) ~ (12) (Liu et al., 2020; Chang, 1996).

1) Construction of fuzzy judgement matrix

According to the triangular affiliation rule of TFN-AHP, as presented in Table 1 and Eq. (8), the criteria matrix and sub-criteria matrix require conversion into fuzzy judgement matrices for flood risk assessment of shelters.

$$P_n = (l_{ij}, m_{ij}, u_{ij})_{n \times n}$$

$$= \begin{pmatrix} [1, 1, 1] & [l_{12}, m_{12}, u_{12}] & \cdots & [l_{1i}, m_{1i}, u_{1i}] & \cdots & [l_{1n}, m_{1n}, u_{1n}] \\ [\frac{1}{u_{12}}, \frac{1}{m_{12}}, \frac{1}{l_{12}}] & [1, 1, 1] & \cdots & [\frac{1}{u_{2i}}, \frac{1}{m_{2i}}, \frac{1}{l_{2i}}] & \cdots & [\frac{1}{u_{2n}}, \frac{1}{m_{2n}}, \frac{1}{l_{2n}}] \\ \cdots & \cdots & \ddots & \cdots & \cdots & \cdots \\ [\frac{1}{u_{1i}}, \frac{1}{m_{1i}}, \frac{1}{l_{1i}}] & [\frac{1}{u_{2i}}, \frac{1}{m_{2i}}, \frac{1}{l_{2i}}] & \cdots & [1, 1, 1] & \cdots & [\frac{1}{u_{in}}, \frac{1}{m_{in}}, \frac{1}{l_{in}}] \\ \cdots & \cdots & \cdots & \cdots & \ddots & \cdots \\ [\frac{1}{u_{1n}}, \frac{1}{m_{1n}}, \frac{1}{l_{1n}}] & [\frac{1}{u_{2n}}, \frac{1}{m_{2n}}, \frac{1}{l_{2n}}] & \cdots & [\frac{1}{u_{in}}, \frac{1}{m_{in}}, \frac{1}{l_{in}}] & \cdots & [1, 1, 1] \end{pmatrix} \quad (8)$$

where $P_{ij} = (l_{ij}, m_{ij}, u_{ij})$ ($l_{ij} \leq m_{ij} \leq u_{ij}$), P_{ij} is the triangular fuzzy number of factor i on factor j .

2) Calculation of fuzzy synthetic extent

According to Eq. (9), the computed results of S_i and P_{ij} in the fuzzy matrix.

Table 3
Shelter flood risk assessment weights based on AHP and TFN-AHP methods.

Criteria	Weight (AHP)	Weight (TFN-AHP)	Subcriteria	Weight (AHP)	Weight (TFN-AHP)
hazard exposure	0.493	0.430	—	—	—
			E1	0.310	0.250
			E2	0.310	0.250
			E3	0.112	0.168
			E4	0.078	0.115
vulnerability	0.196	0.212	E5	0.189	0.217
			V1	0.271	0.207
			V2	0.271	0.207
			V3	0.116	0.158
			V4	0.133	0.161
			V5	0.068	0.096
			V6	0.142	0.171

$$P_i = S_i \times \left[\sum_{i=1}^n \sum_{j=1}^n P_{ij} \right]^{-1} \quad (9)$$

The fuzzy synthetic extent P_i is determined by S_i and P_{ij} . S_i and P_{ij} are the sum of the triangular fuzzy numbers from rows and columns.

$$S_i = \left(\sum_{j=1}^n l_j, \sum_{j=1}^n m_j, \sum_{j=1}^n u_j \right) \sum_{i=1}^n \sum_{j=1}^n P_{ij}$$

$$= \left(\sum_{i=1}^n \sum_{j=1}^n l_{ij}, \sum_{i=1}^n \sum_{j=1}^n m_{ij}, \sum_{i=1}^n \sum_{j=1}^n u_{ij} \right) \left[\sum_{i=1}^n \sum_{j=1}^n P_{ij} \right]^{-1}$$

$$= \left(\frac{1}{\sum_{i=1}^n \sum_{j=1}^n u_{ij}}, \frac{1}{\sum_{i=1}^n \sum_{j=1}^n m_{ij}}, \frac{1}{\sum_{i=1}^n \sum_{j=1}^n l_{ij}} \right)$$

3) Calculation of weighting parameter

Fig. 4 shows the affiliation between the triangular fuzzy numbers p_1 and p_2 . The Eq. (10) describes the affiliation formula for p_1 and p_2 , and the weights between criteria and subcriteria are calculated by μ .

$$\mu(d) = \begin{cases} 1 & (m_1 \geq m_2) \\ 0 & (l_2 \geq u_1) \\ \frac{l_2 - u_1}{(m_1 - u_1) - (m_2 - l_2)} & (\text{otherwise}) \end{cases} \quad (10)$$

4) Normalisation of weights

Based on Eq. (10) ~ (12), the weight results for the criteria and sub-criteria in the flood risk assessment for shelters can be calculated.

The minimum value in parameter μ is selected to calculate w_0 .

$$\mu(d_i) = \min[\mu(P_i \geq P_k)] (k = 1, 2, 3, \dots, n, k \neq i) \quad (11)$$

$$w_0 = [\mu(d_1), \mu(d_2), \dots, \mu(d_n)]^T \quad (12)$$

Then, the parameter μ values are normalised to obtain the weights w_b .

$$\mu(d_i)' = \frac{\mu(d_i)}{\sum_{i=1}^n \mu(d_i)} \sum_{i=1}^n \mu(d_i)' = 1 w_b = [\mu(d_1)', \mu(d_2)', \dots, \mu(d_n)']^T$$

The above outlines the detailed weight calculation for the three main criteria and the sub-indicators. Table 3 summarises the weights of criteria and sub-criteria under both AHP and TFN-AHP methods.

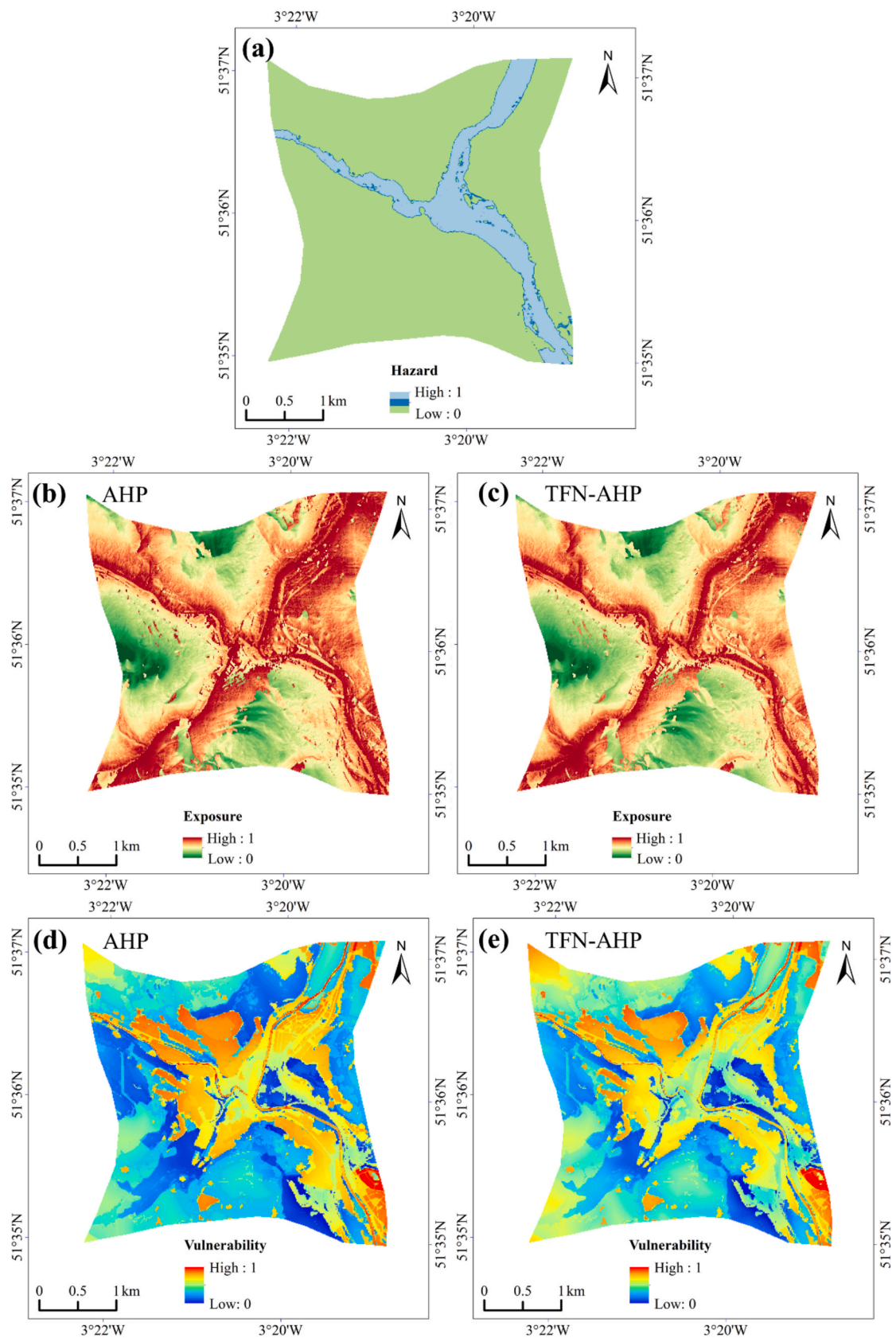


Fig. 5. Maps of different criteria: (a) hazard; (b) exposure for AHP method; (c) exposure for TFN-AHP method; (d) vulnerability for AHP method; (e) vulnerability for TFN-AHP method. The hazards obtained from AHP and TFN-AHP methods were effectively equal.

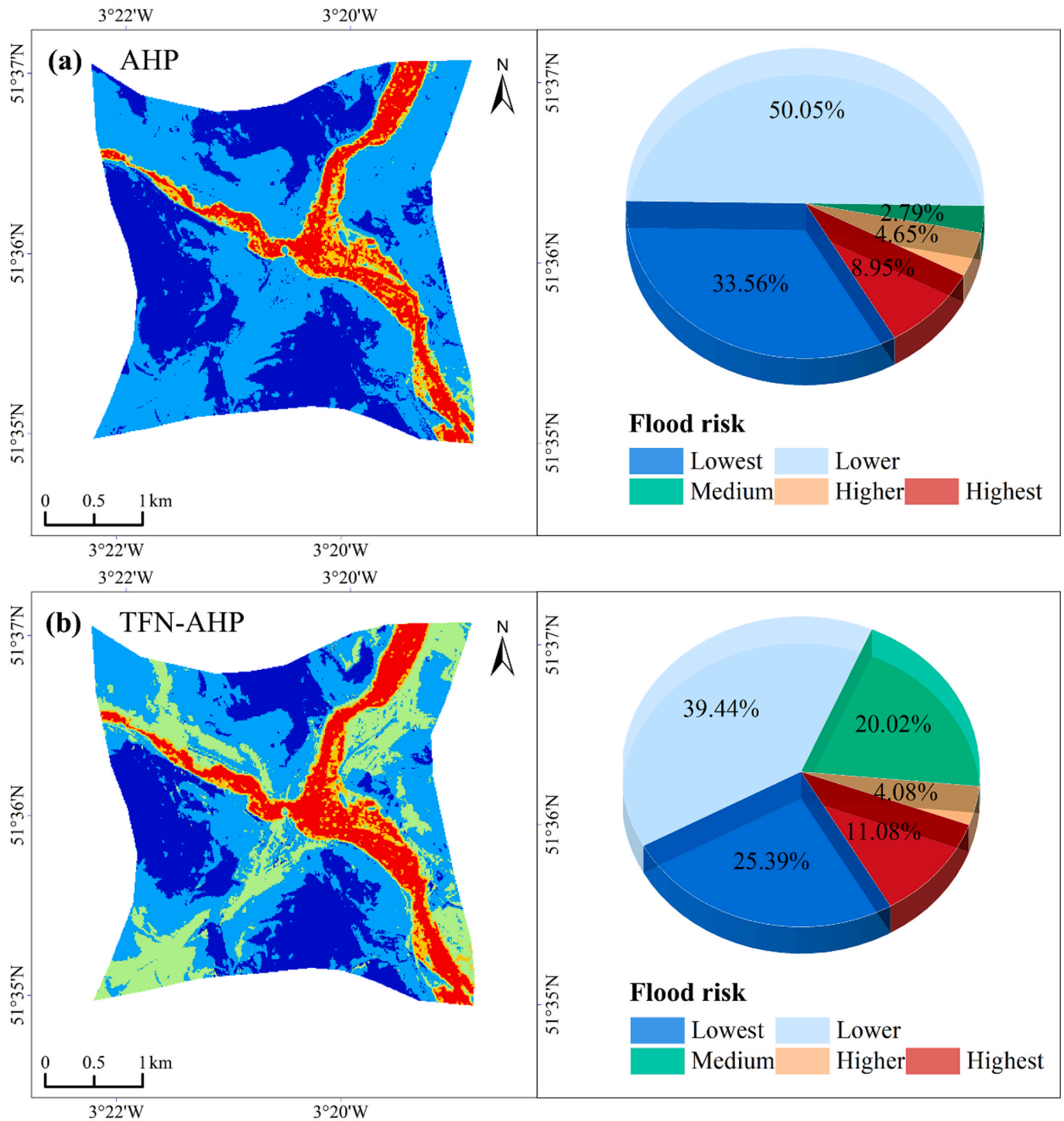


Fig. 6. Map of the spatial distribution for flood risk and proportion of five risk levels: (a) AHP result, (b) TFN-AHP result.

2.6. Geographical detector model

To further investigate the explanatory power of different influencing factors on flood risk, this study employs the Geographical Detector Model (GDM) to analyse the spatially stratified heterogeneity of the variables and to explore their relationships with the driving factors (Jin et al., 2025; Ju et al., 2016). The GDM is a spatial statistical approach designed to examine the relationship between a geographical phenomenon and its potential driving factors. It consists of four components: the factor detector, the risk detector, the ecological detector and the interaction detector. The two principal indicators of the GDM are the q

statistic and the significance test of factor detection, which is usually expressed by the p value. A larger q value indicates stronger explanatory power of an independent factor for the spatial differentiation of the dependent variable. When p is less than 0.05, or a more rigorous threshold such as 0.01, the effect of the independent factor on the dependent factor is considered significant. The interaction detector is employed to quantify the interaction between two influencing factors X_i and X_j , and to assess whether their combined effect on the attribute Y is strengthened or weakened. The change in effect is identified by comparing the maximum q statistic of the two individual factors with the q statistic obtained when they interact.

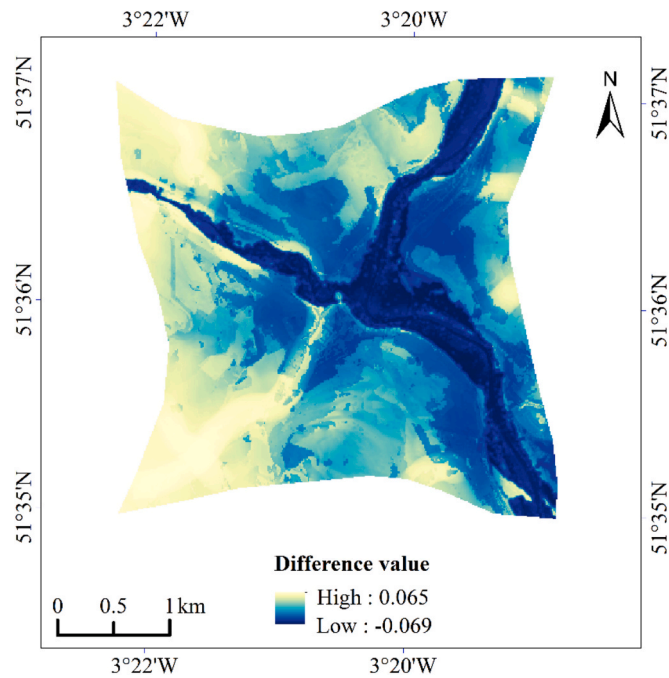


Fig. 7. Differences between the AHP and TFN-AHP methods.

3. Results

3.1. Assessment of hazard, exposure and vulnerability in Pontypridd

Flood risk represents a comprehensive assessment of three components: hazard, exposure, and vulnerability, which collectively indicate flood risk distribution patterns. Based on the calculated weights of each subcriterion in Table 3, the spatial distribution of the first-level criteria was obtained using GIS overlay analysis.

The spatial distribution of hazard criteria calculated with the MBM method is shown in Fig. 5 (a). It shows the high level of flood hazard in

the vicinity of the Taff River and Rhondda River and in the Town centre, such as Berw Roads, Sion Street, Taff Street, Mill Street, Ynysangharad Park, and the Treforest area, which is in agreement with the actual situation. The spatial distribution of exposure criteria calculated with AHP and TFN-AHP weights is shown in Fig. 5 (b, c), respectively. The results calculated by the two methods were roughly the same, and the areas with high exposure were mainly near rivers, so exposure increased as the shelter was closer to the river. The spatial distribution of vulnerability criteria calculated with the AHP and TFN-AHP weights is shown in Fig. 5 (d, e). AHP weights gave a lower estimate of vulnerability in the urban centre, while TFN-AHP weights gave a lower vulnerability estimate outside of the urban centre.

3.2. Flood risk assessment in pontypridd

The weights of the criteria in Table 3 were utilised to obtain the regional flood risk. The flood risk was classified into five levels: lowest, low, medium, high and highest to represent the distribution of flood risk.

The spatial distribution and proportion of flood risk obtained by the AHP method and the TFN-AHP method are shown in Fig. 6. Both methods produced similar overall spatial patterns, with high flood risk concentrated in the urban centre and areas adjacent to the river, whilst lower flood risk was observed farther away from the urban centre and the river. High flood risk areas were mainly located along Berw Roads, Sion Street, Taff Street, Mill Street, Ynysangharad Park, and the Treforest area. The TFN-AHP method identified a larger proportion of medium-risk areas outside the urban centre, whereas these areas were generally classified as low risk by the AHP method, indicating that TFN-AHP provides a more sensitive representation of flood risk. This finding is consistent with previous studies (Guan et al., 2024; Lyu et al., 2020). The two methods produced similar results for the lowest-, high- and highest-risk classes, with the main differences occurring between the low- and medium-risk classes. Compared with the TFN-AHP method, the AHP method classified 10.61% more of the study area as low risk and 17.23% less as medium risk, whilst the proportions of the remaining risk classes were broadly consistent between the two methods.

The spatial distribution of flood risk differences estimated with the two methods is shown in Fig. 7. The differences were generally small and

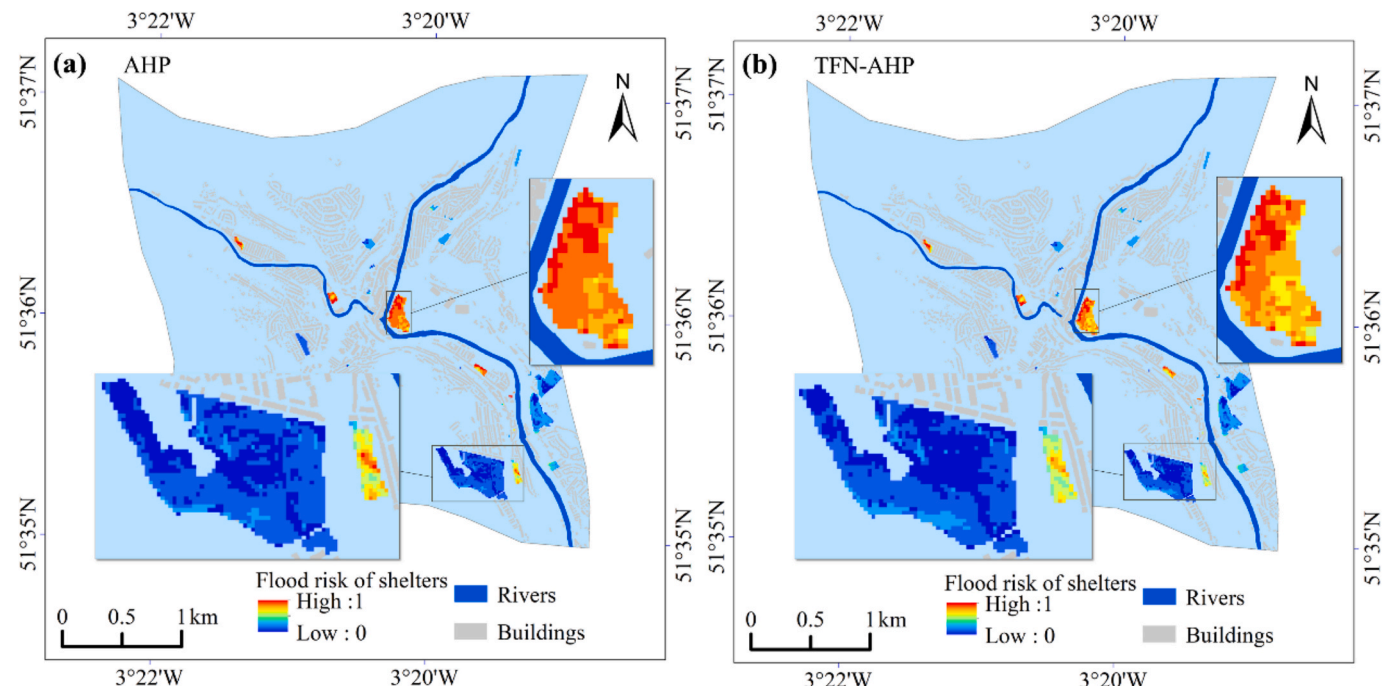


Fig. 8. Spatial distribution of shelter flood risk: (a) AHP results, (b) TFN-AHP results.

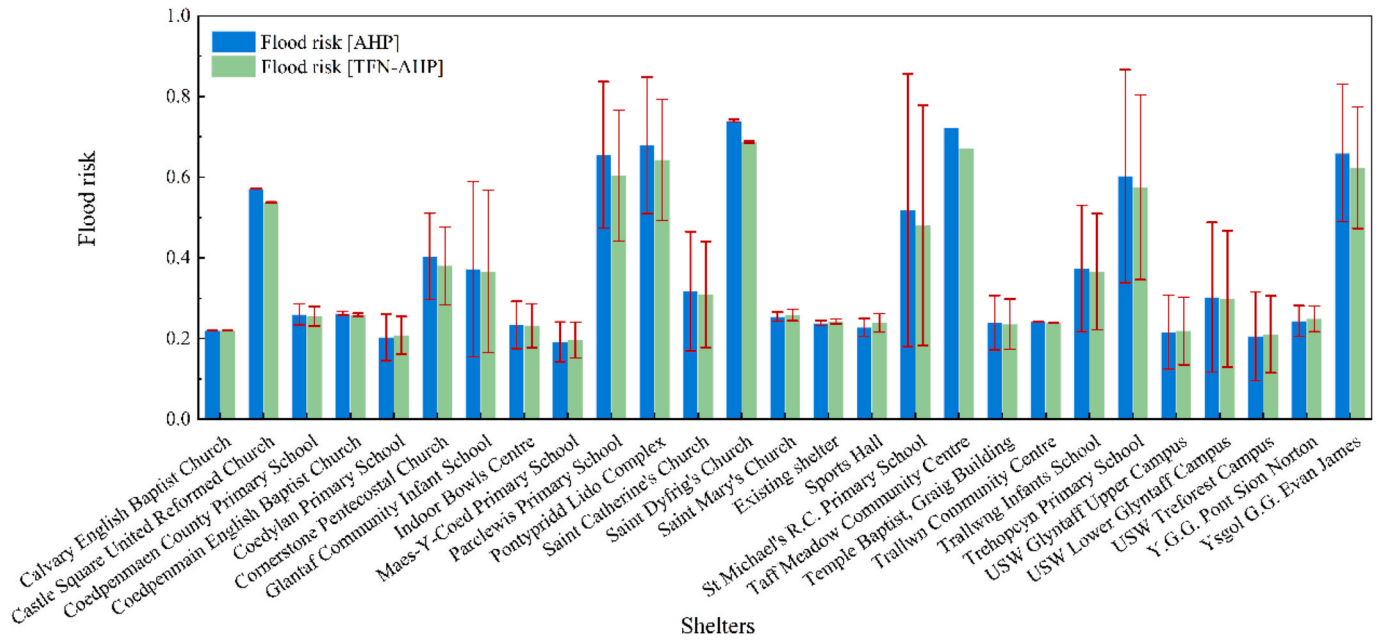
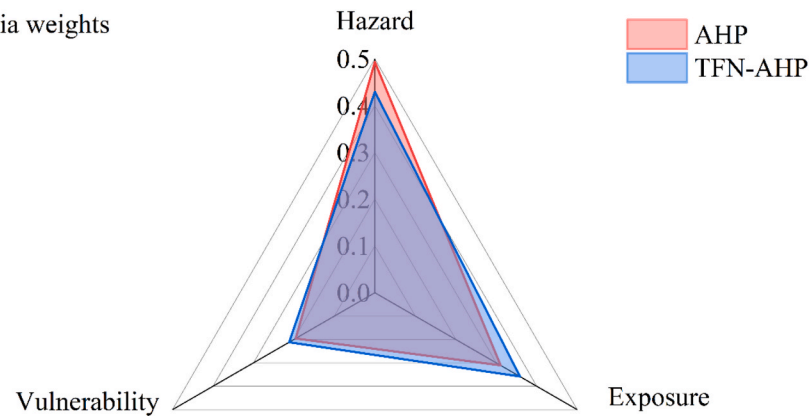


Fig. 9. Flood risk values in shelter areas.

(a) Criteria weights



(b) Subcriteria weights

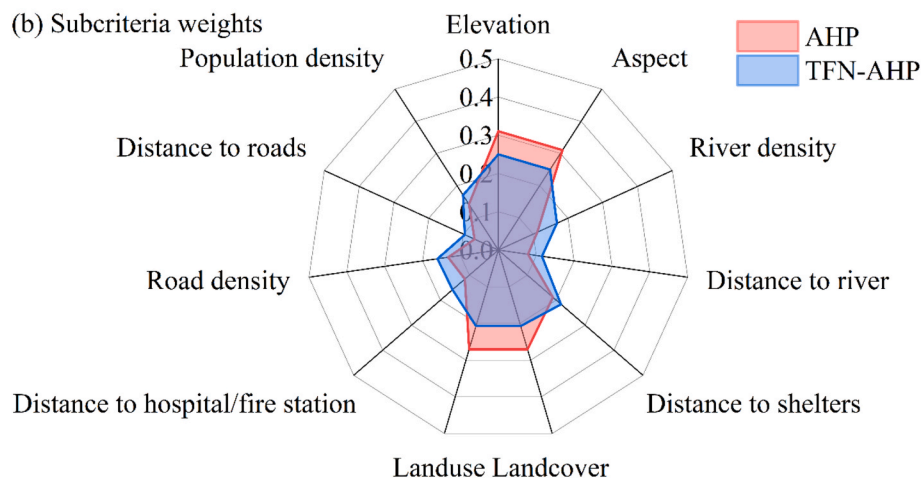


Fig. 10. Weights of the factors under the AHP and TFN-AHP methods: (a) criteria weights, (b) subcriteria weights.

were primarily concentrated in the peripheral urban areas and at the confluence of the Rivers Taff and Rhondda. Overall, the TFN-AHP method produced slightly less extreme risk values than the AHP method.

3.3. Flood risk levels distribution in shelter candidates

Flood risks of the shelters were assessed based on the flood risk assessment maps. The maximum, minimum, and mean risk values for

Table 4

The results of explanatory power and significance tests for the flood risk driving factors.

Methods Factors	AHP q statistic	p value	TFN-AHP q statistic	p value
FHR	0.923	0.000	0.911	0.000
Elevation	0.145	0.000	0.121	0.000
Aspect	0.037	0.000	0.042	0.000
River density	0.550	0.000	0.529	0.000
Distance to river	0.324	0.000	0.369	0.000
Distance to shelters	0.302	0.000	0.345	0.000
Land cover	0.039	0.000	0.026	0.000
Land use	0.181	0.000	0.161	0.000
Population density	0.286	0.000	0.274	0.000
Road density	0.164	0.000	0.149	0.000
Distance to hospital/fire stations	0.212	0.000	0.181	0.000
Distance to roads	0.066	0.000	0.050	0.000

the shelter area were evaluated based on the spatial flood risk distribution within the shelter area. Fig. 8 shows the flood risk distribution for the 27 candidate shelters. This aligns with the overall trend, in which the AHP method estimates slightly higher risk values for shelters located near rivers, while the TFN-AHP method estimates slightly higher risk values for shelters located farther from rivers.

The maximum, minimum, and mean risk values for interior areas of the 27 shelter areas under both methods is shown in Fig. 9. It indicated that Castle Square United Reformed Church, Parc Lewis Primary School, Pontypridd Lido Complex, Saint Dyfrig's Church, Taff Meadow Community Centre, and the Ysgol G.G. Evan James had high flood risk values, greater than 0.5, and were not suitable as shelters. Coedylan Primary School, Indoor Bowls Centre, Maes-Y-Coed Primary School located in the city centre area were in the low flood risk area with a mean risk value of 0.2, which can be set as shelters for residents in the city centre area. USW Glyntaff Upper Campus and USW Treforest Campus in the Treforest area were considered to be low-risk areas for flooding, with a mean value of 0.2. They are large enough to accommodate a large number of people, making them suitable as flood shelters for the Treforest area.

Although the overall shelter classifications were broadly consistent between the two methods, the TFN-AHP method produced a narrower range of flood risk values than the AHP method, indicating a more robust and stable assessment with reduced uncertainty, consistent with previous studies (Guan et al., 2024; Lyu et al., 2020).

The differences between the two methods primarily arise from the weighting of the hazard, exposure and vulnerability criteria., as shown in Fig. 10. Compared with the AHP method, TFN-AHP provides a more balanced weighting scheme by accounting for the uncertainty in expert judgement, thereby improving the robustness of flood shelter risk assessment.

3.4. Detection of flood risk driving factors

To further interpret the mechanisms governing flood shelter risk, this study employs the GDM to quantify the explanatory power of the driving factors. The explanatory power and statistical significance of each factor are presented in Table 4. For both the AHP method and the TFN-AHP method, all influencing factors pass the significance test. FHR exhibits the highest explanatory power, with q-statistics of 0.923 and 0.911, respectively, indicating that flood hazard is the dominant determinant of flood risk. In contrast, aspect has the lowest explanatory power under the AHP method ($q = 0.037$), whilst land cover has the lowest explanatory power under the TFN-AHP method ($q = 0.026$). Only minor differences are observed between the two weighting methods.

The interactive driving force of different factors on flood risk is shown in Fig. 11. The explanatory power of all factor interactions exceed that of the corresponding individual factors, indicating that flood risk is jointly controlled by multiple interacting factors, with most interactions

exhibiting nonlinear enhancement. For both the AHP and TFN-AHP methods, FHR consistently exhibits the strongest interaction with the other factors, followed by river density, highlighting the dominant role of flood hazard and the river network in shaping the spatial distribution of flood risk. Although slight differences exist in the strongest interaction pairs between the two methods, the overall interaction patterns are highly consistent.

4. Discussion

4.1. Advantages of integrating MBM and TFN-AHP

This study applied the DIVAST-TVD hydrodynamic model to simulate water depth and flow velocity for the Pontypridd area and developed an integrated flood shelter assessment framework incorporating hazard, exposure and vulnerability. The framework combines the Mechanics-Based Method (MBM) for hazard assessment with the TFN-AHP method for indicator weighting, thereby integrating physically based hazard estimation with uncertainty-aware multi-criteria decision analysis. In particular, under the hazard criterion, an innovative use of the MBM was introduced to account from evacuee perspectives. Compared with conventional hazard indicators based solely on water depth or rainfall, the MBM incorporates water depth, flow velocity and ground slope, reducing reliance on expert judgement and providing a more objective representation of flood hazard.

The flood risk results derived from the AHP and TFN-AHP methods were compared to evaluate the influence of different weighting strategies. The AHP method relies on pairwise comparisons based on expert judgement, and the weighting results may therefore be influenced by differences in experts' knowledge, experience and individual preferences, particularly when the number of experts is limited. As this study serves as a proof of concept, the limited number of experts does not undermine the validity of the proposed methodology. Nevertheless, future applications should involve a larger and more diverse panel of experts with different professional backgrounds and perspectives to further reduce potential bias in expert judgement. The TFN-AHP method represents pairwise comparisons using triangular fuzzy numbers, allowing judgements to be expressed as ranges rather than single values and better capturing the uncertainty inherent in expert assessments. The TFN-AHP method provides a more balanced weighting of hazard, exposure and vulnerability, resulting in a more robust flood risk assessment with reduced uncertainty whilst maintaining a consistent overall spatial distribution of flood risk. The results also suggest that suitable shelter selection depends not only on flood hazard, but also on environmental exposure and the accessibility of surrounding infrastructure.

A total of 27 candidate buildings were assessed in the Pontypridd area. The framework identified six shelters as high-risk and unsuitable and five low-risk shelters were recommended for the town centre and the Treforest area. These findings demonstrate that integrating MBM with TFN-AHP provides a more objective and reliable basis for flood shelter assessment and evacuation planning than conventional weighting-based approaches.

4.2. Limitations and future work

Evacuation shelters can be classified into temporary shelters, short-term shelters, and long-term shelters. Temporary and short-term shelters are typically located within a 2 km radius, a relatively short distance suitable for evacuation by walking, as is the case in the Pontypridd study area. In contrast, long-term shelters are located more than 2 km away and are suitable for evacuation by vehicle, as seen in megacities like London (UK), New York (USA), and Beijing (China).

This study introduces the use of the MBM in calculating the hazard criterion for shelters. Unlike traditional methods, the MBM does not rely on expert judgement; instead, it scientifically calculates hazard

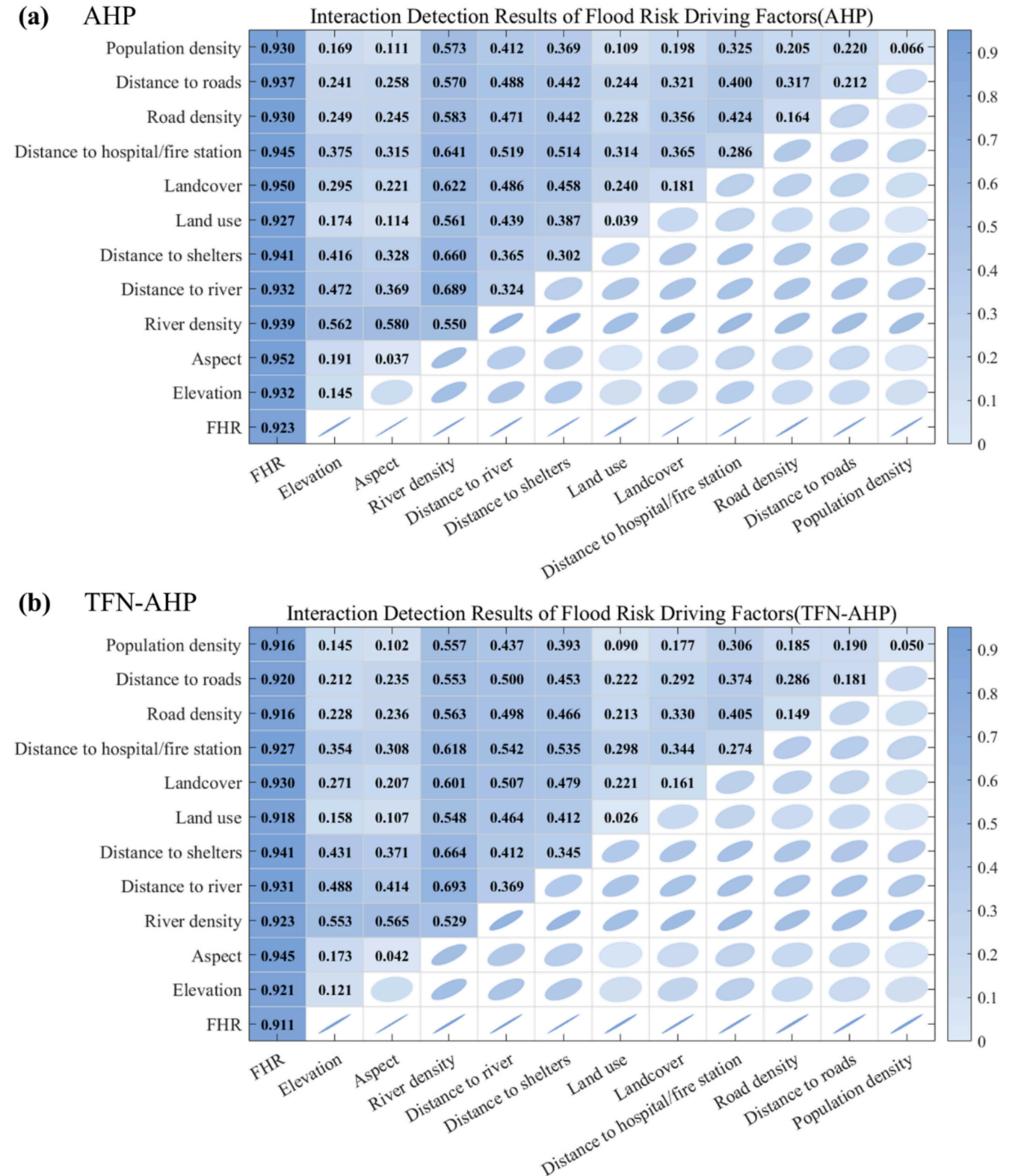


Fig. 11. Interactive driving forces of flood risk from different influence factor.

distribution. Specifically, the MBM differentiates between pedestrians and vehicles, applying distinct hazard calculation formulas for each (Evans et al., 2024; Dong et al., 2022; Chen et al., 2019). In this study, since the Pontypridd area is relatively small and people are more

sensitive, the pedestrian perspective was adopted for hazard calculation. In future applications of this shelter risk assessment framework to megacities, the hazard calculation formula should incorporate the vehicle perspective for long-term shelters.

When planning and managing evacuation shelters, priority is given to maximising residential coverage. Shelter capacity is typically represented by its area, a concept known as horizontal evacuation. Furthermore, with urban and societal development, skyscrapers are increasingly prevalent. These structures offer significant capacity to accommodate large numbers of evacuees through vertical evacuation, a factor that should be considered in future evacuation shelter planning (Wang. et al., 2024; Sun et al., 2022).

Moreover, to reduce the subjectivity of the basic AHP, apart from the proposed TFN-AHP, entropy weight-AHP, etc. Additionally, with the interdisciplinary application of computer algorithms, future research could incorporate methods like neural networks, random forests, and intelligent algorithms to determine factor weights more objectively (Ternero et al., 2024; Samany et al., 2021).

The proposed framework should be regarded as a proof of concept demonstrating the feasibility of integrating flood hazard, exposure, and social vulnerability into shelter assessment. Although the framework produced encouraging results in the study area, further validation using additional case studies, observed evacuation data, and real-world emergency management applications is required before it can be considered a fully operational decision-support tool. Future work will focus on validating the framework across different flood events and geographical settings, as well as assessing its robustness using real evacuation records and stakeholder feedback.

5. Conclusion

This study developed an integrated three-stage framework for flood shelter assessment by combining the Mechanics-Based Method (MBM), the Triangular Fuzzy Number-based Analytic Hierarchy Process (TFN-AHP), and the Geographical Detector Model (GDM). The framework integrates hazard, exposure and vulnerability to support the identification and risk classification of candidate shelters in flood-prone environments. It was applied to the Pontypridd area in the UK, as a demonstration site, to assess the flood risk of 27 candidate shelters and to identify suitable shelters for evacuation planning. The main findings are as follows:

(1). The proposed framework successfully identified the spatial distribution of flood shelter risk in the Pontypridd area, revealing high-risk zones concentrated along the River Taff and lower-risk areas farther from the river. Correspondingly, candidate shelters located within these high-risk areas exhibited higher flood risk.

(2). Based on the integrated assessment of hazard, exposure and

vulnerability, 27 candidate shelters were evaluated and classified according to their flood risk. Six shelters were identified as unsuitable because of their high risk. It was recommended that Coedylan Primary School, Indoor Bowls Centre, and Maes-Y-Coed Primary School could be potentially designated as flood hazard shelters for residents of the Town Centre area and the USW Glyntaff Upper Campus and USW Treforest Campus could serve as regional flood hazard shelters in the Treforest area because of their low risk.

(3). Compared with the conventional AHP-based assessment, the proposed framework, incorporating MBM and TFN-AHP, provides a more objective hazard representation and reduces the uncertainty associated with expert judgement, thereby improving the robustness of flood shelter risk assessment.

(4). The Geographical Detector Model (GDM) further quantified the explanatory power and interactions of the driving factors, demonstrating that flood hazard remains the dominant determinant of shelter risk while river density exhibits the strongest interaction with other factors.

In short, these findings provide additional insights into the mechanisms governing flood shelter safety and support more informed shelter planning.

CRedit authorship contribution statement

Chuannan Li: Writing – original draft, Visualization, Software, Methodology, Conceptualization. **Reza Ahmadian:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Changbo Jiang:** Writing – review & editing, Supervision. **Man Yue Lam:** Writing – review & editing. **He Xu:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

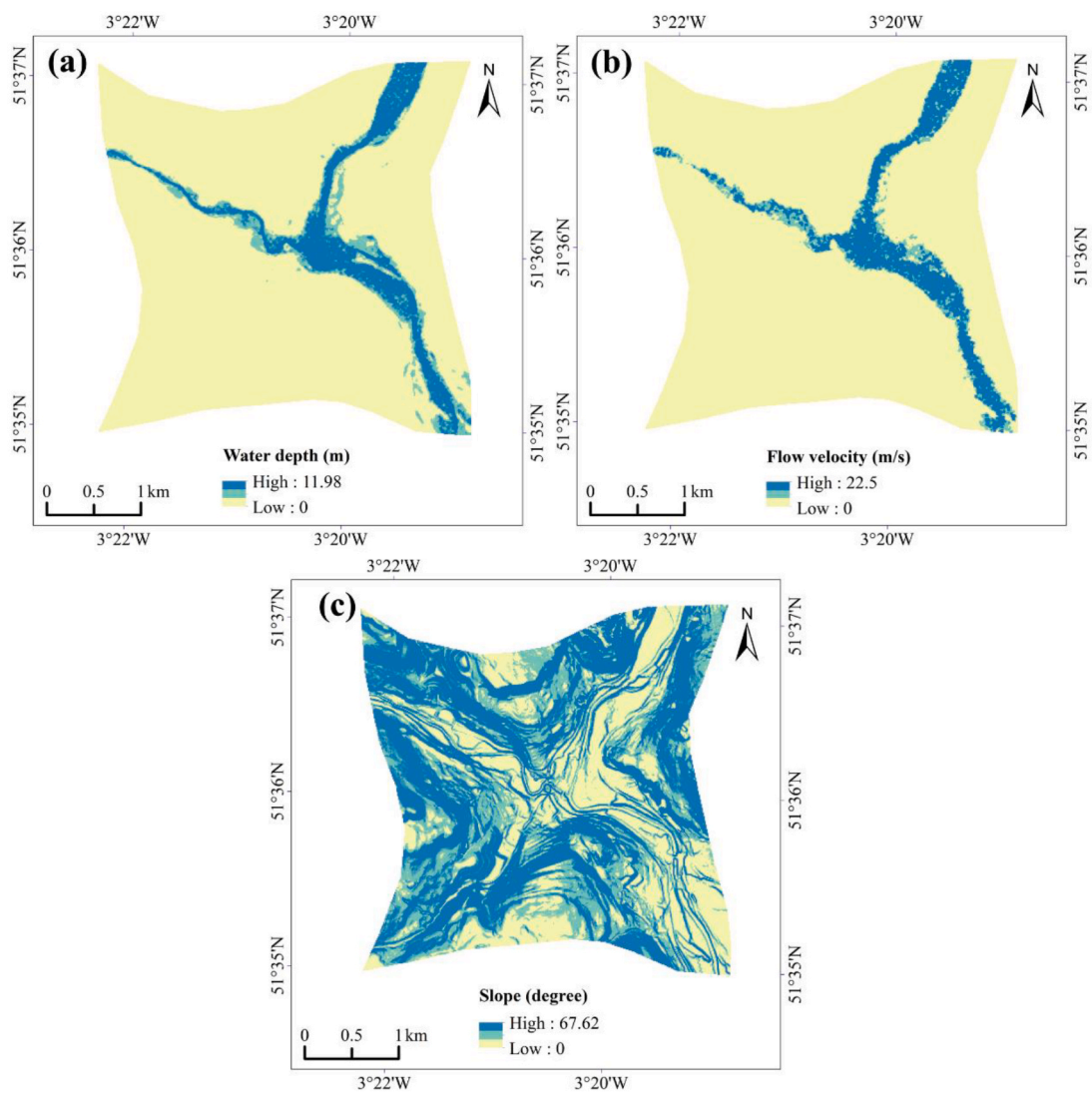


Fig. A.1. Maps of different subcriteria of hazard: (a) water depth; (b) flow velocity; (c) slope.

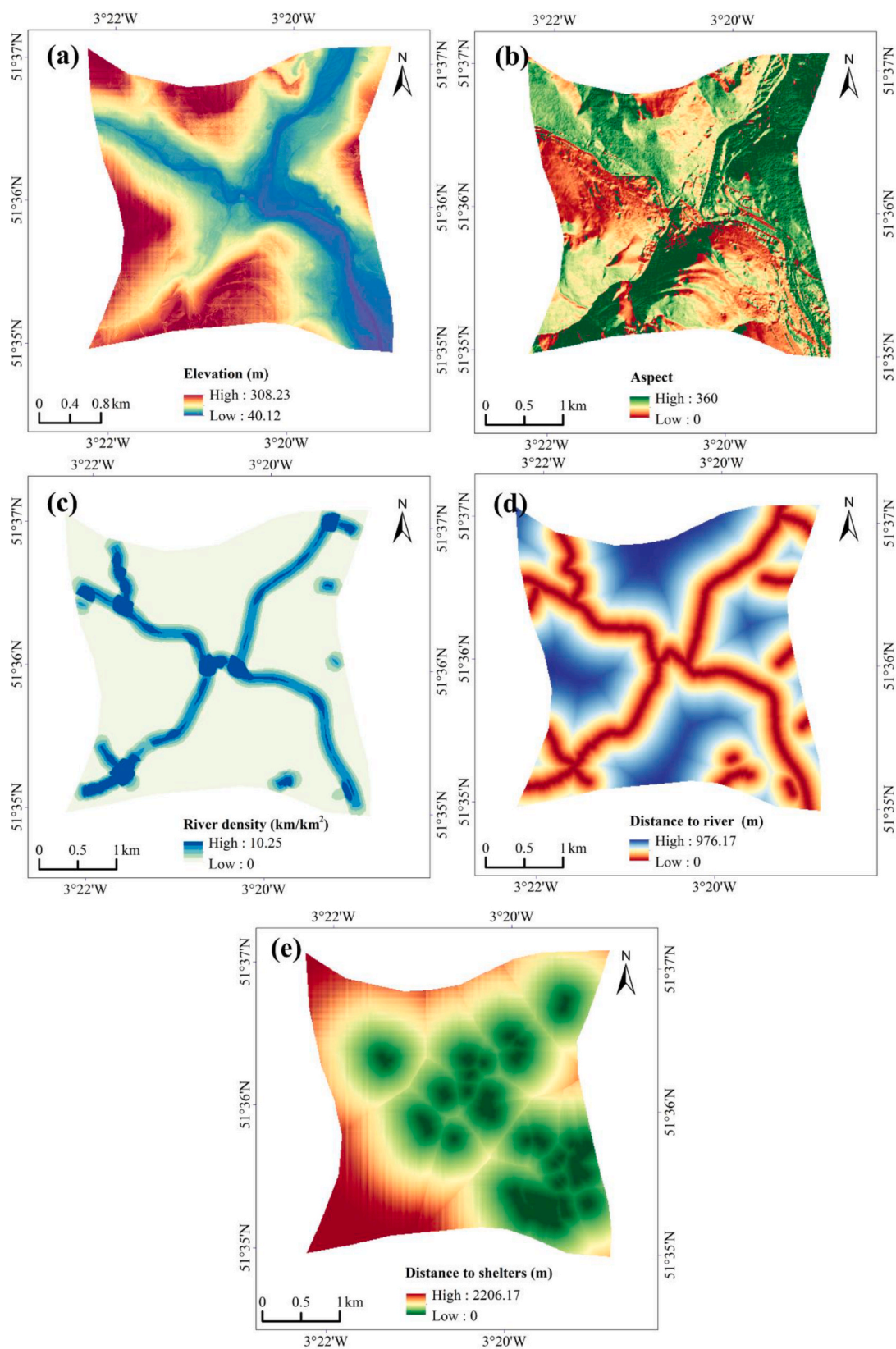


Fig. A.2. Maps of different subcriteria of exposure: (a) elevation; (b) aspect; (c) river density; (d) distance to river; (e) distance to shelters.

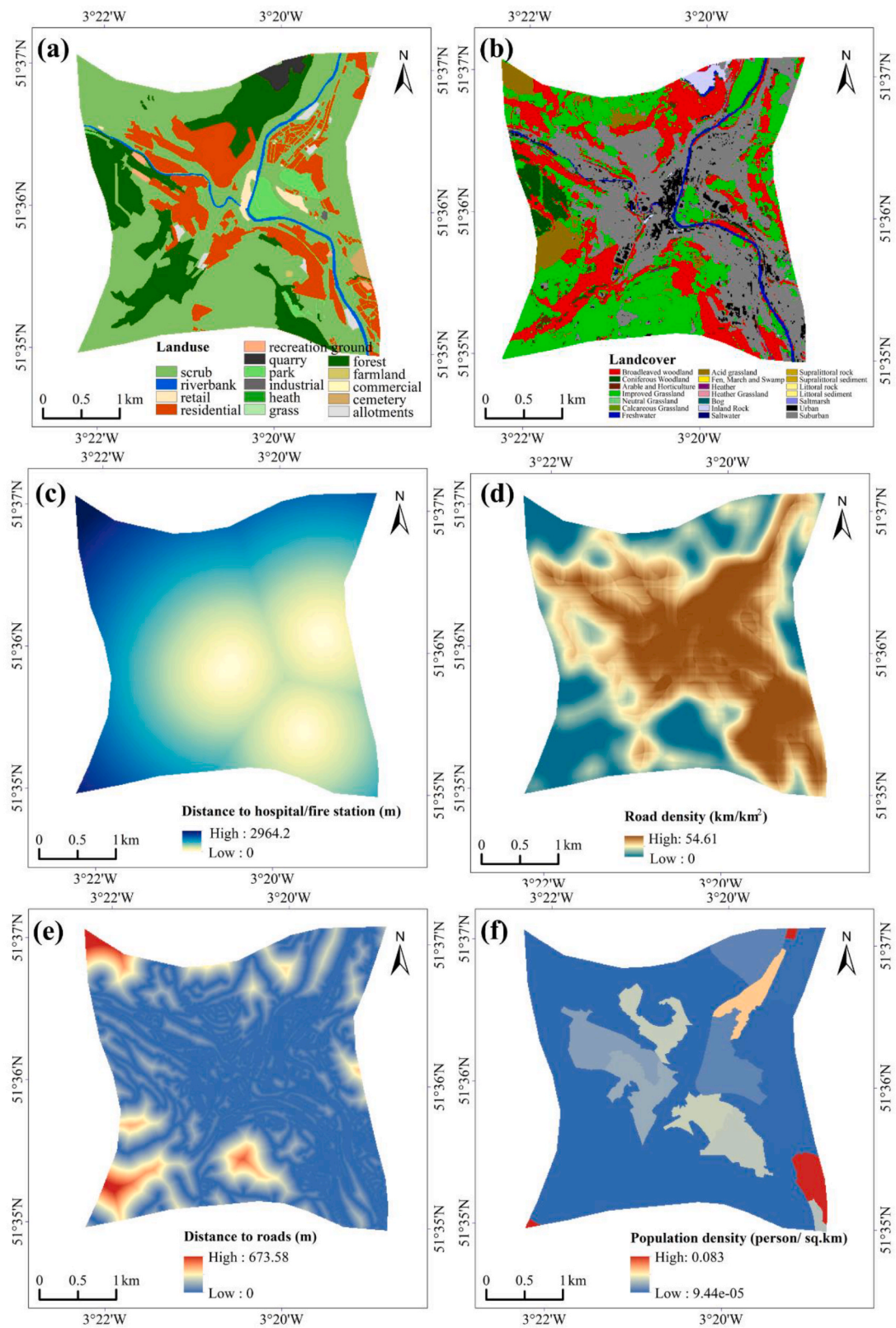


Fig. A.3. Maps of different subcriteria of vulnerability: (a) land use; (b) land cover; (c) distance to hospital/fire station; (d) road density; (e) distance to roads; (f) population density.

Data availability

The research data supporting the findings of this study are openly available via the Cardiff University Research Portal at: <https://doi.org/10.17035/cardiff.33454906>.

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