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Selection of optimal escape routes in a flood-prone area based on 2D hydrodynamic modelling

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Abstract: Optimizing escape routes during an extreme flood event is an effective way to mitigate casualties by instructing local inhabitants to escape along pre-determined routes. In this study, a model for selecting optimal escape routes in a flood-prone area has been proposed, which includes a module for predicting the two-dimensional (2D) hydrodynamics, and modules for assessing the hazard degree for evacuees, calculation of evacuation times and determination of different escape routes. In the module for determining escape routes, two evacuation schemes were used to determine an optimal escape route, with scheme A developed to find optimal escape routes based on established road networks, and scheme B developed to design a new optimal route for evacuation. Extreme overbank flood events occurred in the Lower Yellow River (LYR) in July 1958 (“58.7”) and August 1982 (“82.8”) and the proposed model was applied to select the optimal escape routes on the Lankao-Dongming floodplain area of the LYR for these two overbank floods. The corresponding model predictions indicated that the optimal escape routes and the time to evacuate were determined respectively for three starting locations for these two overbank floods. The optimal escape routes for these two floods were the same for all three starting locations, and the optimized routes provided 3h more time for evacuees to escape. The results also showed that the time of evacuation would need to be earlier for the “58.7” overbank flood scenario because of its larger amount of water volume and higher peak discharge.

Key words: hydrodynamic module; human stability; escape speed; escape route; flood-prone area, Lower Yellow River.

29 **1. Introduction**

30 Due to climate change and intensive anthropogenic activity in recent decades, there has been
31 an increasing occurrence in the probability of extreme floods (Milly et al., 2002; Wang et al., 2016).
32 Various kinds of floods, such as overbank and urban floods, continue to be regarded as one of the
33 main sources of casualties for all natural hazards (Niu et al., 2013; Xia et al., 2014; Zhang et al.,
34 2016). According to incomplete statistics, more than 30 overbank flood events have occurred in the
35 Lower Yellow River (LYR) since 1949, with 13,000 villages and 9 million people being affected in
36 total (Niu et al., 2013). There is a large inhabitant population living on floodplains, especially in
37 China, which is the world's most populated country (Piao et al., 2010). Typically when a farm-dike
38 breaches along a floodplain, then rapid flood inundation frequently occurs resulting in a very
39 limited time for issuing warnings, and the inhabitants usually suffer from potential flood risk
40 (Collier, 2007). Therefore, it is desirable to be able to determine optimal escape routes for potential
41 evacuees in terms of flood mitigation for such types of events.

42 With recent progress in computer-based numerical modelling tools, two-dimensional (2D)
43 hydrodynamic models have been proposed to simulate various processes associated with flood
44 inundation (Liang et al., 2007; Neal et al., 2009; Xia et al., 2010; Liu et al., 2015). These model
45 predictions can present temporal and spatial distributions of the key hydrodynamic parameters for a
46 specific flood scenario, such as flow velocity and water depth. As an important tool for current day
47 flood risk management, such model predictions can be used to assess the flood risk to people and
48 provide the potential to instruct local inhabitants as to when and how to escape. Therefore various
49 evacuation algorithms have been developed for people facing extreme flood events. A Life Safety
50 Model (LSM) developed by BC Hydro in Canada offers a robust method for assessing flood risk
51 associated with the operation of dams or other flood control structures (Johnstone et al., 2005). As a
52 response planning tool, and a means of calculating complex evacuation processes, an evacuation
53 timeline for flood events is an effective procedure, including: flood inundation extent predictions,
54 warning information delivery, and evacuation operation (Stephen et al., 2010). Zhang et al. (2016)

55 analyzed the distribution of water depth in a flood inundation process using the software MIKE
56 Flood, and proposed a method to extract impassable flooded roads using ArcGIS. Lujak and
57 Giordani (2018) proposed a mathematical model based on two node centrality measures and the
58 model not only predicts the shortest evacuation route, but also considers other relevant
59 characteristics in order to predict the safest evacuation route. Soon et al. (2018) used a semi-
60 parametric estimation approach to obtain the marginal effects of explanatory variables on flood
61 victims' evacuation decisions and analysed the determinants of actual evacuation decisions for an
62 unprecedented 2014 flood disaster. Moshtagh et al. (2018) proposed the stochastic queue core (SQC)
63 model for vehicular evacuation problems, with the average travel time and the operation costs being
64 minimized in the model. These models can be integrated, including a module for predicting the
65 flood inundation extent and a module for evacuation planning, to assess the flood risk for the
66 domain and to provide information for optimal evacuation. However, these models do not consider
67 the stability of victims in floodwaters, and they therefore have limited value in practical decision
68 making for effective flood evacuation response. Previous studies indicate that the stability degree
69 and escape speed of people in floodwaters can influence the safety and time expenditure for
70 evacuation (Abt et al., 1989; Karvonen et al., 2000; Ishigaki et al., 2008; Xia et al., 2014), and these
71 influencing factors need to be considered in the module for selecting optimal escape routes.

72 Flood risk to people is often estimated empirically according to the magnitude of the water
73 depth, which means that the hazard degree of a human body in floodwater depends solely on the
74 incoming water depth. This method does not take account of the effect of the flow velocity on the
75 stability of a human body, and therefore does not consider the mechanism of people instability in
76 floodwaters. Various criteria for people instability in floodwaters have been proposed. Abt et al.
77 (1989) reported the results of toppling instability experiments of 20 adults, which were conducted in
78 a 61 m long laboratory flume with different ground surfaces. An equation defining the instability
79 threshold of a person in floodwaters was developed using linear regression of the experimental data.
80 Karvonen et al. (2000) undertook stability tests using 7 human bodies on a steel grating platform,

81 towed in a model ship basin, and the product of water depth and velocity was proposed to describe
82 the degree of people stability based on their experimental data. Xia et al. (2014) derived theoretical
83 formulae for the incipient velocity of a human body in floodwaters for the instability modes of
84 toppling and sliding, with more than 50 tests being undertaken for a model human body, with the
85 experimental data being used to calibrate the parameters in the derived mechanics based formulae.
86 Furthermore, Ishigaki et al. (2005) conducted laboratory experiments on the escape speed for
87 people in floodwaters, with the experimental results indicating that the escape speed is closely
88 related to the water depth. Therefore, the degree of stability and escape speed of people in
89 floodwaters needs to be calculated using hydrodynamic parameters, such as water depth and
90 velocity, and any evacuation predictive method would be more practical and reliable if the
91 instability mechanism of evacuees in floodwaters was included in the analysis.

92 In this study, a model for selecting optimal escape routes in flood-prone areas is therefore
93 firstly proposed. Two algorithms have been developed to determine optimal escape routes,
94 including: (i) scheme A – which has been developed to find the optimal escape routes, based on
95 established road networks, and (ii) scheme B – which has been developed to design a new
96 optimal evacuation route. The 2D hydrodynamic module was then verified against experimental
97 data for flood flows from two physical models of an idealized city (Soares-Frazão and Zech, 2008)
98 and the Toce River (Soares-Frazão and Testa, 1999). Finally, the proposed model was then applied to
99 select the optimal escape routes for two overbank flood events occurring on the Lankao-Dongming
100 floodplain (LDF) area of the LYR, with the optimal escape routes and corresponding final escape
101 times being determined.

102

103 **2. Description of an integrated model for selecting optimal escape routes**

104 This section gives details of an existing 2D hydrodynamic module, the modules for assessment
105 of the hazard degree for evacuees, the calculation of the evacuation time and determination of

106 different escape routes. In general, these modules are integrated as follows: the temporal and spatial
 107 distributions of flood parameters, such as flow velocity and water depth, are first provided by the
 108 2D hydrodynamics module. Based on these flood parameters, the hazard degree and escape speed of
 109 a potential victim, within a computational cell, are then calculated using the calculation modules for
 110 the hazard degree and evacuation time of evacuees. Finally, the optimal escape route and
 111 corresponding final escape time can be obtained using the module for the determination of different
 112 escape routes. More details are given below.

113 2.1 2D hydrodynamic module

114 In order to simulate the flood inundation processes, the depth-integrated 2D shallow water
 115 equations are often used to describe flows in natural rivers, floodplain areas and other flood-prone
 116 areas, with the equations being written in a general conservative form as follows (Xia et al.,
 117 2010a,b):

$$118 \quad \frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{E}}{\partial x} + \frac{\partial \mathbf{G}}{\partial y} = \frac{\partial \tilde{\mathbf{E}}}{\partial x} + \frac{\partial \tilde{\mathbf{G}}}{\partial y} + \mathbf{S} \quad (1)$$

119 where \mathbf{U} = vector of conserved variables; \mathbf{E} and \mathbf{G} = convective flux vectors for flow in the x and
 120 y directions, respectively; $\tilde{\mathbf{E}}$ and $\tilde{\mathbf{G}}$ = diffusive vectors related to the turbulent stresses in the x and
 121 y directions, respectively; and \mathbf{S} = source term including: bed friction, bed slope and the Coriolis
 122 force. The above terms can be written in detail as:

$$123 \quad \mathbf{U} = \begin{bmatrix} h \\ hu \\ hv \end{bmatrix}, \mathbf{E} = \begin{bmatrix} hu \\ hu^2 + \frac{1}{2}gh^2 \\ huv \end{bmatrix}, \mathbf{G} = \begin{bmatrix} hv \\ huv \\ hv^2 + \frac{1}{2}gh^2 \end{bmatrix}, \tilde{\mathbf{E}} = \begin{bmatrix} 0 \\ \tau_{xx} \\ \tau_{yx} \end{bmatrix}, \tilde{\mathbf{G}} = \begin{bmatrix} 0 \\ \tau_{xy} \\ \tau_{yy} \end{bmatrix} \text{ and } \mathbf{S} = \begin{bmatrix} 0 \\ gh(S_{bx} - S_{fx}) \\ gh(S_{by} - S_{fy}) \end{bmatrix} \quad (2)$$

124 where u and v = depth-averaged velocities in the x and y directions, respectively; h = water depth; g
 125 = gravitational acceleration; S_{bx} and S_{by} = bed slopes in the x and y directions, respectively; S_{fx} and
 126 S_{fy} = friction slopes in the x and y directions, respectively; and τ_{xx} , τ_{xy} , τ_{yx} and τ_{yy} = components of the
 127 turbulent shear stress over the plane.

128 A cell-centered finite volume method (FVM) was adopted to solve the governing equations, based

129 on an unstructured triangular mesh. At the interface between two neighboring cells, the calculation
 130 of the flow fluxes was treated as a locally one-dimensional problem, thus the flux can be obtained
 131 by an approximate Riemann solver. A Roe's approximate Riemann solver, with the scheme of
 132 monotone upstream scheme for conservation laws (MUSCL), was employed to evaluate the normal
 133 fluxes, and the predictor-corrector procedure was used for time stepping. This approach provided
 134 second-order accuracy in both time and space (Tan, 1992). The hydrodynamic module was validated
 135 using experimental data from two physical models, with the detailed validation process being given
 136 in the following section.

137 2.2 Assessment of hazard degree of evacuees

138 Flood risk to people at various sites varies owing to the difference in flood parameters, and it is
 139 important to select an appropriate stability criteria for human subjects in flood risk management.
 140 Various criteria have been proposed using theoretical and experimental methods (Abt et al., 1989;
 141 Karvonen et al., 2000; 2008; Xia et al., 2014). For example, Xia et al. (2014) proposed a mechanics-
 142 based formula for the incipient velocity of a human body at toppling instability, and accounted for
 143 the effect of body buoyancy and the influence of a non-uniform vertical velocity profile acting on
 144 the human body in floodwaters, and this formula is given as:

$$145 \quad U_c = \alpha \left(\frac{h}{h_p} \right)^\beta \sqrt{\frac{m_p}{\rho_f h^2} - \left(\frac{a_1}{h_p^2} + \frac{b_1}{h h_p} \right) (a_2 m_p + b_2)} \quad (3)$$

146 where U_c = incipient velocity of a human body at toppling instability; ρ_f = density of water; h_p and
 147 m_p = height and mass of a human body; a_1 and b_1 = non-dimensional coefficients related to the
 148 buoyancy force of a human body, with $a_1 = 0.633$ and $b_1 = 0.367$ for a typical human body of a
 149 Chinese person; a_2 and b_2 = coefficients determined from the average attributes of a human body,
 150 with $a_2 = 1.015 \times 10^{-3} \text{ m}^3/\text{kg}$ and $b_2 = -4.927 \times 10^{-3} \text{ m}^3$.

151 Xia et al. (2014) conducted tests in a flume to obtain the water depth and velocity under the
 152 condition of toppling instability using a model human body, with the experimental data being used

153 to calibrate two parameters, namely α and β in Eq. (3). **Fig. 1** shows the relationship between the
154 water depth and incipient velocity for a general Chinese adult with a height of 1.71 m and a mass of
155 68.7 kg, with close agreement being obtained between the calculated and measured data. As shown
156 in Figure 1, the incipient velocity for an adult for an incoming depth of 0.5 m is 1.3 m/s.

157 The water depth at a computational cell obtained from the 2D hydrodynamic module is used to
158 calculate the corresponding incipient velocity for a specified adult using Eq. (3), as proposed by Xia
159 et al. (2014). The following relationship is used to quantify the hazard degree, as given by:

$$160 \quad HD = \text{Min} (1.0, U / U_c) \quad (4)$$

161 where HD = hazard degree for a human subject in floodwaters. There are three levels of hazard
162 degree for people in floodwaters according to the value of HD , including: (i) safe ($0 \leq HD < 0.6$),
163 (ii) danger ($0.6 \leq HD < 0.9$), and (iii) extreme danger ($0.9 \leq HD \leq 1.0$) (Cox et al., 2010; Xia et
164 al., 2014). This mechanics-based assessment method is more practical and reliable because it
165 accounts for the effects of both water depth and flow velocity.

166 *2.3 Calculation of evacuation time*

167 There exists a time challenge between people evacuation and flood inundation, because these
168 two processes occur concurrently. Therefore, time is regarded as a key factor in an emergent
169 situation during a flood disaster (Pel et al., 2012). The time taken for evacuation is calculated from
170 the escape speed and the corresponding escape distance, which is closely related to the local flow
171 conditions. Ishigaki et al. (2008) conducted evacuation tests in a water tank, for water depths
172 varying from 0.0 m to 0.5 m, with and without a flow velocity of 0.5 m/s. A fitted curve based on
173 the measured speeds of escape on foot and the local water depth is shown in **Fig. 2**. The normal
174 walking speeds of people on dry ground are typically 1.35 and 1.27 m/s for male and female adults,
175 respectively, and the corresponding escape speeds would decrease to 1/2 of the normal walking
176 speed for a typical water depth. However, the transport capacity of a road would also influence the
177 escape speed. An empirical relationship between the water depth and the corresponding escape

178 speed for people is given by:

$$179 \quad v_E = \begin{cases} \eta \cdot (1.31 - 3.1h) & (h \leq 0.2 \text{ m}) \\ \eta \cdot 0.5 v_0 & (0.2 \leq h \leq 0.8 \text{ m}) \end{cases} \quad (5)$$

180 where v_0 = normal walking speed of adults; v_E = escape speed for people in floodwaters; and η =
181 reduction coefficient of 0.90. Eq. (5) shows that it is difficult for people to escape on foot if $h > 0.8$
182 m.

183 The flow conditions along an escape route would change with time, and each escape route is
184 then divided into several short segments. For a segment between the locations A_i and A_{i+1} at the time
185 t , a time challenge between people escaping and flood inundation is shown in **Figs. 3 and 4**. The
186 flow conditions at A_i at time t are determined based on the 2D hydrodynamic module, which can be
187 used to calculate U_c and HD using Eq. (3) and Eq. (4), respectively. If the value of HD approaches
188 1.0, namely $U > U_c$, then people in the floodwaters would be in danger; otherwise the escape speed
189 of an evacuee can be calculated using Eq. (5) and then the time to traverse the segment can be
190 determined. The same approach would be used for the next segment until the location of A_{i+1} is one
191 of the safe havens. The total time of travel along all of the segments from A_1 to A_N is given by:

$$192 \quad t_N = t_0 + \sum_{i=2}^N [\Delta L_{i-1} / (v_{E, i-1})] \quad (6)$$

193 where t_N = time of travel along the segments from A_1 to A_N ; t_0 = initial time for evacuees to receive
194 warning; ΔL_{i-1} = length of the $i-1$ segment between the locations A_{i-1} and A_i , and $v_{E, i-1}$ =
195 corresponding escape speed along the $i-1$ segment.

196 2.4 Determination of different escape routes

197 In the proposed model, a selection method of optimal escape routes is presented, comprising
198 schemes A and B, under two scenarios i.e. both with and without the established road networks
199 being considered. These two schemes are described in detail as follows:

200 (1) For a flood-prone area with completed road networks, the Dijkstra algorithm, which can

201 find the shortest path between a given source node and a specified destination node, was adopted to
202 determine the shortest routes (Dijkstra, 1959). These routes were taken to be alternative escape
203 routes for scheme A. Then the hazard degree for an evacuee, and the corresponding escape speed
204 for each alternative route, were calculated for a specified flood event. When the hazard degree of
205 the route reached 0.9 for the first time, then this time was defined as the final escape time. The route
206 with the latest final escape time was selected as the optimal escape route.

207 (2) For a flood-prone area with uncompleted road networks, a location was defined as the
208 temporary safe haven if the value of HD for an evacuee is less than 0.6. These locations were zoned
209 by the temporal and spatial distributions of the hydrodynamic parameters for different flood
210 frequency occurrences. For a starting location in the flood-prone area, the corresponding shortest
211 route was selected as an optimal escape route to safe havens for scheme B. These routes would
212 provide a reference for the construction of new roads, which would be useful for both transportation
213 and evacuation.

214 In these two schemes, optimal escape routes and corresponding final escape times can be
215 obtained, which provide a scientific basis for planning evacuation. However, these methods are
216 based more on the mechanics-based instability and escape speed of evacuees, and cannot account
217 for the complicated effects of age, gender and educational level of evacuees.

218 **3. Verification of the hydrodynamic module**

219 In order to estimate the escape speed and corresponding flood risk to people predicting, or
220 modelling, the flood inundation extent is the most important precondition. Therefore, the
221 hydrodynamic module presented above was first verified against experimental data of flood flows
222 based on data from two physical model studies, including: (i) an idealized city (Soares-Frazão and
223 Zech, 2008) and (ii) the Toce River (Soares-Frazão and Testa, 1999). These results show that the
224 hydrodynamic module can accurately predict various hydrodynamic parameters factors. The details
225 of the model tests are given in this section.

226 3.1 Flood propagation through an idealized city

227 Experiment of flood flow through an idealized city were conducted in a 36×3.6 m flume
228 located in the civil engineering laboratory of the Université Catholique de Louvain, Belgium
229 (Soares-Frazão and Zech, 2008), with a sketch map of the initial set-up being shown in **Fig. 5**. A
230 gate between the reservoir and downstream was located at $x = 0$ m, and the initial depths were 0.400
231 m and 0.011 m for the reservoir and downstream, respectively. The sketched city was idealized
232 using 5×5 buildings, which were high enough so that they were not submerged by floodwaters, with
233 the buildings being 0.3×0.3 m and with each street being 0.1 m.

234 In the test case, the study domain was divided into 23,346 unstructured triangular cells and the
235 mesh was refined around each building with an area of about 2 cm². A free-slip boundary condition
236 was applied at the walls, and a free outflow boundary condition was used at the downstream outlet.
237 A Manning roughness value of 0.010 m^{-1/3}s (Soares-Frazão and Zech, 2008), a minimum water
238 depth value of 0.001 m and a time step of 0.0001 s were set to simulate the flood inundation
239 processes occurring, following the opening of the gate.

240 **Fig. 6** shows the water level profiles along the longitudinal street at $y=0.2$ m at 5 s and 10 s. It
241 can be seen that the calculated water depth profiles were in close agreement with the measured
242 profiles, with correlation coefficients of $R^2=0.88$ and 0.82 at 5 s and 10 s, respectively. However,
243 the calculated depth-averaged velocity profiles were not in such close agreement with the measured
244 data, with correlation coefficients of $R^2=0.71$ and 0.75 at the respective times. In most cases the
245 measured water-surface velocities (Soares-Frazão and Zech, 2008) were slightly higher than the
246 calculated depth-averaged velocities. This test case therefore indicates that the 2D hydrodynamic
247 module can generally present a credible prediction of the hydrodynamic parameters for flooding in
248 a scaled model environment.

249 3.2 Flood propagation in the Toce River.

250 A physical model of the Toce River was built at ENEL HYDRO laboratories in Milan, Italy,

251 consisting of a 1:100 scaled replication of almost 5 km of the river. As shown in **Fig. 7**, a large
252 reservoir was located in the central part of the model, and a set of water probes were located at
253 various points across the model to record the variation in elevations with time (Soares-Frazão and
254 Testa,1999).

255 In the test case, the study domain was divided into 21,396 unstructured triangular cells and the
256 mesh was locally refined around the upstream and downstream boundaries and near the reservoir,
257 with the minimum and maximum cell areas being 10 cm² and 736 cm², respectively. The initial
258 water depth was set to 0.001 m for the dry bed of the domain and a free outflow boundary condition
259 was applied at the downstream outlet. A constant time step of $\Delta t = 0.001$ s and constant Manning's
260 roughness coefficient of $n = 0.0162$ m^{-1/3}s (Soares-Frazão and Testa, 1999) were adopted in the
261 module. In addition, the minimum water depth for treating the wetting and drying fronts was set to
262 0.001 m for this study.

263 **Fig. 8** shows the variation in the measured and calculated water levels at the sites P₁, P₄, P₁₃
264 and P₁₉. It can be seen that the calculated depths were in close agreement with the measured values,
265 with correlation coefficients of $R^2 = 0.84, 0.75, 0.70$ and 0.88 , respectively. It was concluded from
266 these comparisons that the 2D hydrodynamic module was accurately predicting the hydrodynamic
267 parameters in a flood-prone area with complex topography.

268 **4. Model application**

269 *4.1 Study area*

270 In order to determine optimal escape routes in the LDF, related measurements were collected
271 from the YRCC (Yellow River Conservancy Committee), including: topography, surface landforms,
272 overbank floods occurring in the Dongming floodplain area, and discharge hydrographs at Jiahetan
273 for 1958 and 1982. In total there are about 120 natural floodplain areas in the LYR, which are
274 inhabited by 1.9 million residents, with overbank flood events only occurring on the LDF area
275 during flood seasons. In particular, there was also a serious flood on the LDF area in 2003 due to a

276 farm-dike breach, with 114 villages and 12,000 hm² of farmland being submerged, and with
277 160,000 people being affected. Therefore, it is important for people living on flood-prone areas to
278 be able to escape efficiently in emergency situations. In this study two extreme overbank floods
279 occurred on the LDF area in July 1958 and August 1982, with the corresponding peak discharges
280 being 20,500 and 14,500 m³/s respectively, at the hydrometric station of Jiahetan (**Fig. 9**). The
281 proposed model was applied to select optimal escape routes for these two overbank flood events,
282 assuming that the discharge hydrograph entering the floodplain zone for each flood scenario was
283 equivalent to the hydrograph at Jiahetan, minus the current bank-full discharge (7,000 m³/s) along
284 this reach. The locations of a flood diversion sluice, three starting locations (SL₁₋₃), two observation
285 points (P₁ and P₂) and target safety areas are shown in **Fig. 9**. The flood inundation extent on the
286 LDF area during the “82.8” flood are given in detail. Comparisons of the locations and final escape
287 times for optimal escape routes are presented for the “58.7” and “82.8” flood events.

288 *4.2 Simulation of “82.8” overbank flood*

289 The study domain covered an area of about 250 km² and was divided into 16,064 unstructured
290 triangular cells, which included a significant slope in the southeast direction of the LDF area (**Fig.**
291 **10**). The simulations included: a constant time step of 0.2 s, and a constant Manning roughness
292 coefficient of 0.060 m^{-1/3}s for village areas and 0.035 m^{-1/3}s for other underlying surfaces (Zhang et
293 al., 2016).

294 As shown in **Fig. 11**, the corresponding water depth was 1.2 m when the hazard degree for
295 people at P₁ reached 1.0 at $t=10.9$ h; however, the corresponding water depth was 1.4 m when the
296 hazard degree for people at P₂ was equal to 1.0 at $t=35.6$ h. The location of P₁ was near the flood
297 diversion sluice, with the local velocity being higher than that at P₂. Thus, it is more reliable to
298 evaluate human stability using Eq. (3) and Eq. (4), because people would be swept away under the
299 condition of small water depth and large flow velocity.

300 In addition, the hazard degree distributions for people at $t=9, 13$ and 33 h are shown in **Fig. 12**.
301 It can be seen that the area including the dangerous zone would increase gradually along the levee

302 due to the relatively large slope in the southeast direction on the LDF area. All the inhabitants
303 would be in danger at $t=49$ h, and they would have to escape according to the optimal route.

304 4.3 Determination of optimal escape routes in the “82.8” overbank flood

305 (a) Optimal escape routes for scheme A

306 The optimal escape routes for scheme A are presented for three starting locations. As shown in
307 **Fig. 9**, and using the Dijkstra algorithm, 5 alternative routes for each starting location are presented,
308 with the optimal escape routes for scheme A being selected. The variation in the hazard degree for
309 evacuees along the optimal routes and the worst routes for the three starting locations are shown in
310 **Fig. 13**. The duration was only about 1.5 h when the *HD* value increased from 0.0 to 1.0 for each
311 escape route. However, the evacuees at SL_1 would be eventually rescued if they selected the worst
312 route S_1 to escape and were aware of the danger before $t=5.9$ h, as the *HD* value was equal to 0.9.
313 Similarly, they would be eventually rescued if they were aware of the danger and selected the
314 optimal route S_5 to escape before $t=10.7$ h. Therefore, the route S_5 was selected as the optimal route
315 for SL_1 , with the corresponding final escape time being $t=10.7$ h. In a similar manner, the route S_9
316 was selected as the optimal route for SL_2 , with the corresponding final escape moment of $t=11.7$ h;
317 and the route S_{13} was selected as the optimal route for SL_3 , with the corresponding final escape time
318 being $t=14.7$ h.

319 (b) Optimal escape routes for scheme B

320 People need to escape at SL_1 , SL_2 and SL_3 , since they would be in danger if they were not
321 aware of warnings before $t=19.9$, 20.7 and 22.2 h regards. The optimal escape routes for scheme B
322 are presented in **Fig. 9**, with the corresponding final escape times being given in **Table 1**. For
323 example, the period from the time when people started to escape at $t=19.9$ h increased gradually,
324 and the temporary safe haven would border on the target safe haven at S_1 for the first time after a
325 period of 6.7 h. Thus, the final escape time would be $t = 13.2$ h if evacuees chose the route SL_1-S_1 .
326 In a similar way, the final escape times were $t=16.6$ h and 17.5 h if escapees selected the routes
327 SL_2-S_2 and SL_3-S_3 .

328 A comparison of the final escape times between schemes A and B is shown in **Table 1**. As
329 compared with the optimal routes for scheme B, the time for inhabitants to evacuate based on the
330 optimal times for scheme A were 2.5, 4.9 and 2.8 h respectively for the three routes considered.
331 The optimal route SL₂-S₂ was close to the route SL₂-S₉, and the optimal route SL₃-S₃ was also
332 close to SL₃-S₁₃. The results provide evidence for adjusting the existing routes slightly. However,
333 the optimal route SL₁-S₁' was very different from the route SL₁-S₅. Thus, for a flood-prone area
334 with an incomplete road network, the construction of new routes can be considered based on the
335 current calculation results, since the routes would be useful for evacuation and transportation.

336 *4.4 Optimal escape routes for the “58.7” overbank flood event*

337 The optimal escape routes and corresponding final escape times were also calculated for the
338 “58.7” overbank flood event, with the results for schemes A and B being shown in **Table 1**. The
339 optimal escape routes were the same for these two overbank floods, both for schemes A and B, but
340 the corresponding final escape times for scheme A for the “58.7” flood event were 1-3 h earlier than
341 those for the “82.8” flood, and the final escape times for scheme B for the “58.7” flood event were
342 about 3 h earlier than those for the “82.8” flood event. A comparison of these results indicates that
343 the optimal escape routes for the 3 starting locations could be determined, but the corresponding
344 final escape times for the “58.7” flood were earlier since the peak discharge and water volume for
345 the “58.7” flood event were greater than those for the “82.8” flood event. These results mean that
346 the escape routes would be the same for floods with different occurrence frequencies, but the final
347 escape times should be calculated based on the model predictions of flood inundation extent
348 processes.

349 **5. Conclusions**

350 In the current study, an integrated numerical model has been developed to select optimal
351 escape routes in flood-prone areas, with the model including: a module for predicting the 2D
352 hydrodynamics, and additional modules for assessing the: hazard degree for evacuees, the

353 calculation of evacuation times and the determination of different escape routes. The conclusions
354 obtained from this study can be summarized as follows:

355 (i) A 2D hydrodynamic module was used to simulate the flood inundation extent and processes
356 over a flood-prone area. A detailed validation process was undertaken of the model, which showed
357 that the hydrodynamic module was capable of predicting the hydrodynamic parameters over
358 complex urban and rural topographies. The mechanics-based formula for the incipient velocity of a
359 human body at toppling instability was adopted to assess the stability degree of evacuees in
360 floodwaters. An empirical relationship between the water depth and corresponding escape speed
361 was used to calculate the cumulative time required for evacuation. The selection method of optimal
362 escape routes was presented, comprising schemes A and B, and for scenarios with and without
363 established road networks being considered.

364 (ii) Model application to the LDF area showed that: optimal escape routes and corresponding
365 final escape times were determined for three starting locations, for schemes A and B, for the “58.7”
366 overbank flood event, which would provide about 3 h and 5 h more for issuing warnings and
367 evacuation procedures, as compared to the worst case escape routes. The optimal escape routes for
368 the “82.8” and “58.7” overbank flood events were the same as for the previous three starting
369 locations. However, the final escape time for the “58.7” overbank flood event would be earlier since
370 there was a larger water volume and a higher peak discharge.

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376

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447

Table 1 Optimal escape routes and corresponding final escape times for the “58.7” and “82.8” overbank flood events

Floods		Scheme A			Scheme B		
“82.8”	Optimal escape routes	SL ₁ ~S ₅	SL ₂ ~S ₉	SL ₃ ~S ₁₃	SL ₁ ~S ₁ '	SL ₂ ~S ₂ '	SL ₃ ~S ₃ '
	Final escape moments (h)	10.7	11.7	14.7	13.2	16.6	17.5

“58.7”	Optimal escape routes	SL ₁ ~S ₅	SL ₂ ~S ₉	SL ₃ ~S ₁₃	SL ₁ ~S ₁ '	SL ₂ ~S ₂ '	SL ₃ ~S ₃ '
	Final escape moments (h)	8.4	10.2	13.2	10.5	13.4	14.9

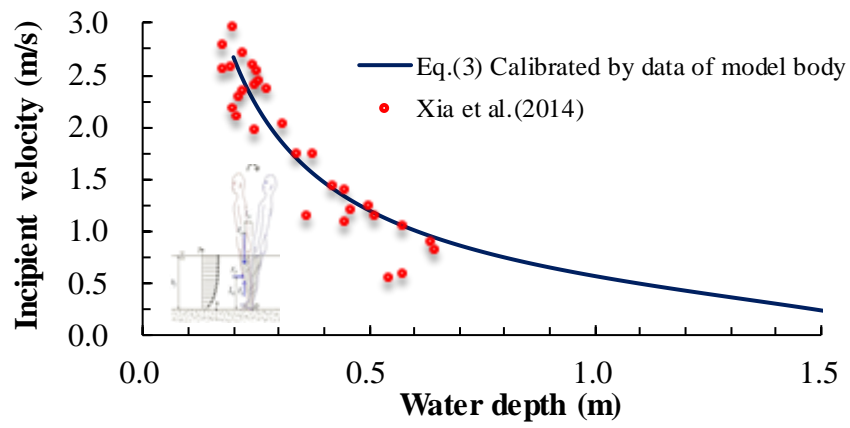


Figure 1. Instability curves between water depth and incipient velocity for Chinese adults in floodwaters

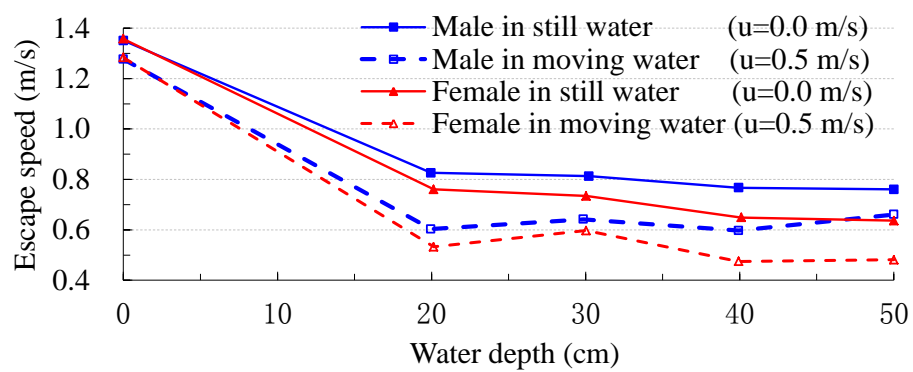


Figure 2. Empirical curves related to the water depths and corresponding escape speeds for adults in floodwaters (From Ishigaki et al., 2008)

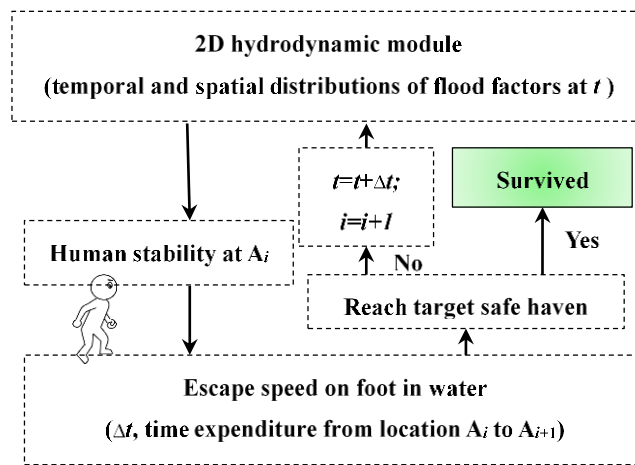


Figure 3. Time competition between people evacuation and flood inundation

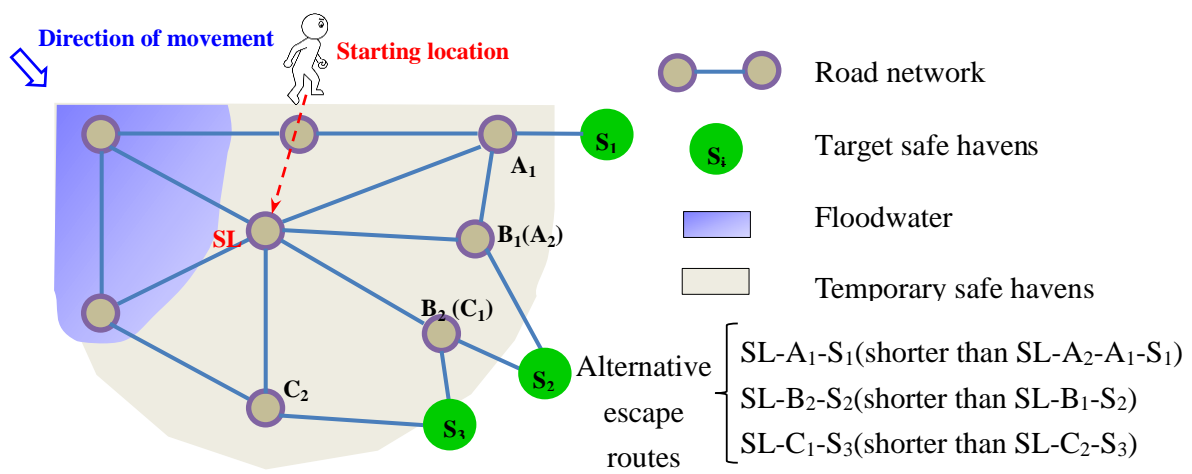


Figure 4. Sketch diagram for an evacuee to escape in a flood-prone area

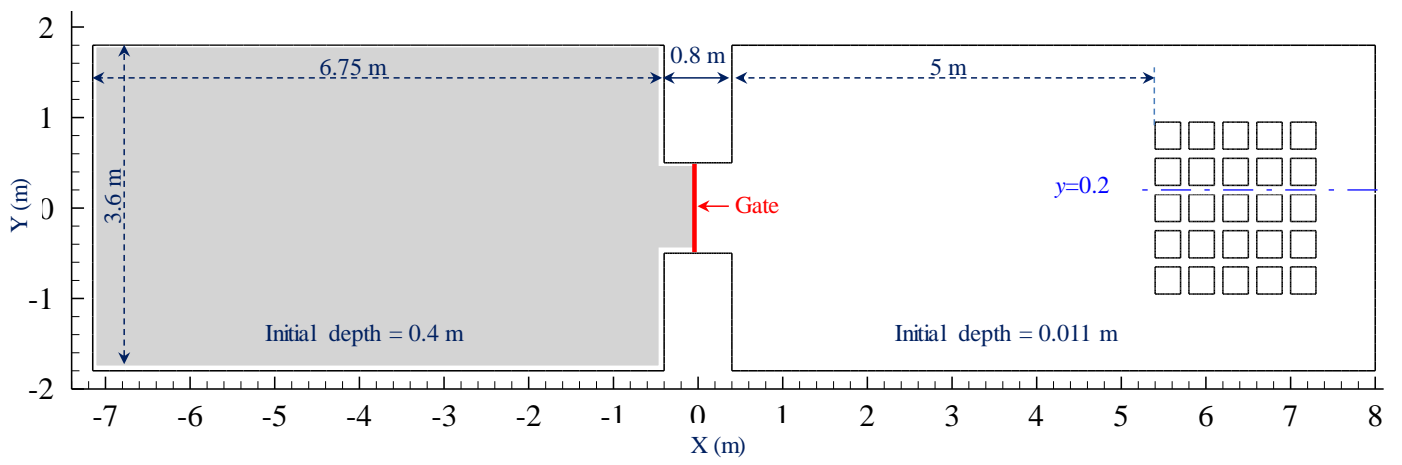


Figure. 5 Sketch of an idealized city in a laboratory flume 虚线

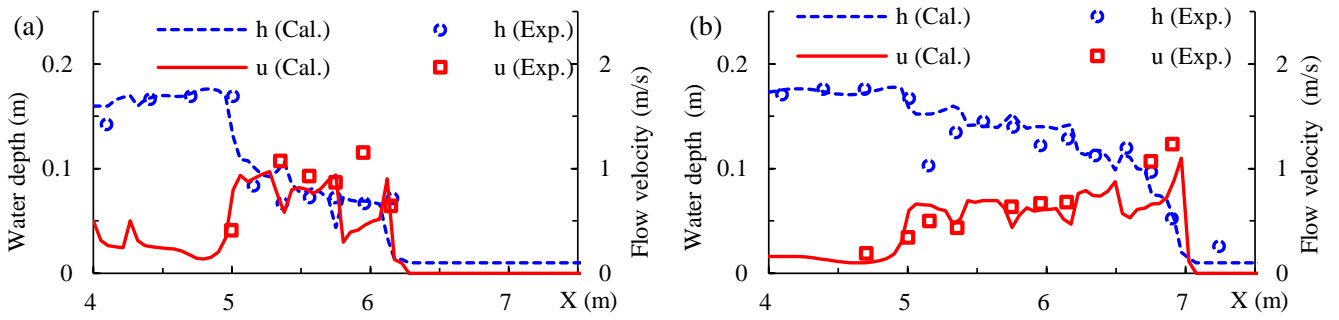


Figure. 6 Comparisons between the calculated and measured water depths and velocities along the longitudinal street at different times: (a) $t=5$ s and (b) $t=10$ s

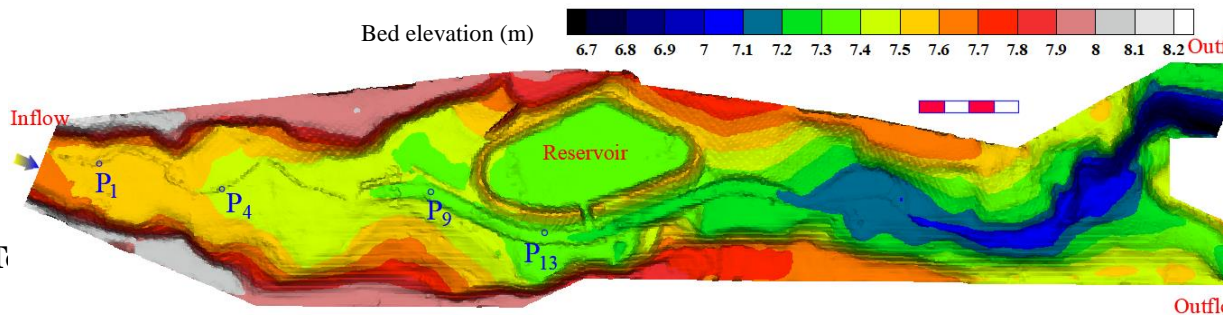


Figure 7. T
monitoring points

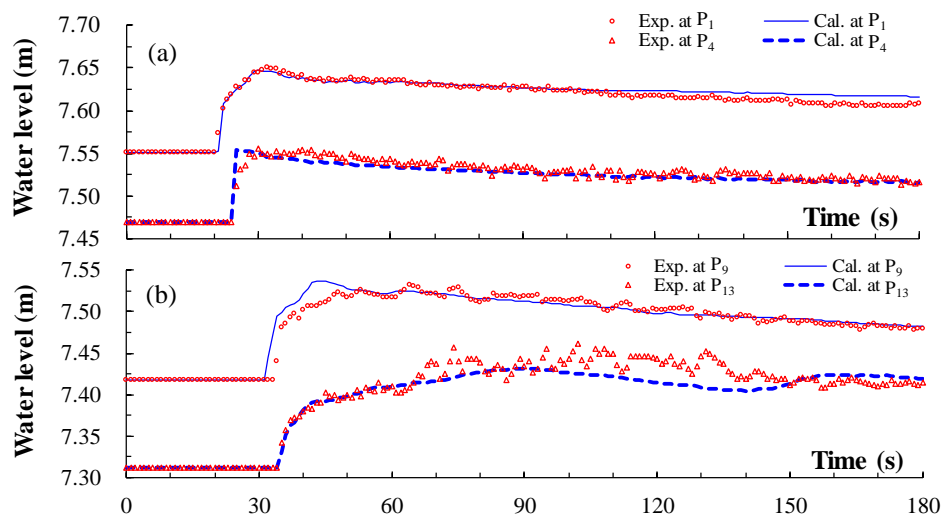


Figure 8. Comparisons between the calculated and measured water levels at different monitoring points: (a) P₁ and P₄; and (b) P₉ and P₁₃.

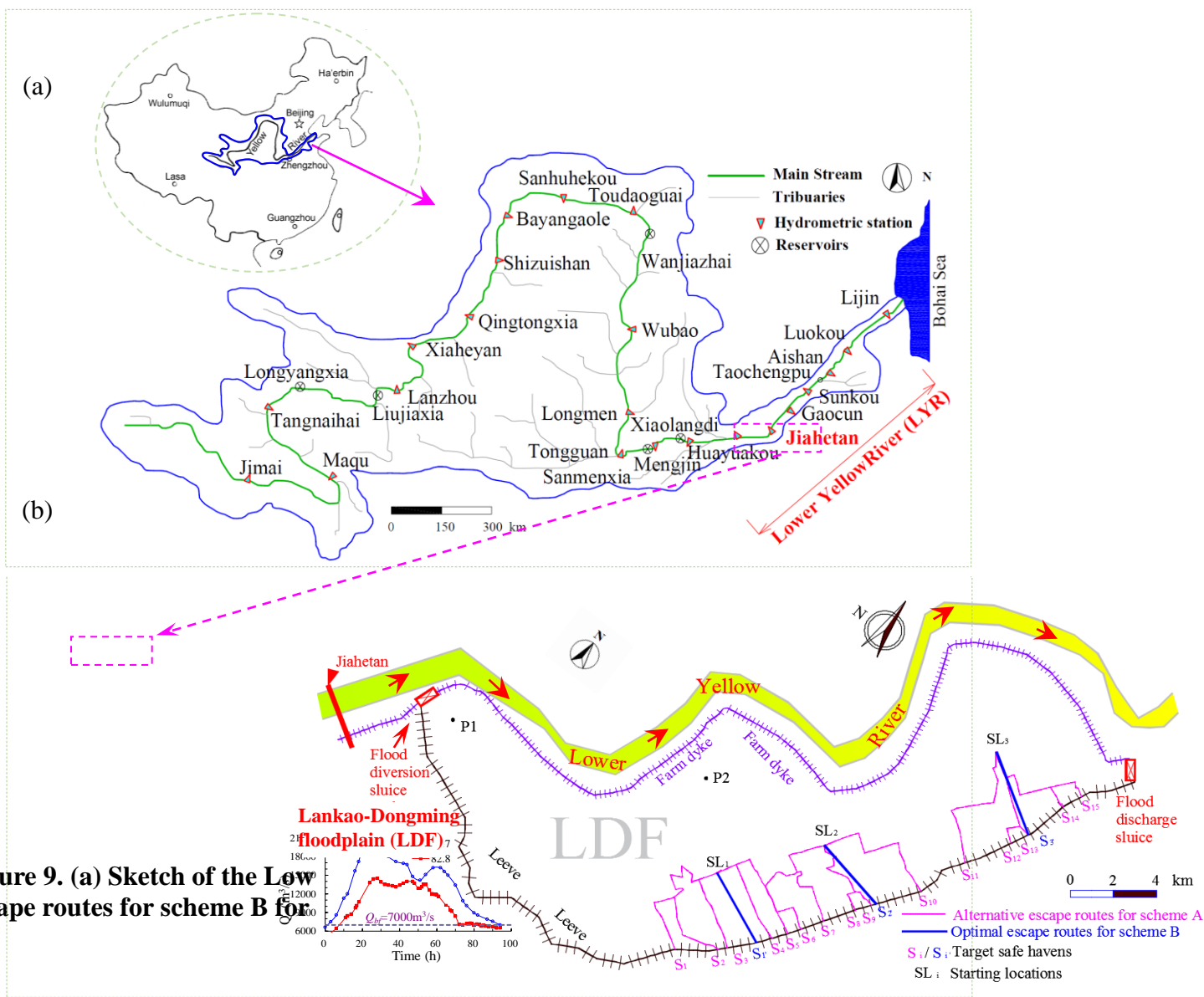


Figure 9. (a) Sketch of the Low Yellow River (LYR) and (b) sketch of the Lankao-Dongming floodplain (LDF) with escape routes for scheme B.

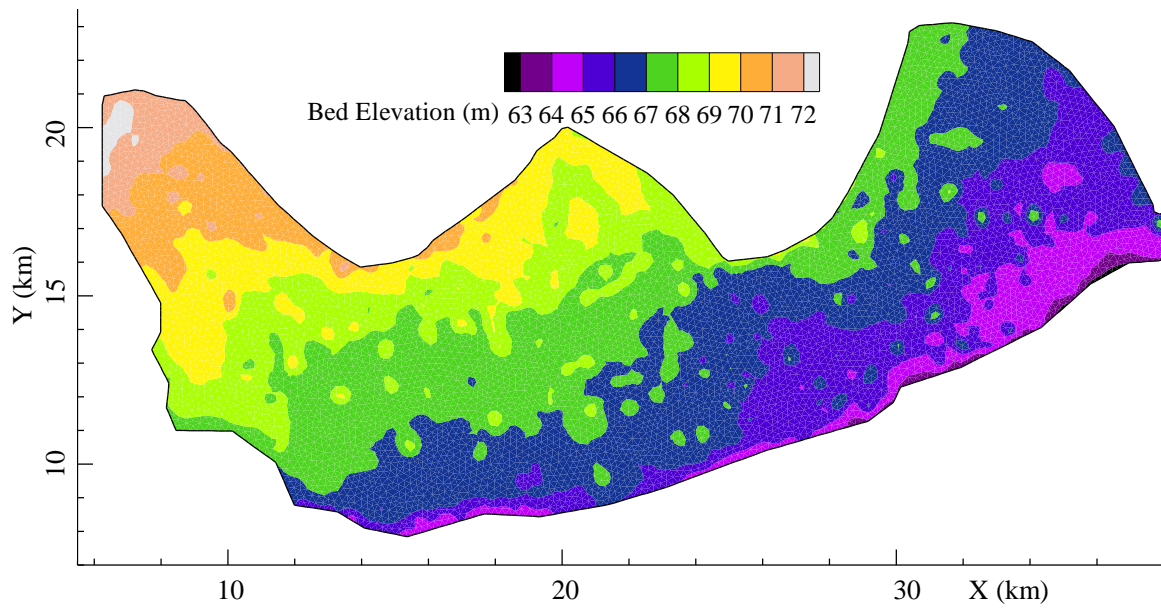


Figure 10. Topography of the study domain

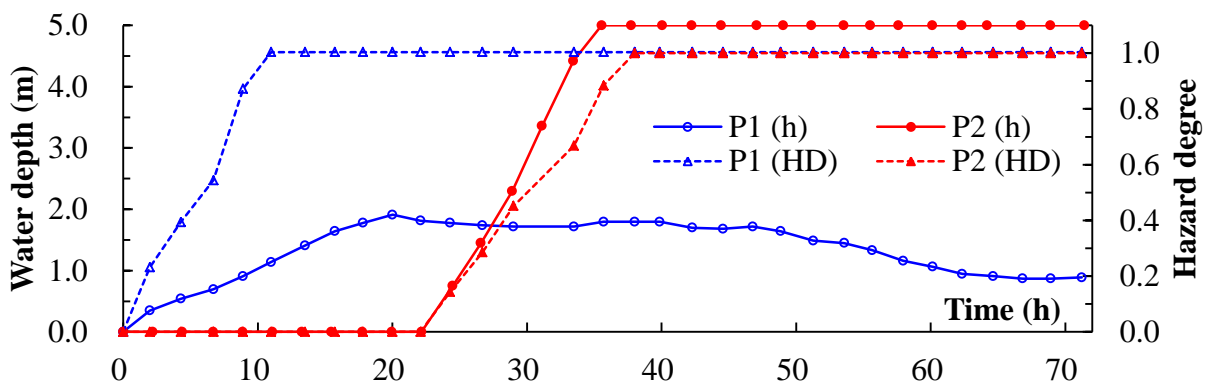


Figure 11. Temporal variations in water depth and hazard degree for people at different points P1 and P2

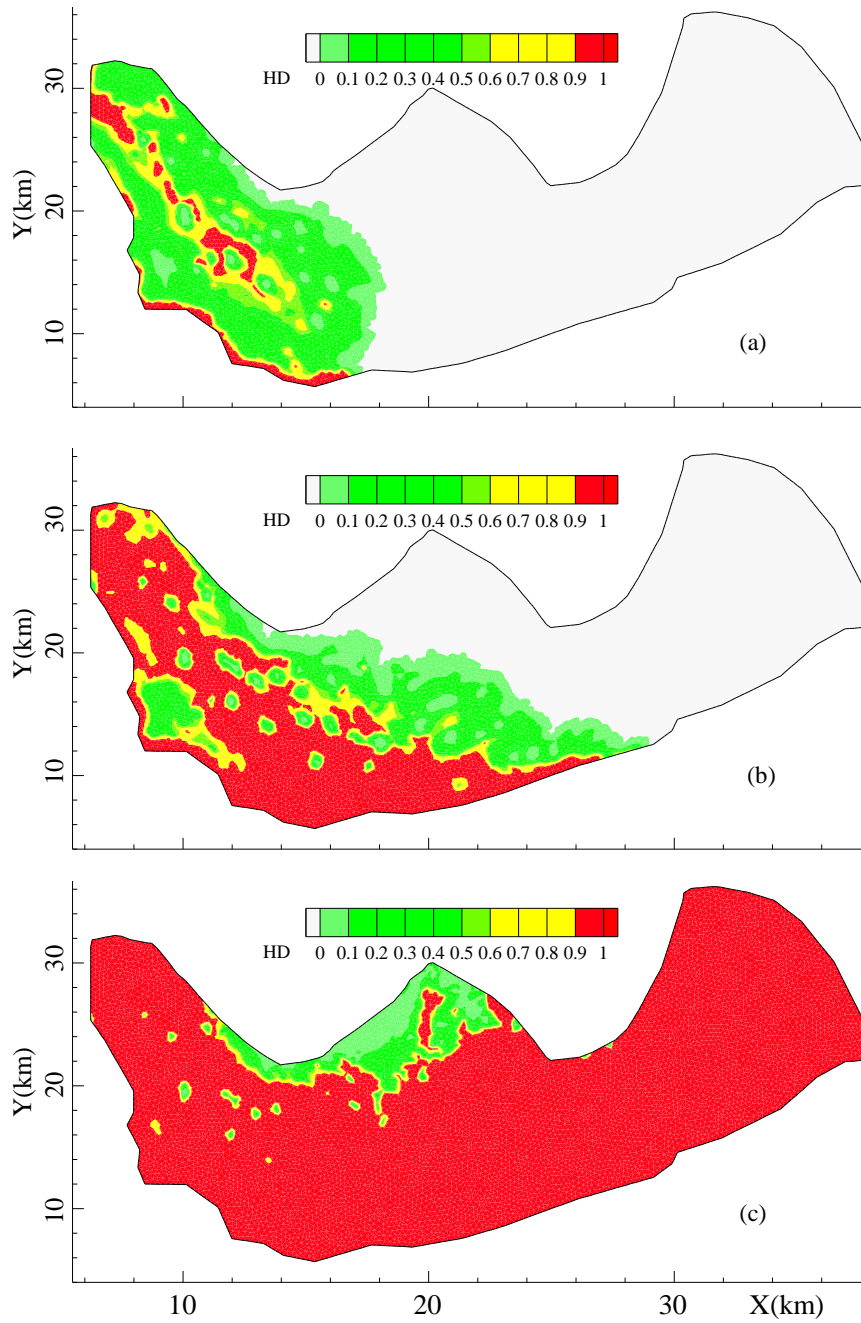


Figure 12. Distributions of hazard degree for people at different times: (a) t=9h, (b) t=13h and (c) t=33h

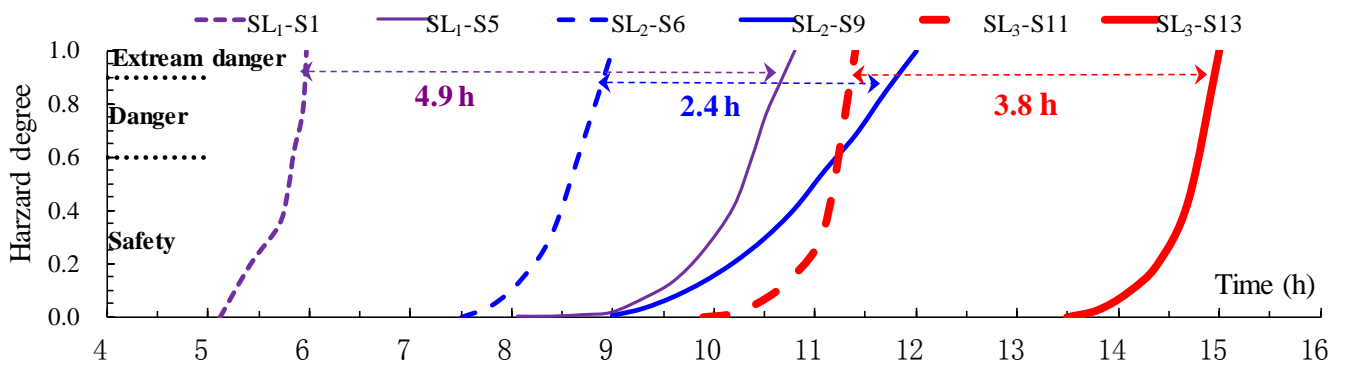


Figure 13. Temporal variations in hazard degree for people using alternative routes