Journal of
Hydroinformatics

Journal of Hydroinformatics Vol 23 No 6, 1325 doi: 10.2166/hydro.2021.044

Numerical assessment of the water-flow hazard to workers in the water disaster of underground mine

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ABSTRACT

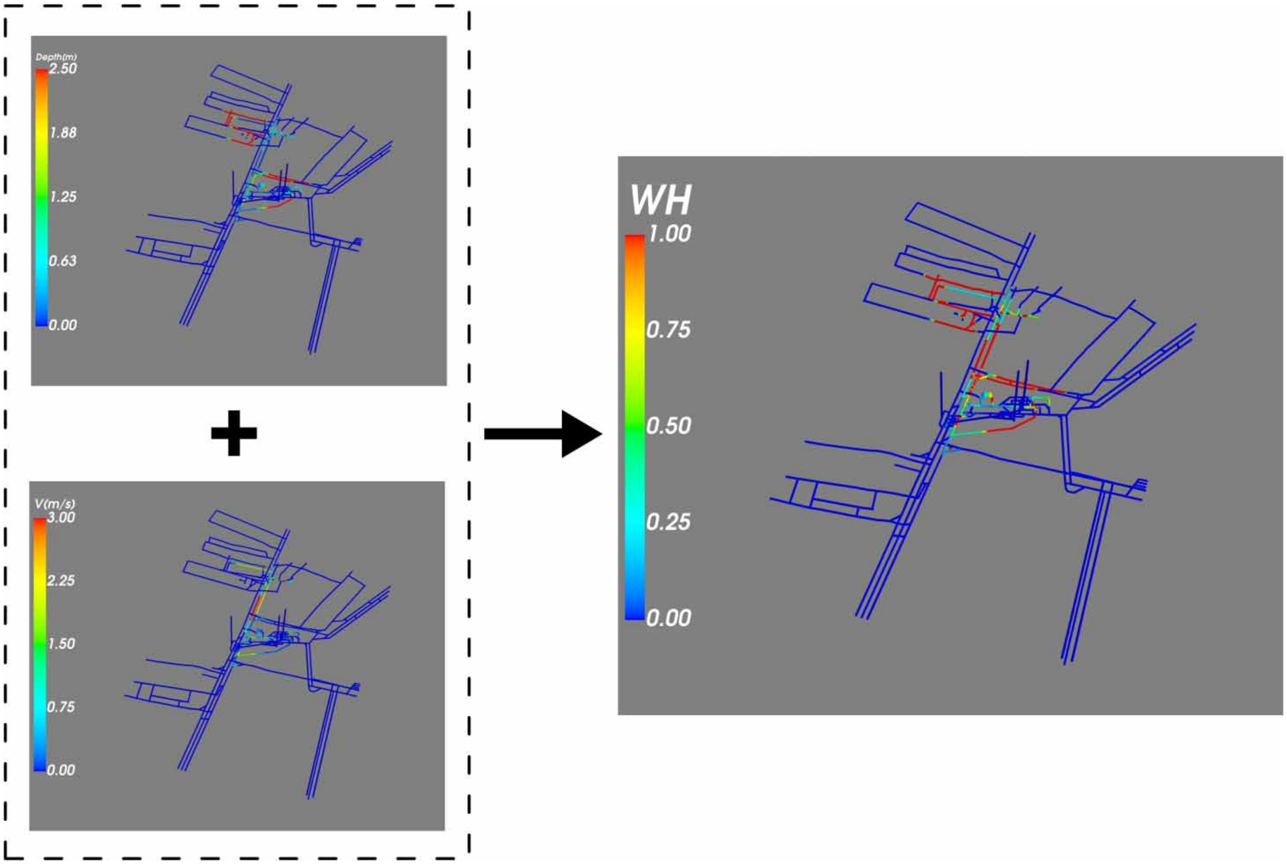
Understanding the details of the water-flow hazard (WH) to workers in water disasters is extremely important in disaster-risk management. This paper aims to develop a numerical assessment model for the WH affecting worker safety. An assessment model of WH is proposed for water disasters in the underground mine, which includes two characteristics: (a) from water-disaster environment to WH of workers and (b) from multiple influencing factors to quantitative comprehensive quantification. To verify the feasibility of WH, it is applied to a water disaster in an underground coal mine. The simulation results highlight that the WH model can assess the hazard value of worker-1 ($m = 72$ kg, $H = 1.72$ m) at paragraph − 6134 and paragraph − 8840 of roadway, with different water-flow conditions, in the whole time of the disaster. Meanwhile, the differences between WH for three workers, worker-1, worker-2 ($m = 95$ kg, $H = 1.82$ m), and worker-3 ($m = 60$ kg, $H = 1.62$ m), under the same flow conditions are provided by the curve. Moreover, dynamic visualization of WH is achieved, which shows how the hazard of worker-1 changes into the time of 2, 5, 11, 19, and 27 h after a disaster in the full mine. Therefore, this numerical assessment can be used to evaluate the hazards posed by water flow to workers, which meets the urgent demands of water-disaster management for underground mines.

Key words: dynamic visualization, numerical assessment, underground mine, water-flow hazard, worker safety

HIGHLIGHTS

- A WH model can assess the hazards of different water-flow conditions at different locations that potentially affect workers' safety in water disasters in the underground mine.
- Dynamic visualization of WH in 3D elucidates the hazard posed by water flow to workers change over time in full space.
- This assessment meets the urgent demands of water-disaster management for underground mines.

GRAPHICAL ABSTRACT



INTRODUCTION

Water disaster is one of the most severe disasters in underground engineering, occurring frequently both in the mining industry and civil construction (Li *et al.* 2013b; Jiang *et al.* 2017; Cui *et al.* 2018). Water inrush accidents greatly endanger workers' lives in underground mines. For example, serious underground water inrush disasters include the Daxing coal mine incident in China, August 7, 2005, which killed at least 121 workers (Cui *et al.* 2018); the Yesanguan tunnel of Yichang-Wanzhou Railway incident, August 5, 2007, where water inrush occurred in the DK124 + 602 karst tunnels, causing the death of 10 workers (Jiang *et al.* 2017).

Workers' safety is always the key concern in a disaster, which has always drawn, therefore, the attention of researchers working in the field of safety (Verma & Gupta 2013). Evacuating workers to the surface safely and quickly is the ultimate goal in an emergency escape from water disasters in underground mines, and during such disasters, the existence of good escape routes is critical. Essentially, most current research focuses on finding escape routes (Jalali & Noroozi 2009; Zhao *et al.* 2019), mainly represented by the shortest-route model and its improvement model, which are based on the theory of the Dijkstra algorithm, Floyd algorithm, or the Ant algorithm. Although much has been achieved from these studies, there is a lack of consideration of the water-disaster environment, especially regarding the water flow in roadways and the worker's own situation. Most evacuation routes are the shortest available, but are not optimal, because they lack quantitative quantification of the specific environment after a water disaster and its impact on workers (Wang 2017; Wu *et al.* 2020). That is why it is difficult for current emergency plans to include intelligent and dynamic avoidance measures for different types of workers and different types of disaster situations (Wu *et al.* 2020; Onifade 2021).

Due to the severity of disasters, most mines in China have adopted active emergency plans, but the hazard to workers and the evaluation of evacuation routes are generally not well covered. In fact, it is not easy for workers to remain safe on roadways, especially when they are wading (walking and running) during a water disaster. Workers are often unaware of the power of water flow and are sometimes unaware of the dangers inherent to emergency escape; workers can also take unacceptable risks in the presence of hazards, all increasing the potential for casualties. If workers are in danger, the escape plan may be useless. A full consideration of existing risk is a key issue to reduce the possibility of potential risk (Levens 1998; Kowalski-Trakofler *et al.* 2010; Verma & Gupta 2013). Eiser *et al.* (2012) emphasized that disaster hazards always involve interactions between natural and human factors. Understanding worker's flood-related risk-taking behaviors may help develop more effective strategies to prevent and mitigate the impact of floods (Garrido *et al.* 2012; Hamilton *et al.* 2020). It is only by considering the hazard posed by water flow to a worker in a water disaster that a clear analysis of worker's safety may be arrived at and a scientific and reasonable evacuation plan provided.

How the professional community should respond to water disasters in underground mines should be based on sound scientific evidence. Therefore, greater attention should be paid to safety work in disaster-risk management, especially concerning the types of danger faced by workers, and numerical assessment should be used to provide an effective management plan for water disasters. However, there is no existing scientific, systematic, or quantitative evaluation framework to address the hazards to workers during underground water disasters.

Fortunately, hazard assessment is currently being developed and improved in the floodwater field, e.g., for flash floods and urban floods. People's stability in floodwaters has seen many advances in the continuous acquisition of stability simulations and real test data in flood (Keller & Mitsch 1993; Endoh & Takahashi 1994; Lind *et al.* 2004; Jonkman & Penning-Rowsell 2008; Xia *et al.* 2014; Milanesi *et al.* 2015; Martínez-Gomariz *et al.* 2016). Three types of instability experienced by humans in floodwater were considered: friction instability (sliding), moment instability (toppling), and floating instability.

For hazard analysis, Ramsbottom *et al.* (2003) developed a methodology for assessing and mapping the hazard caused by flooding to the people involved, with this methodology being developed for the Department for the Environment, Food and Rural Affairs, and the UK Environment Agency. Based on stability analysis, the hazard assessment of people involved in flood disasters is established by Xia *et al.* (2011); Kvočka *et al.* (2016); and Guo *et al.* (2018). Xia *et al.* (2011) and Guo *et al.* (2018) considered that the degree of flood hazard for each instability mechanism can be quantified by the following expression:

$$HR = \min\left[1, \frac{U}{U_c}\right] \tag{1}$$

where U_c is the critical velocity of a human body at toppling instability and U is the flow velocity of floodwater.

Kvočka *et al.* (2016) defined the minimum value of the toppling and sliding incipient velocities as the limiting stability threshold, then they considered the flood-hazard rating quantified by the following expression:

$$HR = \min\left[1, \frac{U}{\min\left(U_{\text{toppling}}, U_{\text{sliding}}\right)}\right] \tag{2}$$

U_{toppling} is the critical velocity of toppling instability and U_{sliding} is the critical velocity of sliding instability.

Regrettably, due to the complex characteristics of water disasters in underground mines, these evaluation methods cannot be fully adapted. First, an underground mine is different from free space, especially with regard to limitations on entrance and evacuation. There are various types of underground roadways, such as the vertical shaft and the stepped roadway, in which the rising rate of water flow is faster, and space will be flooded (or even submerged).

Floodwater characteristics and population behavior determine the likelihood of a death of a disaster victim (Di Mauro *et al.* 2012). Hamilton *et al.* (2020) stressed that further exploration of methods to increase the likelihood of evacuation and reduce 'risky' behavior during a disaster is needed. Therefore, the great value lies in the development of a scientific and quantitative evaluation model for water-flow hazard (WH) in water disasters in underground mines.

In this paper, a new model for evaluating the hazard posed by water flow to workers in water disasters in underground mines is created. According to mine and water-disaster characteristics, creating a hazard assessment for workers is achieved by using existing stability analysis. In other words, this can assess the hazards posed by different water-flow conditions at different locations to the worker with different physical characteristics. Moreover, the dynamic visualization of WH in water disasters is realized in time and space, providing an example of water-resource management (Roushangar & Alizadeh 2019) and the mitigation of water related-risks, discussed in the hydrology editorial of Montanari *et al.* (2013).

METHODOLOGY

The underlying mechanisms in the creation of casualties by water disasters in underground mines are complex. Based on the previous work on the stability of people in floodwater and workers' safety in water disasters of underground mines, we conclude that there are five recurring factors in the hazards that affect workers:

1. *Roadway factors*: such as roadway type, road slope, friction coefficient, traffic equipment, or auxiliary equipment for workers, handrail, and obstacles.
2. *Hydrologic factors*: such as the type of water disaster (surface flooding, water inrush), water inflow, and inrush point.
3. *Hydraulic factors*: such as water depth, flow velocity, water density, water-rise rate, water temperature, the degree of turbidity, and items floating in the flow.
4. *Worker factors*: such as body height, body weight, clothes, physical and psychological health, escape direction, walking way, and familiarity with the roadway.
5. *Other physical factors*: such as oxygen concentration, harmful gas density, light levels on the roadway, wind speed, refuge chamber, and the prewarning time.

Not all factors directly affect the safety of workers facing a disaster because of the particularity of underground mine water disaster. The factors can be divided into direct impact factors (such as water depth and flow velocity) and indirect impact factors (such as hydrologic factors). Indirect impact factors show their hazard effects by influencing direct factors, such as water inrush hydrologic factors, which are reflected by the spread of water flow. The method in this paper considers the WH to workers, mainly analyzing the influencing factors related to roadway and water flow; at the same time, quantitative generalization is a necessary condition.

Framework

Based on the roadway gradient, pedestrian roads in underground mines are generally divided into five categories: horizontal roadway, sloped roadway, stepped roadway, inclined shaft, and vertical shaft. In horizontal, sloped, and stepped roadways, workers can walk through; in vertical and inclined shafts, traffic equipment or auxiliary equipment is needed for workers; for example, cages are often used in coal mine shafts for the vertical transport of workers.

Regarding water disasters in underground mines, three points should be considered for hazard analysis. The first is whether workers can walk through flooded roadways (horizontal roadway and sloped roadway). The second is whether workers can go up by flooded stepped roadway. And the third is whether workers can be raised by auxiliary equipment in a shaft (vertical and inclined shafts), such as by using mine cages in the vertical shaft of an underground coal mine. This paper presents a numerical assessment model for WH to workers in water disasters in underground mines that: (1) takes the disaster environment and workers' physical parameters into account; (2) incorporates increased available information of physical mechanisms from previous studies; (3) facilitates the understanding by workers, intuitively and easily, of the potential hazards they face, via dynamic visualization of WH in time. Based on the pedestrian-roadway type and water-disaster characteristics of an underground mine, we believe that there are seven hazards for workers: floating, slipping, toppling, drowning, sweeping, equipment hazard, and secondary hazard. The framework, shown in Figure 1, shows a model of water flow to a worker in water disasters of underground mines.

Numerical assessment model

Based on previous stability analysis, workers are challenged by their degrees of three types of instability in the horizontal and sloped roadway during water disasters: floating instability, slipping instability, and toppling instability. Combined with the characteristics of the rapid rise of water flow in underground mines, this paper has taken into account the hazard of drowning.

In fact, when we analyze slipping and toppling instability, floating instability has been analyzed. If the worker experiences floating instability, slipping and toppling will not exist; therefore, the WH of floating instability is defined as 1. If no floating instability occurs, then slipping and toppling stability are analyzed.

It is interesting to note that Milanesi *et al.* (2015) developed a new conclusion on instability analysis and took the destabilizing effect of local slope and fluid density into account, expanding the application's scope. Milanesi *et al.* (2015) described the legs as paired cylinders of diameter d (m), spaced $d/2$, and schematized the torso with a single cylinder of diameter $D = 2d$. Then, the critical condition for slipping instability is that the sum of the drag force of the water flow and the projection

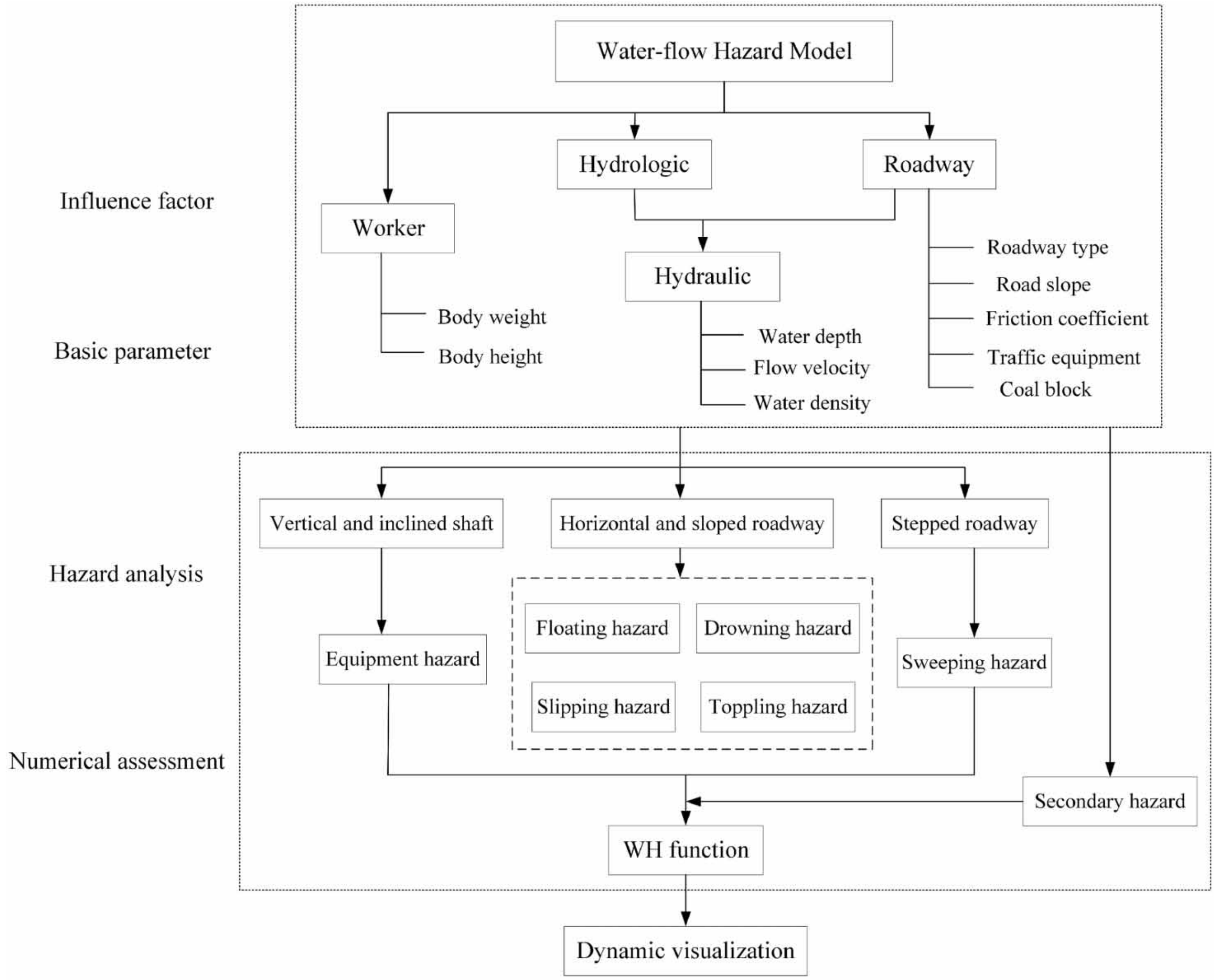


Figure 1 | The framework of the WH model for water disaster in an underground mine.

of weight parallel to the slope is greater than the friction force. The toppling instability occurs if the buckling moment due to the components of hydrodynamics (drag and lift), buoyancy, and weight exceeds the moment calculated at the pivot point relative to the normal component of the weight. The limiting critical depths are regarded as a function of the flow velocity, which is the slipping ($h_s(v)$) and toppling ($h_t(v)$) (Milanesi *et al.* 2015). The validity of its critical condition has verified by comparing with the existing experimental data in Milanesi *et al.* (2015).

However, in terms of mathematical formulas, it is very difficult to simplify the critical depth function based on velocity, and it is extremely complex, vastly reducing its applicability. We suggest using the critical velocity function based on water depth ($v_s(h)$, $v_t(h)$) and deducing the corresponding concrete conclusions which suitable for hazard assessment in this paper. The symbols and meanings of the parameters involved in stability analysis are listed in Table 1.

$$v_s(h) = \begin{cases} \sqrt{\dfrac{mg(\mu\cos\theta - \sin\theta) - \left(\dfrac{\pi}{2}\right)\mu\rho g h d^2}{\rho d h(\cos\theta)[C_C(\cos\theta + \mu\sin\theta)]}}, & \text{if } h \leq \dfrac{H}{2}\cos\theta \\ \sqrt{\dfrac{mg(\mu\cos\theta - \sin\theta) + \left(\dfrac{\pi}{4}\right)\mu\rho g H(\cos\theta)d^2 - \pi\mu\rho g h d^2}{\rho d h(\cos\theta)[C_C(\cos\theta + \mu\sin\theta)]}}, & \text{if } h > \dfrac{H}{2}\cos\theta \end{cases} \tag{3}$$

Table 1 | Nomenclature of parameters associated with stability analysis

Parameters	Meaning
μ	The friction coefficient between sole and surface of roadway (–)
ρ	The density of water flow (kg/m^3)
g	The gravitational acceleration (9.81 m/s^2)
m	The weight of human body (kg)
H	The height of human body (m)
v	The velocity of water flow (m/s)
h	The depth of water flow (m)
θ	Angle of the sloped roadway (°)
C_C	The coefficient of drag force (–)

$$v_t(h) = \begin{cases} \sqrt{\dfrac{2mg\left(d + h\sin\theta - (\frac{7}{6})H\, sin\theta\cos\theta\right) - (\frac{\pi}{\cos\theta})\rho g h d^2 (d - h\sin\theta)}{\rho d^2 h^2 C_C\left[(\frac{\pi}{2})\cos^2\theta + 2\sin\theta\left(\left(\frac{1}{h}\right) + \left(\frac{\sin\theta}{d}\right)\right)\right]}}, & if \quad h \le \dfrac{H}{2}\cos\theta \\ \sqrt{\dfrac{mg\left(A - (\frac{7}{12})H\sin\theta\cos\theta\right) - \rho g\pi d^2 B\left(h - \left(\frac{H}{4}\right)\cos\theta\right)}{\rho d h C_C\left((\frac{1}{2})\cos^2\theta + C\sin\theta\right)}}, & if \quad h > \dfrac{H}{2}\cos\theta \end{cases} \tag{4}$$

where $v_s(h)$ is the critical velocity of slipping instability at water depth h; $v_t(h)$ is the critical velocity of toppling instability at water depth h;

$A = (8h - 7dH\cos\theta)/(8h - 3H\cos\theta) + (8h^2 - H^2\cos\theta)\ sin\theta/[4(4h - H))]$
$B = (8h - 7dH\cos\theta)/(8h - 3H\cos\theta) + (8h^2 - H^2\cos\theta)\ tan\theta/[4(4h - H)]$
$C = (8h - 7dH\cos\theta)/(8h - 3H\cos\theta) + h\sin\theta/2$

As the area of the underground mine is limited, the water flow during a disaster rises rapidly. On June 2, 1984, a water inrush occurred in Fangezhuang Mine, Kailuan, Hebei Province, and water filled the whole coal mine. On August 23, 2010, a drowning accident occurred in Dongjiagou Coal Mine, Liulin County, Shanxi Province, which resulted in five deaths. Therefore, we believe that evaluating WH in water disasters in underground mines must include the hazard of drowning, which is independent of flow velocity.

A depth constraint of drowning was suggested by Cox *et al.* (2010) who proposed a maximum admissible water depth of 1.2 (m) for adults. Milanesi *et al.* (2015) introduced a maximum admissible water depth h_d(m) as a function of the height of the neck. The depth limits h_d can be set as functions of the size of the body (H), so that the head is completely above the water surface. In particular, the head can be considered 1/8 H (Drillis *et al.* 1964); in order to keep a freeboard, the head height was assumed to be 3/16 H by Milanesi *et al.* (2015). Therefore, h_d is assumed to be 13/16 H in this study.

Therefore, four kinds of hazards were considered in water disasters in underground mines: floating, slipping, toppling, and drowning. We propose that the hazard rating of water flow to a worker in horizontal and sloped roadways can be quantified with the following expression:

$$HR_{\mathrm{HSR}} = \min\left[1, \max\left(\frac{h}{h_d}, \frac{v}{v_s(h)}, \frac{v}{v_t(h)}\right)\right] \tag{5}$$

For water-flow conditions judged to be greater than critical instability, once wading is a more dangerous action, so it is more dangerous if the corresponding water-flow conditions increase further. In order to ensure the safety and security of miners escaping from disasters, we do not recommend miners to choose this type of roadway by risky actions, so its hazard can still be called 1. If the purpose of the demand is only to obtain a purer hazard-evaluation value, removing the minimum value function that takes 1.0 in Equation (5) is sufficient.

When a worker walks along a stepped roadway, he may be directly swept down by spreading water. Evacuation from an underground space during a flood disaster has been investigated by using a similar-scale or real-size model of a staircase (Ishigaki *et al.* 2006). From previous work, the specific force per unit width (M) is a reasonable criterion for safe evacuation through flooded stairs (Onishi *et al.* 2008), which is:

$$M = \frac{v^2 h}{g} + \frac{h^2}{2} \tag{6}$$

$M = 0.125$ (m^2) is the criterion for a safe evacuation, and 0.250 is the limiting value of evacuation without any help for normal persons (Ishigaki *et al.* 2009). Therefore, we can define the hazard function of water flow concerning a worker in stepped roadways as follows:

$$HR_{\mathrm{SR}} = \begin{cases} \frac{M - 0}{0.125 - 0} \times s, & 0 \leq M < 0.125 \\ s + \frac{M - 0.125}{0.25 - 0.125} \times (1 - s), & 0.125 \leq M < 0.25 \\ 1.0, & 0.25 \leq M \end{cases} \tag{7}$$

where s is the acceptable value of WH in water flow. Guo *et al.* (2018) believed that a location can be defined as safe if the value of HR for people is less than 0.6. Therefore, it can be assumed that $s = 0.6$ in this paper.

When workers need to be raised in vertical and inclined shafts whether the traffic equipment or auxiliary equipment (such as mine cages) is working normally or not is critical for hazard analysis. In an actual traffic section of the roadway, this hazard requires a safety monitoring system to report, identify, and alert anomalies through sensors or workers in the current location. So that an equipment hazard can be quantified by an assessment function, which is:

$$HR_{\mathrm{VIS}} = \begin{cases} 1, & \text{Equipment abnormal} \\ 0, & \text{Equipment normal} \end{cases} \tag{8}$$

In actual disaster situations, the initial value of HR_{VIS} is set to 0. Once the interactive information alerts the relevant equipment to abnormalities, it is set to 1. When it can be restored to normal use after repair, it is then set to 0.

Therefore, the direct hazard of water flow to workers in a water disaster in the mine roadway can be quantified as WH_1, which is:

$$WH_1 = \begin{cases} HR_{\mathrm{HSR}}, & \text{Horizontal and sloped roadway} \\ HR_{\mathrm{SR}}, & \text{Stepped roadway} \\ HR_{\mathrm{VIS}}, & \text{Vertical and inclined shaft} \end{cases} \tag{9}$$

In addition, dangerous debris and other (even heavy) objects may be transported by the water flow in the water disaster. Mine roadways such as driving faces cannot be hardened immediately due to production reasons, and there will be coal blocks of varying sizes in the unhardened sections. Therefore, in the course of a water disaster, the water flow can not only directly act on the workers, but also impact the transport of coal, making it float or roll. Moving coal may strike a worker's body, causing injury or death, thereby causing secondary hazards (WH_2) to escaped workers. The impact of debris factor in floods was quantified based on empirical methods by Ramsbottom *et al.* (2003, 2006) and Kvočka *et al.* (2018). In the mine water disaster, this hazard depends mainly on the type of water disaster, the location of inrush point, the characteristics of the water flow, and the size of the block. If the block particles are too small or remain stationary under the action of water flow, then define its hazard as 0. If the block floats and moves in the tunnel and its particle size will have an impact on miner safety, then define its hazard as 1. The underground space of the coal mine is complex, and it is difficult to obtain data on the movement of coal in the water flow in the post-disaster environment. At present, it is mainly based on the discovery of underground mine workers during escape and evacuation and reporting to the ground for interactive acquisition. For the roadway sections that may have problems with predictive analysis, video surveillance should be strengthened. With the continuous construction and development of smart mines, rich dynamic data can be obtained through video, mobile robots, and other methods in the later period.

Consequently, a numerical assessment model was developed for the WH to workers in a water disaster in an underground mine, and the WH function is:

$$WH = \max(WH_1, WH_2) \tag{10}$$

According to the previous research on water inrush spreading processes in the underground mine (Li *et al.* 2013a; Wu *et al.* 2018; Zhao *et al.* 2020), the corresponding spatial and temporal data such as water height and velocity can be obtained through numerical simulation for further discussion. The spreading process of one water inrush can be represented as a high-dimensional vector, x, by connecting the values at different locations over time (Zhao *et al.* 2020), which is

$$x = (x^{t_1}, x^{t_2}, \cdots, x^{t_n}) \tag{11}$$

where $x^t = (x_1^t, x_2^t, \cdots, x_m^t)$ is the value vector at a given time, x_i^t is the water depth (h_i^t), or flow velocity (v_i^t) on node i along the underground roadway. Based on the connected network of the underground mine, it is assumed that h_{ij}^t is the water depth from node i to adjacent node j departing at time t, v_{ij}^t is the flow velocity, which is

$$h_{ij}^t = (h_i^t + h_j^t)/2 \tag{12}$$

$$v_{ij}^t = (v_i^t + v_j^t)/2 \tag{13}$$

Moreover, a dynamic evaluation of hazard level for a worker (m, H) at any roadway segment (ij) of the mine and any time of the water disaster can be expressed as $WH(x, y, z, t)$, that is

$$WH(x, y, z, t) = WH(t, h_{ij}^t, v_{ij}^t) \tag{14}$$

Therefore, the WH for different workers at any point of the mine can be evaluated by the WH model dynamically at any time during the disaster process or in the post-disaster environment.

APPLICATION

Study area

The Beiyangzhuang Coal Mine is located in Yuxian County, Hebei province, Northern China. The total mining area is about 52 km^2, its north-south length is about 10 km, and its east-west width is between 5 and 8 km. The method of minefield development is vertical shaft development, with three vertical shafts designed: main shaft, auxiliary shaft, and air shaft. Figure 2 shows the structure of the mine roadway and the distribution of the working face.

As of September 2019, there have been three water-burst accidents in the mine, occurring in March 2012, May 2012, and September 2014. Based on an analysis of the mine's history, it can be concluded that under the influence of karst Ordovician limestone water, the mine has experienced the hazard of floor water inrush, and the water-rich is strong in this area.

Identification of the parameters

The roadway is modeled as a topological structure consisting of 8,761 points and 8,850 segments. The paragraphs of 6,134, 8,600, and 8,840, as well as the water inrush point, are clearly marked on the 2D map of the mine roadway. The 3D display of a mine roadway is shown in Figure 3, and the water inrush point is assumed to be at driving face No. 1. Wu *et al.* (2016) had assessed the risk of water inrush at the Yuzhou mining area using the vulnerability index method, which is extracted from the Beiyangzhuang coal mine. The driving face No.1 is located in a strong vulnerable zone and contains faults, so it is very likely to burst water. The basic law of curves of inrush flux at the bottom of this mine was outlined and designed by Zhao *et al.* (2020). The water inrush from Ordovician limestone was simulated in this study, and the curve of which is shown in Figure 4. The water inrush was simulated for 28 h, in order to make the case can fully analyze and demonstrate the depth, speed, and WH value characteristics of each water flow in the early, middle, and late stages after the occurrence of water disaster. The

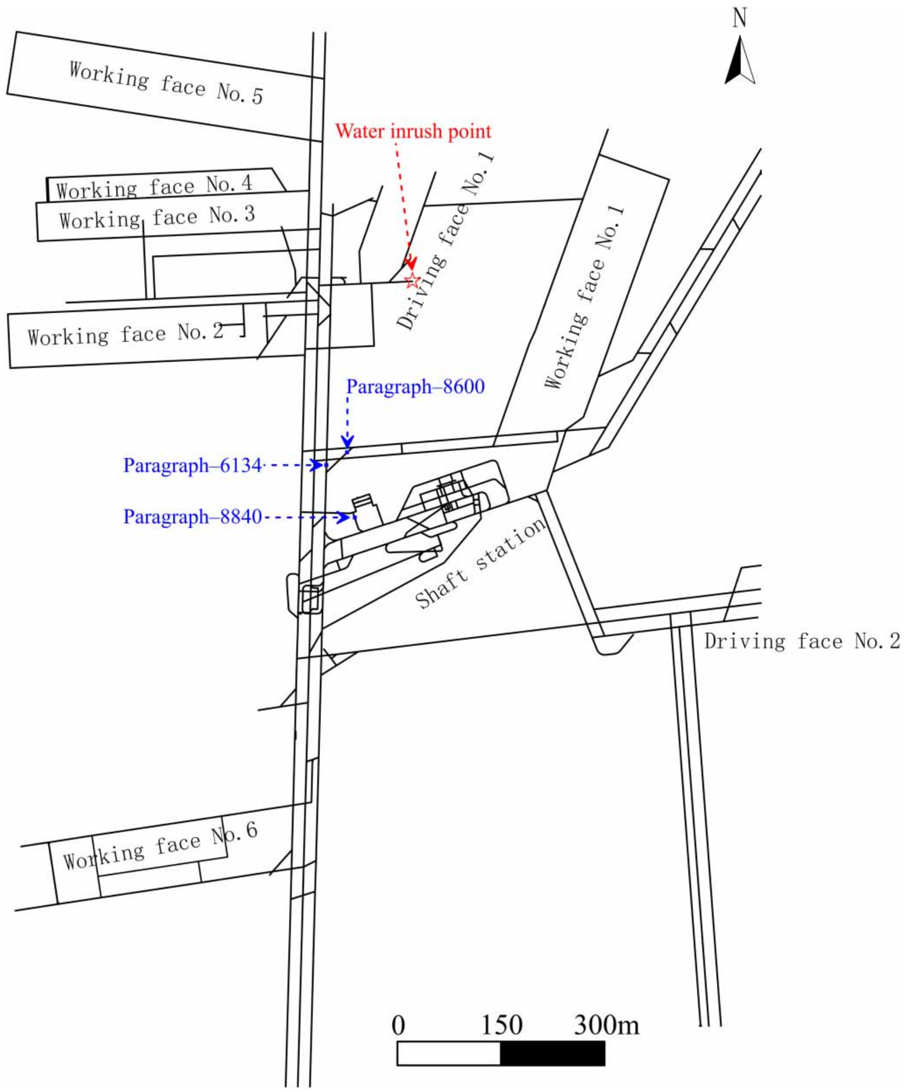


Figure 2 | The roadway structure and working face distribution in Beiyangzhuang mine (water inrush point and paragraphs 6134, 8600, and 8840 are displayed).

diffusion process of mine water can be simulated as one-dimensional, unsteady, and non-uniform open channel flow (Zhao *et al.* 2020). The de Saint-Venant system of equations is established, according to the law of conservation of mass and the law of conservation of momentum. The corresponding water spreading processes can be simulated by the Storm Water Management Model (SWMM) (Zhao *et al.* 2020) to obtain the water depth and flow velocity of inrush water along the mine roadways. In the future, these data could also be monitored by sensors during a mine water disaster, even identified and predicted by numerical models using artificial intelligence technologies (Alizadeh *et al.* 2020; Zhao *et al.* 2020).

Most mine water in China contains suspended solids (He *et al.* 2002), consisting of materials such as silt or small coal particles; thus, the density of mine water is usually greater than normal water. It can be supposed that the density of mine water (ρ) is 1,010 kg/m^3 in this simulation. The value of the drag coefficient C_C depends on the shape of the exposed object (Jonkman 2007). Among the studies on the human body, a value of C_C ranging from 1.1 to 2.0 was adopted by Keller & Mitsch (1993), Lind *et al.* (2004), and Jonkman & Penning-Rowsell (2008). To take into account the roughness that would characterize a clothed human body, a value of $C_C = 1$ was adopted by Milanesi *et al.* (2015). Accordingly, it is also assumed to be 1 in this study.

Karvonen *et al.* (2000) have conducted experiments on human stability in water flow, with the body heights ranging from 1.60 to 1.95 m, and the body weights vary from 48 to 100 kg. According to the 'Report on Nutrition and Chronic Diseases in

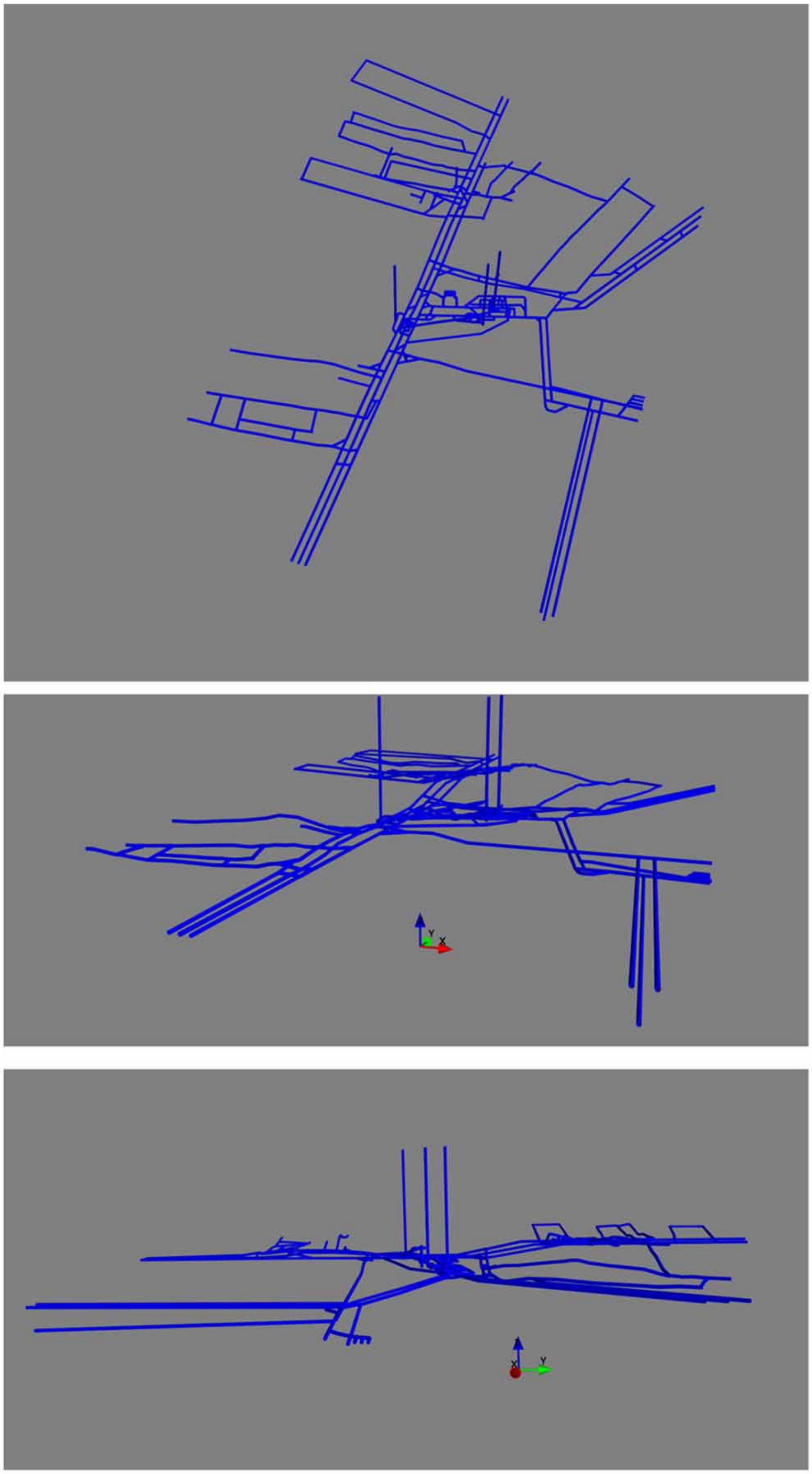


Figure 3 | 3D map of coal mine roadway.

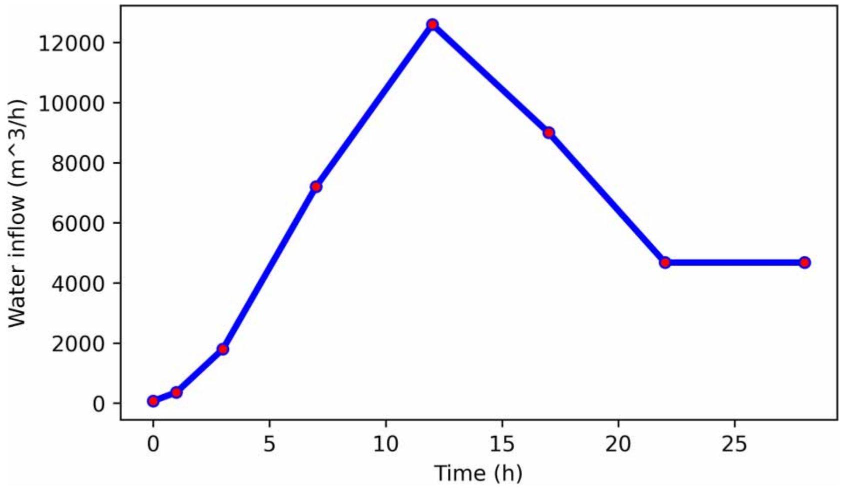


Figure 4 | Water inrush curve of water disaster.

Table 2 | The physical parameters assumed for the model of workers

Parameters	Worker-1	Worker-2	Worker-3
m (kg)	72	95	60
H (m)	1.72	1.82	1.62
d (m)	0.13	0.13	0.13

China (2015)' released by the National Health and Family Planning Commission of China, the average height of adult men in China is 1.671 m and the average weight is 66.2 kg. Underground miners in China are basically all adult males with their own physical parameters. The physical parameters assumed for the model of underground workers are shown in Table 2.

Xia *et al.* (2014) revealed that the selection of μ needs to be estimated using the ground surface roughness and the characteristics of shoe soles. A friction coefficient of 0.3–1.0 was used in the human-stability analyses conducted by Keller & Mitsch (1993) and Jonkman & Penning-Rowsell (2008). For the study of human stability in the breakwater, Endoh & Takahashi (1994) conducted a series of tests on the friction coefficient for a range of leather and rubber-soled shoes on various ground surfaces as shown in Table 3.

To determine the coefficient of friction provided by each of the different shoe types, an experiment was developed by Martínez-Gomariz *et al.* (2016) who showed that the friction coefficients for a waterproof boot and wet surface are 0.58. Therefore, based on the result of Martínez-Gomariz *et al.* (2016) and Table 3, it can be assumed that the value of μ for a mine roadway is 0.60 in this simulation.

Table 3 | Mean values of friction coefficient between shoe and wet concrete (from Endoh & Takahashi 1994)

	Shoe	
Roadway	Leather shoe	Rubber shoe
Smooth concrete	0.66	0.62
Rough concrete	1.12	0.95
Concrete covered with algae	0.86	0.56
Concrete covered with seaweed	0.38	0.44

Simulation results and discussion

Through the WH model, we can evaluate the hazard posed by mine water flow to a worker at every position during the disaster process. Furthermore, the changing process of WH in a certain period deserves attention, and the overall status of a hazard at a certain time is critical.

To better understand the dangers of disaster to workers, the temporal variations of water depth, flow velocity, and WH for worker-1 ($m = 72$ kg, $H = 1.72$ m) at different sites are shown in Figure 5, which gives a clear picture of the water-flow information and the WH to a worker for the whole time of the disaster. From the data in Figure 5, it is apparent that the depth of

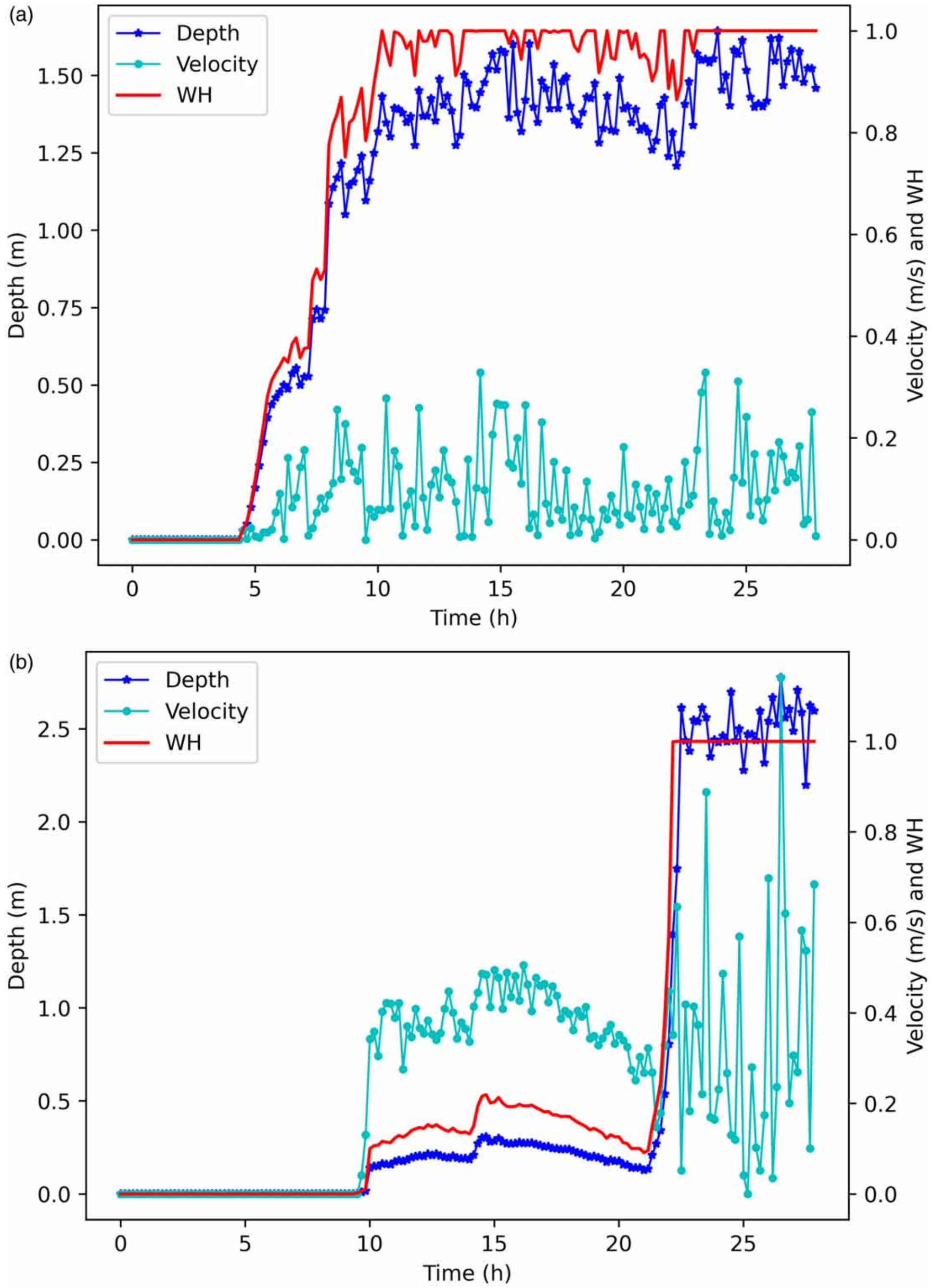


Figure 5 | Temporal variations of water depth, flow velocity, and WH for worker-1 at different sites. (a) Paragraph – 6134; (b) paragraph – 8840.

the water increases continuously, and the trend of flow velocity is complex, with its variation greatly fluctuating as the water-disaster unfolds. Based on the comparison of water depth, flow velocity, and WH break-line changes in Figure 5, we believe that the characteristics of mine water flow are fully taken into account in the quantification process of WH. In Figure 5, there is a clear upward trend in WH to worker-1 with increasing water depth at the site. Finally, when the comprehensive hazard-effect of the water flow is inevitably going to cause danger to workers, the hazard-evaluation value is still considered as 1, even if the depth and velocity of the flow are changing slightly. This is to ensure the safety of workers, and water-flow conditions are considered dangerous whenever they exceed critical conditions. The risky actions are not recommended in the disaster escape.

To eliminate the influence of data with different dimensions on the analysis results and to facilitate further comparative analysis between different variables and WH, it is necessary to normalize the data set. The data of water depth and flow velocity are normalized to be dimensionless quantities, which is implemented through the function method of min-max scaling. Furthermore, the dynamic visualization of normalized water depth, flow velocity, and WH also can understand how these change over time in the whole roadway, which are shown in Figure 6. For an emergency to be declared, it is critical to recognize, in detail, the degree of hazards facing workers. Obviously, it is not reasonable to evaluate the hazards of water flow to workers according to only water depth or flow velocity. As can be seen from Figure 6, the dynamic visualization of WH combines the dynamic changes of water depth and flow velocity. Compared with the spread of normalized water depth and flow velocity, the area of WH is larger because it not only includes water depth and velocity, but also quantifies the type and gradient of the roadway, water density, worker physical characteristics of body weight and height, and applies the physical mechanism of stability. For example, when $T = 5$ h, the practical guiding significance of WH is stronger than that of water depth and flow velocity through visualization. It can be seen from the WH diagrams of $T = 2$, 5, 11, 19, and 27 h in Figure 6 that the scope of the hazards of water flow to underground workers at different times is very different. That is to say, the latest escape time for workers at different locations during the flooding process is different. In fact, the WH information of this model can be displayed at any time through dynamic visualization. Therefore, the WH can help workers make decisions about the time to escape.

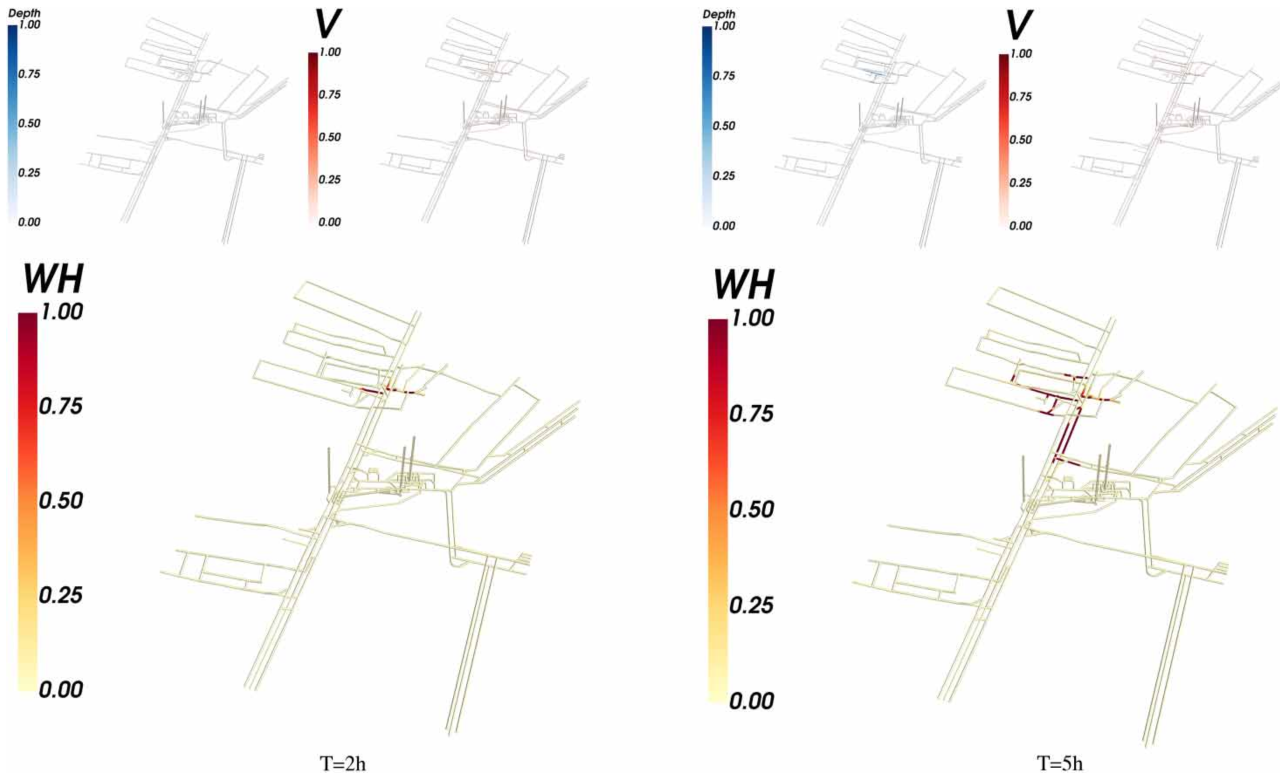


Figure 6 | The distributions of normalized water depth, flow velocity, and WH for worker-1 in whole roadway at different times ($T = 2$, 5; 11, 19, 27 h). *(Continued.)*

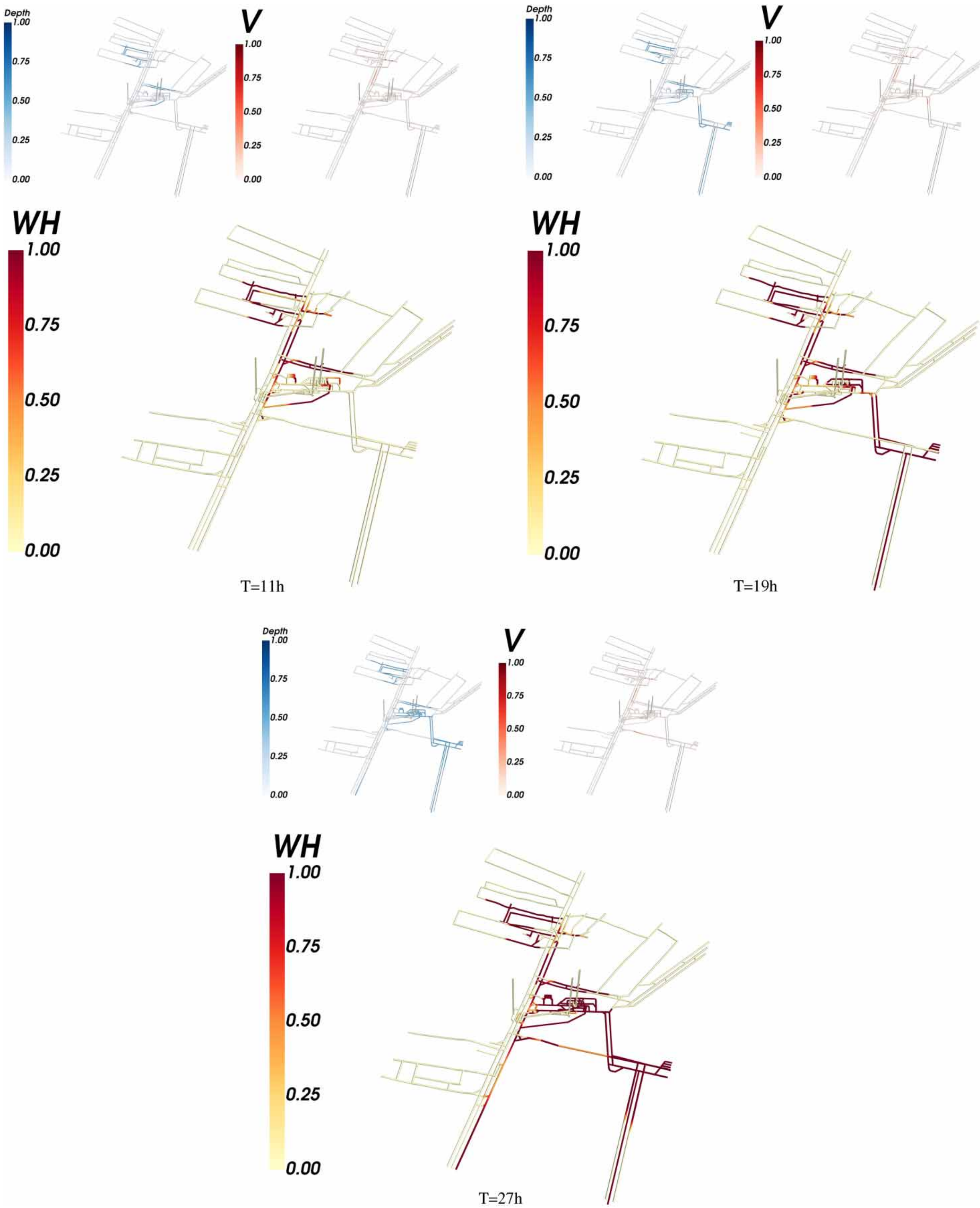


Figure 6 | Continued.

Comparing the distribution of water depth and flow velocity at the same time, we can conclude that the change in water depth is more prominent in Figures 5 and 6. This is also why the traditional methods of assessing workers' hazards directly use water depth. However, it is not enough to just use the water depth and ignore the flow velocity. The comparative analysis of the normalized water depth, flow velocity, and WH diagrams of $T = 5$, 11, and 27 h in Figure 6 confirms this point.

Due to differences in the human body, the impacts of water disasters on the hazards to different workers are different, even under the same water-flow conditions at the same location. Figure 7 provides the WH for three workers (worker-1, worker-2 ($m = 95$ kg, $H = 1.82$ m), and worker-3 ($m = 60$ kg, $H = 1.62$ m)) under the same flow conditions. Overall, the trends of WH for different workers are consistent with the change in disaster. Microscopically, worker-3 is more dangerous than or equal to

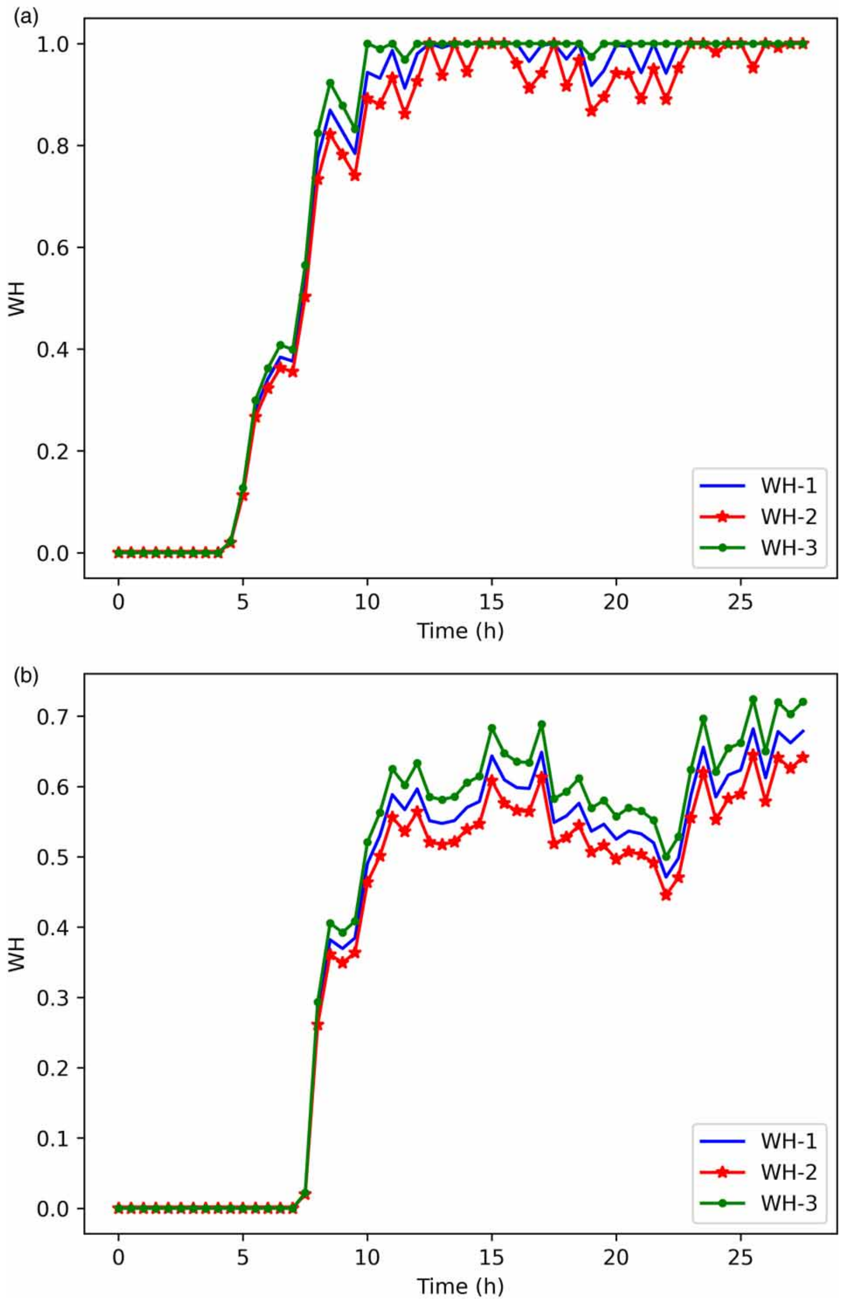


Figure 7 | WH comparisons among different workers under the same disaster conditions. (a) Paragraph – 6134; (b) paragraph – 8600.

worker-1, and worker-1 is more dangerous than or equal to worker-2. In other words, workers who are taller and heavier in an underground water disaster are more conducive to safety.

The WH at the early stages of a water disaster (e.g. $T = 2$ h) and the WH at the late stages (e.g. $T = 11$, 19, and 27 h) are obviously different in Figure 6. This difference indicates that the escape routes should be different at different times, and reasonable routes should be planned according to the WH in the water disaster. Furthermore, for different workers, due to different physical qualities, the ability to cope with water disasters is also different, as shown in Figure 7. Therefore, it is necessary to develop corresponding dangerous dynamic visualizations for workers with different physical conditions.

For a simple mine water disaster, such as a small water inrush with slow inflow speed, the shortest escape route can be effective. But for a complex disaster, the shortest route is difficult to guide workers through in an emergency, if the water flow can lead to the direct death of workers in the dangerous location of the escape route, such as in the roadway of WH = 1 in the WH of Figure 6. To draw up a safe and reliable evacuation plan, evaluating the safety of escape routes is essential. In other words, it is necessary to assess the hazards to workers in evacuating routes; this is the value of the hazard assessment in this study.

The numerical setting of some parameters of the simulation analysis in this paper is based on literature references and actual assumptions. In fact, the simulation results of the WH model can not only serve the work of escape and evacuation, but also adapt to emergency training, drill operations, and even design for part of the roadway. Therefore, the various possible parameters need to be analyzed in future work. The hazard value calculated by the WH model can not only display visualization to help escape and rescue work but also has a negative correlation with the safe wading speed of workers in mine water disaster. In the next work, the safety wading speed model is mainly established, and the WH hazard value is used to directly plan the escape and evacuation route under the condition of enough to ensure the safety of workers.

CONCLUSIONS

Water accidents are one of the major accidents in underground mines, which greatly endanger workers' lives. This study was aimed at establishing a systematic and quantitative evaluation model for numerical assessment of the WH to workers in the water disaster of an underground mine, which is from multiple influencing factors to quantitative comprehensive quantification. Nine factors, namely roadway type, road slope, friction coefficient, traffic equipment or auxiliary equipment, water depth, flow velocity, water density, body height, and body weight, were directly utilized in a WH model. At the same time, hydrologic factors (like the type of water disaster, water inflow, and inrush point) were indirectly reflected in the evaluation model by affecting the water spreading process.

The methodology described in this paper provided a solution to characterizing WH and worker safety in underground mines by understanding the details of danger in water disasters while using human-stability analysis in water flows and real features of water disasters in underground mines. A case study of a coal mine in China has also proved the efficiency of this WH model. The results illustrate that this WH model can assess the hazards of different WH conditions to workers with different physical characteristics at different locations. Therefore, the WH model overcomes the shortcomings of current approaches to model escape routes, which cannot quantitatively describe disasters and individual physical differences, and is an expression of a more detailed categorical evaluation of the hazard to workers from various water-flow conditions. Under different water-flow conditions, the magnitude of the hazard to each miner affected by the water flow can be clearly and unambiguously recognized. Thus, it also meets the urgent demands of water-disaster management for underground mines.

This study also gave a new approach to mine disaster emergency responses by dynamically visualizing the hazard of workers. Mapping hazards is an important step towards disaster-risk management. The dynamic visualization of WH in water disasters is realized in time and space to help workers to understand the degree of WH in real time, intuitively, and easily. Finally, the WH model can serve not only the workers in an underground mine but also rescuers. It is a significant measure for rescuers' safety to choose a suitable time to rescue, avoid dangerous roads, and have a better judgment on the locations of hazards based on the dynamic visualization of WH.

ACKNOWLEDGEMENTS

This research was financially supported by the China National Natural Science Foundation (41877186, 42027801), the Inner Mongolia Science and Technology Major Project (2020ZD0021), Fundamental Research Funds for the Central Universities

(2010YD02), and State Key Laboratory of Coal Resources and Safe Mining. Lastly, the authors would like to thank the editor and the reviewers for their constructive suggestions.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Alizadeh, F., Gharamaleki, A. F. & Jalilzadeh, R. 2020 A two-stage multiple-point conceptual model to predict river stage-discharge process using machine learning approaches. *J. Water Clim. Chang.* **12** (1), 278–295.

Cox, R. J., Shand, T. D. & Blacka, M. J. 2010 *Appropriate Safety Criteria for People*. Report No. P10/S1/006. Australian Rainfall and Runoff (AR&R), Manly Vale, Australia.

Cui, F., Wu, Q., Lin, Y., Zeng, Y. & Zhang, K. 2018 Damage features and formation mechanism of the strong water inrush disaster at the Daxing Co Mine, Guangdong Province, China. *Mine Water Environ.* **37**, 346–350.

Di Mauro, M., De Bruijn, K. & Meloni, M. 2012 Quantitative methods for estimating flood fatalities: towards the introduction of loss-of-life estimation in the assessment of flood risk. *Nat. Hazards* **63**, 1083–1113.

Drillis, R., Contini, R. & Bluestein, M. 1964 Body segment parameters: a survey of measurement techniques. *Artif. Limbs* **25**, 44–66.

Eiser, J. R., Bostrom, A., Burton, I., Johnston, D., Mcclure, J., Paton, D., Pligt, J., van der & White, M. P. 2012 Risk interpretation and action: a conceptual framework for responses to natural hazards. *Int. J. Dis. Risk Reduc.* **1**, 5–16.

Endoh, K. & Takahashi, S. 1994 Numerically modeling personnel danger on a promenade breakwater due to overtopping waves. In: *Proceedings of 24th International Conference on Coastal Engineering*. Edited by Billy L. Edge. Kobe, Japan, pp. 1016–1029.

Garrido, J., Requena, I. & Mambretti, S. 2012 Semantic model for flood management. *J. Hydroinform.* **14** (4), 918–936.

Guo, P., Xia, J. Q., Zhou, M. R., Falconer, R. A., Chen, Q. & Zhang, X. L. 2018 Selection of optimal escape routes in flood-prone areas based on 2D hydrodynamic modelling. *J. Hydroinform.* **20** (6), 1310–1322.

Hamilton, K., Demant, D., Peden, A. & Hagger, M. 2020 A systematic review of human behaviour in and around floodwater. *Int. J. Dis. Risk Reduc.* **47**, 101561.

He, X., Xiao, B. & Wang, P. 2002 *Wastewater Treatment and Mine Water Resources*. Coal Industry Press, Beijing, China (in Chinese).

Ishigaki, T., Toda, K., Baba, Y., Inoue, K. & Nakagawa, H. 2006 Experimental study on evacuation from underground space by using real size models. *Proc. Hydraul. Eng.* **50**, 583–588.

Ishigaki, T., Kawanaka, R., Onishi, Y., Shimada, H., Toda, K. & Baba, Y. 2009 Assessment of safety on evacuating route during underground flooding. In: C. K. Zhang & H. W. Tang (eds). *Advances in Water Resources and Hydraulic Engineering*. Springer, Berlin, Heidelberg, pp. 141–146.

Jalali, S. E. & Noroozi, M. 2009 Determination of the optimal escape routes of underground mine networks in emergency cases. *Saf. Sci.* **47** (8), 1077–1082.

Jiang, H., Li, L., Rong, X., Wang, M., Xia, Y. & Zhang, Z. 2017 Model test to investigate waterproof-resistant slab minimum safety thickness for water inrush geohazards. *Tunn. Undergr. Space Techn.* **62**, 35–42.

Jonkman, S. N. 2007 *Loss of Life Estimation in Flood Risk Assessment; Theory and Applications*. PhD Thesis. Delft University, Delft, The Netherlands.

Jonkman, S. N. & Penning-Rowsell, E. 2008 Human instability in flood flows. *J. Am. Water Resour. Ass.* **44** (5), 1208–1218.

Karvonen, R. A., Hepojoki, A., Huhta, H. K. & Louhio, A. 2000 The use of physical models in dam-break analysis. RESCDAM Final Report. Helsinki University of Technology, Helsinki, Finland.

Keller, R. J. & Mitsch, B. 1993 *Safety Aspects of the Design of Roadways as Floodways, Final Report for Urban Water Research Association, Melbourne Water Research Project*. Monash University, Australia.

Kowalski-Trakofler, K. M., Vaught, C., Brnich, M. J. & Jansky, J. H. 2010 A study of first moments in underground mine emergency response. *J. Homel. Secur. Emerg. Manag.* **7** (1), 39.

Kvočka, D., Falconer, R. A. & Bray, M. 2016 Flood hazard assessment for extreme flood events. *Nat. Hazards* **84**, 1569–1599.

Kvočka, D., Ahmadian, R. & Falconer, R. A. 2018 Predicting flood hazard indices in torrential or flashy river basins and catchments. *Water Res. Manage.* **32**, 2335–2352.

Levens, R. 1998 A general framework for prioritizing research to reduce injuries and diseases in mining. *Hum. Ecol. Risk Assess.* **4** (6), 1285–1290.

Li, C., Li, J., Li, Z. & Hou, D. 2013a Establishment of spatiotemporal dynamic model for water inrush spreading processes in underground mining operations. *Saf. Sci.* **55**, 45–52.

Li, S., Zhou, Z., Li, L., Xu, Z., Zhang, Q. & Shi, S. 2013b Risk assessment of water inrush in karst tunnels based on attribute synthetic evaluation system. *Tunn. Undergr. Space Techn.* **38**, 50–58.

Lind, N., Hartford, D. & Assaf, H. 2004 Hydrodynamic models of human stability in a flood. *J. Am. Water Resour. Assoc.* **40**, 89–96.

Martínez-Gomariz, E., Gomez, M. & Russo, B. 2016 Experimental study of the stability of pedestrians exposed to urban pluvial flooding. *Nat. Hazards* **82**, 1259–1278.

Milanesi, L., Pilotti, M. & Ranzi, R. 2015 A conceptual model of people's vulnerability to floods. *Water Resour. Res.* **51** (1), 182–197.

Montanari, A., Blöschl, G., Cai, X., Mackay, D. S., Michalak, A. M., Rajaram, H. & Sander, G. 2013 Toward 50 years of water resources research. *Water Resour. Res.* **49** (12), 7841–7842.

Onifade, M. 2021 Towards an emergency preparedness for self-rescue from underground coal mines. *Process Saf. Environ.* **149**, 946–957.

Onishi, Y., Ishigaki, T., Baba, Y. & Toda, K. 2008 Criterion and its application for safety evacuation during underground flooding. *Proc. Hydraulic Eng.* **52**, 841–846.

Ramsbottom, D., Floyd, P. & Penning-Rowsell, E. 2003 Flood Risks to People: Phase 1. R&D Technical Report FD2317, Department for the Environment, Food and Rural Affairs (DEFRA), UK Environment Agency, London.

Ramsbottom, D., Wade, S., Bain, V., Hassan, M., Penning-Rowsell, E., Wilson, T., Fernandez, A., House, M. & Floyd, P. 2006 Flood Risks to People: Phase 2. R&D Technical Report FD2321/IR2. Department for the Environment, Food and Rural Affairs (DEFRA), UK Environment Agency, London.

Roushangar, K. & Alizadeh, F. 2019 Scenario-based prediction of short-term river stage–discharge process using wavelet-EEMD-based relevance vector machine. *J. Hydroinform.* **21** (1), 56–76.

Verma, S. & Gupta, M. 2013 Risk assessment in mining industry. *Int. J. Min. Miner. Eng.* **4** (4), 312–332.

Wang, R. 2017 A research on the weighted improvement of Dijkstra algorithm in optimal path calculation. In: *5th International Conference on Frontiers of Manufacturing Science and Measuring Technology*, Vol. 130. Advances in Engineering Research (AER), pp. 159–163.

Wu, Q., Li, B. & Chen, Y. 2016 Vulnerability assessment of groundwater inrush from underlying aquifers based on variable weight model and its application. *Water Resour. Manage.* **30**, 3331–3345.

Wu, Q., Zhang, X., Zhao, Y., Xu, H. & Du, Y. 2018 Research and application of water bursting spread model in roadway. *Coal Eng.* **50**, 1–5 (in Chinese).

Wu, Q., Du, Y., Xu, H., Zhao, Y., Zhang, X. & Yao, Y. 2020 Finding the earliest arrival path through a time-varying network for evacuation planning of mine water inrush. *Saf. Sci.* **130**, 104836.

Xia, J., Falconer, R. A., Lin, B. & Tan, G. 2011 Numerical assessment of flood hazard risk to people and vehicles in flash floods. *Environ. Model. Softw.* **26**, 987–998.

Xia, J., Falconer, R. A., Wang, Y. & Xiao, X. 2014 New criterion for the stability of a human body in floodwaters. *J. Hydraul. Res.* **52**, 93–104.

Zhao, X., Wang, Q., Xie, B., Pan, S. & Ji, M. 2019 A dynamic rescue route planning method based on 3D network in mine water inrush hazard. *Geomat. Nat. Hazards Risk* **10** (1), 2387–2407.

Zhao, Y., Wu, Q., Chen, T., Zhang, X., Du, Y. & Yao, Y. 2020 Location and flux discrimination of water inrush using its spreading process in underground coal mine. *Saf. Sci.* **124**, 104566.

First received 28 March 2021; accepted in revised form 27 September 2021. Available online 11 October 2021