Safety Science 161 (2023) 106083

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/safety

Investigating pedestrian behavioral patterns under different floodwater conditions: A video analysis on real flood evacuations

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ARTICLE INFO

Keywords:
Behavioral design
Evacuation
Flood
Human behaviors
Video analysis
Risk management

ABSTRACT

Understanding how people behave during emergencies is fundamental to improve their safety. In the case of flood evacuation, people have to deal with built environments extremely modified by the floodwaters and that hence influences human-environment interactions both from a qualitative and quantitative standpoint. In this sense, the observation of real events is fundamental to define behavioral patterns and their relation to floodwater conditions. To this end, in this work, we analyzed 139 videotapes of recent real-world flood evacuations in outdoor Built Environments involving about 1000 people all over the World (the largest set analyzed so far). The frequencies of behavioral patterns are associated with water depth (measured with respect to ankles, knees, and waist), flow (i.e., still or flowing), and evacuation phase in which they are observed (that is before, during, and after the evacuation). Specific factors like voluntariness, human response, and presence of reference elements in the flooded built environment are also considered. Frequent by-literature behaviors have been considered, and new-noticed ones have been assessed. Results unveil that the most frequent floodwater conditions and thresholds to trigger each behavior concern waters between the ankles and the waist, thus excluding slight and extreme interactions with floodwater. The retrieved behavioral patterns could be employed to develop and validate behavioral models for flood evacuation simulators, and to create critical scenarios for people's training. Furthermore, they trace quick insights to help safety planners in the design of risk-reduction measures also considering local and/or temporary risks due to the floodwater conditions.

1. Introduction

In recent years, as a consequence of factors like the climate change and the growing urbanization and densification of urban areas (Grahn & Jaldell, 2019; Lan et al., 2022; Santoro et al., 2022), floods emerged as the most disastrous natural hazards around the world both in terms of the number of events and people affected (World Health Organization, 2014). Recent studies revealed that, globally, flood events and related deaths are on a rising trend: more than 2 billion people were affected by floods in the last 25 years[1], of which 6171 only in 2020 (representing 42 % of annual deaths from natural disasters (UNDRR, 2021)). The majority of those fatalities are due to drowning[2] and occur in outdoor built environments, while people attempt to move in floodwaters, either on foot or by vehicles (Hamilton et al., 2020; Petrucci et al., 2019; Salvati et al., 2018; Xia et al., 2011). When catastrophic events occur, evacuation operations may become necessary due to the failure of risk-reduction solutions, or to unpreparedness, unwillingness, or difficulty by public/private entities in implementing them and ensuring their effectiveness (Abass et al., 2022; Bischiniotis et al., 2020; Grahn & Jaldell, 2019; S. Li et al., 2020; Rezende et al., 2019).

In such critical circumstances, dynamic interactions between people and floodwaters become unavoidable, and understanding their influence on evacuation behaviors assumes a key role in view of planning and developing sustainable risk-reduction measures for people's safety (Alonso Vicario et al., 2020; Kvočka et al., 2016; Musolino et al., 2022). Most research approaches generally take advantage of traditional laboratory tests, involving the use of mannequins, equipped volunteers or stuntmen, and controlled floodwater conditions that do not fully represent the complexity of real flood events (Bae et al., 2016; Bernardini et al., 2020; Dias et al., 2021; Lee et al., 2019; Milanesi et al., 2015; Xia et al., 2014, 2016). Conversely, still few studies concern behavioral analysis involving people in real emergencies (Bernardini, Camilli, et al., 2017; Bernardini, Postacchini, et al., 2017; Chanson et al., 2014;

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[1] https://www.who.int/health-topics/floods and https://public.emdat.be/mapping (Accessed: 16/06/2022).
[2] https://www.who.int/news-room/fact-sheets/detail/drowning (Accessed: 01/03/2022).

https://doi.org/10.1016/j.ssci.2023.106083
Received 12 July 2022; Received in revised form 10 January 2023; Accepted 24 January 2023
Available online 8 February 2023

Nomenclature

BE	Built Environment
PM	"Pre-Movement" phase
PM1	Pre-Movement Behavior #1: Attachment to belongings
PM2	Pre-Movement Behavior #2: "Curiosity" effect ("flood tourism")
M	"Motion towards the evacuation target" phase
M1	Motion towards the evacuation target Behavior #1: Attraction towards safe areas
M2	Motion towards the evacuation target Behavior #2: Attraction towards unmovable obstacles
M3	Motion towards the evacuation target Behavior #3: Fear of moving elements
M4	Motion towards the evacuation target Behavior #4: Increased guide effect
M5	Motion towards the evacuation target Behavior #5: Moving through the water with vehicles
M6	Motion towards the evacuation target Behavior #6: Social influence and group phenomena
M7	Motion towards the evacuation target Behavior #7: Floodwaters effects on motion speed
M8	Motion towards the evacuation target Behavior #8: Human body instability
M9	Motion towards the evacuation target Behavior #9: Clinging to ropes and arranging "human chains"
PE	"Post-Evacuation" phase
PE1	Post-Evacuation Behavior #1: Reaching temporary safe areas
PE2	Post-Evacuation Behavior #2: Reaching indoor safe areas
PE3	Post-Evacuation Behavior #3: Reaching outdoor safe areas
A	Water up to the ankles
K	Water up to the knees
W	Water up to the waist
HW	Water higher than the waist
S	Still water
F	Flowing water
PO [pp]	People overall
PI [pp]	People involved
PI_d [pp]	People involved per water depth
PI_f [pp]	People involved per water flow
$PI_{d,f}$ [pp]	People involved per floodwater conditions
PI/PO*100 [%]	Overall frequency
PI_d/PI*100 [%]	Situational frequency (with respect to the water depth)
PI_f/PI*100 [%]	Situational frequency (with respect to the water flow)
$PI_{d,f}$/PI_d*100 [%]	Situational frequency per water depth (with respect to the water flow given the same water depth)

Milanesi et al., 2016). Works concerning other kinds of disasters like fires, earthquakes, and terrorist attacks have shown the potential and increasing exploitation of videotapes of real evacuations to perform situational analyses aimed at defining qualitative and quantitative evacuation data (Arce et al., 2021; Bernardini & Quagliarini, 2021; Haghani & Sarvi, 2018; van der Wal et al., 2021; Zhou et al., 2018).

In view of the above, the analysis of videotapes of real flood evacuations performed in this work aims at providing first insights into causal relationships between human behaviors during flood emergencies and the floodwater features. In particular, we took advantage of qualitative data to identify behavioral patterns as a function of the flood situational conditions, defined in terms of water depth and flow (i.e., still or flowing water), and of reference elements within the built environment (e.g., buildings, furniture, vehicles, other people). This research focuses on outdoor Built Environments (BEs) contexts, in view of their aforementioned impact on people's safety, by verifying the frequency of both literature-based behaviors (see Section 2) and new noticed ones, thanks to the application of well-established videotapes analysis procedures (see Section 3) (Bernardini & Quagliarini, 2021). The outcoming behavioral patterns are shown in Section 4 and discussed in detail in Section 5 also in view of possible specific use by authorities, safety planners, and software developers.

2. State of the art on flood evacuation behaviors

Despite the growing attention that this type of disaster is arousing in the scientific community, in literature there is still a lack of clear definitions for *flood risk* (Nguyen et al., 2021). However, according to the most popular definitions, floods can be defined as "an overflow of water in areas that are usually dry caused by rising water escaped or released from the normal confines of any lake, or any river, creek or other natural watercourses whether or not altered or modified; or from any reservoir, canal, dam, or drainage ditch" (Bromhead, 2021), or as a"ponding of water at or near the point where the rain fell"[3].

As for other kinds of disasters affecting urban BEs, flood evacuation is characterized by different types of behaviors according to which three main evacuation phases are generally distinguished (Bernardini & Quagliarini, 2021; Nakanishi et al., 2019; Wang et al., 2021): (1) a *pre-movement* phase, involving behaviors performed before the evacuation starting that generally concerns the recognition/evaluation of the hazard, and are still unrelated with searching and reaching a safe area (e.g., trying to save other people or personal belongings, spending time recording with smartphones); (2) a *motion towards the evacuation target* phase, referred to the actual physical evacuation of people from the flooded areas; (3) a *post-evacuation* phase at the end of the motion process, after the arrival to a safe area.

Previous studies identify several factors leading or forcing people to take part in a flood evacuation (by foot or vehicle, that is pedestrians or drivers), thus exposing them to potentially dangerous (deadly) interactions with the floodwaters. Such interactions can be deliberately chosen or passively suffered by people (Diakakis, 2020). The voluntariness to come in contact with floodwaters as a result of a decision can be traced back to *human factors* (Wang et al., 2021), involving people's physical, psychological, cognitive, motivational, and social features. The main factors refer to: (a) the experience with previous floods (Freimund et al., 2022; Tanaka & Shimomura, 2021); (b) the preparedness to cope with similar emergencies (Freimund et al., 2022; Sadeghi-Pouya et al., 2017); (c) the familiarity with the environment and the eventual knowledge of safe evacuation plans/sites (Freimund et al., 2022; Sadeghi-Pouya et al., 2017); (d) the perception of risk, as well as the trust and attitude towards public authorities and rescuers (Mahdavian et al., 2020; Santoro et al., 2022; Yari et al., 2021); (e) the expected personal impact basing on self-confidence, "heroism", and personal skills (e.g., swimming, escaping, requesting help) (Gissing et al., 2016; Yari et al., 2021); (f) people's age, gender, health, foot size, height, body shape, mass, abilities/impairments, geographical area, cultural background, education level, socio-economic status, and occupational duty (Gomes et al., 2022; Mallick et al., 2022; Na & Grace, 2022; Nakanishi et al., 2019; Rufat & Botzen, 2022).

On the other hand, *environmental factors* can impose additional risks when the floodwater conditions are such to prevent people from

[3] https://www.weather.gov/mrx/flood_and_flash (Accessed: 11/10/2022).

Table 1
List of frequent by-literature human behaviors observed in the "pre-movement" phase, and their classification according to type, voluntariness, human response, and reference elements.

ID	Behavior and Definition	Type	Voluntariness	Human Response	Reference Elements	References
PM1	*Attachment to belongings*: before starting the evacuation pedestrians try to save personal belongings (including animals, vehicles, and excluding other individuals) once they are aware of the hazard in terms of floodwater conditions and damages	Common	Deliberately Chosen	Hazardous Behavior	Environmental Elements	(Bernardini, Camilli, et al., 2017; Diakakis, 2020; Petrucci et al., 2018)
PM2	*"Curiosity" effect ("flood tourism")*: pedestrians delay the evacuation starting since they spend time looking at floodwater conditions and recording with smartphones or cameras	Peculiar	Deliberately Chosen	Hazardous Behavior	–	(Bernardini, Camilli, et al., 2017; Diakakis, 2020; Petrucci et al., 2018)

Table 2
List of frequent by-literature human behaviors observed in the "motion towards the evacuation target" phase, and their classification according to type, voluntariness, human response, and reference elements.

ID	Behavior and Definition	Type	Voluntariness	Human Response	Reference Elements	References
M1	*Attraction towards safe areas*: pedestrians (try to) move towards safe areas, or considered as such, to restore adequate safety conditions (e.g., areas with lower levels of damage, lower floodwaters depth)	Common	Deliberately Chosen	Protective Behavior	Environmental Elements	(Bernardini, Camilli, et al., 2017; Petrucci et al., 2018)
M2	*Attraction towards unmovable obstacles*: pedestrians prefer to move towards (and along) elements that cannot be dragged by the floodwaters, looking for physical support (e.g., walls, street signals, trees, fences)	Peculiar	Deliberately Chosen	Protective Behavior	Environmental Elements	(Bernardini, Camilli, et al., 2017)
M3	*Fear of moving elements*: pedestrians prefer to move far from floating objects dragged by the floodwaters (e.g., debris, vehicles, bins)	Peculiar	Deliberately Chosen	Protective Behavior	Environmental Elements	(Bernardini, Camilli, et al., 2017)
M4	*Increased guide effect*: pedestrians benefit from the presence of rescuers and/or evacuation leaders thus improving the evacuation process (e.g..: choosing appropriate behaviors and evacuation directions, increasing motion speeds)	Common	Deliberately Chosen	Protective Behavior	Human Elements	(Bernardini, Camilli, et al., 2017)
M5	*Moving through the water with vehicles*: drivers prefer still moving through the floodwaters with vehicles (including cars, motorcycles, buses, bikes, and excluding fire trucks) rather than moving on foot	Peculiar	Deliberately Chosen	Hazardous Behavior	–	(Arrighi et al., 2015; Diakakis, 2020; Hamilton et al., 2016; Petrucci et al., 2018)
M6 *	*Social influence and group phenomena*: pedestrians move in groups, activate herding behaviors, share information, and perform pro-social actions (e.g., try to rescue other individuals)	Common	Deliberately Chosen	Protective Behavior	Human Elements	(Bernardini, Camilli, et al., 2017; Diakakis, 2020)
M7 *	*Floodwaters effects on motion speed*: pedestrians are slowed down by floodwaters depending on the water depth and flow	Peculiar	Passively Suffered	–	–	(Bernardini, Camilli, et al., 2017; Cox et al., 2010; Ishigaki et al., 2009)
M8 *	*Human body instability*: pedestrians experience instability problems due to the water depth and flow	Peculiar	Passively Suffered	–	–	(Bernardini, Camilli, et al., 2017; Cox et al., 2010; Milanesi et al., 2016)

* Although the marked behaviors can be generally observed during all the evacuation phases, previous works' evidence shows significant relevance for what concerns the "motion towards evacuation target" phase (Bernardini, Camilli, et al., 2017). However, these findings were also confirmed during preliminary video observations made early in this study.

performing the desired behaviors (Chanson & Brown, 2018; Wang et al., 2021). Correlations between floodwater conditions and walking behaviors and quantities (e.g., speed, trajectory, step frequency, lateral swaying, instability thresholds) generally highlight how the increase in water depth and speed: (a) slows down pedestrians' desired evacuation speed (Bernardini et al., 2020; Dias et al., 2021; Lee et al., 2019; Ishigaki et al., 2009); and (b) triggers the main mechanism of instability, namely sliding (that is more frequent with high speed above the knees waters), and toppling (that is more common when the water depth approaches the height of the waist) (Chanson et al., 2014; Milanesi et al., 2015; Xia et al., 2014; Yee, 2003).

In view of this general behavioral framework, Table 1, Table 2, and Table 3 resume the most relevant and frequent *by-literature* behaviors according to the evacuation phase in which they are observed. To

Table 3
List of frequent by-literature human behaviors observed in the "post-evacuation" phase, and their classification according to type, voluntariness, human response, and reference elements.

ID	Behavior and Definition	Type	Voluntariness	Human Response	Reference Elements	References
PE1	*Reaching temporary safe areas*: pedestrians reach temporary safety in spontaneous areas waiting for rescuers (e.g., vehicle roofs, trees), and eventually restart the evacuation motion	Common	Deliberately Chosen	Protective Behavior	Environmental Elements	(Bernardini, Camilli, et al., 2017; Petrucci et al., 2018)
PE2	*Reaching indoor safe areas*: pedestrians reach safety at the upper levels of buildings, including non-strictly indoor areas like building roofs, terraces, and balconies to be reached by rescuers.	Peculiar	Deliberately Chosen	Protective Behavior	Environmental Elements	(Adrian et al., 2019; Petrucci et al., 2018)
PE3	*Reaching outdoor safe areas:* pedestrians reach safety on raised areas and street furniture (e.g., benches, sidewalks, raised platforms)	Peculiar	Deliberately Chosen	Protective Behavior	Environmental Elements	(Bernardini, Camilli, et al., 2017)

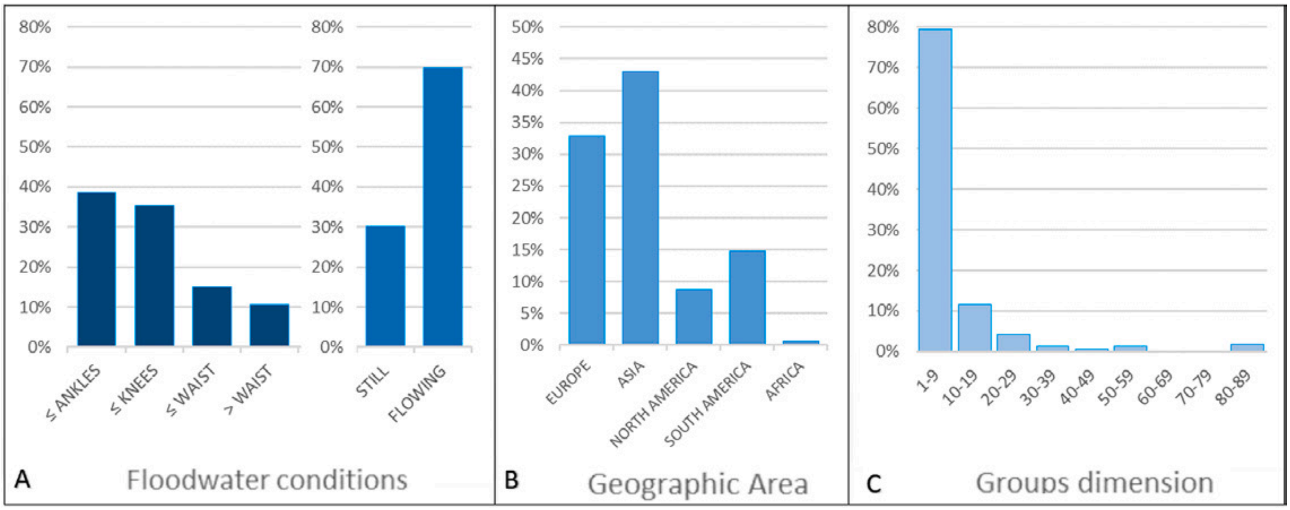

Fig. 1. Videotapes general features in percentages terms according to: (a) the floodwater conditions (water depth and flow); (b) the geographic area; (c) the groups' dimensions.

properly focus on evacuation tasks, the collected behaviors refer to the ones of people exposed to flood, by excluding mandatory behaviors due to occupational duty, such as the ones of rescuers (Diakakis, 2020), and by indifferently including both flash floods and slow-onset floods regardless of their cause or source (Hamilton et al., 2020). Behaviors are listed in alphabetical order, and they are associated with identification codes (ID in Table 1, Table 2, and Table 3) composed by the main reference to the related evacuation phase (that are: PM for *pre-movement*; M for *motion towards the evacuation target*; and PE for *post-evacuation*) and a number. For each behavior, when possible, Table 1, Table 2, and Table 3 also provide:

- the type of emergency in which they are noticed, distinguishing between *peculiar behaviors* that are characteristic only of the flood evacuation, or *common behaviors* that are noticeable also in other emergency conditions (Bernardini, Camilli, et al., 2017);
- the voluntariness in performing the behavior as a result of a decision, as *deliberately chosen* or *passively suffered* (Diakakis, 2020);
- the people's response against the hazard, in terms of *protective behavior* directly aimed at saving their own and/or other's lives, or *hazardous behavior* (Petrucci et al., 2019);
- the required presence of *reference elements* for people to activate the behavior, such as *environmental elements* (e.g., obstacles, debris, urban furniture, tools furnished by rescuers), or *human elements* (i.e., other evacuees or rescuers) (Bernardini, Camilli, et al., 2017).

The proposed behavioral database from Table 1, Table 2, and Table 3 have been used as a reference for the following video analysis introduced in Section 2.

Video-sharing platforms like YouTube, Twitter, Facebook, and Instagram offer a huge and free database of emergency-related multimedia content already used for several applications concerning behavioral analyses, but only reliable sources should be taken into account (e.g. mass-media channels, law enforcement agencies, rescuers, local authorities) (Bernardini & Quagliarini, 2021). Previous works also provided some flood monitoring, mapping, and modeling applications to extract the event's main features (i.e., floodwater depth, flow) from images and videos through comparison with objects having known dimensions (e.g., pedestrians standing in the water, wheels of cars, road signs) (Alizadeh Kharazi & Behzadan, 2021; Assumpção et al., 2018; Coz et al., 2016; Feng et al., 2020; Kutija et al., 2014). However, even though modern technologies allow detailed estimations, these kinds of approaches generally require long-time analyses and high-framing quality multimedia content (Chaudhary et al., 2019; Feng et al., 2020).

Although videotapes analysis are consolidated, and detailed quantitative insights already explain "why" and "which" behaviors are performed (Bernardini, Camilli, et al., 2017; Milanesi et al., 2016), literature works still demonstrate a general lack of explaining "how" floodwater conditions qualitatively affect the pedestrians' behaviors (and so their bodies). In this sense, the following gaps should be considered according to previous investigations: (a) the water depth in relation to notable human body parts (namely the ankle, the knees, and the waist) or vehicles parts (for drivers inside vehicles moving in the floodwaters) (Bernardini et al., 2020; Dias et al., 2021; Feng et al., 2020; Xia et al., 2014); and (b) the water flow by distinguishing between still water and flowing water (that is zero and non-zero in terms of water speed) (Cox et al., 2010; Milanesi et al., 2016).

3. Phases and methods

The work is organized in two steps, adapting a previous methodology tested on terrorist acts and people's behaviors (Bernardini & Quagliarini, 2021) to fit the flood evacuation scenarios analysis. The first step concerns the videotapes collection and the definition of criteria on how to classify the behaviors depending on the floodwater conditions (i.e., water depth and flow), and the people involved (Section 3.1). Afterwards, the second step concerns the analysis of the behaviors and their statistical frequency depending on the criteria introduced in the first step task (Section 3.2).

In the overall process, even though previous literature approaches suggest the use of the number of "scenes" or videotapes to evaluate the frequency of each behavior (Bernardini & Quagliarini, 2021; van der Wal et al., 2021), in this work, the frequency has been calculated considering the number of people within the videotapes scenes in combination with the floodwater and built environment conditions, which is a measure of how much a given behavior is activated rather than observed. In this way, the proposed approach also reduces the possibility of a biased selection of the overall sample of assessed scenes, mainly due to specific floodwater conditions more or less frequent in the sample. Besides, it allows to separately evaluate how floodwaters conditions affect each person (i.e., same water depth but different body parts submerged depending on the individual height).

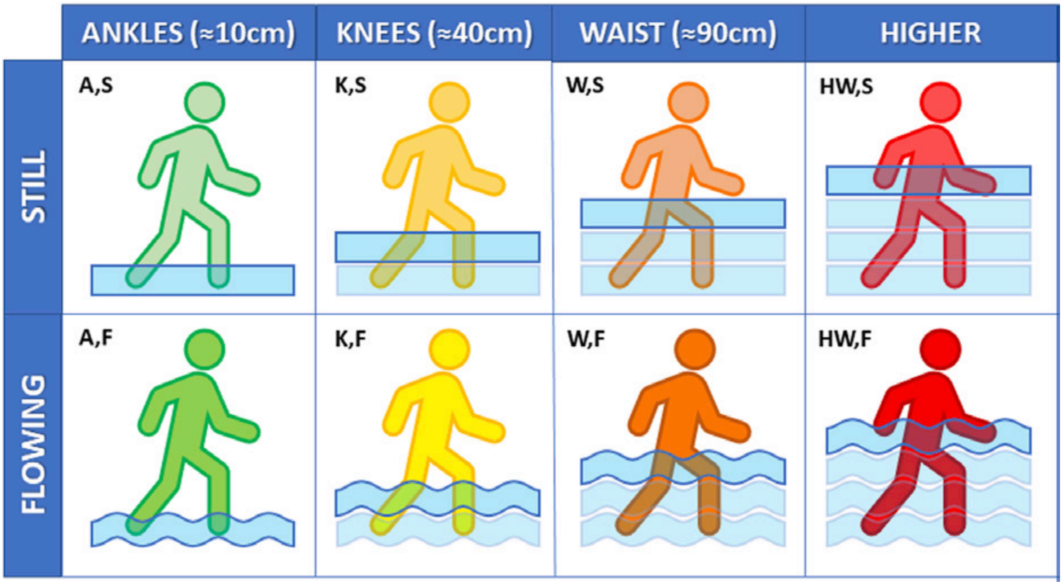

Fig. 2. Illustration of all the floodwater conditions organized per water depth (rows) and water flow (columns), including related acronyms for subsample creation. Numerical values are referred to adults (Dias et al., 2021).

Table 4
Parameters to quantify the number of people [pp] featured in the videotapes.

Parameters [pp]	Meaning
PO - *People overall*	The total number of people who could actually perform a given behavior (Fig. 2). The number of people has been also classified considering the presence of reference elements if their presence is necessary to activate the behavior (e.g., the presence of unmovable obstacles to be attracted by them).
PI - *People involved*	Total number of people who perform a given behavior (Fig. 2).
PI_d - *People involved per water depth*	Total number of people performing a given behavior under the same water depth, that is equal to or lower than the ankle, the knees, the waist, or higher than the waist (d = [A; K; W; HW]).
PI_f - *People involved per water flow*	Total number of people performing a given behavior under the same water flow, that is still or flowing (f = [S; F]).
$PI_{d,f}$ - *People involved per floodwater conditions*	Total number of people performing a given behavior under the same floodwater conditions, that is combining the water depth and flow conditions.

3.1. Videotapes collection and organization

We analyzed 139 videotapes freely available on local news websites[4] and verified YouTube and Twitter channels involving the clear presence of people interacting (by foot or vehicles) with flooded outdoor BEs scenarios from all over the World. The videotapes collection has been carried out by searching in the search engine of the aforementioned repositories the following keywords: “flood(ing)”, “urban flood(ing)”, “flood(ing) evacuation”, “flooded areas” (where “floods” are assessed according to the definitions provided in Section 2). The selected videotapes are identified by a number reported in curly brackets ({num}) and are available at {Flood videotapes SafetyScience}. Each videotape has been divided into one or more “scenes” characterized by the same evacuation (i.e., floodwater) conditions (Bernardini et al., 2019; Bernardini & Quagliarini, 2021) in terms of the water depth and flow, in the same built environment scenario. Fig. 1-A and -B resume the general features (in percentage terms) of the collected videotapes database, respectively in terms of floodwater conditions and geographic area distributions.

In particular, considering floodwater conditions, the water depth - in the following, referring to the subscript *d* - has been evaluated according to the human body parts submerged by the flood, that is equal to or up to ankles (A), knees (K), waist (W), and higher than the waist (HW) (Dias et al., 2021; Feng et al., 2020; Xia et al., 2014). Such an approach ensures the quick application of such analysis on a wide sample by referring to critical body parts submerged by floodwaters, also in case of different heights between the investigated individuals on the scene, which can potentially affect the level of floodwater experienced and the types of behaviors exhibited. However, although differences between individuals can obviously exist due to anthropometric issues, in view of the quantification of such body parts measures, such levels can be roughly traced back to 0.10 m for the ankles, 0.40 m for the knees, and 0.90 m for the waist considering the average measures of an adult (Dias et al., 2021). In particular, in the case of videotapes with adults-assisted children (whose physiological measurements highly differ from adults), the same approach was adopted and the adults’ body was considered as a benchmark. This assumption is consistent with the adults’ active role in children’s safety from both a physical and decisional point of view (Haynes et al., 2017). Videotapes with only children were not found. For what it concerns vehicles, the dimensions[5] of wheels and car body have been used to trace back the water depths to the four levels previously defined.

The water flow - in the following, referring to the subscript *f* - has

[4] e.g.: https://www.ilfattoquotidiano.it/2021/07/15/germania-la-forza-del-fiume-esondato-nelle-strade-e-impressionante-lacqua-porta-via-le-auto-video/6262834/ (last accessed: 02/11/2022).

[5] Cars’ dimensions have been estimated through the official web pages when the models were recognizable, otherwise online sources like https://www.pneumatici.it/calcolatrice-pneumatico were used to estimate the wheels height depending on the cars’ model (e.g., city-cars, sedans, station-wagons, SUVs, trucks…).

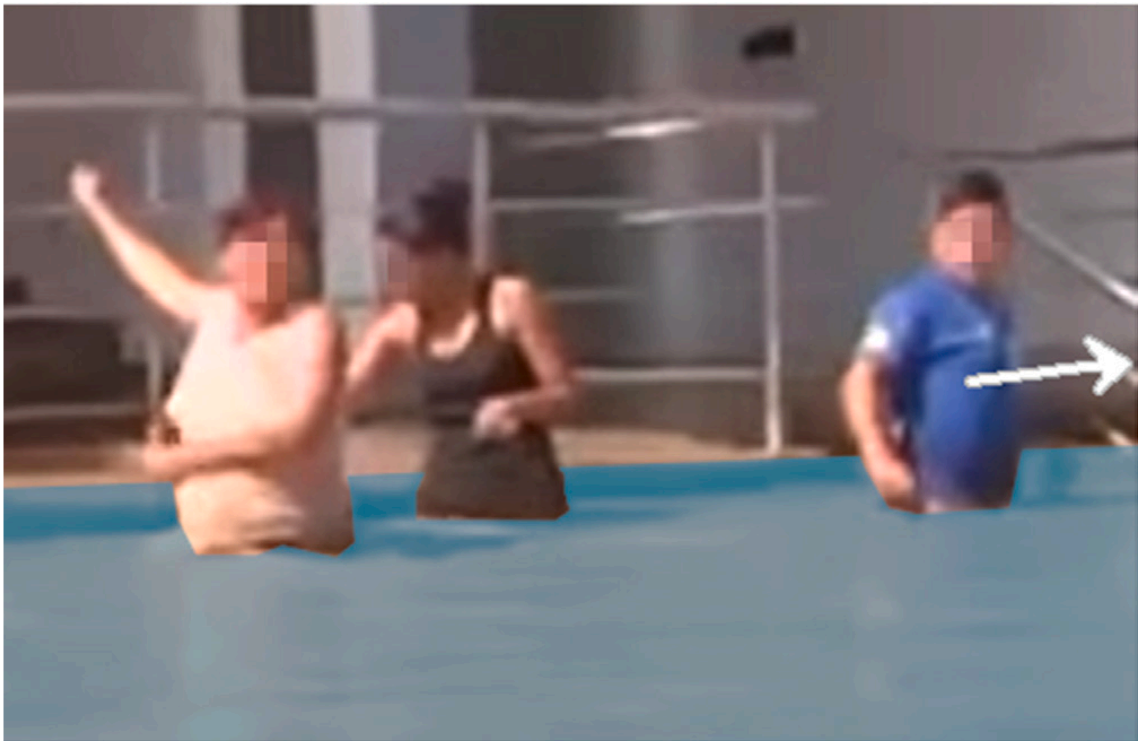

Fig. 3. Example of 2 pedestrians (on the left) performing attraction towards unmovable obstacles M2, while the pedestrian on the right is moving away from the fence (the white arrow indicates his direction). The following parameters are considered in this scene: PO = 3, PI = 2, $PI_W = 2$, $PI_{W,S} = 2$ (reference videotape: {95}).

been distinguished between still water (S) when the surface water seems to be calm (speed close to zero) or not flowing,[6] and flowing water conditions (F) when the surface water speed is visibly different than zero (traceable also with the aid of elements such as waves, dragged objects within the videotapes) (Milanesi et al., 2016). All the floodwater conditions obtained by crossing the water depth and flow levels are resumed in Fig. 2.

A total number of 1269 people have been inspected, distributed in groups of up to 82 individuals, with a medium group dimension equal to 10 individuals. In particular, the number of people featured in each scene has been organized according to the parameters shown in Table 4 and illustrated in Fig. 3. According to the original method adopted by this work (Bernardini & Quagliarini, 2021), the following assumptions were made:

- people not clearly and completely visible were not considered, as well as those behind smartphones and cameras hypothetically involved in "curiosity" effect behavior (PM2) since fundamental factors such as if they are in a safer position and/or if they are reporters (thus filming for job reasons) are unknown. People filming while evacuating were not found;
- *moving through the water with vehicles* (M5) were not considered in relation to empty vehicles or with a not clearly visible presence of people inside. In this case, the analysis of behaviors was performed in relation to the number of vehicles (i.e., of drivers) crossing the floodwater was considered, rather than considering the number of passengers (Diakakis, 2020).

3.2. Behavioral patterns definition with respect to water depth and flow

The behavioral patterns definition has been performed by considering frequent *by-literature* behaviors (those resumed in the previous Table 1, Table 2, and Table 3), and inquiring about *new-noticed* ones, as suggested by the methodological reference work (Bernardini & Quagliarini, 2021). In particular, the *new-noticed* behaviors have been classified according to their related evacuation phase, type, voluntariness, human response, and presence of reference elements.

Then, the statistical frequencies of the *observed behaviors* (i.e., both by-literature and new-noticed ones) have been calculated by considering

Table 5
Behaviors' statistical frequencies and their meaning, evaluated with respect to the number of people (according to Table 4) and the floodwater conditions (in terms of water depth and flow).

Statistical Frequency percentage [%] and related calculation	Meaning
Overall frequency PI/PO*100	Since this percentage is an expression of the voluntariness in performing a given behavior, it is only evaluated for *deliberately chosen* ones (that is excluding behaviors M7 and M8 for which the evaluation of PO strictly depends on physical features not deducible through images, such as the people's age, gender, health, foot size (Cox et al., 2010; Xia et al., 2014).
Situational frequencies $PI_d/PI*100$; $PI_f/PI*100$	These percentages show in which condition the behaviors are more frequent respectively in relation to the water depth and flow. Both *deliberately chosen* and *passively suffered* behaviors are considered.
Situational frequency per water depth $PI_{d,f}/PI_d*100$	This percentage shows in which flow conditions the behaviors are more frequent given the same water depth, also in view of comparisons with previous works' general trends depending on the human kinematics (Bernardini et al., 2020; Cox et al., 2010; Dias et al., 2021; Milanesi et al., 2016). Both *deliberately chosen* and *passively suffered* behaviors are considered.

[6] According to an expeditious approach, there is an inherent margin of error due to image quality and perception.

Fig. 4. Panel A: a group of 4 pedestrians clinging to a rope (in brown) and arranging a human chain {48}. Panel B: a group of 15 pedestrians clinging to a rope and arranging a "human chain" {17}. Jagged lines in blue indicate the waves. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

overall and situational samples in relation to the number of people and the floodwater conditions (i.e., the water depth and flow), as shown in Table 5. Table 5 also resumes the assessed frequency percentage depending on *deliberately chosen* and *passively suffered* behaviors, as defined in Section 2.

Results are first discussed according to less and more frequent floodwater conditions in which behaviors are observed, then inferential statistical analyses are provided to assess relationships between situational frequencies. In particular, Chi-squared tests of independence are performed for categorical data by considering 3 sets of values expression of the performed behaviors and the specific conditions in which they occur, namely: (a) Behaviors × Water depth (14 × 2); (b) Behaviors × Water flow (14 × 4); (c) Behaviors × Water conditions (14 × 8) all of which measured in terms of PI [pp] so as to consider only behaviors actually performed (see Table 4). Finally, behavioral patterns are defined with respect to the most frequent floodwater conditions.

4. Results

Results are organized in two sections: the first one discusses the *overall frequency* PI/PO in relation to the overall sample (Section 4.1), while the second one assesses the *situational frequencies* in relation to the floodwaters' depth and flow evaluated separately (PI_d/PI and PI_f/PI) and jointly ($PI_{d,f}/PI_d$) (Section 4.2). *By-literature* and *new-noticed* behaviors are discussed together.

4.1. Observed behaviors and their overall frequency

For what concerns *new-noticed* behaviors, 444 pedestrians have been observed clinging to ropes and cables during their motion and eventually holding hands to arrange "human chains" (see Fig. 4), making it the second most performed behavior in terms of PI [pp]. In general, such responses allow for improving the evacuation process by mitigating problems related to human speed and body instability in the floodwaters. Although some similarities are shared with other literature behaviors, the following main differences can be respectively noticed:

- while in *attraction towards unmovable obstacles* M2 pedestrians (try to) reach supports, in this case, they can be reached by ropes and cables on site, thus avoiding further dangerous movements in floodwaters;

Table 6
New-observed behavior classified according to the evacuation phase, the type, the voluntariness, the human response, and the reference elements.

ID	Behavior and Definition	Type	Voluntariness	Human Response	Reference Elements
M9	*Clinging to ropes and arranging "human chains"*: pedestrians look for physical support by grabbing ropes and eventually holding hands	Peculiar	Deliberately Chosen	Protective Behavior	Environmental Elements

- differently from *social influence and group phenomena* M6, in this case, physical contacts are not only widely accepted by pedestrians, but also sought after.

Thus, this behavior will be referred to in the following as *clinging to ropes and arranging "human chains"*, and can be classified as: (1) relevant to the *motion toward the evacuation target* phase, as it concerns the actual physical movement through and out of the flooded areas; (2) *peculiar,* as it can be currently observed only for flood evacuations, at the authors' knowledge; (3) *deliberately chosen,* since it is performed as a result of a decision; (4) *protective,* since it is aimed at improving the pedestrian safety; (5) relying on *environmental elements*, as it depends on the presence of i.e. ropes and cables (even though partially also on the direct support of rescuers or other pedestrians by means of their body within the "human chain"). In view of the following behavioral analysis, Table 6 resumes this classification according to the same layout as Table 2, while Fig. 5 resumes all the behaviors considered for the following proper video-analysis.

Fig. 6 resumes the *Overall frequency* PI/PO [%] of the observed behaviors (right y-axis) and the reference number of People Overall PO [pp] as the sample dimension (left y-axis).

For what it concerns the behaviors of the *pre-movement* phase, results confirm the tendency of people in performing *hazardous behaviors* before starting a flood evacuation (Bernardini, Camilli, et al., 2017), as PI/PO is

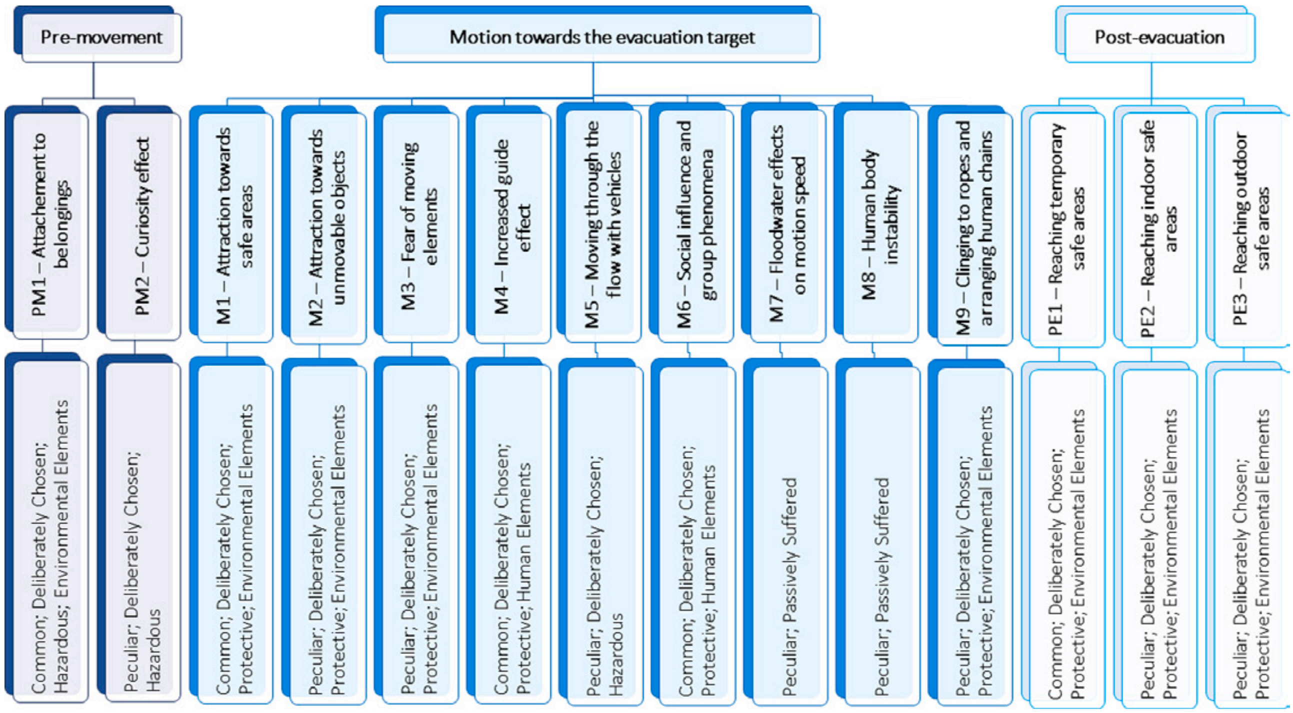

Fig. 5. Final picture of all the behaviors observed in the videotapes organized per evacuation phase, which integrates literature classifications.

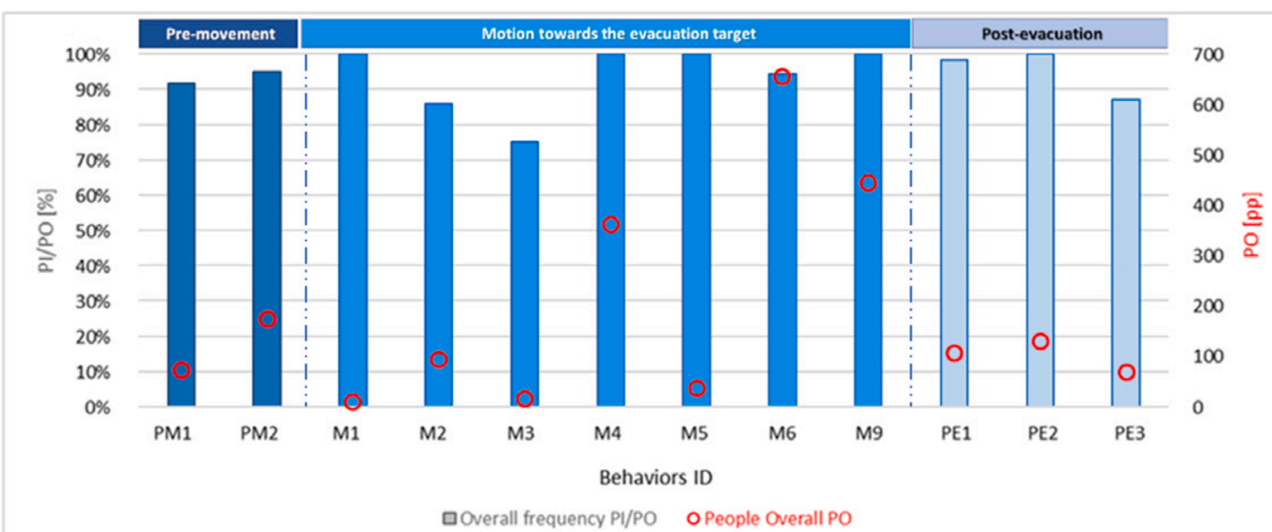

Fig. 6. Overall frequency PI/PO [%] (colored bars; left y-axis) of deliberately chosen behaviors, and People Overall PO [pp] as the sample dimension (red circles; right y-axis). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 7
Situational frequency percentages of the observed behaviors evaluated with respect to the water depth (PI_d/PI [%]) and the water flow (PI_f/PI [%]). Behaviors IDs from Fig. 5.

		Post-evacuation		Motion towards the evacuation target									Post-evacuation		
		PM1	PM2	M1	M2	M3	M4	M5	M6	M7	M8	M9	PE1	PE2	PE3
PI_d/PI [%]	ANKLES	32	47	33	20	0	32	75	23	29	19	20	0	2	73
(Fig. 7)	KNEES	44	53	11	43	8	25	22	46	49	31	38	95	17	7
	WAIST	14	0	56	33	92	32	0	29	16	37	38	0	66	20
	HIGHER	11	0	0	5	0	10	3	2	6	13	4	5	15	0
PI_f/PI [%]	STILL	59	27	89	14	0	49	47	19	46	8	37	0	6	45
(Fig. 8)	FLOWING	41	73	11	86	100	51	53	81	54	92	63	100	94	55

Table 8
Situational frequency percentages per water depth of the observed behaviors ($PI_{d,f}/PI_d$ [%]). Behaviors IDs from Fig. 5, abbreviations from Fig. 2.

	Post-evacuation				Motion towards the evacuation target																		Post-evacuation					
	PM1		PM2		M1		M2		M3		M4		M5		M6		M7		M8		M9		PE1		PE2		PE3	
	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F
A Fig. 10	29	71	55	45	100	0	6	94	–	–	74	26	41	59	17	83	0	100	0	100	88	12	–	–	100	0	61	39
K Fig. 12	72	28	2	98	0	100	12	88	0	100	55	45	75	25	20	80	71	29	2	98	30	70	0	100	0	100	0	100
W Fig. 14	56	44	–	–	100	0	19	81	0	100	15	85	–	–	18	82	31	69	5	95	15	85	–	–	6	94	0	100
HW Fig. 16	100	–	–	–	–	–	25	75	–	–	61	39	0	100	36	64	100	0	43	57	50	50	0	100	0	100	–	–

Table 9
Chi-squared test outcomes. For $S > \chi^2$ the null hypothesis is rejected and provide support that the categories are related. DOF stays for Degree of Liberty. Significance level α is 0.05; p-values are < 0.00001 in all the cases.

Parameter [pp]	CATEGORIES	DOF	Critical Chi-square $\chi^2_{(\alpha;\ DOF)}$	Pearson's Chi-square S
PI_d	Behaviors × Water Depth	39	54.57	645.86
PI_f	Behaviors × Water Flow	13	22.36	323.97
$PI_{d,f}$	Behaviors × Water Conditions	91	114.26	1459.51

higher than 90 % both for *attachment to belongings* PM1 and "*curiosity" effects* PM2 on a sample of, respectively 72 and 173 PO.

As regards the *motion towards the evacuation target* phase, results demonstrate that the presence of evacuation leaders, rescuers, and their equipment (i.e., ropes and cables) almost always triggers behaviors like *increased guide effect* M4, *social influence and group phenomena* M6, and *clinging to ropes and arranging "human chains"* M9, as stated by PI/PO close to 100 % (even if some exception may exist, for instance due to factors like the lack of trust in authorities and warnings (Abass et al., 2022; Yari et al., 2021)). Furthermore, they also are the most observed behaviors as they rank in the top three for the highest number of people involved PI and people overall PO (both greater than 300 pp). Similarly, also the other *observed behaviors* (*attraction towards safe areas* M1, *attraction towards unmovable obstacles* M2, *fear of moving elements* M3, and *moving through the water with vehicles* M5) recorded a high PI/PO, although with smaller samples.

Finally, *post-evacuation* phase results seem to point out a slight, overall preference for people in *reaching indoor safe areas* (PE2, PI/PO = 100 % with PO = 139 pp) rather than *outdoor* (PE3, PI/PO = 87 % with PO = 69 pp).

4.2. Statistical frequencies with respect to situational samples

Situational frequencies contextualize behavioral data with respect to the floodwater conditions in which they are observed. General results are resumed in Table 7 and Table 8. Inferential statistical outcomes are shown in Table 9, according to the Chi-squared test. For all the considered conditions, the test results prove how the performed behaviors can be considered as non-independent from the floodwater situational conditions. Finally, in the following subsections behavioral patterns are organized and discussed per evacuation phase.

4.2.1. Water depth influence

Fig. 7 shows the results concerning the situational frequency with respect to water depth, thus regardless of the water flow. Considering the evacuation phases, it is worthy of notice that:

- *Pre-movement* phase: "*curiosity" effect* PM2 has been observed only with floodwaters lower than the knees, while *attachment to belongings* PM1 phenomena result can be noticed for all the water depth conditions;
- *Motion towards evacuation target* phase: *moving through the water with vehicles* M5 is more frequent for water depths up to the ankles ($PI_A/PI = 75$ %), essentially in view of the lower perception of risk in such conditions. Behaviors (a) aimed at restoring the pedestrians' safety (*attraction towards unmovable obstacles* M2, *increased guide effect* M4, *social influence and group phenomena* M6, *clinging to ropes and arranging "human chains"* M9) and (b) the ones producing dangerous effects on the pedestrians' motion (*floodwaters effects on motion speed* M7 and *human body instability* M8) have a similar frequency in each condition, ranging from 20 to 40 %, while are less frequent for water depth above the waist condition ($PI_{HW}/PI < 10$ %). *Fear of moving elements* M3 is finally more frequent for water levels up to the waist,

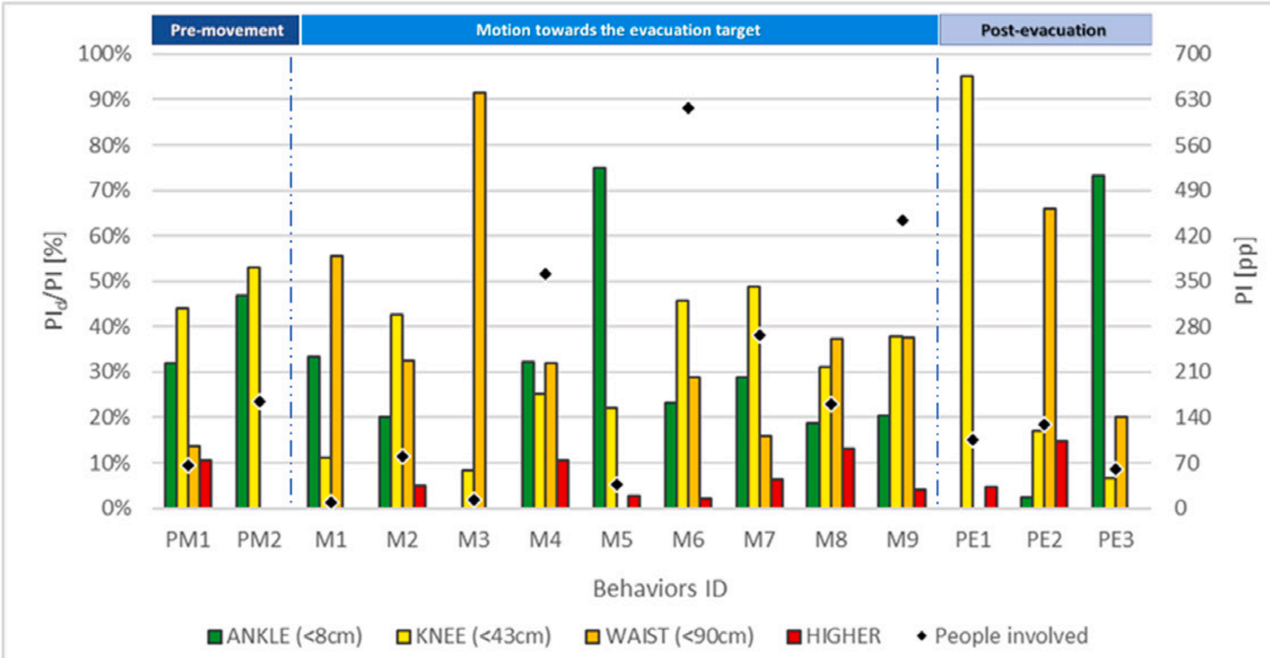

Fig. 7. Situational frequency PI_d/PI [%] (colored bars; left y-axis) of the observed behaviors evaluated with respect to the water depth levels, and People Involved PI [pp] as the sample dimension (black rhombuses; right y-axis). Behaviors IDs from Fig. 5.

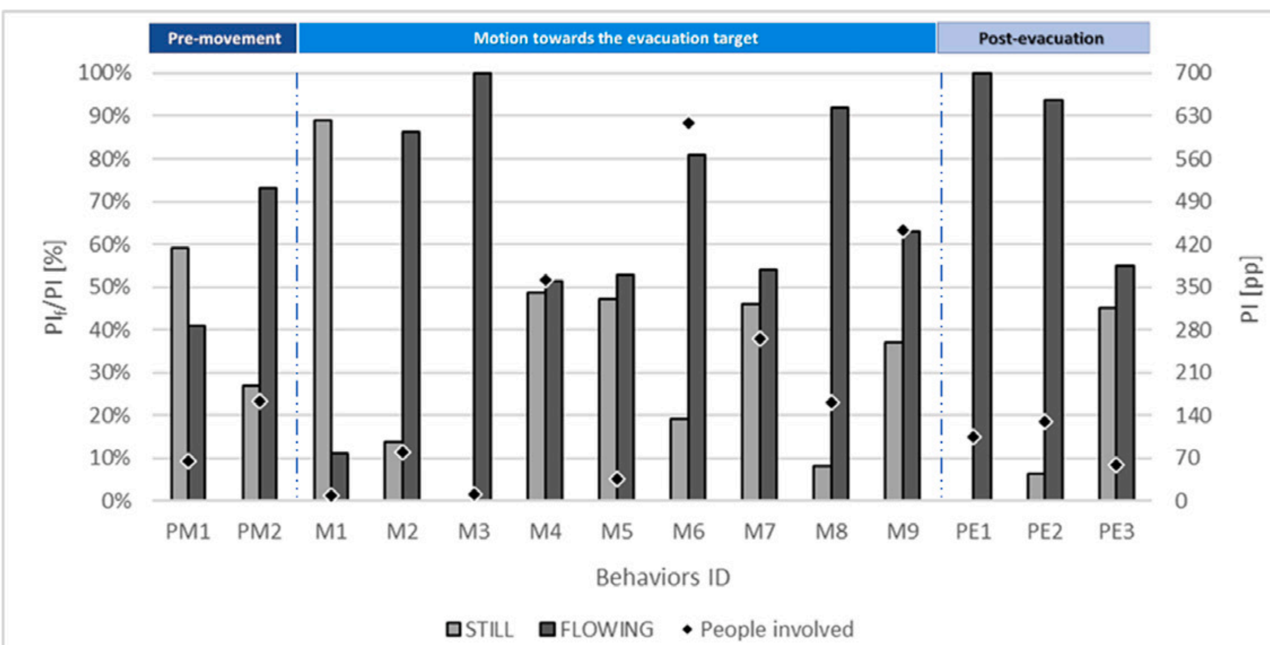

Fig. 8. Situational frequency PI_f/PI [%] (colored bars; left y-axis) of the observed behaviors evaluated with respect to the water flow levels, and People Involved PI [pp] as the sample dimension (black rhombuses; right y-axis). Behaviors IDs from Fig. 5.

that is essentially when objects start floating and then are dragged by floodwaters (compare also Section 4.2.2) (Xia et al., 2011).

- *Post-evacuation* phase: pedestrians generally prefer *reaching outdoor safe areas* PE3 with floodwaters under the ankles ($PI_A/PI = 73$ %), and *reaching indoor safe areas* PE2 with higher depth values ($PI_W/PI = 66$ %). The possibility of *reaching temporary safe areas* PE1 is more frequent for water depths between the ankles and the knees. In such conditions, pedestrians are still able to move without suffering major impediments (Bernardini, Camilli, et al., 2017; Dias et al., 2021).

4.2.2. *Water flow influence*

Fig. 8 shows the results concerning the situational frequency with respect to water flow. Considering the evacuation phases, it is worthy of notice that:

- *Pre-movement* phase: *attachment to belongings* PM1 is more frequent in the case of still water, essentially because of lower possible floodwaters resistance against pedestrians' motion. Vice versa, results show that the *"curiosity" effect* PM2 seems more likely to be activated with flowing water. Thus, such insight seems to suggest that

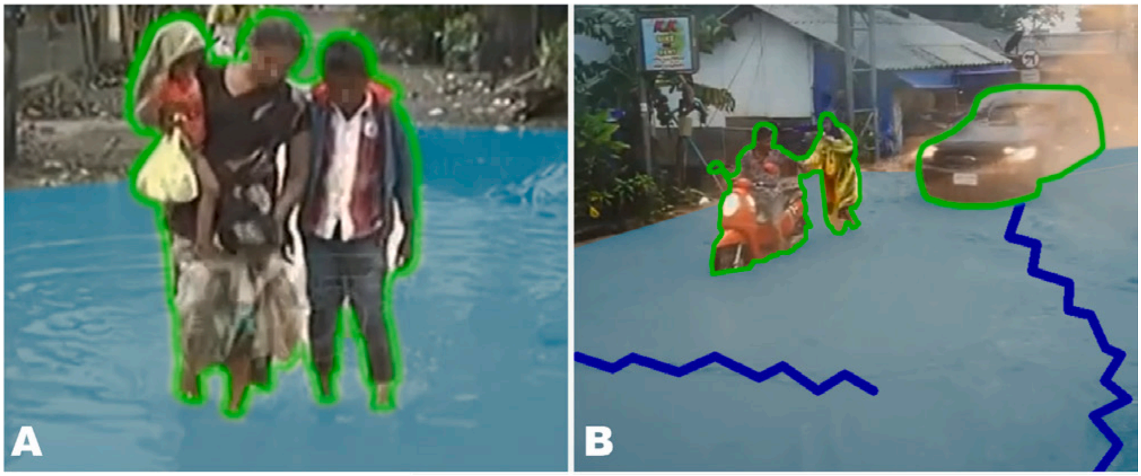

Fig. 9. People dealing with water up to the ankles (outlined in green). panel a is for still water, panel b is for flowing water and the blue jagged lines indicate the waves (reference videotapes: {70}, {119}). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

pedestrians find the water depth more dangerous than its flowing conditions, because, on the contrary, the situational frequency of this behavior decreases with the increasing severity of the event in terms of water depth (see PI_d/PI in Fig. 7).

- *Motion towards evacuation target* phase: *protective behaviors* are more frequent with flowing water ($PI_F/PI > 80$ %) suggesting: (a) a greater sense of danger perceived by the pedestrians in such conditions (considering the increase of, e.g., *social influence and group phenomena* M6); and (b) the suffered impact of effective more severe conditions that trigger *human body instability* M8 (Cox et al., 2010) and so of the related actions to restore it (i.e., *attraction towards unmovable objects* M2 and *clinging to ropes and arranging "human chains"* M9) (Bernardini, Postacchini, et al., 2017). *Fear of moving elements* M3 is due to flowing water dragging objects ($PI_F/PI = 100$ %). Results also seem to point out that *attraction toward safe areas* M1 is more frequent in still waters, but this result could be partially affected by the small sample dimension (<10 pedestrians involved).
- *Post-evacuation* phase: general outcomes seem to highlight that *temporary* PE1 and *indoor safe areas* PE2 are mainly reached in case of flowing waters ($PI_F/PI > 90$ %), mainly because of the efforts due to moving against higher resistance of floodwaters (Ishigaki et al., 2009), while in the case of still water pedestrians choose *outdoor safe areas* PE3 too (PI_S/PI and PI_F/PI between 45 and 55 %).

4.2.3. *Water depth equal to or up to the ankles*

Fig. 10 shows the results concerning the situational frequency with respect to water depth equal or up to the ankles, by distinguishing between still and flowing waters (Fig. 9). Considering the evacuation phases, it is worthy of notice that:

- *Pre-movement* phase: *hazardous behaviors* (*attachment to belongings* PM1 and *"curiosity" effect* PM2) are noticed in both still and flowing waters conditions, although *attachment to belongings* PM1 is less frequent in case of still water ($PI_{A,S}/PI_A = 29$ %), probably due to a

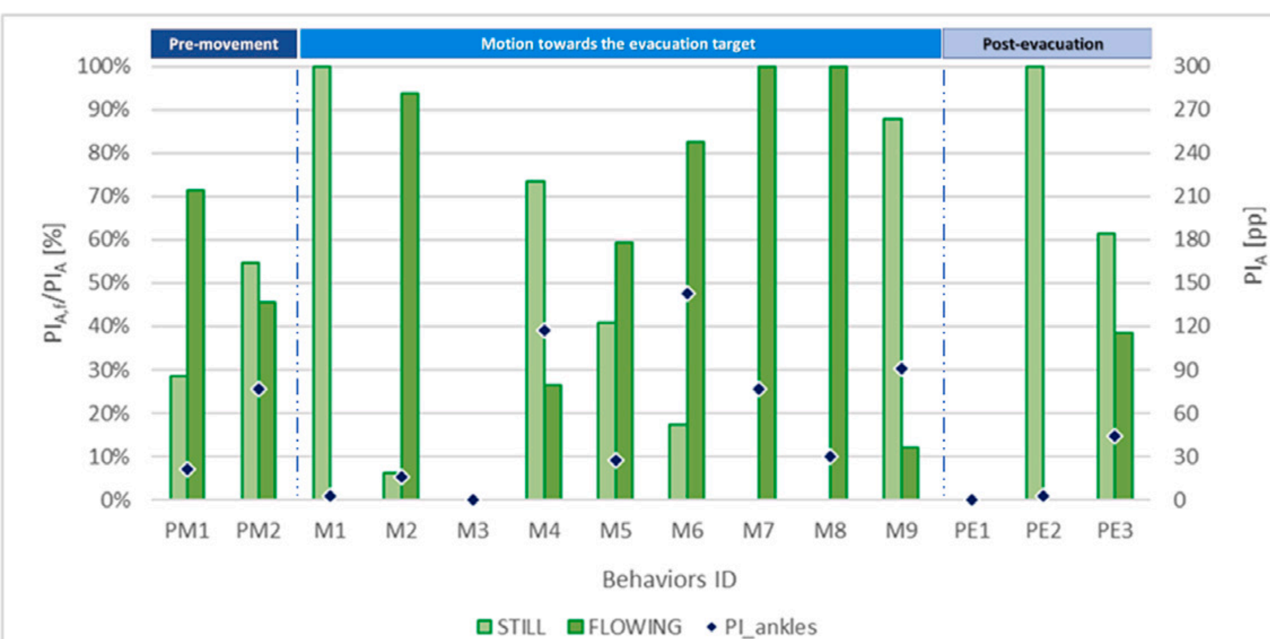

Fig. 10. Situational frequency per water depth equal to or lower than the ankles $PI_{A,f}/PI_A$ [%] (colored bars; left y-axis) of the observed behaviors evaluated by comparing the water flow. The sample dimension is outlined by PI_A [pp] (black rhombuses; right y-axis). Behaviors IDs from Fig. 5.

Fig. 11. People dealing with water up to the knees (outlined in yellow). panel a is for still water, panel b is for flowing water and the blue jagged lines indicate the waves (reference videotapes: {76}, {42}). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

slighter sense of danger felt by pedestrians with regards to their goods (Bernardini, Camilli, et al., 2017).

- *Motion towards evacuation target* phase: behaviors assuming motion problems are essentially activated with flowing water (i.e., for *floodwaters effects on motion speed* M7, *human body instability* M8, and *attraction toward unmovable obstacles* M2, $PI_{A,F}/PI_A > 95$ %), since the possibility to move the feet inside or outside of the water is also affected by the additional resistance of flowing waters (Bernardini et al., 2020; Dias et al., 2021; Lee et al., 2019). Behaviors that typically involve the presence of rescuers (i.e., *increased guide effect* M4 and *clinging to ropes* M9) seem to be more frequent with still water ($PI_{A,F}/PI_A > 70$ %), thus highlighting the importance of safety procedures also in less severe floodwater conditions that can still affect the safety of most vulnerable pedestrians, such as children, elderly, and pedestrians with mobility impairments. *Social influence and group phenomena* M6 are more frequent with flowing water ($PI_{A,F}/PI_A = 83$ %). Videotapes involving the presence of *moving elements* M3 were not found, essentially because of the limited water depth.
- *Post-evacuation* phase: pedestrians selecting *temporary safe areas* PE1 were not found, while *reaching outdoor safe areas* PE3 appears to be a common solution either in the cases of still and flowing waters. The statistical significance of *reaching indoor safe areas* PE2 could be limited in view of the sample dimension ($PI_A = 3$ pp, all in the same videotape).

4.2.4. Water depth equal to or up to the knees

Fig. 12 shows the results concerning the situational frequency in respect to water depth higher than the ankles, but equal or up to the knees, by distinguishing between still and flowing waters (Fig. 11). Considering the evacuation phases, it is worthy of notice that:

- *Pre-movement* phase: differently from the ankle-related situational frequencies ($PI_{A,f}/PI_A$, Fig. 10), *attachment to belongings* PM1 is more

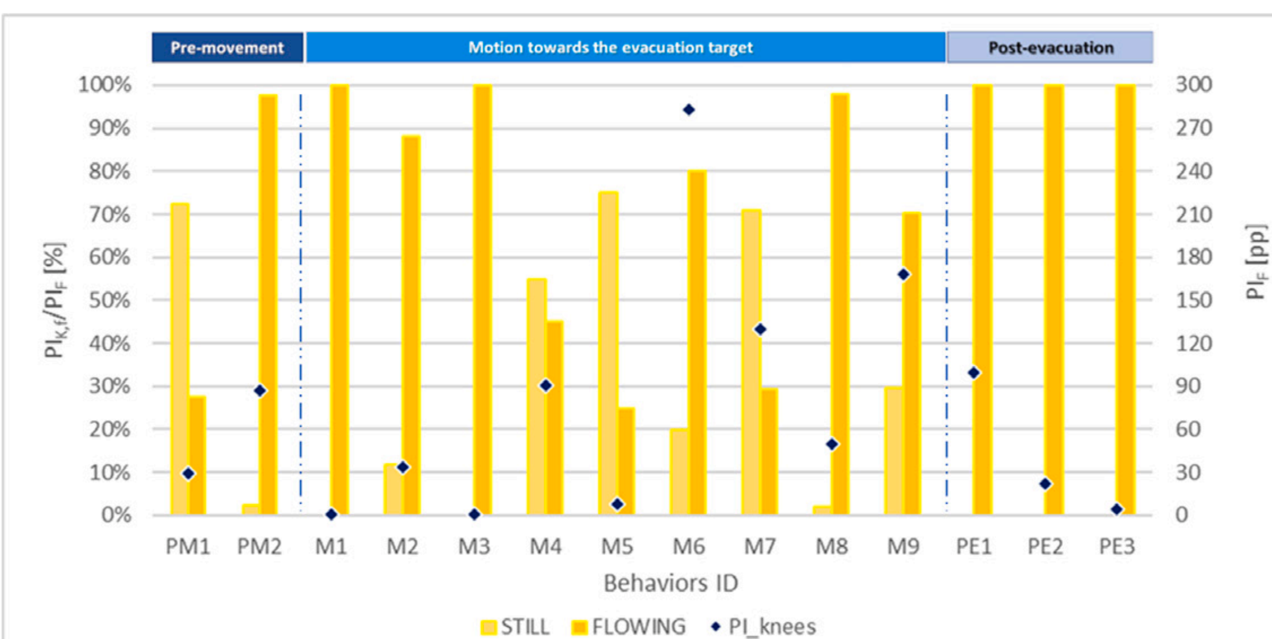

Fig. 12. Situational frequency per water depth equal to or lower than the knees $PI_{K,f}/PI_K$ [%] (colored bars; left y-axis) of the observed behaviors evaluated by comparing the water flow. The sample dimension is outlined by PI_K [pp] (black rhombuses; right y-axis). Behaviors IDs from Fig. 5.

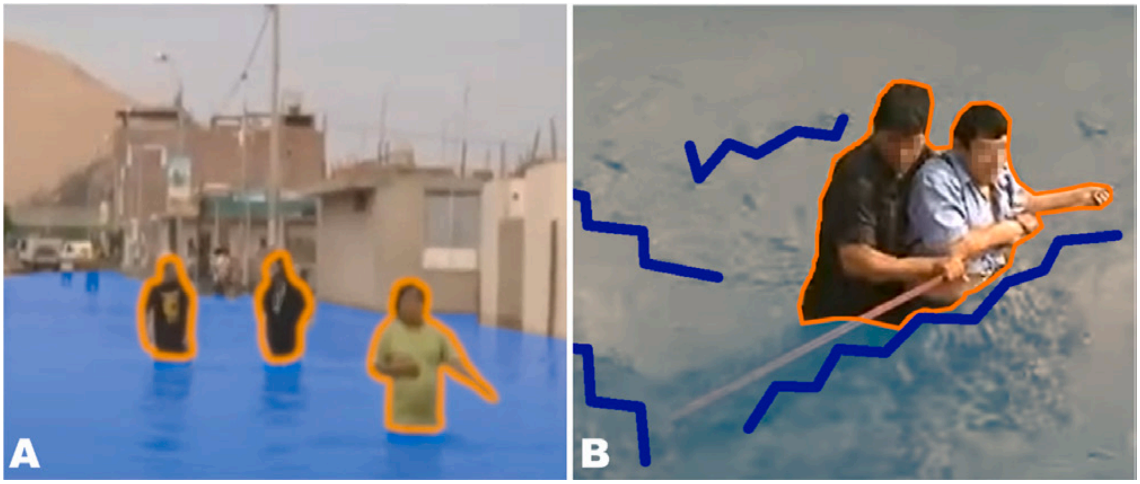

Fig. 13. People dealing with water up to the waist (outlined in orange). panel a is for still water, panel b is for flowing water and the blue jagged lines indicate the waves (reference videotapes: {100}, {84}). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

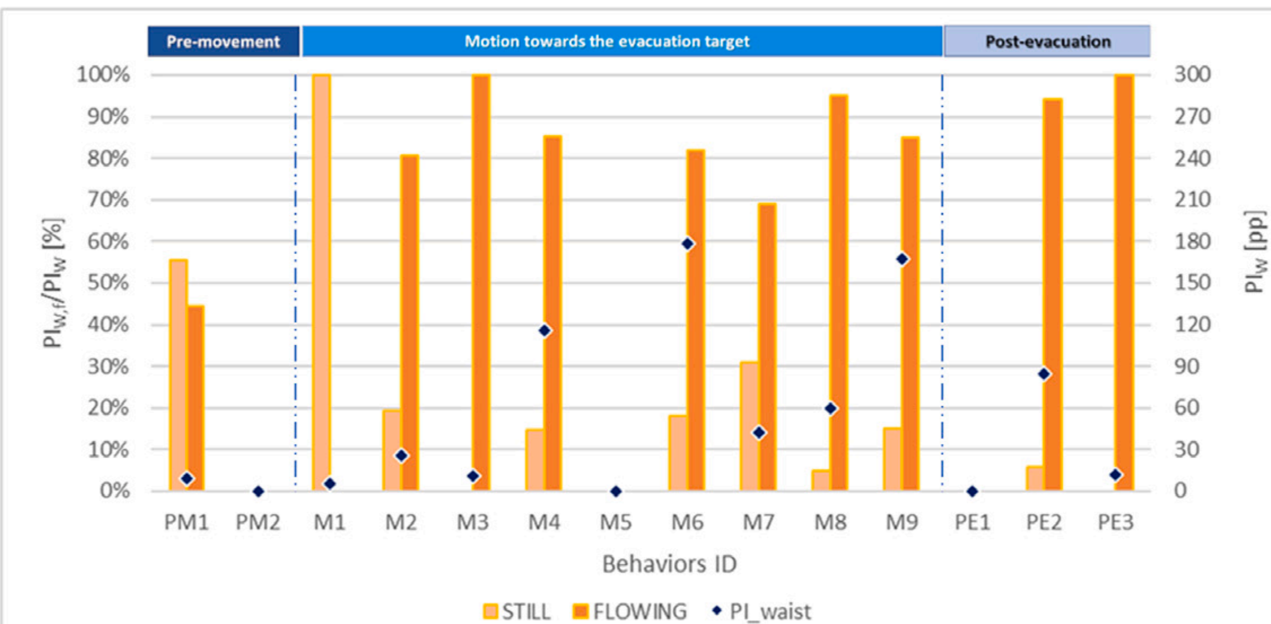

Fig. 14. Situational frequency per water depth equal to or lower than the waist $PI_{W,f}/PI_W$ [%] (colored bars; left y-axis) of the observed behaviors evaluated by comparing the water flow. The sample dimension is outlined by PI_W [pp] (black rhombuses; right y-axis). Behaviors IDs from Fig. 5.

frequent in still water ($PI_{K,S}/PI_K = 72$ %), while "*curiosity" effect* PM2 in flowing conditions ($PI_{K,F}/PI_K = 98$ %).

- *Motion towards evacuation target* phase: *human body instability* M8 still can be essentially noticed in flowing water. On the contrary, *floodwaters effects on motion speed* M7 seem to be more frequent in still water, thus implicitly confirming the possibility to move in such conditions while being affected by a reduction in the evacuation speed (Bernardini et al., 2020; Dias et al., 2021; Lee et al., 2019). The sample dimensions for these behaviors are different, and they could influence the results. However, behaviors aimed at restoring the people's safety like *fear of moving elements* M3, *social influence and group phenomena* M6, and *clinging to ropes and arranging "human chains"* M9 are confirmed to be more frequent in flowing water ($PI_{K,F}/PI_K > 80$ %). *Moving through the flow vehicles* M5 is more frequent in still water, which implies less severe conditions in terms of floodwaters resistance against the vehicles (Xia et al., 2011).
- *Post-evacuation* phase: videotapes with pedestrians *reaching temporary* PE1*, indoor* PE2*,* and *outdoor safe areas* PE3 were only found with flowing waters.

4.2.5. Water depth equal to or up to the waist

Fig. 14 shows the results concerning the situational frequency with respect to water depth higher than the knees, but equal or up to the waist, by distinguishing between still and flowing waters (Fig. 13). Considering the evacuation phases, it is worthy of notice that:

- *Pre-movement* phase: "*curiosity" effect* PM2 was not found in the analyzed sample, while *attachment to belongings* PM1 has a quite similar frequency in both still and flowing waters.
- *Motion towards evacuation target* phase: general outcomes of $PI_{K,f}/PI_K$ (Fig. 12) are confirmed, especially for *fear of moving elements* M3 as the number of people involved increases. *Moving through the water with vehicles* M5 was not found in the analyzed sample. As expected

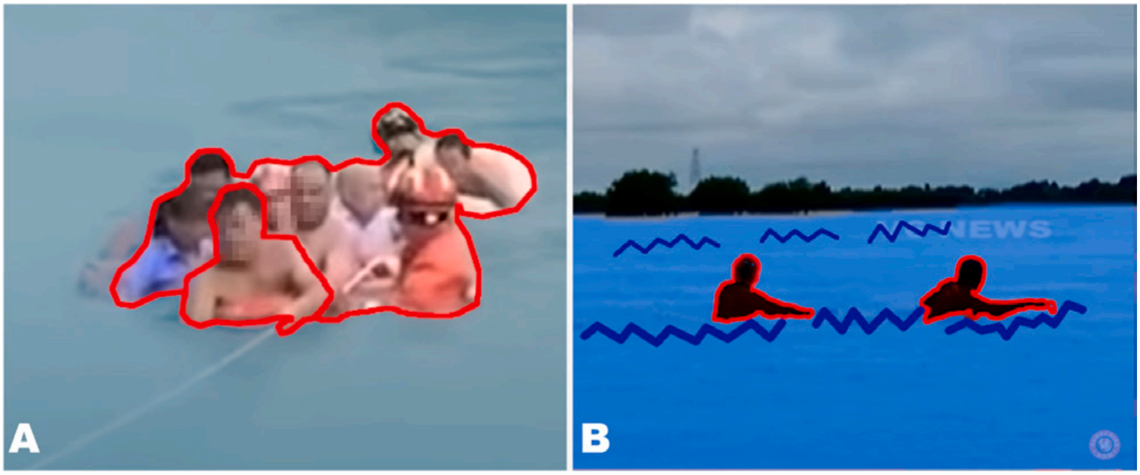

Fig. 15. People dealing with water higher than the waist (outlined in red). panel a is for still water, panel b is for flowing water and the blue jagged lines indicate the waves (reference videotapes: {25}, {55}). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Bernardini et al., 2020; Cox et al., 2010; Ishigaki et al., 2009), issues concerning *Floodwaters effects on motion speed* M7 and *human body instability* M8 are more frequent in flowing waters.
- *Post-evacuation* phase: for what it concerns *reaching indoor safe areas* PE2 and *outdoor safe areas* and PE3, results are similar to the knees-related outcomes ($PI_{K,f}/PI_K$, Fig. 12) and they are also corroborated by a greater number of people involved ($PI_W = 85$ pp, $PI_K = 22$ pp for PE2, $PI_W = 12$ pp, $PI_K = 4$ pp for PE3). On the other hand, *reaching temporary safe areas* PE1 was not found in the analyzed sample.

4.2.6. Water depth higher than the waist

Fig. 16 shows the results concerning the situational frequency with respect to water depth higher than the waist, by distinguishing between still and flowing waters (Fig. 15). Considering the evacuation phases, it is worthy of notice that:

- *Pre-movement* phase: *attachment to belonging* PM1 is the unique noticed behavior within the analyzed sample, and only in the case of still water.
- *Motion towards evacuation target* phase: in general, analyzed people managed to perform few behaviors in such high-water depth conditions. In particular, *increased guide effect* M4 and *clinging to ropes and arranging "human chains"* M9 are the most frequent in both the water flow conditions, thus highlighting the importance of rescuers' presence and rescue tasks in such critical situations. Compared to the previous cases (Figs. 10, 12, and 14), *social influence and group phenomena* M6 and *human body instability* M8 become more frequent with still water ($PI_{HW,S}/PI_{HW}$ respectively up to 36 % and 43 %). Finally, *floodwaters effects on motion speed* M7 can be observed only with still water, thus confirming that pedestrians can be able to additionally move in still floodwaters deeper than 1.20 m (Cox et al., 2010).
- *Post-evacuation* phase: *reaching outdoor safe areas* PE3 was not found in the analyzed sample and the statistical significance of *reaching temporary safe areas* PE1 could be limited in view of the sample dimension ($PI_{HW} = 5$ pp, all in the same videotape). On the other hand, the frequency of *reaching indoor safe areas* PE2 underlines the impact of critical flow conditions on pedestrians' preferences to

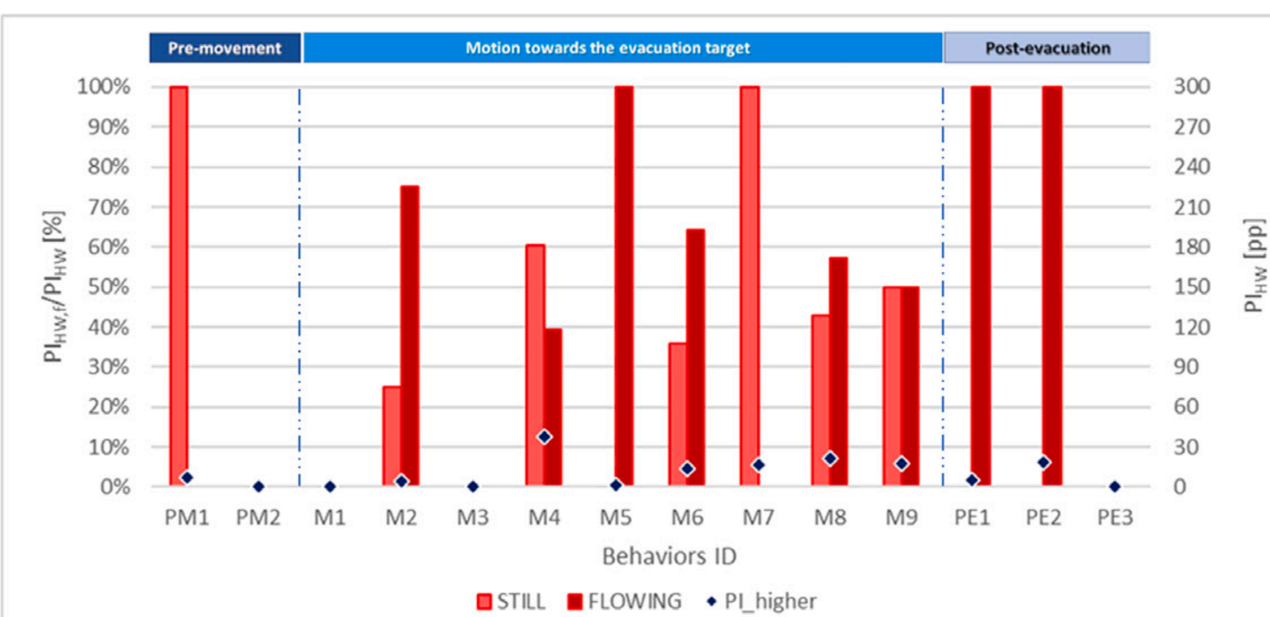

Fig. 16. Situational frequency per water depth higher than the waist $PI_{HW,f}/PI_{HW}$ [%] (colored bars; left y-axis) of the observed behaviors evaluated by comparing the water flow. The sample dimension is outlined by PI_{HW} [pp] (black rhombuses; right y-axis). Behaviors IDs from Fig. 5.

Table 10
Observed behaviors and frequent floodwater conditions in which they are performed.

Pre-movement

ID – *Observed Behavior*	Most frequent floodwater conditions	
PM1 - *Attachment to belongings*	Water up to the knees	
PM2 - *"Curiosity" effect*	Flowing water up the knees	

Motion towards the evacuation target

ID – *Observed Behavior*	Most frequent floodwater conditions	
M1 - *Attraction towards safe areas*	Still water up to the waist	
M2 - *Attraction towards unmovable obstacles*	Flowing water between the ankles and the waist	
M3 - *Fear of moving elements*	Flowing water between the knees and the waist	
M4 - *Increased guide effect*	Water up to the waist	
M5 - *Moving through the water with vehicles*	Water up to the ankles	
M6 - *Social influence and group phenomena*	Flowing water between the knees and the waist	
M7 - *Floodwaters effects on motion speed*	Water between the ankles and the knees	
M8 - *Human body instability*	Flowing water between the ankles and the waist	
M9 - *Clinging to ropes and arranging "human chains"*	Flowing water between the ankles and the waist	

Post-evacuation

ID – *Observed Behavior*	Most frequent floodwater conditions	
PE1 - *Reaching temporary safe areas*	Flowing water between the ankles and the knees	
PE2 - *Reaching indoor safe areas*	Flowing water between the knees and the waist	
PE3 - *Reaching outdoor safe areas*	Water up to the ankles	

move far from the flooded areas reaching raised indoor positions (for *reaching indoor safe areas* PE2).

4.3. *Most frequent floodwater conditions for behavioral patterns*

The use of human body parts as references for the behavioral patterns activations pursues a quick but reliable assessment of people's response to flood evacuation. Behavioral key findings are summarized in Table 10, which resumes the most frequent floodwater conditions in which behaviors are observed.

For what concerns the *pre-movement* phase, although the observed behaviors can be classified as *hazardous behaviors*, some interesting differences can be found. Indeed, even though both *attachment to belongings* PM1 and *curiosity" effect* PM2 are characterized by a sort of "warning threshold" for pedestrians at the level of the knees, the latter is observed predominantly with flowing conditions, thus suggesting that pedestrians are more influenced by the water depth than its flowing conditions. This threshold decreases down to the ankles level for *moving through the water with vehicles* M5, which is in line with previous works findings carried out through questionnaires, according to which people's perception of the risk increase with the water depth (Papagiannaki et al., 2021; Pearson & Hamilton, 2014). Moreover, considering its occurrence during the evacuation phases, *moving through the water with vehicles* M5 can also be associated with the *pre-movement* phase in view of the similarities with *attachment to belonging* PM1 (i.e., the vehicles), which can delay the actual evacuation on foot (Arrighi et al., 2015; Hamilton et al., 2016). These differences can be also traced back to the significant worsening in the walking behaviors (i.e., speed, trajectory, step frequency, lateral swaying, stability) that arise when the knees articulations are even partially submerged, thus suggesting a different acceptance of the risk depending on the context and the reference elements (Bernardini et al., 2020; Dias et al., 2021).

Motion towards evacuation target behaviors strongly depend on (1) the presence of reference elements in the flooded scenarios and (2) the possibility for pedestrians to move without restrictions imposed by the water. As a consequence, behaviors like *attraction towards safe areas* M1 or *fear of moving elements* M3 only rely on a few observations (respectively, PI = 9 pp on 3 videotapes and PI = 16 pp on 3 videotapes). However, comparing our findings with those on human body instability and motion speed in floodwaters (Bernardini et al., 2020; Chanson et al., 2014; Cox et al., 2010; Dias et al., 2021; Milanesi et al., 2016), it could be noticed that:

- *attraction towards safe areas* M1 was observed for still waters up to the waist, essentially because these conditions still avoid buoyancy problems for pedestrians, and so they allow pedestrians to move towards an evacuation target;
- *attraction towards unmovable obstacles* M2 was noticed for flowing waters between the ankles and the waist. These conditions can provoke human body instability problems thus leading pedestrians at searching for physical support;
- *fear of moving elements* M3 concerns scenarios in which flowing water (that is consistent with having objects dragged by floodwater) is combined to water depth between the knees and waist (that is excluding limited and extreme interactions with floodwaters).

As expected, the main intent of *deliberately chosen* behaviors performed during the actual movement within the floodwaters is to recover from human body instability problems and speed up the restoration of safety conditions. Thus, the most frequent conditions for *passively suffered* behaviors represent a benchmark also for behaviors aimed at improving the pedestrians' mobility into the floodwaters. In this sense, *floodwaters effects on motion speed* M7 can be noticed especially in water up to the knees, thus excluding conditions that impede human motion (Cox et al., 2010). Furthermore, it is worthy of notice that this behavior was not observed at all with still water under the ankles, where pedestrians are still capable to move without significant problems (Bernardini et al., 2020; Dias et al., 2021). Besides, *human body instability* M8 is mostly observed for flowing water between the ankles and the waist (Cox et al., 2010; Milanesi et al., 2016), even if a wide number of observations were retrieved also with higher/lower water depth. As a consequence, *protective behaviors* that could involve also the presence of rescuers like *increased guide effect* M4, *clinging to ropes and arranging "human chains"* M9, and *social influence and group phenomena* M6 (which includes also pro-social actions such as trying to rescue other pedestrians) are attempted in whatever kind of condition, especially in flowing water up to the waist (basically the same conditions provoking human body instability and motion speed problems (Cox et al., 2010; Milanesi et al., 2015, 2016)). However, it is worthy of notice that these behaviors are the three most observed in terms of people involved (Fig. 6), which confirms the importance of actions aimed at saving their own lives and those of others during flooding disasters (Hamilton et al., 2020).

Furthermore, *post-evacuation* behaviors highlight a trend for *reaching indoor safe areas* PE2 in case of flowing water higher between the knees and the waist, while *outdoor safe areas* PE3 in water up to the knees. This result is consistent with differences in risk perception depending on water depth and flow (Tanaka & Shimomura, 2021), besides the availability of outdoor areas in case of extreme events. On the other hand, *temporary safe areas* PE1 can be substantially traced back to flowing water between the ankles and knees, which can be probably considered sufficiently severe to induce pedestrians to stop during their motion to target (thus excluding still water and less deep than the ankles), but not to threaten the safety of the selected area (floodwaters above the knees can reasonably induce threat in temporary areas like vehicle roofs) (Bernardini et al., 2020; Cox et al., 2010; Dias et al., 2021).

5. Discussion

Observations of real floods in outdoor BEs empirically (1) confirmed that the floodwater conditions strongly affect people's behaviors before, during, and after the evacuation, and (2) demonstrated that critical thresholds with respect to water depth and flow vary for each of the observed behaviors. In this sense, the outcomes of this work can support the development of risk-mitigation strategies and simulation modeling approaches (Section 5.1), even though some limitations need to be discussed (Section 5.2).

5.1. Implications on modeling approaches

This work findings can support the development and validation of simulation tools based on microscopic approaches relying on the representation of people's tasks with respect to the surrounding floodwater conditions, such as agent-based models (Alonso Vicario et al., 2020; Nakanishi et al., 2019; Shirvani et al., 2020). These approaches can be then combined with modeling approaches to estimate pedestrians' behaviors, velocity, and paths, such as cellular automata (Y. Li et al., 2019) or force-based models (Bernardini, Postacchini, et al., 2017). Since this work focuses on qualitative aspects of human response, works to consolidate motion speed assessment are needed. In particular, considering *attraction towards unmovable obstacles* and *clinging to ropes and arranging "human chains"* behaviors, experiments could be conducted toward the quantification of human stability and evacuation speed improvements thank to supporting elements like ropes and cables that resulted to be widely used by evacuees and rescuers. These studies could then move towards the analysis of rescuers' operations and equipment during the evacuation in order to improve their design and use under specific hydrodynamic conditions. In this way, additional tests through evacuation simulators could be also conducted for testing new equipment for rescue tasks and their implementation within the urban layout.

5.2. Relations with risk-mitigation strategies

Behavioral results retrieved in the *pre-movement* phase of the emergency demonstrate that future efforts should move towards the study of risk-reduction measures to speed the (right) decision-making process and reduce the time spent performing pre-movement hazardous behaviors which can often mark the difference between surviving or not, or at least avoid that the best option becomes the "least harmful one" (e.g., to be obligated to cross deep flowing waters rather than not). Indeed, floods are disasters whose impact can locally vary depending on specific conditions of the meteorological event or of the built environment, which can be partially subject to prediction biases (e.g., in the case of flash floods). Therefore, solutions may include the provision of communication strategies, wayfinding systems, and Early Warning Systems to be implemented, for instance, in form of reliable social-media alerts or apps for mobile devices, so as to reduce the reaction time (i.e., the overall "pre-movement" phase) to avoid floodwater interactions at all, and ease the evacuation timing and path selection (Chaudhary et al., 2019; Cools et al., 2016; Coz et al., 2016; Feng et al., 2020; Haer et al., 2016).

Similarly, qualitative findings in the *motion towards the evacuation target* phase can help local authorities and technicians in planning and designing targeted interventions in flood-prone built environments (some examples are shown in Fig. 17). Possible applications could include: (1) the improvement and proper positioning of "passive" architecturally-implemented solutions such as handrails, benches, and raising floor systems, as well as traditional signage systems such as hazard signs, water heights indicators, wayfinding systems (Bernardini, Postacchini, et al., 2017; Gissing et al., 2016; K Haynes et al., 2009; Musolino et al., 2022)); (2) the implementation of "active" systems for emergency warning and wayfinding, including both visual (e.g. through variable and luminescent directional signs) and acoustic indications (Cools et al., 2016; Diakakis, 2020)); (3) the improvement of evacuation planning with innovative and retrofitted solutions evaluated on the basis of local and/or temporary risks (Bischiniotis et al., 2020; Quagliarini et al., 2022); (4) the promotion of exercises and awareness campaigns to improve the community resilience and educate people on the danger of walking and driving in floodwaters, also with the aid of innovative immersive techniques like virtual reality (VR) or augmented reality (AR) serious games (Bernardini et al., 2019; Fujimi & Fujimura, 2020; Sörensen et al., 2016); (5) the wide use of ropes and cables (that can be more effective than expected especially if considering their general low cost) regardless of the floods magnitude, since future events harsher than usual cannot be excluded at all in flood prone areas even in presence of specific data linked to recurring conditions.

In this sense, this work also supports the identification of necessities behind the selection of a certain type of safe area. Results emerging from the analysis of *post-evacuation* behaviors can be used to evaluate aspects like the safe areas' position, dimensions (i.e., height, area, density), and type also as a function of the expected risk in a given scenario (e.g., evaluating the prearrangement of indoor areas or temporary forecast-based solutions aimed at gathering a certain number of evacuees), and so depending on the general features of the floodwater conditions in terms of water depth (in respect to the human body parts) and of the presence of still or flowing waters.

5.3. Work limitations and future aims

Finally, it is worth noticing that the work insights are mainly affected by some limitations, which can be overcome by future works. The presence of some situations with a limited number of involved and assessed people could be overcome by enlarging the videotapes database. Furthermore, results could be influenced by additional factors such as physical (different body parts submerged under the same water depth, different weight, and so on), geographical, cultural, and risk-awareness-related features of people, which could be not directly and easily

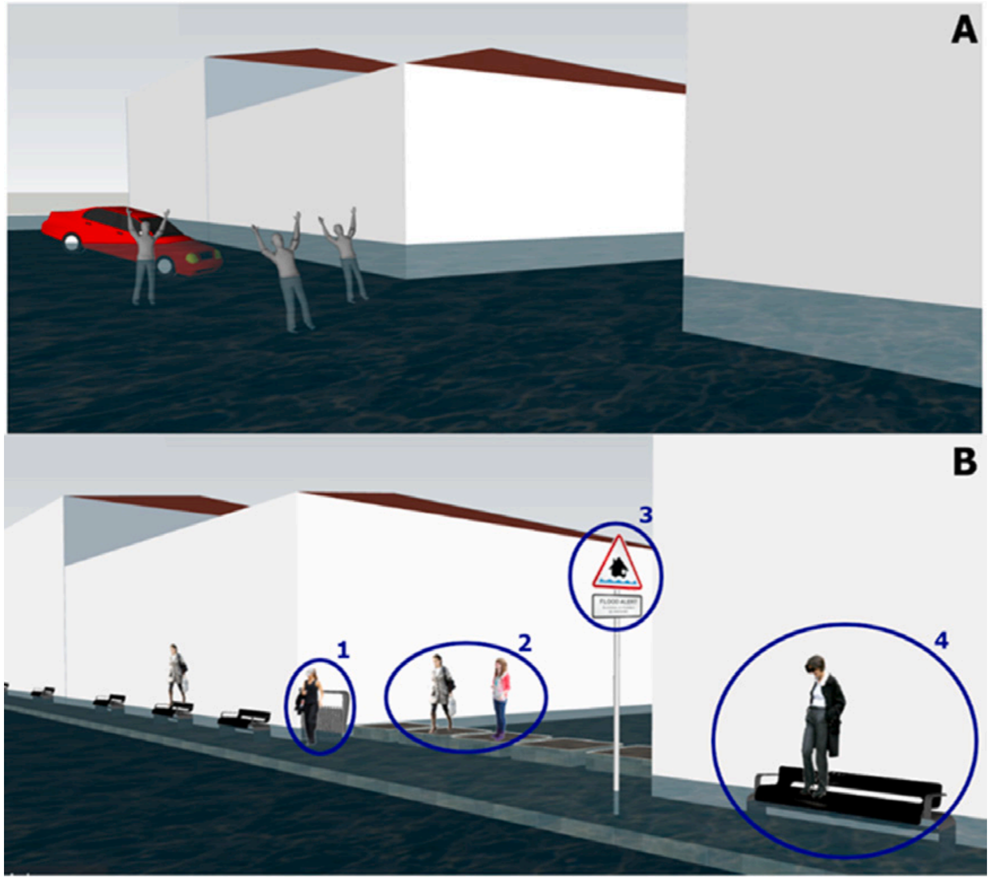

Fig. 17. Example of how "passive aids" can be implemented in the outdoor BE. Scenario A lacks of targeted interventions; Scenario B includes the presence of handrails (1), raised platforms (2), road signs (3), and benches (4).

assessed by videotapes analysis. In this sense, this work considers a worldwide database as a unique sample, so as to point out "average" behavioral responses to floods in the investigated outdoor BEs, as for previous methods applied to other kinds of disasters (Bernardini & Quagliarini, 2021; Haghani & Sarvi, 2018; van der Wal et al., 2021; Zhou et al., 2018). Similarly, results could be affected also by external factors like the presence of individuals with cameras or smartphones, who could hardly decide to film unless something is happening (see for example the lack of post-evacuation scenes). However, the approach pursued by this work allows taking advantage of unbiased sources, differently from controlled experimental tests that inevitably are influenced by simplified laboratory conditions both in terms of environmental and human factors. In this sense, future works could: (1) integrate the database enlargement with specific analysis, e.g. on geographical areas or including standard analyses through gender, age, and/or height estimation when possible by the videotapes; (2) move towards quantitative assessment of floodwater conditions, by also using image processing (Alizadeh Kharazi & Behzadan, 2021), which could reduce the quickness of the proposed approach but could also improve their reliability and the detail level of the results (e.g. measuring "how much" the individual body is submerged by the floodwaters rather than just defining general conditions based on body parts); (3) investigate recurring evacuation "storylines" so as to additionally inquire "when" each behavior is usually performed, thus retrying the recurrent order of activation of the behaviors during a flood evacuation, or even behavioral patterns differences over the evacuation time. At the same time, collected data could be also exploited by machine learning approaches to investigate situational influences affecting behavioral patterns (Zhao et al., 2020). In this sense, this work approach could provide simple but reliable bases for the situational features' selection while creating structured databases in the flood context.

6. Conclusions

Comprehending decision-making processes and reasons behind human behaviors in flood emergencies is fundamental for the development of risk assessment tools and risk-reduction strategies. Floodwater-human evacuation interactions are deeply influenced by the event features and the people's perception of surrounding conditions and related risk. A large number of studies already define flood-related behaviors and evacuation physical quantities, but the relationship between frequent behaviors and floodwater conditions is not yet really clarified from this point of view. This work aims at filling this lack by using for the flood case an approach already tested on other type of emergencies (i.e., earthquakes, fire, terrorist attacks) that consists of the analysis of real evacuations.

Starting from previous works' findings, a reference behavioral database has been organized in relation to the evacuation phases and the main literature classifications, and new-noticed behaviors have been also inquired to enlarge the reference database. Up to 139 videotapes from relevant social media sources and more than 1000 people involved in flood evacuation were considered, representing the largest set in the field of video analysis for human behaviors. In particular, we focused on outdoor Built Environments from all over the world.

The behavioral patterns have been defined according to statistical frequencies innovatively evaluated through the number of people performing and that could actually perform the behaviors. The presence of reference elements necessary to activate the behaviors have been also considered for this purpose. Collected qualitative data have been organized according to the floodwaters' conditions in which the behaviors were observed. In particular, the water depth has been classified into 4 classes identified by the knees, the ankles, and the waist, and the water flow has been distinguished in still and flowing conditions. This quick approach has been selected since it seems to be reliable with respect to the main man-floodwater interactions noticed in previous works on human motion in flood evacuation.

Such a significant overview of flood evacuation behaviors can find application in different fields of risk management and assessment, spacing from supporting safety planners in designing evacuation plans and installations for resilient built environments, to the employment for the development and validation of dedicated simulation tools.

CRediT authorship contribution statement

Enrico Quagliarini: Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Guido Romano:** Writing – original draft, Visualization, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gabriele Bernardini:** Writing – original draft, Validation, Methodology, Conceptualization.

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.

Data availability

The source data (i.e. videotapes) are included in the manuscript. Please contact us for additional analysis data to be shared on request.

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