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Key parameters to improve prediction of the drift and resurfacing of human bodies following drowning in rivers

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Abstract. Drowning is a major global health concern, and urban rivers pose a significant risk. Climate change is leading to increasingly frequent extreme floods and heatwaves, which drive people to bathe in urban water bodies. The rapid recovery of victims is critical for their survival, as well as for investigations, and first responder safety. Recent research highlights the potential of combining hydrodynamic computer simulations with drift modelling to predict the trajectory of drowning victims' bodies. The present study uses a unique dataset of 50 real-world fatal drowning cases to identify two key parameters needed to improve computer simulations of body drift in urban rivers: the initial body buoyancy (i.e. before the effects of decomposition) and the body submersion interval. The results reveal that older age and a higher body mass index are significantly correlated with increased initial buoyancy, due to physiological factors such as lower bone density and higher body fat content. Bodies of victims over the age of 65 are almost four times more likely to remain afloat. A temperature threshold of around 7 °C appears to limit body floatability, and lower water temperatures are associated with longer body submersion intervals due to slower decomposition. A resurfacing value of 97 °C·days was estimated for the 'accumulated degree days' (ADD), a criterion which has been recommended for predicting the body resurfacing time but has barely been quantified in prior studies. Additionally, older female individuals with a higher BMI were found to be significantly more likely to be victims of suicidal drowning, indicating a distinct risk profile that is important for prevention strategies. These findings emphasize the importance of incorporating empirical data into drift models and building larger, transnational databases to improve predictive accuracy and save lives.

1 Introduction

1.1 Context

Unintentional drowning is a major public health issue worldwide, resulting in around 400,000 fatalities each year (WHO, 2014). In many regions in the world, rivers are a common location for drowning (Peden et al., 2016a, 2016b; Maghakian et al., 2024). Climate change exacerbates this risk by intensifying hydro-meteorological extremes (Musolino et al., 2020), such

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as riverine and flash floods, which can sweep individuals away (Milanesi et al., 2015; Chen et al., 2019; Musolino et al., 2020; Lazzarin et al., 2022). The increasing frequency of heatwaves, which are associated with the urban heat island effect (Heaviside et al., 2017), leads to more people bathing in unsupervised urban rivers to cool off, thereby further increasing the risk of drowning (Fralick et al., 2013; Sindall et al., 2022).

A rapid response is crucial after drowning, as victims can be resuscitated for up to about one and a half hours after the accident, depending on the water temperature (Tipton and Golden, 2011). Therefore, the time taken to recover the victim has a critical influence on their chances of survival. Speeding up body recovery is also essential for other reasons: it reduces the burden on first responders, the risks taken by staff involved in aquatic and subaquatic search operations, and the time families and loved ones have to wait for news about the missing person. It also facilitates subsequent police and court investigations, as a less decomposed body tends to provide more evidence on the circumstances of drowning.

Search operations in urban rivers are challenging due to the potentially high velocity and momentum of the flow (Byard, 2017), as well as the poor visibility caused by suspended materials and dissolved compounds (Horn, 2014). Traditional search technologies, such as sonar, tend to be ineffective in urban rivers due to debris and artefacts present on the riverbed (Blondel, 2014). Floods exacerbate these challenges, rendering boating or diving unsafe, hence hindering the localisation of drowning victims (Ray, 2014). Despite considerable resources mobilized for aquatic and subaquatic search operations, victims of drowning are mostly found after several days, when their body resurfaces (Dennison-Wilkins et al., 2023). Improving our understanding and prediction capacity of the drift of a drowning victim is essential to guide more targeted search and rescue operations and to inform more tactical allocation of resources after a drowning accident. So far, very little academic research has been conducted into predicting the movement of a body in a river environment. This contrasts with the abundant existing research on predicting the behaviour of missing persons on land based on insights from the social sciences (Dennison-Wilkins et al., 2023).

The combination of computational simulations of river hydrodynamics and Lagrangian drift modelling has recently been explored as a promising method for predicting the trajectory of a drowning victim's body in a river (Gonzalez et al., 2022; Delhez et al., 2023). A pioneering modelling study by Delhez et al. (2023) has shown that determining whether the victim's body floats or lies on the riverbed is instrumental to enable reliable predictions of the body location over time. This is due to the considerable difference in drift velocity between a body floating at the surface and a body moving on the riverbed, where hydrodynamic driving forces (e.g., drag) are lower and resistance forces (e.g., solid-solid friction between the body and the riverbed) are higher. Hence, predicting whether the body of a particular drowning victim is likely to initially sink or remain at the surface, as well as estimating how long a sunk body would remain on the riverbed before resurfacing, is of critical importance to inform detailed modelling of the drift of drowning victims in urban rivers. Distinguishing between initial body buoyancy (i.e. before the effects of decomposition) and body buoyancy at subsequent times was also adopted in previous research (Dennison-Wilkins et al., 2023).

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1.2 Initial body buoyancy

In the case of drowning in sea or coastal environments, the victim's body usually floats due to the widespread use of lifejackets in the marine context and the higher density of seawater compared to freshwater (Byard, 2017). In the case of river drowning, the body may be either positively or negatively buoyant (Donoghue and Minnigerode, 1977; Martlin et al., 2023) depending on factors such as the body morphology (Modell and Davis, 1969; Gallagher et al., 1996; Barwood et al., 2011; Laurent et al., 2013; Van Hoyweghen et al., 2015), the presence of air or water in the lungs (Modell and Davis, 1969; Gallagher et al., 1996; Barwood et al., 2011; Laurent et al., 2013; Van Hoyweghen et al., 2015), the amount of water swallowed by the victim (Modell and Davis, 1969), the type of clothes (Modell and Davis, 1969; Gallagher et al., 1996; Barwood et al., 2011; Laurent et al., 2013; Van Hoyweghen et al., 2015), or the presence of accessories such as a backpack.

Although experimental studies have been conducted to assess the buoyancy of living humans, they are barely representative of typical drowning conditions. For instance, Donoghue and Minnigerode (1977) analysed the buoyancy of U.S. Navy officers (aged between 20 and 40 years) based on experiments conducted by Behnke et al. (1942). At functional residual capacity (FRC) of the lungs, which is similar to the lungs volume of a recently deceased person, they found that only 7% of the subjects would float in freshwater. This rate is expected to be significantly higher in a sample that is more representative of the general population than a group of Navy officers. To date, no study has attempted to predict whether a drowning victim's body would float or sink based on their physical characteristics (such as sex, age, and build) and environmental parameters (such as water temperature and season).

1.3 Body submersion interval

When a body sinks to the bottom of a river and remains there for a period of time, the decomposition processes release putrefaction gases within the body. These gases cause the body to swell and decrease in density (Heaton et al., 2010; Mateus et al., 2013; Lunetta, Ebbesmeyer, et al., 2014; Daalen et al., 2017). Consequently, the body usually refloats after a time interval that depends on various factors controlling the kinetics of body decomposition, with water temperature being the main factor. In a specific drowning case, significant uncertainty remains in the prediction of the body submersion interval (BSI), i.e. the time elapsed between body sinking and resurfacing.

To establish a relationship between the degree of body decomposition and time and temperature, Megyesi et al. (2005) introduced the concept of accumulated degree days (ADD). ADD is defined as the integral of the external temperature (in this case, the water temperature) over time since the body entered water:

$$ADD(t) = \int_{t_0}^{t} T_w(\tau)\, d\tau \,, \tag{1}$$

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with t_0 the time of the drowning, t the considered time and T_w the water temperature (in °C). This definition of ADD has also been adopted in many subsequent studies (Heaton et al., 2010; Mateus et al., 2013; Lunetta, Zaferes, et al., 2014; Daalen et al., 2017; Delhez et al., 2023).

Heaton et al. (2010) and Daalen et al. (2017) have matched different degrees of body decomposition in water with ADD values at the time of body recovery. Assuming the water temperature is known, these results can be used to estimate the time elapsed since body submersion based on observations made on the recovered body. However, this approach cannot predict the body submersion interval, as it relies on observations made on the recovered body.

Mateus et al. (2013) proposed a threshold of 95–117 °C days for ADD to predict body resurfacing, but these values were derived from only two cases of drowning in a marine environment. It is unclear whether this threshold can be applied to drowning in freshwater environments, such as in urban rivers. Currently, there is no predictive approach for estimating the submersion interval of a drowning victim's body in urban rivers. This would be highly valuable for optimally allocating resources between surface and subaquatic search operations, and for modelling the drift of a drowning victim's body.

1.4 Specific objectives of the present study

The objective of the present research is to investigate whether analysing a database of past drowning cases could provide valuable insights into the initial body buoyancy of river drowning victims and, in cases where the body sank, the submersion interval (i.e., the time elapsed between drowning and body resurfacing). Table 1 provides an overview of recent drowning studies based on drowning databases. The databases reported in literature cover drowning occurrences in a limited number of countries (Australia, New Zealand, Canada, United Kingdom and France), some of which include large samples (up to over 8,000 entries). These databases are mostly restricted to fatal drowning cases, as the source of information often comes from coronial and police reports (Peden et al., 2016b, 2019, 2023; Dennison-Wilkins et al., 2023). Only those populated by data from first responders (e.g., the fire brigade or rescuers) include non-fatal drowning cases (Ung, 2014; Maghakian et al., 2024), but these non-fatal cases are not always analysed (Hills et al., 2021). Only two of the reported databases focus solely on river drowning (Peden et al., 2016b; Maghakian et al., 2024), but neither report information on initial body buoyancy nor the body submersion interval.

Five of the reviewed studies primarily aim to inform drowning prevention strategies (Ung, 2014; Peden et al., 2016b, 2023; Hills et al., 2021; Maghakian et al., 2024). As such, these studies focus on various aspects of drowning epidemiology, such as identifying the profile of drowning victims and predicting circumstances that lead to drowning (Peden et al., 2016b). Another study solely aims to assess the comparability of existing databases in three countries: Australia, Canada and New Zealand. Similarly, Hills et al. (2021) audited the quality of an official database in the United Kingdom.

Of the seven studies reported in Table 1, the study by Dennison-Wilkins et al. (2023) stands out as the only one that aligns with the present research objective. They focus on river drowning as we do here, and they aim to guide search operations and

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to increase the chances of prompt body recovery. This contrasts with most other studies, which address means for preventing drowning. Dennison-Wilkins et al. (2023) were the first to use a database of real-world inland and near-shore drowning cases to analyse factors affecting the body motion in water, particularly initial body buoyancy and submersion interval. Here, we aim to extend the work initiated by Dennison-Wilkins et al. (2023) by complementing their analysis using data from a different context, mostly two cities in continental Europe, whereas Dennison-Wilkins et al. (2023) solely relied on data collected in the United Kingdom.

In the present study, we have gathered and analysed a database of 50 real-world river drowning cases, primarily from two Belgian cities (Liège and Antwerp). This dataset was used to predict two essential features for reliable calibration and validation of drift modelling of drowning victims in urban rivers: the initial body buoyancy of the body and the body submersion interval. These predictions are based on environmental variables (water temperature, season and drowning circumstances, i.e., accident or suicide) and five pre-mortem body characteristics, i.e., body mass index, victim's age, height, sex, and type of clothing.

Section 2 introduces the dataset used in this paper and how it was collected, while Section 3 presents the methods used for data analysis. The results are depicted in Section 4 and discussed in Section 5. Conclusions are drawn in Section 6.

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Reference	**Region covered**	**Types of water bodies**	**Analysed period**	**Number of cases**	**Fatal and/or non-fatal cases**	**Main sources of information**	**Study main objective**	**Initial body buoyancy**	**Body submersion interval**
Maghakian et al. (2024)	Lyon (France)	Rivers	2015-2021	386	Fatal and non-fatal	Fire brigade (rescuers) reports	Predict the occurrence of drowning (epidemiology)	Not reported	Not reported
Peden et al. (2023)	Australia	Diverse, incl. rivers, ocean, swimming pools …	2002-2022	5,692	Fatal	Mostly coronial records, supplemented by other reports (media, police)	Mostly inform drowning prevention strategies	Not reported	Not reported (only 'date of incident' and 'date of death')
Ung et al. (2022)	France	Diverse, incl. rivers and lakes (~ 23%)	Summer 2021	1,753 (incl. 1,480 accidental ones)	Fatal (31%) and non-fatal	Survey of first respondents (fire brigade, police, emergency care units …)	Inform drowning prevention strategies	Not reported	Not reported
Hills et al. (2021)	United Kingdom	Not explicitly reported, but includes coastal and river environments	2012*-2019	5,051 (fatal cases)	Fatal*	Multiple sources, including safety, rescue and public organisations	Audit an existing official database, inform drowning prevention strategies	Not reported	Date and time of incident and/or of body recovery

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Peden et al. (2019)	Australia, Canada and New Zealand	Diverse, incl. ocean, harbour, ponds, lakes and bathtubs	2005-2014	8,176	Fatal	Mostly coronial records, supplemented by other reports (media, police)	Assessing the comparability of database from different countries	Not reported	Not reported
Peden et al. (2016a)	Australia	Rivers	2002-2012	2,892	Fatal	Coronial data	Identify the profile of drowning victims (epidemiology)	Not reported	Not reported
Dennison-Wilkins et al. (2023)	United Kingdom	Inland waters (or near-shore)	2008 onwards	280 (quantitative analyses based on $n = 74$ to 77)	Fatal	Police reports	Inform search operations by predicting body movement in water	Reported and analysed (see Figure 1 in Dennison-Wilkins et al., 2023)	Reported and analysed (see Table 3 in Dennison-Wilkins et al., 2023)
Present study	Mostly Liège and Antwerp (Belgium)	Mostly urban rivers (two cases of other water bodies)	2019-2022	50	Fatal	Forensic medicine reports, missing notices, media	Examine key inputs for modelling of the drift of the body	Reported and analysed	Reported and analysed

* Non-fatal drowning cases are also included in the corresponding database, but the analyses by Hills et al. (2021) focus on the fatal cases. Similarly, drowning cases from 2009 onward are reported in the database but the study focuses on the period 2012-2019.

Table 1: Overview of recent studies based on the analysis of drowning database.

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2 Data

The dataset considered here contains information on 50 cases of drowning in urban water bodies between 2019 and 2022. Most of them occurred in or nearby the Belgian cities of Liège (36 cases) and Antwerp (11 cases). Only three cases occurred elsewhere (in Ghent, Namur and Strasbourg). The dataset includes two variables describing the behaviour of the victim's body after drowning (i.e., whether it sank or remained at the surface and, if it sank, its submersion interval), as well as seven potential explanatory variables, characterizing the victim (sex, age, height, body mass index, and clothing type) and the context of the drowning (water temperature and circumstances).

Table 2 provides an overview of the data types, their distribution and the sources of information used to retrieve them. Comprehensive forensic reports, including photographs, were available for all 11 cases in the Antwerp region. This made it possible to retrieve all the necessary data for these cases. For the 36 cases in the Liège region, forensic reports were also available, but with missing information. Therefore, information from wanted notices and/or media reports was used to supplement the Liège reports. Previous studies based on drowning databases recommended employing such mixed data collection approach to supplement the weaknesses of some data sources (Peden et al., 2023). For the remaining three cases (in Ghent, Namur and Strasbourg), only wanted notices and media reports were available. Further insights into the collected data are provided below, while descriptive statistics for each variable can be found in Supplements S1 and S2.

2.1 Body behaviour after drowning

A first variable in the dataset indicates whether the victim's body sank or remained at the surface after drowning. Cases were registered in the latter category when the body was found at the surface and showed no signs of decomposition. Otherwise, it was assumed that the body had sunk and resurfaced. The degree of decomposition was systematically recorded in the forensic medicine reports for the cases in Liège and Antwerp, and this information was often corroborated by the media reports. In most cases of drowning where the body did not sink, forensic medicine reports indicate that witnesses have kept the body in view from the moment it entered the water until it was recovered. This provides strong evidence that the body did not sink in these cases. For the three cases outside of Liège and Antwerp, information from media reports was used. Overall, the victim's body sank in approximately 70% of the considered cases, with no significant difference in this rate between the cases recorded in the Liège and Antwerp regions (Figure S1 in Supplement S1).

For the cases involving sinking and resurfacing of the victim's body, the submersion interval was estimated as the time elapsed between the victim's reported disappearance and the body recovery. In all cases in Antwerp and in most cases in Liège, the date and time of drowning and of body recovery were recorded in the forensic medicine reports. In some cases in Liège region, drowning date and time were derived from media or wanted notices information. For the three cases outside of Liège and Antwerp, media reports and wanted notices were used. The median submersion interval for bodies which sank is 5.5 days (Table 2). The 25th and 75th percentiles correspond respectively to 2.9 and 22 days. One outlier case shows a submersion interval of 111 days, while in all other cases the submersion interval does not exceed 41 days (Figure S2 in Supplement S1). Differences remain limited between the samples from Liège and Antwerp regions.

2.2 Victims' characteristics

In the Liège region cases, the age and sex of the victims were obtained from the forensic medicine reports and confirmed by media reports and/or wanted notices. For the Antwerp region cases, only the forensic reports were used. For the cases in other regions, only media reports were consulted. The dataset contains 16 cases involving a female victim and 34 cases involving a male victim. In all cases, the victim was an adult, and female victims in our sample tend to be older than male victims (Table 2).

Information on body height is rarely included in forensic reports. Conversely, it is often given in wanted notices (Figure S5 in Supplement S2). When the body height could not be found in either of these two sources, it was considered unknown (23 out of the 50 cases). In one case, the height was estimated using a photograph of the body on an autopsy table of known dimensions. The median reported heights are 1.61 m for female victims and 1.79 m for male victims (Table 2).

Body mass index (BMI) was estimated using pictures (e.g., from wanted notices) or based on a qualitative description of the victim's body available in forensic reports (e.g., 'of slim build'), wanted notices or media reports (Figure S6 in Supplement S2). The estimated BMI was then combined with the height value (generally inferred from wanted notices) to provide an estimate of body mass. In only four cases, the victim's height and mass were reported in the wanted notices, enabling the direct computation of the BMI.

A typology inspired by Barwood et al. (2011) was used to define four categories of clothing worn by the victims: underwear or no clothing; summer clothing (shorts and a T-shirt); spring/autumn clothing (trousers, a T-shirt, a pullover, and possibly a waterproof or windproof jacket); and winter clothing (a T-shirt, a pullover, and a heavy, warm jacket, or additional layers of clothing). In cases where a forensic report was available, the type of clothing was determined based on the descriptions given in the report, which were generally confirmed by wanted notices and photographs. Otherwise, descriptions in wanted notices and media reports were used. As shown in Figure S7 in Supplement S2, spring/autumn clothing is the most frequently reported type of clothing in the dataset (60%), followed by summer clothing (18%), winter clothing (12%) and underwear or no clothing (10%). No accessories of significance, such as a backpack, were reported in the considered cases.

2.3 Drowning context

The water temperature is recorded in the database (Figure S8 in Supplement S2). In nine cases (eight of which from the Antwerp region), the recorded water temperature corresponds to that measured on site by the forensic doctor. In all other cases, this information was not included in the forensic medicine report. To overcome this lack of information, the average water temperature recorded at the nearest measurement station (retrieved mainly from waterinfo.be, rijkwaterstaat.nl or https://eautemp.com/current/france/water-temp-in-strasbourg-in-rhine) during the body submersion period was considered.

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The median reported values of water temperature is 12.2 °C, with the 25th and 75th percentiles corresponding respectively to 7.0 and 19.58 °C.

Finally, the dataset indicates whether the drowning was accidental or resulted from a suicidal act. This information is only available for 29 cases out of a total of 50. This information was inferred from the context of the drowning, as reported by eyewitnesses, or from forensic reports mentioning a suicide note or relatives mentioning suicidal intentions (as reported in the media or in official reports). In our dataset, suicidal acts (66% of the reported cases) are more frequent than accidental circumstances (33% of the reported cases), as shown in Figure S9 in Supplement.

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Feature	Data type	Distribution of values. Counts for data of types B and C; median and quartile for data of types I and R.	Forensic medicine report	Photographs	Wanted notices and/or media reports
Body buoyancy (1 = 'sank'; 0 = 'remained at the surface')	B	Floated (14), Sunk (36)	A and L		L and O
Body submersion interval (days), for sinking cases	R	5.5 (2.9 – 22)	A and L		L and O
Victim's sex (1 = 'female', 0 = 'male')	B	Female (16), Male (34)	A and L		L and O
Victim's age (years)	I	Female: 56.5 (46 - 64.5) Male: 46.5 (27 - 62)	A and L		L and O
Body height h_b (m)	R	Missing values (23) Female: 1.61 (1.60 - 1.67) Male: 1.79 (1.70 - 1.88)	A (seven cases)	A (one case: ID A-42)	L and O
Victim's BMI (kg/m²)	R	Female: 25 (23.5 - 26.5) Male: 24.2 (22.5 - 26)	A and L	A	L and O
Clothing type	C	Underwear/none (5), Summer (9), Spring/fall (30), Winter (6)	A and L	A	L and O
Water temperature (C°)	R	12.3 (7.0 – 19.8)	A and L		
Circumstances (0 = accident, 1 suicide)	B	Accident (10), Suicide (19), Unknown (21)	A and L		L and O

Table 2: Overview of data types, distribution of data and sources of information. The data types are classified as categorical (C), binary (B), integer (I), or real values (R). For numerical variables, data ranges are described by the median and, in brackets, the quartiles of the data distributions. The source for each variable is provided as a function of the location of the cases, either in the regions of Liège (L) or Antwerp (A), or in another region (O).

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3 Methods

The existence of correlations between the considered response variables (initial body buoyancy and body submersion interval) and each explanatory variable was evaluated using different methods depending on the type of involved variables (Table 3). As the initial body buoyancy is a binary variable and our dataset includes both categorical and numerical explanatory variables, two different approaches were used to analyse the potential relationships between these variables. For the numerical explanatory variables (age, body height, BMI and water temperature), a point-biserial correlation coefficient and its corresponding significance (p-value) were computed. The point-biserial correlation coefficient measures the extent to which the variation in a continuous variable is associated with the difference between the two groups defined by the binary response variable.
For binary (sex) and categorical (clothing type and drowning circumstances) explanatory variables, we applied a Pearson's chi-squared test to contingency tables, based on dichotomized data in the case of categorical variables (Pearson, 1896; Mickey et al., 2004). This test enables us to assess whether variables are independent or not by using a significance threshold (p-value).
For the second response variable (body submersion interval), we computed Pearson correlation coefficients for the numerical explanatory variables (age, body height, BMI and water temperature), and point biserial correlations for the binary (sex) and dichotomized categorical (clothing type and drowning circumstances) explanatory variables, together with their significance levels (Table 3).

Explanatory variables	Response variables	
	Initial body buoyancy (binary)	Body submersion interval (numerical)
Age, body height, BMI, water temperature (numerical)	Point biserial correlation	Pearson correlation coefficient
Sex (categorical, binary)	Pearson's chi-square test applied to contingency table	Point biserial correlation
Clothing, drowning circumstances (categorical, nominal)	Pearson's chi-square test applied to contingency table	Point biserial correlation

Table 3: Correlation coefficients utilized as a function of the tested variables type.

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4 Results

The main results are briefly summarized in this section and further discussed in Section 5. Table 4 shows the correlation coefficients and their significance (p-value) for pairs of explanatory and response variables, provided that at least one of them is numerical. For binary and categorical explanatory variables combined with the binary response variable 'Initial body buoyancy', Table 4 shows the p-value obtained from a Pearson's chi-squared test applied to the relevant contingency tables. The considered sample size (n) is specified for each case. The full dataset (n = 50) was used to analyse the response variable 'Initial body buoyancy', whereas a subsample involving only cases where the body sank (n = 36) were used for the response variable 'Body submersion interval'. Due to missing values in the explanatory variable 'Body height', the samples had to be further reduced for analysing the influence of this variable (n = 26-27, Table 4).

4.1 Initial body buoyancy

The results presented in Table 4 show that only two numerical explanatory variables are significantly correlated with the initial body buoyancy: the BMI (p-value = 0.03) and the victim's age (p-value = 0.003), with the latter correlation being even highly significant, as the corresponding p-value is way below 0.01. For the BMI, the Pearson correlation coefficient is negative (– 0.31), suggesting that, in the case of victims with a higher pre-mortem BMI, there is a lower chance that the body sinks shortly after entering the water. For the victim's age, the highly significant Pearson correlation coefficient is – 0.41, which is even stronger than the correlation with BMI. It indicates that the older the victim, the higher the chance that the body remains at the surface.

4.2 Body submersion interval

When a standard threshold of 5 % ($p \leq 0.05$) is considered to assess the significance of correlations, no numerical explanatory variable shows a statistically significant correlation with the body submersion interval (Table 4). At a slightly higher threshold ($p \approx 0.1$), the water temperature appears correlated with the body submersion interval. The Pearson correlation coefficient is negative, indicating that body submersion intervals tend to be longer when the water is colder.

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	Initial body buoyancy (float = 0; sink = 1)			Body submersion interval (days)		
	Correlation co-efficients	*p*-values	*n*	Correlation coefficients	*p*-values	*n*
Sex (male = 0; female = 1)		0.73	50	– 0.015	0.93	36
Age	**– 0.41**	**0.003**	50	0.03	0.87	36
Body height	0.03	0.88	27	– 0.08	0.69	26
BMI	**– 0.31**	**0.03**	50	– 0.015	0.93	36
Clothing type						
- Underwear/none		0.14	50	– 0.11	0.53	36
- Summer		0.69	50	– 0.096	0.58	36
- Spring/fall		0.70	50	0.15	0.38	36
- Winter		0.76	50	– 0.003	0.99	36
Water temperature (T_w)	– 0.19	0.18	50	– 0.27	0.11	36
Suicide		0.51	29	– 0.18	0.44	21

Table 4: Correlation coefficients and corresponding significance (*p*-value) for pairs of variables involving at least one numerical variable. Significance of chi-square test on contingency table for pairs of variables involving binary or dichotomized categorical variables. The sample size (*n*) depends on the considered response variable and missing values for body height.

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5 Discussion

5.1 Initial buoyancy estimation

Statistical analysis reveals that age is a key parameter to evaluate the initial body buoyancy and that elderlies have a higher probability to float. This outcome is statistically highly significant (p-value = 0.003).
This result can also be emphasized through contingency tables, as shown in Figure 1. Contingency tables are based on a dichotomized version of the age variable. We systematically tested multiple thresholds to dichotomize age and examined the p-value obtained from a Pearson Chi-square test applied to the corresponding contingency tables (Figure S16 in Supplement S4). The lowest p-value (i.e., highest significance) was obtained for an age threshold of 65 years (p-value lower than 0.001). According to the dataset, drowning victims older than 65 years have 70 % chance of initially floating, whilst below this age, the chance of floating drops below 20 % (Figure 1a). If an age threshold of 45 years is considered, the chance that the victim's body younger than 45 years initially floats is as low as 5 % (Figure 1a, p-value = 0.002).

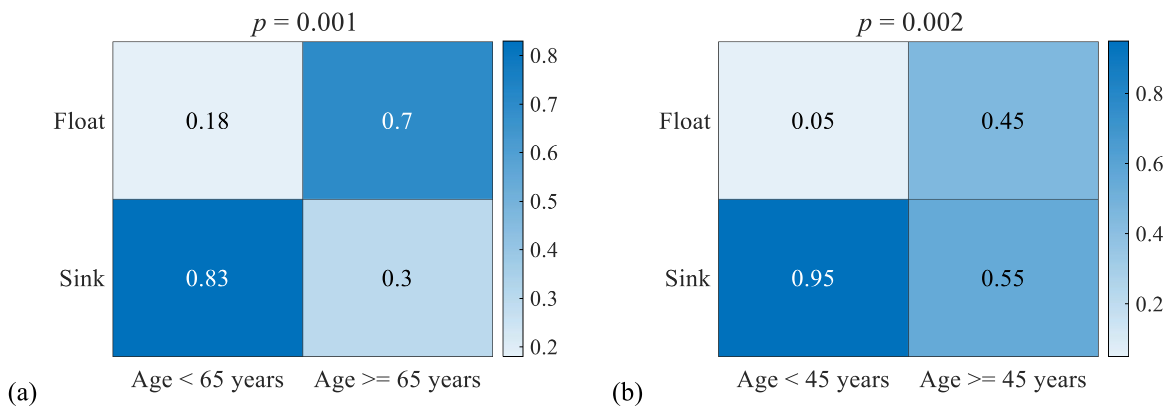

Figure 1: Contingency tables representing the relationship between initial body buoyancy and the victim's age. The age was dichotomized considering (a) 65 years and (b) 45 years as thresholds. The entries in the tables are the percentage of bodies associated to each category in the respective columns.

The overwhelming influence of age on the initial buoyancy of a drowned victim was also highlighted in a recent study by Dennison-Wilkins et al. (2023). These authors did not find a link between more advanced age and body mass. Therefore, they attributed the influence of advanced age on the initial body floatability to body characteristics typical of older persons, such as reduced bone density and reduced muscle mass. They also hypothesized an influence of other features such as clothing type and footwear typically worn by older people. Conversely, in the present dataset, a highly significant positive correlation between age and BMI was found (p-value below 0.005), as can be seen in Figure 2 and Figures S10 and S11 in Supplement S3. This is also consistent with the statistically significant direct correlation found between initial body buoyancy and BMI (Table

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4). From a physical perspective, these relationships between higher age, higher BMI, and more positive body buoyancy relate to the known tendency of people of more advanced age to generally have more body fat, so that they have a more buoyant body given the lower density of fat compared to that of water (Siri, 1956a, 1956b; Visser et al., 1997; Wang et al., 1998; Ward and Lieber, 2005; Moon et al., 2013; Nickerson et al., 2018).

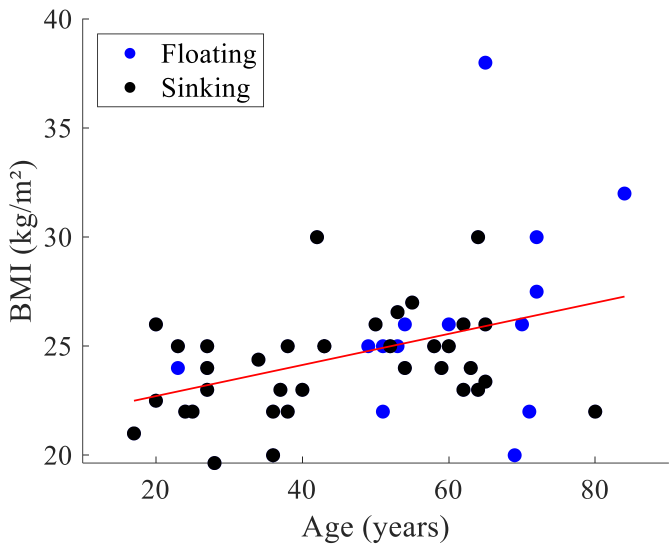

Figure 2: Relationship between age and BMI (Pearson correlation coefficient = 0.39; *p*-value = 0.005).

Dennison-Wilkins et al. (2023) proposed a mathematical model to estimate the probability of a drowning victim to remain floating at the surface as a function of the victim's age and the drowning circumstances, i.e., accident or suicide (Figure 3). This model relies on 74 observations, but the authors did not report how the model was set up nor its statistical significance. Based on the present dataset, a similar model was calibrated using a binomial logistic regression to predict the probability of the body to float as a function of its age. The present dataset did not allow to calibrate statistically significant separate models for the subsets of data corresponding respectively to accidents and to suicides, due to a too low sample size (e.g., $n = 10$ for accidents). As shown in Figure 3, a remarkable agreement is found between the model calibrated on the present dataset (p-value = 0.008 for the variable age) and the model independently developed by Dennison-Wilkins et al. (2023) for the case of accidents. Even if we do not capture the influence of the drowning circumstances (accident vs. suicide), the consistency between our results and those of Dennison-Wilkins et al. (2023) appear promising in light of the relatively small sample sizes on both sides and the exploratory nature of such studies. Building consistent transnational database of drowning, containing relevant information to inform modelling (such as the body initial buoyancy), would certainly enable reaching more robust outcomes.

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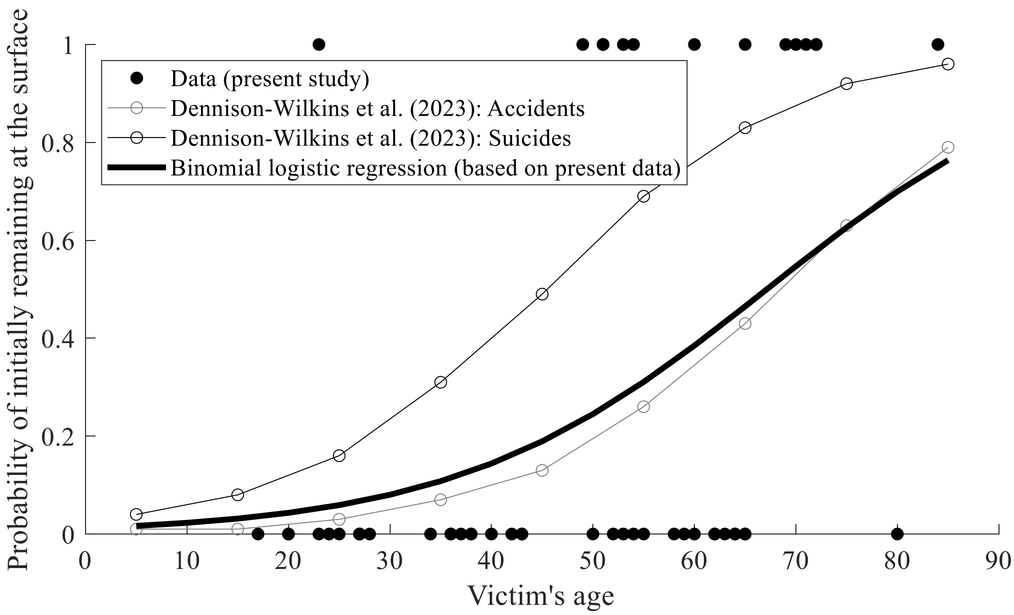

Figure 3: Probability for the drowned body to remain floating at the surface as a function of the victim's age.

Although no statistically significant correlation could be highlighted between the circumstances of drowning (accidental vs. suicidal) and initial body buoyancy, Figures S10 and S11 in Supplement S4 reveal highly significant correlations between suicidal drowning and the victim's age and sex. A statistically significant correlation was also found with the victim's BMI. Overall, this suggests that older female victims with a higher BMI are significantly more likely to drown as a result of a suicidal act than an accident. This constitutes a well-defined profile of victims of suicidal acts leading to drowning and should be considered particularly relevant when targeting prevention policies.

Another variable for which a moderate p-value is obtained in the correlation analysis is the water temperature (p-value = 0.18, see Figure S11 in Supplement S3). In a strict sense, this does not reveal a statistically significant correlation between the numerical variable 'water temperature' and the initial body buoyancy, but nonetheless it hints at a possible relationship between the two. To investigate this further, we dichotomized the variable 'water temperature' and resorted to contingency tables. Similarly to the procedure applied for the victim's age (see Figure S16 in Supplement S4), different thresholds were systematically tested for dichotomizing the variable 'water temperature'. A threshold of 7 °C was found to lead to the most significant classification (p-value = 0.009) between cases where the body sank or remained at the surface (Figure 4).

This result suggests that in colder water, victim's bodies have less chance of remaining floating at the surface. This trend was not reported in literature earlier. Numerous studies have examined the body's metabolic response to a cold-shock (Hayward et al., 1984; Tipton et al., 1991; Golden et al., 1997; Shattock and Tipton, 2012; Farstad and Dunn, 2019). This mechanism, as well as the hypothermia (Cooper and Ross, 1960; Tipton and Golden, 1998), could have an influence on the quantity of water

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swallowed or inhaled (Modell et al., 1976; Conn et al., 1995), and hence on the body buoyancy. This aspect deserves further analyses in future studies.

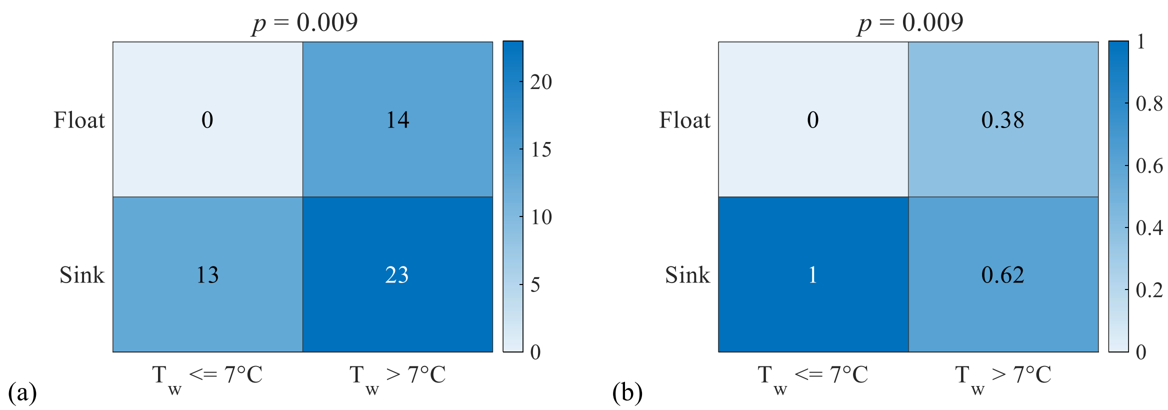

Figure 4: Contingency tables representing the relationship between initial body buoyancy and the water temperature (T_w). The entries in the tables are expressed either as counts (a), or as a percentage of the sum of the counts in the respective columns (b).

5.2 Body submersion interval

A negative correlation was found between the water temperature and the body submersion interval, which is physically sound: the lower the water temperature, the longer it takes for the body to bloat and resurface (Heaton et al., 2010; Madea and Doberentz, 2010; Mateus and Vieira, 2014; Reijnen et al., 2018; Dalal et al., 2023). Putrefaction processes are indeed slowed down at lower water temperatures, leading to a greater body submersion interval. This observation closely aligns with previous studies using the concept of ADD to predict the time elapsed until body resurfacing (Megyesi et al., 2005; Heaton et al., 2010; Mateus et al., 2013; Daalen et al., 2017; Delhez et al., 2023).

Figure 5 shows the reported body submersion interval as a function of the water temperature, which is the only explanatory variable significantly correlated with the body submersion interval. The markers are coloured according to the corresponding ADD value at the time of body recovery. Figure S18 in Supplement S5 shows that three entries correspond to outliers in terms of ADD (above 500 °C·days, whereas the 75th percentile of the ADD distribution is 22.3 °C·days), with one of these also being an outlier in terms of submersion interval (111 days). Figure 5 highlights that longer body submersion intervals are associated with lower water temperature and higher ADD values.

Past studies have related specific values of ADD to different stages of body decomposition, which in turn influence body resurfacing and the body submersion interval (e.g., Dalal et al., 2023; Heaton et al., 2010; Mateus and Vieira, 2014 and Reijnen et al., 2018). Therefore, here, we fitted a regression corresponding to a constant value of ADD, i.e., a constant value of the product of the body submersion interval, BSI, by the water temperature, T_w:

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$$T_w \; BSI = \alpha \; , \tag{2}$$

with α representing the ADD value at body resurfacing (Figure 5). The regression yields a value of 97 °C days for α, with a 95% confidence interval of [46, 147] °C days. Despite a relatively large confidence interval due to scatter in the observational data, the regression is found statistically significant (p-value = 0.0004). While this regression, solely based on water temperature, provides a first estimate of the value of ADD when the body resurfaces, it fails to capture all the variability of the body submersion interval. Some of the variability in the body submersion interval cannot be explained by water temperature alone. Due to the complexity of the processes underlying human body decomposition in environments such as urban rivers, other parameters influence the BSI. These include random factors, such as trapped air bubbles in clothing or the body becoming temporarily entangled at the bottom of the river, but such aspects remain impossible to predict in a deterministic way.

The resurfacing ADD values found here generally align with the 95-117°C days range reported by Mateus et al. (2013), who only used two drowning cases. Similarly, the distribution of body submersion intervals in our dataset is relatively close to that obtained by Dennison-Wilkins et al. (2023), as shown in Figure 6. Given that these two studies were conducted independently, the similarity in the reported distributions lends credibility to the respective datasets. It also highlights the need to assemble larger, transnational datasets to support more robust findings. This entails overcoming challenges related to the sharing of sensitive datasets.

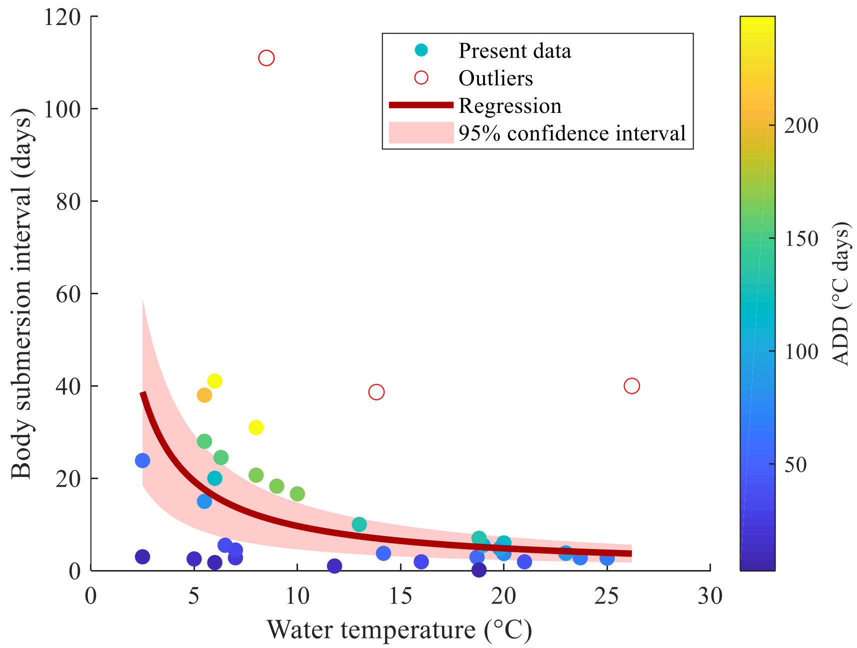

Figure 5: Body submersion interval (BSI) as a function of water temperature (T_w). The data markers are coloured as a function of the accumulated degree days (ADD) when the body resurfaced.

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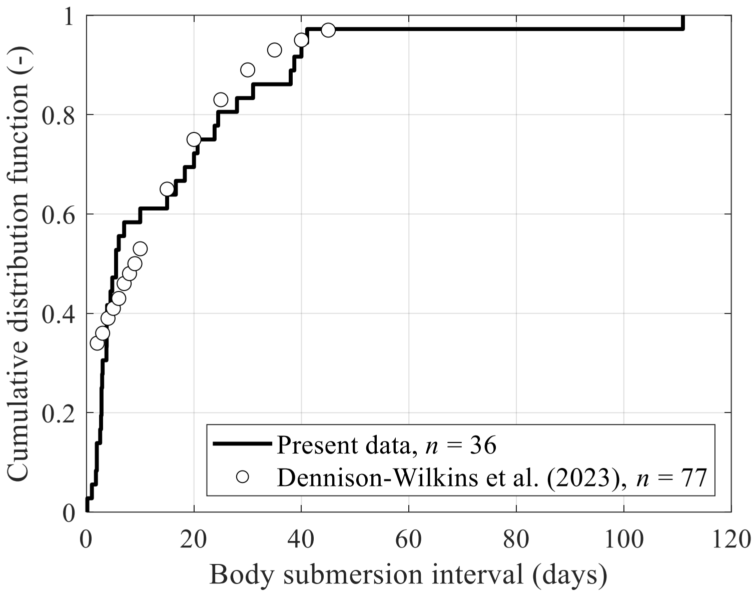

Figure 6: Cumulative distribution function of the body submersion interval in the present dataset compared to the distribution reported by Dennison-Wilkins et al. (2023).

5.3 Limitations

The dataset collected for the purpose of this study reflects the inherent challenges of retrospective forensic analysis. While certain variables, such as season, age, and sex are recorded relatively reliably, many others are subject to imprecise estimation. For instance, victim height is usually only documented if an autopsy has been performed or if data are provided by close relatives. In the absence of either of these, this information remains unknown. Similarly, body mass cannot be accurately measured post-mortem due to the physical changes that occur during immersion and decomposition. Consequently, it must be estimated visually from photographic evidence. In cases where no photographs or witness reports were available, this variable was excluded. To limit inter-observer variability, all BMI estimations were performed by the same researcher.

Classifying clothing also presents complexities. Due to the wide variety of clothing types, materials, cuts, and accessories, creating a fully detailed classification system would be impractical. For the purposes of this study, clothing types were categorised into four broad groups. However, this simplification could mask meaningful differences. For example, a woollen jumper and a leather jacket may have markedly different buoyant properties, yet they are both classified in the same category.

In some cases, a less stringent threshold than $p = 0.05$ was used when examining the results of the correlation analysis (e.g., for the correlation between water temperature and body submersion interval). This is deemed acceptable in exploratory studies

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with relatively small sample sizes like here ($n = 50$), as it helps to avoid overlooking potentially interesting relationships that warrant further investigation. Hopefully, larger datasets will reveal more significant correlations in the future.

It is anticipated that expanding the dataset in terms of both size and the reliability of recorded variables will enhance the robustness and predictive capacity of the statistical analyses (e.g., Hills et al., 2021). Increased diversity among registered cases would further improve the generalisability of the findings and enable more rigorous testing of correlations. So far, existing large international databases seem to focus primarily on medical aspects and prevention policies (see Table 1), rather than reporting on the variables of interest for guiding computer simulations of drowning victims' body drift.

6 Conclusion

Computer simulations of the drift of a drowning victim's body appear to be a promising technology to improve the success rate of search operations in rivers. This study is one of the few to use a database of real-world fatal drowning cases ($n = 50$) to predict two important variables for simulating the drift of a drowning victim in urban rivers, namely the initial body buoyancy and the body submersion interval.

The results show a highly significant correlation between the victim's age and the initial body buoyancy ($p < 0.003$), meaning that the body of an older victim is more likely to remain at the surface than that of a younger victim. For victims aged over 65 years, the probability of their body remaining afloat is almost four times higher than for younger victims ($p = 0.001$). This may be attributed to body characteristics typical for older people, such as lower bone density and higher body fat content. The latter aligns with the statistically significant correlation found between the victim's pre-mortem body mass index (BMI) and the body buoyancy ($p \sim 0.03$), given that fat is less dense than water. In addition to the importance of age and BMI in estimating body buoyancy, there appears to be a temperature threshold (~ 7 °C) below which no instances of body floating have been documented, suggesting that temperature could be a limiting environmental factor in body floatability.

Statistical analyses also suggest a strong association between a prolonged body submersion interval and lower water temperatures, due to putrefaction processes slowing down at lower temperatures. The regression analysis estimates a resurfacing ADD value of 97 °C days ($p < 0.001$), which largely aligns with the findings of a previous study. While this value does not fully account for the variability of body submersion intervals due to the complex and partly unpredictable nature of decomposition processes and urban river environments, it is highly valuable for improving simulations of body drift. These findings highlight the need for larger, transnational datasets to enhance the robustness and generalizability of such estimates.

Finally, significant correlations were found between suicidal drowning and certain characteristics of the victim, such as being older and female, and having a higher BMI. These findings suggest a distinct victim profile related to suicidal drowning. This should be considered in prevention efforts.

Data availability

The datasets generated and/or analysed during the current study are not publicly available due to ethics reasons.

Author contributions

CD: Conceptualization, Methodology, Investigation, Data curation, Software, Formal analysis, Visualization, Writing - original draft, PhB, WJ: Conceptualization, Investigation, Resources, SE: Funding acquisition, Writing – review and editing, MP: Funding acquisition, PA: Data curation, Software, Funding acquisition, BD: Conceptualization, Methodology, Software, Formal analysis, Visualization, Writing - original draft, Writing - review and editing, Supervision, Funding acquisition, Project administration.

Competing interests

The authors declare that they have no conflict of interest.

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