



The suitability of visual decomposition scoring systems for estimating post-mortem submersion interval: a human skin tone and weather perspective

Ibukunoluwa Olowe^{a,*}, Laura J. Heathfield^b, Lisa Malan^b, Calvin Mole^b, Victoria Gibbon^d, Wilma Duijst^c, Anna Williams^a

^a School of Law and Policing, University of Lancashire, Preston, PR1 2HE, UK

^b Division of Forensic Medicine and Toxicology, Department of Pathology, Faculty of Health Sciences, University of Cape Town, Cape Town, South Africa

^c University of Maastricht, Maastricht, The Netherlands

^d Division of Clinical Anatomy and Biological Anthropology, Department of Human Biology, Faculty of Health Sciences, University of Cape Town, Cape Town, South Africa

ARTICLE INFO

Keywords:

Skin-tone
Post-mortem interval
Skin pigmentation
Scoring
Decomposition scoring system
Drowning
Aquatic mortality
Medico-legal death investigations
Forensic taphonomy

ABSTRACT

The estimation of Post-Mortem Interval (PMI) remains a global challenge, but the estimation of Post-Mortem Submersion Interval (PMSI) in cases of drowning or those submerged from aquatic ecosystems is still particularly difficult. Decomposition Scoring Systems (DSS) are currently used to estimate PMSI for drowning cases. The most used DSS methods include the Heaton et al. (2010), van Daalen et al. (2017) and Reh (1967), which have been developed in temperate climates with predominantly lighter skin-toned populations. This posed the question, 'Are these DSS useful for drowning cases involving individuals with darker skin tone?' We aimed to validate whether current DSS are applicable to forensic cases involving individuals with darker skin tones who were recovered from water. Accurate estimates of the PMSI were assessed using the Heaton, van Daalen and Reh DSS to measure decomposition visible in photographs of 73 cases of bodies recovered from water compared with the stated PMSI in their case notes from the Netherlands, United Kingdom, and South Africa. The results showed that discolouration changes in skin can be misleading when using the current DSS for individuals with darker skin tone, and these DSS are erroneous for estimating the PMSI of individuals with darker or lighter skin tones in an advanced decomposition stage or those recovered in cold months. Therefore, current DSS are only applicable to cases with comparable climates and aquatic environments, but also to individuals with lighter skin tones. To improve the PMSI estimation, recommendations are provided to apply the current DSS to individuals with darker skin tones. Additionally, global studies are required to improve the suitability of current DSS to assess decomposition and estimate PMSI for individuals with darker skin tones.

1. Introduction

Accurately estimating the postmortem interval (PMI) is important for medico-legal death investigations as it is often fundamental to determining the sequence of events leading to the death of the individual and can aid in the determination of the nature of the death [1,2]. Decomposition scoring methods in the early postmortem interval rely on assessing changes in skin texture and colour [2,3]. In aquatic environments, when bodies have been partially or fully submerged in water, there are additional challenges of the effect of water saturation on the body [2,3]. Estimating time since death in these environments is based

on estimation of the postmortem submersion interval (PMSI), or how long the body has been submerged [1,2]. There are a few usable methods, the most used of which are visual decomposition scoring systems, which include the Heaton et al. [4], van Daalen et al. [5] and Reh [6]. These were created in Europe and North America, regions with temperate climates and predominantly lighter skin toned populations. While these methods rely on skin colour changes, there is no mention of the ancestral affiliation, amount of skin pigmentation, or baseline skin tone of the individuals used [4–6]. The tone of human skin is correlated with the type, size and quantity of melanocytes eumelanin (black and brown pigment) and pheomelanin (yellow and red pigment) cells

* Corresponding author at: Present address: 56 Topper Street, Cambridge CB4 2WL, UK.

E-mail address: Ibukunolowe@gmail.com (I. Olowe).

<https://doi.org/10.1016/j.scijus.2026.101531>

Received 28 April 2026; Received in revised form 24 September 2026; Accepted 12 October 2026

Available online 14 October 2026

1355-0306/© 2026 The Authors. Published by Elsevier B.V. on behalf of The Chartered Society of Forensic Sciences. This is an open access article under the CC BY-NC license (<http://creativecommons.org/licenses/by-nc/4.0/>).

located in the basal layer of the epidermis and occurs on a continuous spectrum of human variation [7–9]. The diversity of human skin tone has been underrepresented in the investigative methods and techniques for many scientific fields, including the forensic sciences [10–12]. In this study we have not measured skin pigment, thus, use the word “skin tone” to refer to and represent the continuous spectrum of human variation from lighter tones to darker tones. During decomposition, the skin tone can appear lighter or darker due to the absence of blood beneath the skin surface; this could lead to difficulty in assessing the discolouration changes described in these DSS, and mistaking the original skin colour could lead to incorrect assumptions being made about the ancestral affiliation of the unknown individual, potentially delaying identification [13,14]. Gelderman et al. [15] argue that it is challenging to identify the presence of liver mortis in bodies with darker skin tones. Our research question was ‘Are the current DSS methods accurate for estimating PMSI in cases of decedents with darker skin tones from aquatic environments in regions such as Africa, South Asia, the Caribbean, with tropical climates?’ We aimed to investigate the ease of scoring and observing the descriptive changes listed in the DSS for the various body regions and stages of decomposition, and validate whether the Heaton et al. [4], van Daalen et al. [5] and Reh [6] DSS can achieve accurate PMSI estimates for drowning cases involving individuals with different skin tones.

2. Materials and methods

2.1. Collation of images and case notes

Hard copies and electronic copies of images, closed case files, autopsy files, and case notes of a total of 143 drowning cases concerning bodies recovered from 2014 to 2022 were initially obtained from databases in the UK, Netherlands, and South Africa. The Netherlands database used was the Maastricht University/Netherlands Forensic Institute “Water Decomposition Atlas” (Duijst, 2023). The cases from South Africa were obtained through a memorandum of understanding and research collaboration agreement with the University of Cape Town Division of Forensic Medicine and Toxicology; case note data was retrieved from the “Office Autopsies database” (Ethics reference- HREC: R036/2014), while the pictures for each case were retrieved from electronic records stored on “Livelihood (Open Text, Canada)”. Approval for the inclusion of these cases in this study was granted by the Director of the Forensic Pathology Services in the Western Cape, South Africa, as well as the Directorate of Health Intelligence, Department of Health, Western Cape Government. Ethical approval was obtained from the University of Cape Town, Faculty of Health Sciences, Human Research Ethics Committee (HREC: 416/2022).

For the cases from the United Kingdom, permission was granted by HM Coroner for Blackpool and Fylde to assess the extent of decomposition visible in drowning cases. After searching, 32 cases (from 2015 to 2021) were selected from the Water Decomposition Atlas, while 89 cases (from 2017 to 2021) were retrieved from the Office Autopsies database and 22 cases (from 2014 to 2022) from the Blackpool and Fylde Coroner’s service.

2.2. Exclusion criteria

Cases were excluded when:

- The decedent was a child (below 18 years).
- The decedent was skeletonised with no trace of skin attached to the body.
- The body was dismembered with missing limbs, head, or trunk.
- No images of the deceased were available, and descriptions of the physical conditions or descriptions of decomposition changes of the remains were missing.

- No images of one or more of the following: head, neck, limbs, and trunk were available
- No estimated PMSI for the decedent was available, or there was uncertainty regarding the time of death, the date and time of the body’s entry and exit from the water.
- The decedent had received medical intervention, such as resuscitation; or the decedent was still alive after the body was retrieved from the water, or the decedent died in the hospital (or ambulance) or at the scene but not in the water.
- The forensic case was still active and under investigation, or the decedent remained unidentified.

Table 1 details the number of cases selected from each source after exclusion. Ethical approval was granted by the University of Central Lancashire Research Ethics Committee (SCIENCE 0172).

2.3. Demographic data

The following variables were collected from each case file: age and sex of the decedent, the date, location and type of water environment (e. g. river, ocean, swimming pool, etc.) the decedent was recovered from, as well as the estimated PMSI. If the following additional variables were available, they were also collected: weight and height of the decedent, body temperature at recovery, type of clothing or objects covering the body, whether the body was found submerged or floating, water current and pH of water, and cause of death.

Anonymous demographic data were collected from the information provided with the case notes, including the age and biological sex of the individuals. Biological sex was recorded as either male or female. The age of the decedent was categorised in the following categories: 18–29 years old, 30–39 years old, 40–49 years old, 50–59 years old, and over 60 years old, or unknown if the case notes did not specify or estimate the age of the individual. In this study, the ages were categorised into 10-year bands for clarity, consistency, and statistical usefulness. These categories often correlate with major life stages such as early adulthood and midlife, and these can help summarise trends of drowning across these life stages.

As the ethnicities or ancestral affiliations of most of the cases were not recorded in the case files, the authors decided to stratify the cases based on the Massey-Martin skin tone guide [16]. The skin tone of the least decomposed parts of the torso, hand and face of the bodies was examined to give an estimated original skin tone score. However, it is important to note that these are post-mortem scores and may not represent the antemortem skin tone of the individual. Cases with a skin tone score between 1 and 3 were categorised as “lighter”, while those with a score between 4 and 10 were categorised as “darker”.

In addition, a categorisation of the water type where the body was found was applied. This information was obtained from the case notes; the type of water body from which each body had been retrieved was stated in these case notes. Water types were categorised as natural or artificial. Natural water types included: sea, river, canal, lake or brook, and artificial water courses included: dam, bath, ditch.

Table 1
Breakdown of cases that met the study criteria.

Country	Database	No. of Cases	Year Period
Netherlands	Water Decomposition Atlas	20	2015–2021
South Africa	Office Autopsies database/ Livelihood	44	2017–2021
United Kingdom	Blackpool and Fylde Coroner’s Service	9	2017–2022

2.4. Temperature data

The retrospective daily ambient temperatures of the location of each case were obtained from online sources such as the Global Historical Weather and Climate and Weather Underground websites [17,18]. The geographical location and date of the body retrieval were used to obtain the average daily temperatures using these websites.

2.5. Measuring decomposition

The extent of decomposition of the bodies in the photographs, along with the description of the physical conditions or decomposition changes of the remains in the case notes, was visually assessed using the Heaton, van Daalen and Reh DSS [4–6]. The Heaton DSS was derived from a study on human remains recovered from freshwater in the United Kingdom, while the van Daalen DSS was derived from the North Sea borders in the Netherlands [4,5]. Both methods assess the extent of decomposition through scoring changes observed in the face, head, neck, trunk, and limbs of a body; the sum of the decomposition scores of the body parts assessed is referred to as the Total Aquatic Decomposition Score (TADS). Full descriptions associated with each score can be found in [4,5].

The Reh DSS was derived from a study on human remains recovered from the Rhine and Rhine harbour, running waters, lakes, and pools in Germany [6]. The Reh DSS also considers physical signs of decomposition on a body, but does not consider decomposition scores or Accumulated Degree Days (ADD). Instead, Reh created a table for PMSI estimation by considering the month the body was discovered, the actual water temperature and the external or internal physical changes in the bodies immersed in water [6].

2.6. PMSI estimations

2.6.1. Heaton DSS

The TADS calculated when using the Heaton DSS were substituted into the regression formula developed by Heaton et al. [4] to extrapolate an ADD value:

$$\text{TADS} = -3.706 + 7.778 \log_{10}\text{ADD}.$$

To estimate the PMSI, the average daily ambient temperature values obtained from the weather forecast websites were added retrospectively and cumulatively from the day the body was discovered until the ADD value was reached.

2.6.2. van Daalen DSS

The van Daalen et al. [5] method predicts the PMSI directly from the TADS using a prediction model; however, the study did not provide the prediction formula or equation. Hence, a conversion factor was needed to convert the van Daalen scores to the 25-point scale used for the Heaton scores (Heaton maximum score = 25, van Daalen maximum score = 18). To do this conversion, each van Daalen score was divided by 0.72 (which is 18/25). For example, a van Daalen score of 18 was divided by 0.72 to give 25, and a van Daalen score of 10 was divided by 0.72 to give 13.9 [or $(10/18) \times 25$]. These converted values were then substituted into the Heaton regression formula to extrapolate an ADD for each case. The PMSI of each case was estimated by cumulatively adding the average daily ambient temperature values retrospectively from the day the body was discovered until the ADD value was reached.

2.6.3. Reh DSS

Unlike the Heaton and van Daalen DSS, the estimated PMSI of a body using the Reh DSS is not extrapolated from an equation. In the Reh [6] table, decomposition changes were correlated with a minimum time in which this sign can develop. The immersion time taken for the last decomposition feature to be visible is considered the minimum PMSI, while the maximum PMSI was estimated by considering the putrefaction changes that have not yet occurred in the body.

2.6.4. Statistical analyses

Intraclass correlation coefficients (ICC) for the PMSI stated in the case notes compared to the estimated PMSI from the three DSS were calculated to assess the level of agreement between methods. ICC was calculated using a two-way mixed-effect model with absolute agreement for single measurements [19]. ICC scores below 0.25 were classed as “exceptionally poor agreement”, while those between 0.25 and 0.49 were tagged as “poor agreement”. “Moderate agreement” was classed as 0.50–0.74, and “good agreement” was tagged as 0.75–0.99 [19]. This ICC was also used to determine the agreement of the three DSS methods in comparison to PMSI reported in the case notes. Good agreement scores (0.75–0.99) were denoted as accurate estimations, moderate agreement (0.50–0.74) was classed as relatively accurate estimates, while the poor and exceptionally poor agreement scores (0–0.49) were deemed as inaccurate estimates.

To assess systematic differences between the stated and estimated PMSIs a linear mixed-effects model (LMM) was fitted. Model residuals were examined using untransformed and natural log transformation PMSI. Residuals associated with the natural log transformation of PMSI more closely approximated a normal distribution and were therefore chosen as the primary outcome. Graphical examination of residuals following the final model showed no substantial deviation from normality.

The LMM included natural log-transformed PMSI (logPMSI) as the dependent variable and the fixed effects of DSS method, skin tone (darker/lighter pigmentation), season (hot/cold), decomposition stage (fresh/advanced) and geographic location, along with the two-way interactions of DSS method with each of these factors. A random intercept for individuals was added to account for the correlation of repeated measures within individuals. Simple main effects were assessed using the estimated marginal means with post-hoc Bonferroni correction applied for multiple comparisons. Estimated marginal means and Bonferroni-adjusted 95% confidence intervals were back-transformed from the log scale and are presented as PMSI ratios for ease of interpretability.

Effect sizes for the effects included in the model were calculated using Cohen's f^2 , following the approach described by Selya et al. [20]. For each effect of interest, f^2 was calculated from the change in the proportion of variance explained by comparing the full model containing the effect with a reduced model in which the effect was omitted, thus quantifying the incremental contribution of each effect (and its associated interaction terms where applicable) to the variance explained by the model. The random-intercept variance was constrained when calculating the change in explained variance, such that the effect size reflected the contribution of the fixed effect rather than changes in the estimated random-effect variance. Effect sizes were interpreted using Cohen's guidelines [21], with $f^2 > 0.15$ indicating a moderate effect and $f^2 > 0.35$ indicating a large effect.

All statistical analyses were conducted using Stata Ver 13 (StataCorp, Tx, USA), with $p < 0.05$ considered statistically significant.

3. Results

3.1. Demographic profile of the sample population

The demographic profile of the 73 cases used for this study is listed in Table 2.

3.2. Water-type profile of the sample population

The water types from which the bodies were recovered are given in Table 3.

3.3. TADS

The results of the TADS for each case when using the Heaton and van

Table 2
Demographic Profile of the Sample Population.

Demographic data from case notes	Category	n (%)
Sex	Male	61 (84%)
	Female	12 (16%)
	Total	73
	18–29	18 (25%)
Age (years)	30–39	13 (18%)
	40–49	5 (7%)
	50–59	12 (16%)
	60 and above	21 (29%)
	Unrecorded	4 (5%)
	Total	73
Skin Tone (Massey-Martin scale)	Darker	35 (48%)
	Lighter	38 (52%)
	Total	73

Table 3
Water types from which the bodies were recovered.

Water type	Description	n (%)
Natural	Sea	32 (44%)
	River	6 (8%)
	Canal	15 (21%)
	Lake	2 (3%)
	Brook	1 (1%)
	Dam	6 (8%)
Artificial	Bath	5 (7%)
	Ditch	6 (8%)
Total		73

Daalen DSS are listed in Table 4. The TADS values indicate that the decomposition across the cases ranged from a fresh appearance to an advanced stage of decomposition, with most cases in the fresh stage. Some of the fresh cases in the study had no visible decomposition change, whilst some fresh cases exhibited signs of mild wrinkling of the flesh of the hands and feet, epidermis peeling off, and discolouration changes. The advanced decomposed cases were identified as cases with a minimum TADS of 12, meaning they were past the bloating stage of decomposition; they exhibited decomposition features such as skin slippage, bone exposure, liquefaction, degloving of the hands and feet, and advanced soft tissue and internal organ decomposition. Only 10 cases exhibited advanced decomposition in the sample – these have been

Table 4
TADS of the 73 cases; scores are /25.

Case	TADS		Case	TADS		Case	TADS		Case	TADS	
	Heaton	van Daalen		Heaton	van Daalen		Heaton	van Daalen		Heaton	van Daalen
1	4	5.6	19*	15	13.9	37	4	5.6	55	3	4.2
2	4	5.6	20	7	9.7	38	6	6.9	56	5	5.6
3	5	5.6	21	4	4.2	39	4	5.6	57	4	5.6
4*	14	12.5	22	9	9.7	40	3	4.2	58	3	4.2
5	6	8.3	23	6	8.3	41	6	6.9	59	4	4.2
6*	15	16.7	24	6	8.3	42	10	9.7	60	3	4.2
7	5	6.9	25	6	8.3	43	3	4.2	61	3	4.2
8*	16	12.5	26	6	8.3	44*	15	12.5	62	7	5.6
9	5	6.9	27	6	8.3	45	4	5.6	63	4	5.6
10*	17	13.9	28*	19	19.4	46	6	8.3	64	5	5.6
11	6	6.9	29	7	8.3	47	3	4.2	65	5	5.6
12*	16	12.5	30	4	5.6	48	6	9.7	66	6	8.3
13	11	11.1	31	4	5.6	49	3	4.2	67	3	4.2
14	6	6.9	32	3	4.2	50	4	5.6	68*	14	11.1
15	5	5.6	33	3	4.2	51	5	5.6	69	4	5.6
16	6	6.9	34	9	8.3	52	3	4.2	70	7	8.3
17	6	6.9	35	3	4.2	53*	13	9.7	71	3	4.2
18	5	6.9	36	4	5.6	54	5	5.6	72	4	5.6
									73	3	4.2

*: bodies in advanced stages of decomposition
van Daalen scores have been converted to match the Heaton scoring system (i.e. they have been divided by 0.72).

highlighted in Table 4. Most of the bodies retrieved in this study were in a fresh or pre-bloated stage.

3.4. PMSI estimates

The PMSI of each case was estimated using the Heaton, van Daalen and Reh DSS. Table 5 shows the post-mortem skin tone, the season the body was recovered, the PMSI recorded in the case notes, and the maximum PMSI estimates obtained using the Heaton, van Daalen and Reh DSS. There was no clear pattern in the accuracy of the three DSS in relation to location, months and season; there were overestimations and underestimations across the three DSS, the three countries and the different months, but these over- and under-estimations were more evident in cases with bigger stated PMSIs.

In 27 cases (40%), the PMSI estimated using the Heaton, van Daalen, or Reh methods matched the PMSI given in the case notes. In Table 5, a PMSI estimation with a + symbol indicates an overestimation by <3 days and a ++ symbol indicates an overestimation by >3 days. Similarly, a – symbol indicates an underestimation by <3 days and a – – symbol indicates an underestimation by >3 days. In total, the PMSI was overestimated in 41 cases (56%) and underestimated in 12 (18%) cases. Overestimations and underestimations were common with all three DSS across different months, with no obvious pattern. However, the PMSI in cases involving individuals with darker skin tones were more likely to be incorrectly estimated.

Intraclass correlation coefficients (ICC) (Table 6) indicated moderate agreement with case note PMSI overall, with the Reh DSS providing the greatest agreement in PMSI overall. The ICC also indicated greater agreement with the Heaton and van Daalen DSS in cases involving individuals with darker skin tones and in hot months. However, the Reh DSS had greater agreement in cold months than hot months. Similar ICC values were obtained for cases in the fresh and advanced stages of decomposition; the ICC for each DSS in advanced decomposition cases was not statistically significant, with extremely wide 95% confidence intervals.

Assessing cases from specific regions showed that the Heaton and van Daalen DSS had moderate agreement with cases in the Netherlands (ICC = 0.73, 0.61) and South Africa (ICC = 0.61, 0.76), but poor agreement with cases in the UK (ICC = 0.47, 0.43). The Reh DSS showed good agreement for cases in the Netherlands (ICC = 0.84) and the UK (ICC = 0.87); however, agreement was exceptionally poor for cases from

Table 5

PMSI from case notes compared to the estimated PMSIs using the three DSS. Cases 1–20: Netherlands; Cases 21–29: UK; Cases 30–73: South Africa.

Lighter Skin Toned Cases		PMSI (days)				Darker Skin Toned Cases		PMSI (Days)			
Case	Season	PMSI	Heaton	V Daalen	Reh	Case	Season	PMSI	Heaton	V Daalen	Reh
3	Hot months	1	1	1	2 ⁺	1	Hot months	1	1	1	1
5	Hot months	1	2 ⁺	3 ⁺	9 ⁺⁺	30	Hot months	1	1	1	1
6	Hot months	–	11	20	3	31	Hot months	1	1	1	1
7	Hot months	1	1	2 ⁺	3 ⁺	32	Hot months	1	1	1	1
8	Hot months	8	17 ⁺⁺	8	11 ⁺	33	Hot months	1	1	1	1
10	Hot months	18	24 ⁺⁺	11 ⁻⁻	10 ⁻⁻	34	Hot months	6	3 ⁻⁻	2 ⁻⁻	23 ⁺⁺
11	Hot months	1	1	1	2 ⁺	35	Hot months	1	1	1	1
12	Hot months	27	49 ⁺⁺	19 ⁻⁻	35 ⁺⁺	43	Hot months	1	1	1	1
16	Hot months	1	1	2 ⁺	2 ⁺	44	Hot months	8	17 ⁺⁺	8	14 ⁺⁺
19	Hot months	7	13 ⁺⁺	9 ⁺	3 ⁻⁻	49	Hot months	1	1	1	1
21	Hot months	1	1	1	2 ⁺	50	Hot months	1	1	1	1
22	Hot months	2	3 ⁺	4 ⁺	3 ⁺	52	Hot months	1	1	1	1
23	Hot months	1	2 ⁺	3 ⁺	1	53	Hot months	2	8 ⁺⁺	4 ⁺	4 ⁺
24	Hot months	1	2 ⁺	3 ⁺	1	56	Hot months	2	1 ⁻	1 ⁻	1 ⁻
26	Hot months	1	2 ⁺	3 ⁺	2 ⁺	57	Hot months	2	1 ⁻	1 ⁻	1 ⁻
29	Hot months	2	2	3 ⁺	2	58	Hot months	1	1	1	1
36	Hot months	1	1	1	1	59	Hot months	1	1	1	1
41	Hot months	2	2	2	3 ⁺	60	Hot months	1	1	1	1
42	Hot months	5	4 ⁻	4 ⁻	8 ⁺⁺	61	Hot months	1	1	1	1
45	Hot months	1	1	1	7 ⁺⁺	63	Hot months	1	1	1	1
46	Hot months	2	2	3 ⁺	10 ⁺⁺	67	Hot months	1	1	1	1
47	Hot months	1	1	1	1	68	Hot months	3	8 ⁺⁺	4 ⁺	35 ⁺⁺
48	Hot months	1	1	3 ⁺	10 ⁺⁺	69	Hot months	1	1	1	1
51	Hot months	1	1	1	1	71	Hot months	1	1	1	1
62	Hot months	1	1	1	1	13	Cold months	29	16 ⁻⁻	15 ⁻⁻	35 ⁺⁺
64	Hot months	1	1	1	1	15	Cold months	3	3	3	1 ⁻
65	Hot months	1	1	1	1	37	Cold months	1	1	2 ⁺	1
70	Hot months	1	2 ⁺	2 ⁺	25 ⁺⁺	38	Cold months	1	2 ⁺	3 ⁺	1
2	Cold months	1	5 ⁺⁺	7 ⁺⁺	1	39	Cold months	1	1	2 ⁺	2 ⁺
4	Cold months	7	14 ⁺⁺	8 ⁺	7	40	Cold months	1	1	1	1
9	Cold months	1	3 ⁺	5 ⁺⁺	17 ⁺⁺	54	Cold months	1	1	2 ⁺	1
14	Cold months	1	17 ⁺⁺	22 ⁺⁺	1	55	Cold months	1	1	1	1
17	Cold months	2	3 ⁺	4 ⁺	1 ⁻	66	Cold months	2	2	4 ⁺	2
18	Cold months	5	2 ⁻⁻	4 ⁻	1 ⁻⁻	72	Cold months	1	1	2 ⁺	1
20	Cold months	7	4 ⁻	9 ⁺	1 ⁻⁻	73	Cold months	1	1	1	1
25	Cold months	1	2 ⁺	3 ⁺	7 ⁺⁺						
27	Cold months	1	6 ⁺⁺	9 ⁺⁺	1						
28	Cold months	28	107 ⁺⁺	117 ⁺⁺	45 ⁺⁺						

Table 6

Intraclass correlation coefficients for each DSS compared to the observed PMSI.

DSS	Heaton		van Daalen		Reh	
	ICC	95% CI	ICC	95% CI	ICC	95% CI
Overall	0.56	0.38–0.70	0.47	0.27–0.63	0.66	0.50–0.78
Skin tone						
Darker	0.76	0.57–0.87	0.79	0.61–0.89	0.61	0.36–0.78
Lighter	0.53	0.26–0.73	0.44	0.15–0.66	0.69	0.46–0.83
Season						
Cold	0.46	0.06–0.74	0.41	0.01–0.71	0.85	0.67–0.94
Hot	0.82	0.69–0.89	0.89	0.82–0.93	0.49	0.25–0.68
Decomposition stage						
Fresh	0.62	0.45–0.75	0.49	0.28–0.66	0.56	0.36–0.71
Advanced	0.41	–0.15–0.81	0.36	–0.35–0.81	0.54	–0.05–0.87
Location						
Netherlands	0.73	0.43–0.89	0.61	0.22–0.83	0.84	0.64–0.94
UK	0.47	–0.18–0.84	0.43	–0.21–0.83	0.87	0.56–0.97
South Africa	0.64	0.43–0.79	0.76	0.60–0.86	0.19	–0.08–0.44

South Africa (ICC = 0.19).

Overall, the linear mixed-effects model was statistically significant ($p < 0.001$). Significant effects were observed for DSS method ($p < 0.001$; $f^2 = 0.41$), season ($p = 0.002$; $f^2 = 0.11$), and decomposition stage ($p < 0.001$; $f^2 = 0.18$). DSS method had a large effect on PMSI, although significant interactions indicated that the magnitude of the differences between DSS-derived PMSI and the PMSI recorded in the case notes varied in magnitude according to season ($p < 0.001$; $f^2 = 0.10$), skin tone ($p = 0.029$; $f^2 = 0.04$), decomposition stage

($p = 0.011$; $f^2 = 0.05$), and location ($p = 0.027$; $f^2 = 0.06$).

Following Bonferroni correction, in comparison to the case notes, The Heaton DSS (PMSI ratio: 1.85; 95% CI: 1.33–2.59; $p < 0.001$) and van Daalen DSS (PMSI ratio: 1.74; 95%CI: 1.25–2.42; $p < 0.001$) generated PMSI larger than the case notes. As expected, the PMSI was significantly longer for cases in cold seasons (PMSI ratio: 1.74; 95%CI: 1.18–2.06; $p = 0.002$) and cases with advanced decomposition (PMSI ratio: 6.6; 95%CI: 4.59–9.49; $p < 0.001$). Owing to the large effect of DSS method with smaller effects associated with the interactions, systematic

differences between DSS methods within levels of the interacting variable were assessed. Within individuals with darker skin tones, no significant systematic differences were observed between the PMSI stated in the case notes and the PMSI estimated from each of the DSS. However, in individuals with lighter skin tones, the Heaton (PMSI ratio: 2.09; 95% CI: 1.39–3.12; $p < 0.001$) and van Daalen (PMSI ratio: 2.14; 95% CI: 1.43–3.21; $p < 0.001$) scoring systems significantly overestimated the PMSI. For decomposition stage the Heaton DSS (PMSI ratio: 2.58; 95% CI: 1.38–4.83; $p < 0.001$) significantly overestimated cases in advanced stages of decomposition and the van Daalen DSS (PMSI ratio: 1.77; 95% CI: 1.31–2.38; $p < 0.001$) significantly overestimated cases in the fresh stage of decomposition.

Similarly, significant differences between DSS-derived PMSI and case-note PMSI varied according to geographic location. These were primarily associated with cases in South Africa and the UK. No significant difference in the estimated PMSI and the PMSI given in the case notes was observed between the DSS in the Netherlands. In cases from South Africa, significant differences were observed between the stated PMSI in the case notes and the PMSI calculated using the Heaton (PMSI ratio: 1.62; 95% CI: 1.01–2.64; $p = 0.045$) DSS. In UK cases, the Heaton (PMSI ratio: 2.45; 95% CI: 1.18–5.09; $p = 0.006$) and van Daalen DSS (PMSI ratio: 2.45; 95% CI: 1.18–5.09; $p = 0.006$) significantly overestimated the PMSI. Regarding season, the Heaton DSS significantly overestimated the PMSI in hot (PMSI ratio: 1.57; 95% CI: 1.06–2.32; $p = 0.014$) and cold (PMSI ratio: 2.19; 95% CI: 1.35–3.57; $p < 0.001$) seasons. The van Daalen DSS (PMSI ratio: 2.39; 95% CI: 1.46–3.90; $p < 0.001$) significantly overestimated the PMSI in cold seasons.

4. Discussion

4.1. Demographic profile

Seventy-three cases met the inclusion criteria, with 61 (84%) male individuals and 12 (16%) female individuals. Despite this small sample size, the sex distribution aligns with existing research that shows most victims of fatal drowning tend to be male [22–24]. It has been suggested that males are known to intentionally partake in more high-risk activities around water bodies compared to females; therefore, this could be the reason for a higher number of males represented in the sample used for this study [25,26].

It is estimated that for individuals less than 29 years of age, drowning is among the three major leading causes of unintentional death [27]. However, global variations exist in age-related mortality rates derived from medico-legal death investigations; some countries record the highest mortality rates in children, while some record the highest rates in younger adults [28]. Peden et al. [29] revealed that from 2005 to 2014, the percentage of drowning deaths in children aged 0–17 years in Australia, Canada, and New Zealand was 17.6%, 12.1%, and 17.0%, respectively. More recent Australian evidence further demonstrates changing patterns in drowning mortality across age groups. Miller et al. [30] analysed 5692 unintentional drowning deaths in Australia between 2002 and 2022 and reported a significant decline in drowning rates among children aged 0–4 years, whereas no statistically significant change was observed among older adults aged 65 years and over, highlighting the continued importance of older age groups in drowning prevention efforts. In the current study, variation in the number of deaths for each age category was also observed, with most cases occurring in the age range of 18–29 years [18 cases (25%)] and the greater than 60 years category [21 cases (29%)].

In the 73 cases used for this study, the skin tones of 38 cases (52%) were categorised as lighter, while 35 cases (48%) were categorised as darker. A Clemens et al. [31] study reviewed the drowning cases involving people below the age of 29 years in the United States from 1999 to 2019. Their study found that drowning was more prevalent among African Americans or darker skin-toned people (1.5 times more)

and Native American or Alaska Native ethnicities (2.0 times more) when compared to non-Hispanic lighter skin-toned persons. A 2022 study found that in the United States, there was a 23.73% increase in the occurrence of death by drowning in African American or darker skin-toned persons from 2019 to 2020 [27]. Africa accounts for the highest drowning mortality rate globally, while low- and middle-income countries (LMICs) contribute approximately 92% of the global burden of drowning [32–35]. More recently, the World Health Organization [35] reported that the African Region had the highest drowning death rate globally, at 5.6 deaths per 100,000 population, and that drowning mortality rates in LMICs were more than three times those in high-income countries. This is consistent with previous research identifying a disproportionate burden of drowning in LMICs and highlighting the challenges associated with limited drowning prevention measures, regulations and policies, swimming skills, education and awareness campaigns in these settings [34,36,37]. The persistence of these disparities, despite increasing international attention to drowning prevention [33], demonstrates the continuing need for effective prevention strategies in these regions. It is important to note that these LMICs, indigenous populations, and Africa are predominantly made up of individuals with darker skin tones. The high rates of drowning in these regions reiterate the importance of validating whether the DSS used for PMSI estimation is suitable for individuals with darker skin tones.

4.2. Water-type profile

The bodies of 56 out of the 73 cases (77%) were retrieved from natural water sources such as seas, rivers, canals, brooks, and lakes, while 17 (23%) bodies were retrieved from artificial sources such as dams, sewage channels, and ditches. These results follow the trend that drowning more frequently occurs in natural water sources compared to artificial sources [38]. Lin et al. [28] investigated unintentional drowning cases in 60 countries, revealing that in most countries, drowning occurs more in natural water bodies such as lakes, seas, and ponds, compared to man-made water sources such as swimming pools and bathtubs. Lithuania (85%), Finland (93%), and Panama (87%) had the highest occurrence of drowning in natural water sources.

4.3. PMSI estimation

The results indicate significant variability in the accuracy of each DSS, dependent on the country, as well as the skin tone and stage of decomposition of the individual. The PMSI estimation results (Tables 5 and 6) indicate that the Heaton and Reh DSS were relatively accurate for estimating the PMSI of bodies in a fresh stage of decomposition (ICC = 0.56–0.62), while only the Reh DSS was relatively accurate for bodies in advanced decomposition stages (ICC = 0.54). The PMSI estimation of each DSS is explained below.

4.4. Heaton DSS

Skin tone did not directly determine PMSI estimation accuracy of the Heaton DSS but interacted with the decomposition stage and temperature to influence the estimated PMSIs. The Heaton DSS and regression formula were relatively accurate (ICC = 0.62) for estimating the PMSI of bodies exhibiting fresh decomposition features, regardless of skin tone. This suggests that in the early stages of decomposition, the Heaton DSS was not significantly biased by skin tone. The Heaton DSS had the higher relative accuracy (ICC = 0.62) for estimating the PMSI of bodies in a fresh decomposition stage, compared to the Reh DSS (ICC = 0.56). The van Daalen DSS was inaccurate (ICC = 0.49). Although it should be noted that effect sizes were small.

A body was described “fresh” when it had a maximum TADS of 7–9; such bodies had discolouration features such as pink, red, yellow, green, and white and the wrinkling of the palms and the soles of the feet. For most of the bodies in a fresh stage, the known PMSIs and estimated

PMSIs using the Heaton DSS matched, and there was a difference of only one day between the known PMSIs and the estimated PMSIs in a few cases. Only four fresh cases (Cases 2, 9, 14 and 27; all decedents with lighter skin tones from the Netherlands and UK) had more than one day difference between the known PMSIs and the estimated PMSIs; these cases occurred during the European cold months of February and December. It is possible that the low air and water temperatures experienced during the cold months could be the reason for this major difference between the case note PMSIs and the estimated PMSIs of these cases [39]. The low temperatures mean more daily temperatures are required to equate the ADD, leading to an overestimated PMSI value. Yet, the absence of such discrepancies in darker-skin toned individuals in similar conditions might indicate that the Heaton DSS performs slightly more consistently for darker skin in fresh decomposition stages during cold months, but the sample size is too small for certainty.

Across all skin tones, the Heaton DSS significantly over- and underestimated PMSI in advanced decomposition. There were overestimated PMSIs in five cases with lighter skin tones (4, 8, 10, 12, 19; all Netherlands) and two cases with darker skin tones (44, 53; both South Africa); all occurring in warmer months (Table 5). In these cases, estimated PMSIs were about twice the actual value. This overestimation was not uniquely tied to skin tone but to the high TADS (13–17) and the environmental temperatures influencing the ADD extrapolation. However, most affected cases had lighter skin tone, suggesting a possible trend toward greater overestimation in lighter skin toned bodies during warmer months, though this might reflect regional case distribution (i.e. more “lighter skin” toned decedents in the Dutch dataset).

There were underestimated PMSIs for one darker skin case (13) and two lighter skin cases (18 and 20) in the cold months (January–March, Netherlands), likely due to suppressed decomposition under cold environmental conditions and the resulting low TADS. Here, skin tone did not appear to influence the direction of PMSI error, reinforcing the idea that temperature has a more dominant role in early decomposition stages than skin tone.

Two outlier cases involved significant PMSI overestimation. Case 28 (Lighter skin, February, UK) and case 68 (Darker skin, January, South Africa) had their PMSI overestimated by 4 and 3 times more than the known PMSI, respectively. Both cases had high TADS values, leading to high ADD extrapolation and, subsequently, inflated PMSIs. Despite differing skin tones and locations, the core issue was the same: extreme decomposition paired with environmental factors that distorted the ADD-to-PMSI relationship. This suggests that skin tone alone does not account for extreme PMSI discrepancies when using the Heaton DSS but may contribute to how decomposition features are scored or interpreted.

Overall, darker skin toned individuals were underrepresented in the dataset, yet when included, they displayed similar PMSI estimation trends to lighter skin toned cases in advanced decomposition stages. Notably, no darker skin toned cases in a fresh stage of decomposition showed PMSI estimation errors greater than one day, which may suggest that early post-mortem changes in darker skin are either more consistently interpreted or less prone to visual ambiguity. However, PMSI estimation inaccuracies for darker skin toned decedents were more common in advanced decomposition, indicating that reduced visual contrast in tissue discolouration may hinder accurate scoring using the Heaton DSS at later stages. Lighter skin toned individuals were more prevalent in the dataset, particularly from European regions, and exhibited a broader range of PMSI estimation errors. Both underestimations and overestimations were observed, particularly in relation to seasonal extremes in some of the cold months and hot months. This variability in PMSI accuracy among lighter skin toned cases could stem from the more pronounced or inconsistent visibility of decomposition features, such as colour changes, which may be more susceptible to subjective interpretation across lighting conditions or stages of discolouration.

4.5. van Daalen DSS

When examined from a skin tone perspective, the van Daalen DSS, like the Heaton DSS, demonstrates notable limitations in estimating the PMSI across skin tones, particularly in fresh and advanced decomposition stages. Although the van Daalen DSS yielded PMSI estimations like those of the Heaton DSS, it recorded the lowest ICC (0.49) among the three DSS when applied to both lighter- and darker skin toned individuals in a fresh stage of decomposition, indicating reduced reliability. Notably, the four fresh cases (Cases 2, 9, 14, and 27), all involving individuals with lighter skin tones, exhibited greater discrepancies between the case note PMSIs and the van Daalen DSS estimates than when assessed using the Heaton DSS. This suggests that even in cases involving lighter skin, the van Daalen DSS was less accurate.

Its lower ICC in advanced decomposition cases (0.36 compared to 0.41 for Heaton) further underscores its limited reliability, particularly in scenarios where visual indicators of decomposition are more difficult to interpret on darker skin. Although two darker skin toned decedents in advanced decomposition (Cases 8 and 44) were accurately assessed using the van Daalen DSS, where the Heaton DSS had previously overestimated their PMSIs, the remaining five cases (4, 10, 12, 19, and 53) were overestimated, again highlighting inconsistent performance for bodies with darker skin tones.

Importantly, the van Daalen DSS also failed to accurately estimate PMSIs for three bodies (Cases 13, 18, and 20) recovered during European cold months. These bodies, which likely presented decomposition features affected by both cold conditions and potential skin tone-related visual obscurities (e.g., decomposition changes, bruising, lividity, or discolouration may be harder to detect or interpret [15]), had PMSIs estimated at roughly half the duration of those recorded in case notes when scored using the Heaton DSS, and were similarly incorrectly estimated by van Daalen. In the most extreme cases, Cases 28 and 68, the van Daalen DSS significantly overestimated PMSIs for bodies with darker skin tones by three to four times the actual PMSIs noted in case files. For Case 28, the van Daalen DSS estimated a PMSI ten days longer than the Heaton DSS, further reinforcing the compounded error.

Collectively, these findings underscore that both the van Daalen and Heaton DSS are insufficiently calibrated to account for the visual presentation of decomposition in individuals with darker skin tones. This reinforces the urgent need for DSS frameworks that are sensitive to the effects of skin tone on observation of post-mortem changes, and for more inclusive forensic tools that can support accurate estimation across diverse populations.

4.6. Reh DSS

From a skin tone-centred perspective, the Reh table demonstrated a relatively strong performance in estimating PMSI for both lighter- and darker skin toned individuals in a fresh stage of decomposition (ICC = 0.56), particularly when clear physical features such as wrinkling of the feet and palms were present. However, this apparent accuracy did not extend to cases dominated by skin discolouration changes, which are more difficult to identify or interpret reliably on darker skin tones.

In advanced decomposition stages, the Reh table showed slightly higher accuracy (ICC = 0.54) compared to the Heaton (ICC = 0.41) and van Daalen (ICC = 0.36) DSS, with smaller day-to-day differences between estimated and actual PMSIs. However, this marginal improvement did not eliminate skin tone-related limitations. For example, cases dominated by discolouration features, such as green, pink, red, or purple hues, frequently resulted in PMSI overestimations, particularly when applied to individuals with darker skin, on whom these colour changes are not always visibly apparent. Across the cases presented, clear differences emerge between the stated and estimated post-mortem submersion interval (PMSI), as well as the influence of environmental conditions and skin tone. In Case 5, involving a lighter skin toned individual recovered in the Netherlands during a warm April, the stated

PMSI of 1 day was significantly lower than the estimated 9–10 days. A similar pattern appears in Case 9, also from the Netherlands but in colder December conditions, where a stated PMSI of one day contrasts with a much higher estimate of 17 days, suggesting temperature may slow decomposition and affect accuracy. In warmer climates, discrepancies are even more pronounced: Case 70 (lighter skin tone, South Africa, February) shows an increase from one day stated to 25 days estimated. For darker skin toned individuals in South Africa, Case 34 (March) shows a stated PMSI of six days compared to an estimated 23 days, while Case 68 (January) shows a rise from three days to 35 days. Overall, estimated PMSI consistently exceeds stated values, particularly in warmer environments, indicating that both climate and potentially skin tone may influence decomposition rates and the accuracy of initial PMSI assessments.

While all five cases (including those with lighter skin tones) had PMSIs overestimated, the extent of overestimation was more pronounced in individuals with darker skin. The most substantial overestimations occurred in darker skin toned cases (e.g., Cases 34 and 68), where decomposition signs were likely misinterpreted due to poor visibility of discolouration on darker skin. This pattern demonstrates how skin tone-related biases in decomposition descriptors can lead to disproportionately inaccurate PMSI estimations.

Moreover, despite the Reh table's relatively strong performance in cold-weather cases across Europe (ICC = 0.85), its accuracy was drastically reduced in warmer climates, specifically in South African cases (ICC = 0.19), where darker skin toned decedents were predominant, and where decomposition progressed differently due to temperature and humidity. These findings underscore that regional climate variations intersect with skin tone to further complicate PMSI estimation, especially when tools like the Reh table are used outside their originally validated contexts [40].

Overall, while the Reh table performs better than the Heaton and van Daalen DSS in some decomposition contexts, its limited adaptability to warmer climates and its reliance on colour-based indicators not always visible on darker skin tones highlight its insufficiency as an inclusive tool. These results further reinforce the need for decomposition scoring systems that account for skin tone variability and regional environmental differences to avoid introducing bias and inaccuracy into forensic investigations.

4.7. DSS recommendations

4.7.1. Assessing decomposition changes

From this study, the Heaton DSS was the most suitable DSS among the three DSS used for assessing decomposition changes, but the Reh table had a higher ICC of 0.66 compared to the 0.56 ICC for the Heaton DSS. The Heaton DSS is the most specific for describing the decomposition changes expected in a body; it uses fewer vague terms to classify the decomposition changes, and it includes more decomposition changes and features. The only decomposition change listed in the van Daalen et al. [5] and Reh [6] table, but missing in the Heaton DSS, is the absence or loss of finger or toenails.

Regarding discolouration changes observed in the decomposition process, the Heaton DSS is more specific and considers more colour changes; it notes colours such as pink/white/red (used to describe early decomposition changes in the colour of the skin, wrinkling of limbs and marbling), yellow/green/purple (used to describe marbling and bloating changes) and black (used in describing post-bloating stages and drying of the skin and soft tissues). The van Daalen DSS only considers white (used to describe wrinkling of limbs) and grey (used to describe post-bloating stages) colours. The Reh table makes mention of “discolouration of the body” in its description of decomposition changes, but it does not give any specific colour change or specific body part where the colour change is expected. More colours, such as different shades of brown, grey, and black, should be added to the descriptions listed in the van Daalen DSS and Reh table to give more specific descriptions of the

decomposition features observed in individuals with darker skin tones. Therefore, more studies need to be conducted to improve the descriptions listed in these three DSS, while the colours listed in the Heaton DSS can be adapted into the van Daalen DSS and Reh table.

The Heaton DSS mentions decomposition changes such as “soft tissue, tendon, and bone exposure”; and “extensive disarticulation and skeletonisation” before “complete disarticulation and skeletonisation”; as such, it differentiates bone exposure from partial or complete skeletonisation. The van Daalen DSS only mentions partial and complete skeletonisation; so, it is challenging to differentiate between bone exposure and partial skeletonisation when using this DSS. In this study, when using the van Daalen DSS, cases where “bone exposure” was evident it was scored as “partial skeletonisation” because the feature “bone exposure” was not listed in the DSS descriptions, and this choice can be utilised in other studies before any review of the van Daalen DSS. Providing picture descriptions for terms such as “bone exposure” and “partial and complete disarticulation” to be used along with the Heaton and van Daalen DSS would improve and make scoring easier. The Reh table makes no mention of “soft tissue, tendon, and bone exposure”, “extensive disarticulation and skeletonisation”, and “complete disarticulation and skeletonisation”. Bone disarticulation is a fundamental decomposition change that can be utilised in PMSI estimation; therefore, more studies need to be conducted to improve the Reh table concerning disarticulation and skeletonisation changes, or the Reh table should be used with caution in further studies.

The Heaton DSS description mentions the presence of possible features that can be observed in aquatic decomposition, such as “adipocere” and “animal activity/predation”, but these features are not listed in the van Daalen DSS or the Reh table. The van Daalen DSS and Reh table could be amended to add these missing features. Also, in cases when scoring two limbs with different decomposition changes leads to difficulties in assigning a score, it has been suggested that each limb is scored, and an average score of the four limbs is calculated as the final LAD score [41].

In summary, it is recommended that the Heaton DSS be used preferentially for assessing decomposition changes in most individuals.

4.7.2. Suitability for decedents with darker skin tones

It was challenging to assess discolouration changes in the darker skin toned image cases because fewer colour changes were observed in the bodies with darker skin tones. However, in all DSS, the accuracy of PMSI estimates was better for individuals with darker skin tones (ICC = 0.61–0.79) compared to individuals with lighter skin tones (ICC = 0.44–0.69). This may be due to overconfidence in assessing colour changes in individuals with lighter skin tones, but the variety of colours listed in the Heaton et al. [4] DSS made it easier to assess the extent of decomposition in cases of individuals with darker skin tones, especially in the fresh and bloat stages of the decomposition process. It was easier to detect one or two of the white, pink, red, yellow, green, purple, and black colour changes from the Heaton DSS in bodies with darker skin tones compared to the white/grey colour changes in the van Daalen DSS and the “discolouration of the body” from the Reh table. The advanced decomposition stages exhibited more anatomical changes than discolouration changes; therefore, it was easier to use the three DSS to assess the extent of decomposition of a body with darker skin tones in an advanced decomposition stage.

In this study, when observing marbling and wrinkling of the skin, the skin of individuals with darker skin tones did not appear pink, red, yellow, purple, or green, but as a lighter or paler shade of their original skin tone, with the blood vessels beneath the skin appearing more visible. When discolouration changes, such as pink, green, and red, are not visible, the pale appearance of the skin of a decedent with darker skin tones, along with visible blood vessels beneath the skin, could be used as a sign to identify marbling and wrinkling. In addition, further studies where pictures of the colour change expected in a body with darker skin tones could be included with the DSS as a reference guide.

4.7.3. PMSI estimation

The three DSS were relatively accurate for estimating the PMSI of bodies with both darker and lighter skin tones in a fresh stage of decomposition, and the Heaton DSS was the most reliable, with an ICC of 0.62. The Reh table was the only relatively accurate DSS for estimating the PMSI of bodies in advanced decomposition stages (ICC = 0.54) because it gave the smallest difference between the stated and estimated PMSI. The Heaton and van Daalen DSS overestimated the PMSI of bodies recovered in cold months by at least two times longer than the PMSIs stated in the case notes. It is possible that the low temperatures experienced during the cold months could be the reason for the over-estimation of the PMSIs of the cases when using the Heaton and van Daalen DSS.

The Heaton DSS overestimated the PMSI of bodies in advanced decomposition stages by approximately double that of the PMSIs stated in the case notes. These overestimated PMSIs could be a result of flaws in the regression formulae because advanced decomposition stages led to a high TADS value, resulting in a high extrapolated ADD from the regression formula. Therefore, a lot of average daily temperatures were needed to add up to the high ADD values, thereby increasing the days of the estimated PMSI. The Reh table is also not suitable for estimating the PMSI of bodies recovered from regions or countries with a different climate or weather pattern from Germany, especially when there is a significant difference in the monthly temperatures of the regions. It will be necessary to make temperature adjustments to the table to make it suitable for other regions. More studies need to be conducted on bodies with lighter and darker skin tones in different regions with varying climates across the world to improve the estimation of the PMSI of a body using these DSS.

4.8. Study limitations

A total of 73 deceased persons were used for this study. This is a small sample size, which could decrease the confidence level, reliability, and statistical power and increase the margin of error and bias in the study [42]. In addition, analysis was based on photographs of the deceased persons' bodies, not the actual bodies; some vital decomposition changes might have been missed in the pictures, or there may have been inconsistencies in lighting or artefacts from flash/shadow that can confuse colour identification and affect the process of assessing the extent of decomposition in the human remains. None of the post-mortem photographs included colour correction or reference cards, meaning that lighting and camera variations could not be controlled or corrected retrospectively. This may have affected colour assessment and contributed to scoring errors. Future studies should use standardised photography with colour reference cards to improve the reliability of colour-based assessments.

The skin tone of the deceased persons was quantified using the NIS Skin Colour Scale created by Massey & Martin [16]; a limitation of using this scale is that it does not consider the effect of sun-tanning or other light ray effects [10]. The skin tone was assessed using the pictures of the body after it was recovered; this was not a reflection of their ante-mortem skin tone, but rather a (fresh as possible) post-mortem assessment. In addition, scoring the skin tone and assigning a decomposition score to each body was a subjective choice; there could have been some hidden/subconscious forms of bias included in the study when scoring through visual observations. In future, pictures of the colour change expected in a body with darker skin tones should be included with the DSS.

The van Daalen et al. [5] study did not provide the prediction model used to estimate the PMSI values from the TADS; therefore, this study had to use a conversion factor to convert the van Daalen TADS to a scale of over 25 (like the Heaton DSS) to substitute the van Daalen TADS into the Heaton et al. [4] regression formula. These converted TADS did not reveal the actual extent of decomposition of these bodies. For example, a body with no visible decomposition change would be assigned a TADS of

3 when using both the Heaton and van Daalen DSS, but this conversion factor converts a van Daalen TADS of 3 to a 4.2 for Heaton TADS. A Heaton TADS above 3 indicates that a visible decomposition change has occurred compared to no visible decomposition change for a TADS of 3, so an element of error has been integrated into the conversion.

Finally, there is a potential inaccuracy of the stated PMSI values in the case notes because these stated PMSIs were probably reported when the bodies were found and based on witness statements; there is a possibility that these bodies might have washed up on the shores for a while before they were discovered.

4.8.1. Other considerations

Several additional factors should be considered when interpreting these findings. Firstly, the time between removal of a body from water and post-mortem photography was not available in the case records. This may be important because decomposition can continue and potentially change rapidly following removal from water and exposure to air. Differences in recovery and post-mortem procedures between countries may therefore have contributed to variation in the appearance of decomposition.

Information on whether bodies were found submerged or floating, as well as the type of clothing covering the body, was collected where available but was not sufficiently complete to be included as independent variables in the analysis. These factors may influence decomposition and should be systematically recorded in future studies. Similarly, water movement and characteristics of the water environment may affect decomposition [43]; however, although water current and pH were collected where available, these data were not consistently available across cases.

The PMSI values used for comparison were obtained from the case notes. Although cases with uncertainty regarding the relevant dates and times were excluded, the researchers were unable to independently verify how all PMSI estimates had originally been determined. Therefore, variation in the methods used by different jurisdictions or investigators to establish PMSI may have influenced comparisons with the estimates produced by the three DSS.

The decomposition scoring systems were applied retrospectively, by one observer, to available photographs and case descriptions. The use of retrospective material may introduce potential observer bias, particularly where assessors have access to case information that could influence expectations regarding decomposition or PMSI. Future studies should consider blinded assessments and examine inter-observer reliability.

Finally, temperature data should be interpreted cautiously. The Heaton et al. [4] and van Daalen et al. [5] DSS used retrospectively obtained ambient temperature data to estimate PMSI, whereas the Reh [6] DSS incorporates water temperature and observed decomposition changes. Ambient air temperature may not accurately represent the thermal conditions experienced by a submerged body, and water temperature data may not have been consistently measured across jurisdictions. Therefore, future research should prioritise recorded water temperatures where available and clearly distinguish between air and water temperatures when estimating PMSI.

Future studies should adopt a more standardised and prospective approach by systematically recording the time between body recovery and photography, whether the body was submerged or floating, clothing, water movement and characteristics, and accurately measured water temperatures. Clear documentation of how the reference PMSI was established should also be provided to improve confidence in comparisons with decomposition scoring systems. In addition, photographs should ideally be assessed by multiple independent and blinded observers, with inter-observer reliability evaluated to reduce potential bias. Collecting these variables consistently across jurisdictions would allow future research to better control for environmental and recovery-related factors and improve the reliability and applicability of decomposition scoring systems for PMSI estimation.

5. Conclusions

This study highlights skin tone as an important variable influencing the accurate assessment of decomposition and the estimation of post-mortem submersion interval (PMSI). While environmental factors such as temperature and water immersion were important factors, this research shows that bodies with darker skin tones are disproportionately affected by the limitations of existing decomposition scoring systems (DSS). Specifically, although the Heaton, van Daalen, and Reh DSS provided relatively accurate PMSI estimations for both lighter- and darker skin toned individuals in a fresh stage of decomposition (ICC = 0.49–0.62), they consistently overestimated PMSI for bodies in more advanced decomposition stages or recovered in cold months. This overestimation poses a risk of misidentification and investigative delays, particularly for individuals with darker skin.

Importantly, the study reveals that skin discolouration changes central to DSS scoring, such as pink, green, red, and purple, are not reliably visible on darker skin tones. Instead, decedents with darker skin tones may exhibit a pale or lighter appearance and visible subdermal blood vessels, which could serve as alternative indicators of marbling and skin wrinkling. However, such cues are not currently included or well-described in the standard DSS frameworks. The study also identifies compounding factors such as climate variability, inadequate representation of darker skin features in DSS descriptors, and biases embedded in the regression formulae used for ADD extrapolation, all of which contribute to inaccurate PMSI estimation.

In conclusion, this research demonstrates that currently validated DSS are insufficient for accurate PMSI estimation in individuals with darker skin tones and that forensic methodologies must evolve to include inclusive, skin tone-responsive criteria. Without such adjustments, significant disparities in post-mortem interval estimation will persist, potentially compromising forensic outcomes and justice for underrepresented populations and their families.

CRedit authorship contribution statement

Ibukunoluwa Olowe: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Laura J. Heathfield:** Writing – review & editing, Resources, Investigation, Formal analysis, Conceptualization. **Lisa Malan:** Investigation. **Calvin Mole:** Writing – review & editing, Formal analysis. **Victoria Gibbon:** Writing – review & editing. **Wilma Duijst:** Writing – review & editing, Resources. **Anna Williams:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Ethics statement

Ethical approval for this study was obtained from the University of Cape Town Human Research Ethics Committee (HREC: 416/2022) and the University of Central Lancashire Research Ethics Committee (SCI-ENCE 0172). Additional permissions were granted by the Western Cape Forensic Pathology Services and HM Coroner for Blackpool and Fylde. All data were retrospectively collected from medico-legal case records and anonymised before analysis. No identifiable personal information was used, and all procedures complied with relevant institutional and international ethical standards for research involving human remains.

Funding source

The Decolonising and Diversifying Osteology and Biological Anthropology (DDOBA) grant by the British Association for Biological Anthropology and Osteoarchaeology (BABAO) is a strategic funding initiative designed to make osteology and biological anthropology more inclusive, representative, and critically reflective of its historical biases. The award of the DDOBA grant in 2022, worth £1000, supported this

research addressing structural biases in forensic and osteological methodologies.

Declaration of competing interest

All authors declare no conflict of interest.

Acknowledgments

The authors would like to thank Melanie Need and Deborah Spin from Van Hall Larenstein University in The Netherlands for their valuable help in supplying resources for this project.

References

- [1] S.B. Giles, D. Errickson, N. Márquez-Grant, A retrospective comparative study to evaluate the reliability of post-mortem interval sources in UK and US medico-legal death investigations, *Sci. Justice* 62 (2) (2022) 246–261.
- [2] J. Singh, A. Kumar, S. Trivedi, S.K. Pandey, Advancements in estimating post-mortem interval in medico-legal practice: a comprehensive review, *Legal Med.* 75 (2025) 102627.
- [3] J.W. Brooks, Postmortem changes in animal carcasses and estimation of the postmortem interval, *Vet. Pathol.* 53 (5) (2016) 929–940.
- [4] V. Heaton, A. Lagden, C. Moffatt, T. Simmons, Predicting the postmortem submersion interval for human remains recovered from U.K. waterways, *J. Forensic Sci.* 55 (2) (2010) 302–307.
- [5] M. van Daalen, D. de Kat, B. Oude Grotebevelsberg, R. de Leeuwe, J. Warnaar, R. Oostra, W. Duijst-Heesters, An aquatic decomposition scoring method to potentially predict the post-mortem submersion interval of bodies recovered from the North Sea, *J. Forensic Sci.* 62 (2) (2017) 369–373.
- [6] H. Reh, Anhaltspunkte für die Bestimmung der Wasserzeit, *Dtsch. Z. Gesamte. Gerichtl. Med.* 59 (2–3) (1967) 235–245.
- [7] R.A. Sturm, R.D. Teasdale, N.F. Box, Human pigmentation genes: identification, structure and consequences of polymorphic variation, *Gene* 277 (1–2) (2001) 49–62, [https://doi.org/10.1016/S0378-1119\(01\)00694-1](https://doi.org/10.1016/S0378-1119(01)00694-1).
- [8] J.L. Rees, Genetics of hair and skin color, *Annu. Rev. Genet.* 37 (2003) 67–90, <https://doi.org/10.1146/annurev.genet.37.110801.143233>.
- [9] G. Tully, Genotype versus phenotype: human pigmentation, *Forensic Sci. Int. Genet.* 1 (2) (2007) 105–110, <https://doi.org/10.1016/j.fsigen.2007.01.005>.
- [10] P. Louie, R. Wilkes, Representations of race and skin tone in medical textbook imagery, *Soc. Sci. Med.* 202 (1) (2018) 38–42, <https://doi.org/10.1016/j.socscimed.2018.02.023>.
- [11] L. Hannon, R. DeFina, Reliability concerns in measuring respondent skin tone by interviewer observation, *Public Opin. Q.* 80 (2) (2016) 534–541.
- [12] A. Sitek, I. Rosset, E. Żądzińska, A. Kasielska-Trojan, A. Neskoromna-Jędrzejczak, B. Antoszewski, Skin color parameters and Fitzpatrick phototypes in estimating the risk of skin cancer: A case-control study in the polish population, *J. Am. Acad. Dermatol.* 74 (4) (2016) 716–723.
- [13] D.C. Cornett, D.S. Bolme, D.W. Steadman, K.A. Sauerwein, T.B. Saul, 2019 IEEE 10th International Conference on Biometrics Theory, Applications and Systems (BTAS), IEEE, 2019, pp. 1–8. Effects of postmortem decomposition on face recognition.
- [14] O. Morgan, P. Sribanditmongkol, C. Perera, Y. Sulamsi, D. Van Alphen, E. Sondorp, Mass fatality management following the South Asian tsunami disaster: case studies in Thailand, Indonesia, and Sri Lanka, *PLoS Med.* 3 (6) (2006) 809–815.
- [15] H. Gelderman, L. Boer, T. Naujocks, A. IJzermans, W. Duijst, The development of a post-mortem interval estimation for human remains found on land in the Netherlands, *Int. J. Legal Med.* 132 (3) (2018) 863–873.
- [16] D. Massey, J. Martin, The NIS Skin Color Scale, Office of Population Research, Princeton University, 2003.
- [17] The Global Historical Weather and Climate, *Climate zone finder*. Global Historical Weather and Climate Data | Weather and Climate, 2026. Retrieved December 28, 2022, from <https://tckctck.org/>.
- [18] Weather Underground, Local Weather Forecast, News and Conditions, 2026. Weather Underground. Retrieved November 15, 2022, from <https://www.wunderground.com/>.
- [19] T.K. Koo, M.Y. Li, A guideline of selecting and reporting intraclass correlation coefficients for reliability research, *J. Chiropr. Med.* 15 (2) (2016) 155–163.
- [20] A.S. Selya, J.S. Rose, L.C. Dierker, D. Hedeker, R.J. Mermelstein, A practical guide to calculating Cohen's f^2 , a measure of local effect size, from PROC MIXED, *Front. Psychol.* 3 (2012) 111, <https://doi.org/10.3389/fpsyg.2012.00111>.
- [21] J.E. Cohen, Statistical Power Analysis for the Behavioral Sciences, Lawrence Erlbaum Associates, Inc., Hillsdale, NJ, 1988.
- [22] R. El Sibai, R. Bachir, M. El Sayed, Submersion injuries in the United States: patients characteristics and predictors of mortality and morbidity, *Injury* 49 (3) (2018) 543–548.
- [23] R. Franklin, A. Peden, E. Hamilton, C. Bisignano, C. Castle, Z. Dingels, S.L. James, The burden of unintentional drowning: global, regional and national estimates of mortality from the global burden of disease 2017 study, *Inj. Prev.* 26 (Suppl. 2) (2020) i83–i95.

- [24] K. Roberts, O. Thom, S. Devine, P. Leggat, A. Peden, R. Franklin, A scoping review of female drowning: an underexplored issue in five high-income countries, *BMC Public Health* 21 (1) (2021) 1–13.
- [25] I. Ajibade, G. McBean, R. Bezner-Kerr, Urban flooding in Lagos, Nigeria: patterns of vulnerability and resilience among women, *Glob. Environ. Chang.* 23 (6) (2013) 1714–1725.
- [26] A. Peden, D. Demant, M. Hagger, K. Hamilton, Personal, social, and environmental factors associated with lifejacket wear in adults and children: a systematic literature review, *PLoS One* 13 (5) (2018) 1–15.
- [27] B. Moreland, N. Ortmann, T. Clemens, Increased unintentional drowning deaths in 2020 by age, race/ethnicity, sex, and location, United States, *J. Saf. Res.* 82 (1) (2022) 463–468.
- [28] C. Lin, Y. Wang, T. Lu, I. Kawach, Unintentional drowning mortality, by age and body of water: an analysis of 60 countries, *Inj. Prev.* 21 (e1) (2015) 43–50.
- [29] A. Peden, R. Franklin, T. Clemens, Exploring the burden of fatal drowning and data characteristics in three high income countries: Australia, Canada and New Zealand, *BMC Public Health* 19 (1) (2019) 1–12.
- [30] L. Miller, S. Willcox-Pidgeon, J.-P. Scarr, W. Koon, Analysis of unintentional fatal drowning in Australia 2002–2022: Progress, challenges and data to inform prevention, *Aust. N. Z. J. Public Health* 49 (4) (2025) 100258.
- [31] T. Clemens, B. Moreland, R. Lee, Persistent racial/ethnic disparities in fatal unintentional drowning rates among persons aged ≤29 years — United States, 1999–2019, *MMWR Morb. Mortal Wkly. Rep.* 70 (24) (2021) 869–874.
- [32] M. Cenderadewi, R. Franklin, A. Peden, S. Devine, Fatal intentional drowning in Australia: a systematic literature review of rates and risk factors, *PLoS One* 15 (5) (2020) 1–20.
- [33] J. Scarr, K. Buse, R. Norton, D. Meddings, J. Jagnoor, Tracing the emergence of drowning prevention on the Global Health and development agenda: a policy analysis, *Lancet Glob. Health* 10 (7) (2022) 1058–1066.
- [34] M. Tyler, D. Richards, C. Reske-Nielsen, O. Saghafi, E. Morse, R. Carey, G. Jacquet, The epidemiology of drowning in low- and middle-income countries: a systematic review, *BMC Public Health* 17 (1) (2017) 1–7.
- [35] World Health Organization, Global status report on drowning prevention 2024, World Health Organization, 2024.
- [36] J. Leavy, G. Crawford, F. Leaversuch, L. Nimmo, K. McCausland, J. Jancey, A review of drowning prevention interventions for children and young people in high, low and middle income countries, *J. Community Health* 41 (2) (2016) 424–441.
- [37] T. Mott, K. Latimer, Prevention and treatment of drowning, *Am. Fam. Physician* 93 (7) (2016) 576–582.
- [38] W. Koon, A. Peden, J. Lawes, R. Brander, Coastal drowning: a scoping review of burden, risk factors, and prevention strategies, *PLoS One* 16 (2) (2021) 1–22.
- [39] S. Forbes, K. Perrault, P. Stefanuto, K. Nizio, J. Focant, Comparison of the decomposition VOC profile during winter and summer in a moist, mid-latitude (CFB) climate, *PLoS One* 9 (11) (2014) 1–11.
- [40] B. Madea, E. Doberentz, Commentary on: Heaton V, Lagden A, Moffatt C, Simmons T. Predicting the postmortem submersion interval for human remains recovered from U.K., *J. Forensic Sci.* 55 (6) (2010) 1666–1667, <https://doi.org/10.1111/j.1556-4029.2010.01517.x>.
- [41] G. Dabbs, M. Connor, J. Bytheway, Interobserver reliability of the total body score system for quantifying human decomposition, *J. Forensic Sci.* 61 (2) (2016) 445–451.
- [42] J. Faber, L. Fonseca, How sample size influences research outcomes, *Dental Press J. Orthod.* 19 (4) (2014) 27–29.
- [43] L.J. Heathfield, L. Malan, C. Finaughty, C.G. Mole, V.E. Gibbon, A retrospective case review of decedents recovered from aquatic environments in Cape Town, South Africa, *Forensic Sci. Med. Pathol.* (2026), <https://doi.org/10.1007/s12024-026-01229-2>.