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PAPER

ANTHROPOLOGY

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Predicting the Postmortem Submersion Interval for Human Remains Recovered from U.K. Waterways*

ABSTRACT: This article aims to increase accuracy in estimating the postmortem submersion interval (PMSI) for bodies recovered from rivers in the United Kingdom. Data were collected from closed case files, crime scene reports, and autopsy files concerning bodies recovered over a 15-year period from the River Clyde, Scotland, and the River Mersey and canals in northwest England. One hundred and eighty-seven cases met the study criteria and were scored by quantifying the overall amount of decomposition observed in each case. Statistical analysis showed that the duration of a body's submergence in water and the temperatures to which it was exposed, as measured in accumulated degree days (ADD), had a significant effect on the decay process. Further analysis indicated that there were no significant differences in decomposition between the waterways. By combining the data from all study samples, it was possible to produce a single linear regression model for predicting ADD from observed decomposition.

KEYWORDS: forensic science, forensic anthropology, decomposition, waterways, accumulated degree days, postmortem interval

Each year, more than 140,000 individuals fall victim to the waters that cover 77% of the earth's surface (1). In the United Kingdom alone, there are over 400 cases of drowning reported each year, 39% of which occur in rivers and streams (2). Because some of the most densely populated areas of the planet are situated adjacent to a body of water, these figures are perhaps not surprising. There are a multitude of reasons why human remains can be found deposited in aquatic environments, including industrial or work-related incidents (3), boating and ferry disasters (4), recreational accidents (5,6), the disposal of murder victims (7), suicides (8–11), or the devastation caused by natural disasters such as the Indian Ocean Tsunami or Hurricane Katrina in New Orleans.

Water is a very important variable in the preservation and dispersal of human remains, creating a number of challenges to investigators assigned to the case. In lotic systems, a body can be transported great distances from its point of entry (12) and this, combined with the effects of decomposition, makes identification of the individual and the circumstances surrounding death hard to determine (13–16). Even though it is widely accepted in the forensic community that terrestrial decomposition differs from aquatic decomposition, there has been little investigation carried out in this area of forensic taphonomy. The few published reports that do involve human remains in a water environment primarily concern single case studies with which forensic investigators have been involved (12,17,18). Although there is something to be learnt from each of these cases, there is a growing need for more systematic studies of human decomposition in aquatic environments.

Bodies deposited in waterways are subjected to diverse and constantly changing conditions. Each river or canal is a separate dynamic system, with its own biological, physical, and chemical properties, which combine to make it a unique environment. One might assume, therefore, that each waterway has a distinctive and specific effect on the decomposition of bodies deposited in them. Previous studies have already shown that bodies decomposing in water display similar soft tissue modifications relative to bodies decomposing on land (19,20). However, the visual markers appear at different time intervals and progress at different rates compared to those of terrestrial decomposition. River systems have a high number of variables that can potentially influence this process, including temperature, water depth, currents, tides, season, dissolved oxygen, debris, substrate type, salinity, acidity, interactions between chemical and physical processes, and insect and scavenging activity.

The aim of this article is to increase accuracy in estimating the postmortem submersion interval (PMSI) for bodies recovered from major rivers located within the United Kingdom. Because previous studies (21) indicated that ambient temperature is a major factor in determining the rate at which human remains decompose, decompositional timetables incorporating accumulated degree days (ADD) based on water temperature are constructed to aid in the estimation of PMSI for bodies recovered from aquatic environments. Megyesi et al. (22) produced an equation for calculating ADD in terrestrial decomposition. This system measures the process of decomposition as the summation of progressive numerical scores, i.e., Total Body Score, based on the appearance of three separate regions, the head, trunk, and limbs. If the date of disappearance can be calculated

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from a decomposition score (22) and a summation of temperature and time (ADD), such data may aid in the identification of badly decomposed victims when compared with missing person records. The same principles should also be applicable to the summation of water-based decomposition scores and the accumulation of aquatic temperatures over time.

Methods

Two primary study sites were used in this investigation: the River Clyde in Scotland and the River Mersey in the northwest of England. Both are tidal rivers with a length of *c.* 110 km and were chosen as they flow through some of the most densely populated areas of the country. Further data for the study were collected from a small number of cases recovered from two canals located in Cheshire, the Bridgewater Canal and the Manchester Ship Canal. These waterways were constructed during the height of industrialization in the northwest to aid large vessel navigation and reduce river traffic on the Mersey.

Data for the Mersey were collected through the examination of closed case files, crime scene photographs and reports; for the River Clyde, data were derived from crime scene reports, autopsy files, and minutes supplied by the Glasgow Humane Society, which was actively involved in the recovery of the majority of cases. For the River Clyde, 125 cases between the years 1991–2006 met the study criteria, while 47 cases from the River Mersey and 15 from its associated canals between the years 1992 and 2007 were included. Cases were rejected from the study if there was uncertainty regarding the time of death, a lack of information relating to the condition of the remains, or if a victim received medical intervention on recovery. Data collected from reports included the biological profile of the individual; the degree to which the individual was clothed; the date/time the body entered and exited the water, its location, its position in the water column; the date of postmortem examination; descriptions of decomposition; and information in regard to trauma sustained by the body.

The majority of bodies recovered from the two primary sites were male and ages ranged from 5 to 84 years with the mean age being 41 years in the Clyde and 45 years in the Mersey. The PMSI was calculated for all cases in the study as the time between entry into the river and recovery of the body. Entry dates were deduced from eye witness statements, 999 emergency calls, suicide notes, and missing persons reports. The recovery date was the time and date the individual was located in the water or on the river bank. The PMSI ranged from a few minutes (0 days) to 192 days in the Clyde (mean 16.6 days) and 0–69 days (mean 10.1 days) in the Mersey.

Measuring Decomposition

The degree of postmortem modification was visually assessed and scored using methods derived from Megyesi et al. (22), which divided the body into three areas, the head, torso, and limbs, to account for variation in the rate of decay. The ability to score decomposition from reports and photographs is dependent on the quality of the descriptions in the postmortem report as well as the quantity and quality of the accompanying photographs. The use of standardized terminology by forensic pathologists, presented below in Tables 1–3, would be useful in the future.

Multiple postmortem modifications were observed at varying levels of progression throughout the body. These included bloating, marbling, skin slippage, follicle slippage, formation of adipocere, skeletonization, and "washer woman" immersion changes (on hands and feet only). Bodies recovered from all the sites showed the same types of soft tissue modifications and in the same sequence over similar time frames. Therefore, early indications suggest that the process of decomposition is comparable across waterways. Decompositional trends were identified and these were incorporated into descriptive timetables for the head/face, the torso, and the limbs (Tables 1–3). Eight stages of decomposition were identified for both the face (FADS) and the body (BADS) and nine stages for the limbs (LADS), thus producing a possible maximum for the total aquatic decomposition score (TADS) of 25.

These timetables can be used to allocate a single decompositional score to each corresponding area of the body. It should be noted though that when trying to assign a score using the descriptive decompositional scoring systems below, very rarely does a case show all or even the majority of the descriptions in a scoring category. Instead, assigning a score relies on the investigator making an educated assessment of each individual case to select a category that can be described as "best fit." Summing the three scores gives the TADS for a body, which represents the overall extent of decomposition observed for a case. It was possible to calculate a TADS score for 148 cases in this investigation, ranging from a score of 3 (no apparent decomposition) to 25 (complete decomposition—skeletonization and disarticulation). During analysis of the data, outliers were identified and removed. These included cases where remains were located exposed on land, therefore experiencing terrestrial as well as aquatic decomposition, which

TABLE 1—*Descriptive stages for decomposition observed in the face and the assigned facial aquatic decompositional score (FADS).*

FADS	Description
1	No visible changes.
2	Slight pink discoloration, darkened lips, goose pimpling.
3	Reddening of face and neck, marbling visible on face. Possible early signs of animal activity/predation—concentrated on the ears, nose, and lips.
4	Bloating of the face, green discoloration, skin beginning to slough off.
5	Head hair beginning to slough off—mostly at the front. Brain softening and becoming liquefied. Tissue becoming exposed on face and neck. Green/black discoloration.
6	Bone becoming exposed—concentrated over the orbital, frontal, and parietal regions. Some on the mandible and maxilla. Early adipocere formation.
7	More extensive skeletonization on the cranium. Disarticulation of the mandible.
8	Complete disarticulation of the skull from torso. Extensive adipocere formation.

TABLE 2—*Descriptive stages for decomposition observed on the torso and the assigned body aquatic decompositional score (BADS).*

BADS	Description
1	No visible changes.
2	Slight pink discoloration, goose pimpling.
3	Yellow/green discoloration of abdomen and upper chest. Marbling. Internal organs beginning to decompose/autolysis.
4	Dark green discoloration of abdomen, mild bloating of abdomen, initial skin slippage.
5	Green/purple discoloration, extensive abdominal bloating—tense to touch, swollen scrotum in males, exposure of underlying fat and tissues.
6	Black discoloration, bloating becoming softer, initial exposure of internal organs and bones.
7	Further loss of tissues and organs, more bone exposed, initial adipocere formation.
8	Complete skeletonization and disarticulation.

TABLE 3—*Descriptive stages for decomposition observed in the limbs and the assigned limb aquatic decompositional score (LADS).*

LADS	Description
1	No visible changes.
2	Mild wrinkling of skin on hands and/or feet. Possible goose pimpling.
3	Skin on palms of hands and/or soles of feet becoming white, wrinkled, and thickened. Slight pink discoloration of arms and legs.
4	Skin on palms of hands and/or soles of feet becoming soggy and loose. Marbling of the limbs—predominantly on upper arms and legs.
5	Skin on hands/feet starting to slough off. Yellow/green to green/black discoloration on arms and/or legs. Initial skin slippage on arms and/or legs.
6	Degloving of hands and/or feet—exposing large areas of underlying muscles and tendons. Patchy sloughing of skin on arms and/or legs.
7	Exposure of bones of hands and/or feet. Muscles, tendons, and small areas of bone exposed in lower arms and/or legs.
8	Bones of hands and/or feet beginning to disarticulate. Bones of upper arms and/or legs becoming exposed.
9	Complete skeletonization and disarticulation of limbs.

could have an influence on the results seen. Cases were also removed when there were missing data concerning the extent of soft tissue modifications (e.g., areas not described in a pathology report and not photographed), which complicated the assignment of scores. Most importantly, cases where the PMSI equated to an ADD of <10 were also removed from the analysis, because these ubiquitously produced TADS of 3 or "fresh." Time of death for bodies in a fresh state can be estimated via conventional means (23).

ADD

Megyesi et al. (22) stated that decomposition is best modeled as being dependent on temperature and not just time. A recent study by Champaneri (24) using rat carcasses in temperature-controlled aquatic environments demonstrated that decomposition in water is also affected by temperature, with remains in warmer waters decaying more rapidly. However, when the accumulation of aquatic temperature (ADD) against decomposition score is compared, there is no difference in the actual rate (temperature-time) of decomposition. Thus, when ADD is normalized for TADS scores under water, the same principles for terrestrial decomposition (21) apply to submerged remains. In other words, bodies (on land or in water) subjected to temperatures of 20°C for 5 days will decompose at the same rate as those subjected to 5°C temperatures for 20 days; both equate to 100 ADD.

Retrospective temperature data, supplied by regional environmental agencies, were collected for each of the study sites at various points along their length. Temperatures for the Mersey and its associated canals were available for the years 1992–2007 and for the Clyde, 1991–2006. Rather then being recorded daily, temperatures were measured *c.* 1–3 times per month. Water temperatures recorded for all waterways used in the study were taken at various locations along the waterway at *c.* 0.5 m below the surface. Water temperatures thus did vary somewhat according to ambient air temperature. Therefore, it became a necessary, if not desirable assumption of the study that there was little fluctuation in the daily water temperatures; the rate of change of temperature in water is significantly less than it is in air because of differences in specific heat and density (25,26). These monthly readings were used to calculate ADD for cases, resulting in an accurate ADD value rather than a precise one. For experimental research being carried out over a considerable length of time, it may be worthwhile for investigators to take daily temperature readings themselves, rather than having to rely on data from an outside source. ADD was calculated for 144 cases by summing the average temperature over each 24-h period for the number of days that made up the PMSI.

$$\text{ADD} = \sum \text{Average daily temperature (Celsius) for the entire PMSI}$$

The values for ADD ranged from 0.04 to 2151 with a mean of 120.39 and 115.27 in the Clyde and Mersey, respectively. Calculating ADD allows an evaluation of whether cumulative temperature affects decomposition within the study sample. It may then be feasible to construct a decomposition timetable based on ADD that allows investigators to estimate a more accurate PMSI for bodies deposited in U.K. river systems.

Results

Initial Observations

The degree of decomposition within the study sample varied from a "fresh" appearance to extensive decomposition. A high number of cases showed very little or no signs of decomposition (TADS 3), while several cases exhibited advanced postmortem modifications with adipocere formation, skeletonization, and disarticulation, primarily in the hands and forearms (TADS 20). External changes were first visible in the face, neck, and hands, with "washer woman" immersion changes being the most frequently observed form of soft tissue modification. Changes to the hands were often observed as soon as 1–2 h (0.69 ADD) after immersion in water. At autopsy, a large number of cases showed evidence of some type of trauma. The majority of these cases had sustained external trauma, which included superficial cuts and lacerations, abrasions and bruises. These injuries were assessed in the autopsy reports as having been inflicted on the body either while the victim was alive and struggling in the water or after death as the body was moved by currents and impacted with objects, or caught on boat propellers. A small number of cases showed evidence of postmortem aquatic animal scavenging, with the soft tissues of the ears, lips, nose, and eyelids being consumed. Internal injuries were also diagnosed during autopsy and included fractures to the sternum, ribs, clavicles, and femurs; shoulder dislocations; spinal disruptions; and tears in internal organs such as the spleen and lungs. These are typical of deceleration injuries (27,28) and found in cases where the individual was witnessed or believed to have fallen from a great height into the river.

Vertical Positions in the Water Column

Using data from various reports and with the assistance of the Glasgow Humane Society, it was possible to determine the position of 111 bodies in the River Clyde at their time of recovery. Bodies were identified as either initial floating, submerged, or resurfaced on recovery. The majority of cases were found to be floating while only 32 were recovered from below the water's surface. Several bodies remained submerged as a result of being snagged on debris or obstacles, and, once freed, floated immediately to the surface. Bodies categorized as "initial floating" had a PMSI of 0–10 days with a mean of 1.39 days. Bodies at the upper end of this range were floating as a result of small pockets of air caught in their clothing. "Submerged" cases had a PMSI range of 0–72 days, but the majority of these cases were submerged for <12 days with only three cases still showing submergence after this time interval. Bodies that were believed to have resurfaced exhibited a PMSI range of 12–192 days (mean 45 days). Because the Clyde flows through a densely populated city, it appears that the majority of bodies were located and recovered soon after resurfacing. Comparable data were not available for the Mersey and canals.

Statistical Analysis

Figure 1 displays the data points and regression lines for TADS against $\log_{10}$ADD for the three water systems. An analysis of covariance showed no significant difference between any of the slopes or intercepts (Table 4). Thus, the model simplifies to a single regression line through all data points producing a regression equation of:

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

This model fits the data well ($r^2 = 0.77$ and $F_{1,85} = 290.7$, $p < 0.0001$); diagnostic plots also show the residuals to be normally distributed.

Using category variables other than waterway, ANCOVA results show no clear difference in regression slopes for either sex or season of entry. There was a significant but marginal difference between the slopes for unclothed or clothed individuals ($t = 2.21$, $p = 0.031$), but this result should be treated with caution. The comparison was unbalanced for two reasons: (i) the data set was inherently biased, containing only seven cases without clothing vs. 66 clothed cases (Scotland and the northwest of England are relatively cold year-round) and (ii) there were 26 clothed individuals who had scores representative of early decomposition stages (e.g., TADS < 13) but no unclothed individuals in these stages. Most of those recovered in an unclothed condition had been in the water so long that investigators assumed the clothing had decomposed or had been removed by the currents. It is suspected that the observed differences would disappear if additional unclothed bodies displaying early decomposition were added to the data set.

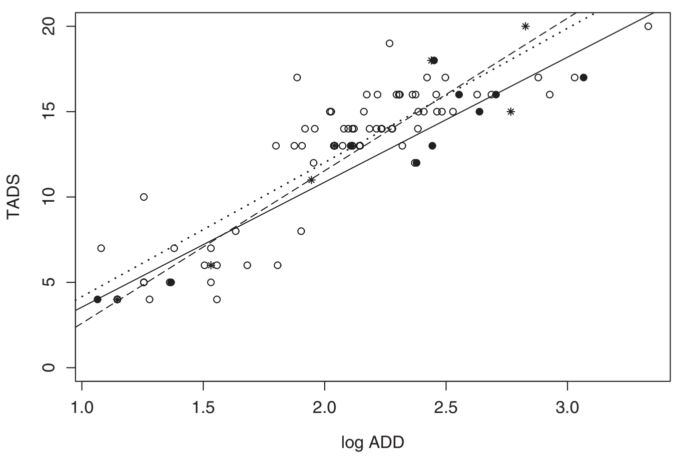

FIG. 1—*Total aquatic decomposition score against log_{10} accumulated degree days for data from U.K. waterways: canals (solid circles, solid line), River Clyde (open circles, dotted line), and River Mersey (asterisks, dashed line).*

TABLE 4—*Summary of ANCOVA analysis comparison of regression lines. Values represent probability (%) of no difference between slopes and intercepts for each pair of water systems.*

	Slope		
Intercept	Canals	Clyde	Mersey
Canals	–	67	37
Clyde	98	–	47
Mersey	52	41	–

Discussion

Bodies recovered from four different waterways in the United Kingdom went through the same stages of decomposition, in the same sequence, and at the same rate. Decomposition observed in U.K. rivers is a mosaic and cumulative process, which follows a generalized pattern for various characteristics. The pattern of decomposition observed in this study sample did not follow the stages originally presented by Payne and King (29), but instead followed the first three stages as outlined by Hobischak and Anderson (30), from fresh, to bloated, and then on to the decay stage.

Decomposition was also observed to occur at different rates in different areas of the body. For example, despite literature suggesting that the head always decomposes at a faster rate than the torso, this was not always the case, with many examples showing the reverse to be true. The position of the body in relation to the currents may also be an important variable that is unaccounted for in fluvial cases. The importance of varying water currents and turbulence can be seen in several cases recovered from the River Clyde. Bodies recovered from locations such as the Tidal Weir have a tendency to show more advanced decomposition because of the extreme rising and falling currents and turbulence that continually agitates and impacts the body backwards and forwards against the weir. Varying rates of decomposition observed between individual cases or areas of the body may be explained by the position of the remains in relation to the currents at various sites.

Locations Within the River

When a body descends below the waterline, the length of time it remains submerged appears to be dependent on the season of entry and/or ADD. Bodies experiencing warmer temperatures during the spring/summer months were observed to resurface earlier than autumn/winter cases. The warmer the water, the sooner the body bloats and floats. This suggests that the depth of the water is an important factor. Sunlight rarely penetrates deeper than 2 m (31), so bodies settled at a depth greater than this are subjected to cooler temperatures. Bodies at depth also experience increased pressure, reduced water movement from bed friction, and potential burying by silt. This all places a body in what can be described as a state of "suspended animation," refrigerating it in a still, dark environment, and severely retarding or even temporarily halting the process of decomposition and hence resurfacing. A body could even be submerged in shallower water, but if positioned in the shade, the rate of decomposition would be greatly reduced because of slower accumulation of temperature.

Bodies deposited in tidal systems such as the Clyde and the Mersey have the potential to be transported upstream from their point of entry as a result of tidal motion. Remains may also be at risk of snagging on ferries and other water vessels that traverse the shipping corridors. The alternating flow of water makes it virtually impossible to know for certain exactly how far a body has drifted from its point of entry. The turning of the tides virtually every 6 h results in bodies experiencing cyclic movements that can convey the body along the same stretch of water recurrently until it is discovered. Likewise, when conducting search and rescue operations, authorities should take into account any recent heavy rainfall, which could have a significant effect on the drifting of bodies. Swollen rivers flowing quickly to discharge their excess volume have the ability to transport objects several kilometers in just a few hours while prevailing winds can push bodies at the surface to specific spots along the river. However, this is a topic that should be studied further in nontidal systems because calculating drift distances, and hence speeds, in a tidal environment is a complicated and unreliable process.

The Regression Model

ADD have a significant and essentially identical relationship with decomposition at each of the study sites. Bodies in the water for a prolonged length of time in cooler temperatures and those subjected to warmer temperatures for a shorter time showed similar rates of decomposition.

Using a regression model to make a prediction of the explanatory variable for a given value of the response variable inherently produces relatively large errors, and confidence intervals are consequently wide. Based upon the model mentioned earlier, rearranging the regression equation to predict ADD produces:

$$\mathrm{ADD} = 10^{\frac{(\mathrm{TADS}+3.706)}{7.778}}$$

Ninety-five percent confidence intervals for the prediction were calculated (32) and superimposed onto the regression as shown in Fig. 2. Note that these confidence intervals are not symmetrical about the regression line, despite appearing so. Thus, an additional term cannot be simply tacked on to the prediction equation mentioned earlier to reflect estimate error. The confidence intervals were smaller than for a model which also included data points where ADD was <10, reflecting the subjective variability of scoring decomposition in early stages. For practical applications, Table 5 presents calculated prediction and confidence intervals for all values of TADS between 5 and 25 from the regression model. However, because the greatest TADS value used to produce the model was 20, predictions beyond this value are extrapolated, and therefore more tenuous.

Once ADD has been predicted from TADS, the PMSI can be inferred by summing the average daily temperatures from the date the body was recovered retrospectively until the estimated ADD is reached. This should indicate the time frame in which the body entered the water.

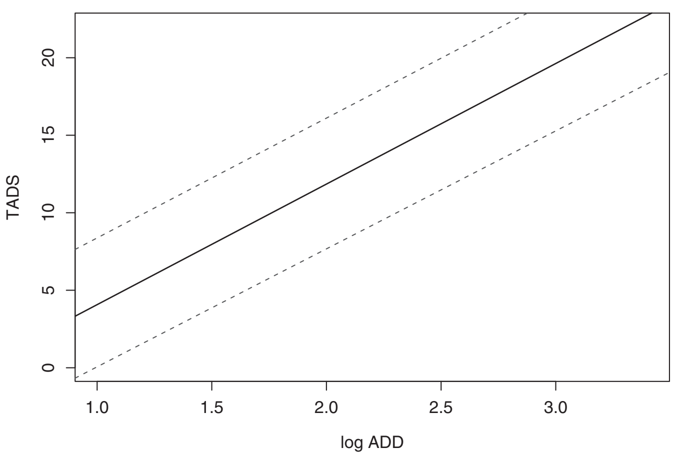

FIG. 2—*Ninety-five percent confidence intervals around the regression slope as predicted by the model.*

TABLE 5—*Total aquatic decomposition score (TADS) and the predicted accumulated degree days (ADD) and confidence intervals, back transformed from the logarithmic model.*

TADS	Predicted ADD	Lower 95% Confidence Interval	Upper 95% Confidence Interval
5	13.16	3.550	45.88
6	17.70	4.825	61.52
7	23.79	6.552	82.58
8	31.99	8.889	110.9
9	43.01	12.05	149.2
10	57.83	16.31	200.8
11	77.76	22.07	270.5
12	104.5	29.82	364.9
13	140.6	40.26	492.6
14	189.0	54.31	665.6
15	254.1	73.18	900.3
16	341.7	98.51	1219
17	459.4	132.5	1652
18	617.7	178.0	2241
19	830.5	238.9	3043
20	1117	320.4	4135
21	1501	429.3	5625
22	2019	574.7	7659
23	2714	768.6	10437
24	3649	1027	14235
25	4906	1371	19432

The formation of adipocere may also have an effect on the accuracy of the model and the results in this study because it has been known to preserve body tissues, delaying or even halting the appearance of later decompositional characteristics past a certain point despite ADD increasing. This will result in a much wider variation of decomposition scores for cases with higher ADD values. Extreme care should therefore be taken when applying this model to cases where adipocere is present.

Limitations to the Study

While conducting this research, a number of limitations were realized, which, for the benefit of future studies, are discussed. One factor that should be taken into account when working with tidal systems is that not all cases will have spent 100% of their estimated PMSI submerged in the water. In rivers such as the Clyde and Mersey, it is reasonable to assume that a body can be deposited on land at a high tide or after flooding, and left to decompose in the air unnoticed at an accelerated rate before being resuspended in the river at the next high tide. Whether this has occurred for a case is difficult to prove and, if gone unnoticed, may affect PMSI estimates.

Future studies would also benefit from a data sample containing more cases showing moderate to advanced decomposition. The larger the study sample, the more likely that representatives of all stages of decomposition are present which may strengthen the predictive capacity of a model. When working with real-life cases involving human remains, this factor cannot be controlled. However, it does reflect exactly how a body decomposes in a specific environment.

Conclusions

The process of decomposition in fluvial environments is a cumulative event comprised of various stages, the rate at which they occur being strongly related to time and temperature, and hence, ADD. The study demonstrated that the decomposition of human remains does not differ significantly among aquatic environments in the United Kingdom. Data from the Clyde, Mersey, and canals were combined to derive a linear regression model to aid in the estimation of time since death using ADD. It should be noted that this model is not suitable for estimating PMSI for cases where the ADD value is <10. Extra care should also be taken when applying this model to cases where the formation of adipocere is observed as this process may provide unreliable results.

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