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# An investigation into the use of riverine mesocosms to analyse the effect of flow velocity and recipient textiles on forensic fibre persistence studies

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ABSTRACT

Textile fibre evidence can provide important activity level information in criminal cases. To date, very few studies have investigated fibre persistence on fabrics exposed to aquatic conditions, even though items of evidence and victim's bodies can regularly be found in aquatic environments. This lack of research on whether fibres (and other trace evidence) persist on evidence submerged in water, has shown to impact practice as it is reported that crime scene examiners do not attempt to recover this evidence, due to the belief that it would not be present. The dynamic nature of aquatic environments mean that the studies are difficult to conduct in situ and variables, such as water flow rate are not possible to control and thought to be difficult to monitor. To address these challenges, artificial streams (also known as mesocosms) were employed in this study to investigate the persistence rate of polyester fibres on different fabric types (Woollen/nylon mix carpet, 100% polyester fleece, and 95% polyester/5% elastane sports vest) for a four week exposure time (1, 8, 24, 48, 120, 168, 264, 336, 504 and 672 hrs). The effect of water flow rate on the persistence of fibres was investigated by conducting the experiment with two flow velocities; 'high' (~2.75 L/s) or 'low' (~0.7 L/s). Significant differences between textile type were seen at 504 hrs under low flow conditions and 8, 24, 168 and 264 hrs under high flow conditions. When comparing flow velocities, a significant difference was seen at 1 hr exposure for the fleece textile only, indicating that the two flow rates used in this study do not significantly affect fibre persistence. Initial loss rates were highest for the first hour of submergence for the carpet, fleece and sports vest. Fibre persistence rates were highest on the carpet, followed by fleece and then sports vest. Persistence rates remained mostly constant after 24 hrs for all textiles but with redistribution of fibres between textiles being seen after this exposure time. The use of artificial flumes in this study provided a balance between realistic experimentation and a controlled study; key experimental variables could be continously and safely monitored. This study provides the first fibre persistence data in river type environments and proposes a new method for testing persistence in aquatic environments. This approach is not limited to fibres evidence and could be employed for other evidence such as glass, pollen, fingerprints and DNA.

## 1. Introduction

Fibres are a form of ubiquitous trace evidence that easily transfers from the original fibrous item to a surface or location it has come into contact with. This transfer mechanism is underpinned by Locard's exchange principle [21], where evidence may move between clothing or objects either through direct contact, categorised as primary transfer, or indirect contact, categorised as secondary transfer [13,28]. Tertiary and quaternary transfer can also occur if contact continues but the probability of secondary transfer, or a higher order, varies considerably between trace evidence types and are rarely studied [28]. This guarantees, to an extent, an exchange of evidence which is especially advantageous in cases where no presence of individualising evidence, such as biological evidence, is found. In addition to its ubiquitousness, by

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understanding and quantifying the transfer and persistence mechanisms of fibres, it is possible to conclude how and when these fibres were transferred, providing important activity level information. It is therefore common to use fibre evidence not only to associate a suspect with an object, scene or victim, but also to reconstruct the crime and provide timelines in a case.

To provide activity level information regarding fibres evidence, it is necessary to understand their mechanisms of transfer, how they persist under varying conditions and what factors would affect their transfer and persistence. Numerous transfer and persistence studies have been conducted over the years to address these questions, with variables under investigation representing common crime scene scenarios, such as contact between suspects and victim's clothing. The main factors found to affect fibre transfer are; the type of donor fibre & recipient surface, thickness of fibres and force/pressure of or number of contacts [14,15,18,30,34,6]. Persistence studies specifically provide information regarding timelines of when initial transfer may have occurred. Research has shown that fibre persistence is predominantly affected by exposure time, recipient surface type and location of fibres on items [1,13,14,17,25,26,31,36,39,4,48]. Fibre persistence studies have also investigated other variables including washing of recipient garments [25,38,45] and exposure to wind and rain [17,33]. For generating activity level information for a case, appropriate persistence data must be used that reflects the variables and scenario of the case as closely as possible. Due to this, persistence studies conducted in a realistic environment, in comparison to lab-based set-ups, are preferred. However, the multitude of possible variables present in these realistic environments create difficult conditons to track the fibres or control the variables and thus lab-based set-ups are favoured to avoid basing persistence findings on assumptions of what occurred underwater [19]. Fibre persistence studies which have utilised realistic environments to expose the fibres include those investigating fibres on skin and garments in outdoor conditions ([27] and, [17] and [33] respectively) and on buried carcasses [5]. Currently, there is a paucity of research into the transfer and persistence of fibres on items exposed to more challenging outdoor environments, such as aquatic environments (freshwater and saltwater, still and moving). This is likely due to the challenges of setting up realistic experimentatal conditions in these environments and instead the majority of these studies have been conducted in laboratory or simplified outdoor environments. Understanding the persistence rates of fibres (and other evidence) when submerged in water is valuable in cases where bodies and items (such as weapons) have been disposed of in aquatic environments. The effect of exposure to such environments is still little understood. An ENFSI European Fibres Group survey of forensic practitioners in 2010, highlighted the need for this information as the survey results indicated that crime scene professionals believed that there would be no fibres remaining after 7 days exposure in an aquatic environment, and therefore protocols were to not search and recover this form of evidence after this time [8]. Since this survey, there has been two main studies investigating fibre persistence in water, conducted by Lepot et al. [20] and Lepot and Vanden Driessche [19], in an attempt to better understand the effects of this exposure on the evidence. These two studies were the first to report the significant influence of recipient fabrics on fibre persistence when exposed to aquatic environments and the effect of varying water flow. Lepot et al. [20] transferred green acrylic fibres onto four types of knitted garments which varied in structure and fibre type. A 'dummy' was used as a proxy for a human body, which was covered with the recipient garment, and immersed into a barrel of water. The dummy was rotated, lifted from the water and any remaining fibres counted. The study reported a fibre persistence of 20% for smooth polyester fabrics compared to a fibre persistence of 80–90% on textured cotton, fleece and acrylic, emphasising a strong influence from the structure and surface texture of the recipient materials on the persistence [20]. A subsequent study [19] furthered this research by submerging the 'dummy', covered with a cotton t-shirt, in gentle (~0.4 L/s) and medium (~2000 L/s) water flow rates for exposure times ranging from 1 hr to 7 hrs. This second study used both a laboratory and real aquatic environment for testing, specifically; a barrel with running water set-up for the gentle flow rate and the Brussels–Charleroi Canal for the medium flow rate experiment. The difficulty of using real aquatic environments was noted in the Lepot and Vanden Driessche [19] study including the inability to measure actual flow rate. Although these studies have pioneered the investigation of fibre persistence in water, there is still much to be investigated, particularly the effects of being exposed to a variety of real water bodies. In the authors' experience, experiments using rivers, lakes and marine environments are difficult to conduct due to access to waterways, health and safety of the researcher, issues with loss and contamination of samples and finally the ability to account for the dynamic nature of the aquatic environment. A potential solution to these challenges is the use of aquatic mesocosm systems which allow substantial control and monitoring of simulated aquatic environments.

Aquatic mesocosms are model ecosystems constructed to simulate natural bodies of water [10,40]. They are utilised in numerous environmental and ecological studies, including those seeking to better understand ecosystem functioning and global processes [2,24,43,9], studies conducting toxicity tests on aquatic communities [29,46,47] and those addressing environmental policy questions [44]. They are designed to mimic natural conditions in order to create an ideal balance between a controlled and a realistic environment [44]. To date, aquatic mesocosms have not been used in forensic persistence based studies, yet have the potential to improve water-based studies due to their ability to; recreate a real aquatic ecosystem, be easily adapted for different variables, be comprehensively monitored and controlled, enable standardised methods which are easily replicated, and provide; protection from public interference/disturbance, consistent experimental conditions and a safer environment for researchers to submerge and recover samples with constant access.

This study investigates the innovative use of artificial streams (also called flumes) for the investigation of the persistence of polyester fibres on a variety of different textile types under two different flow velocities for a four week exposure time. This study provides new evidence of fibres persisting for as long as four weeks in riverine conditions and outlines the effect of both recipient surface type and flow velocity. This study also critiques the use of mesocosm systems for fibre persistence studies and more broadly the challenges of conducting water related persistence experiments to aid future researchers in this area.

## 2. Methods

### 2.1. Experimental setup: Flumes

The study was performed from 16th June to 14th July 2021 in Lunzer:::Rinnen experimental flumes located in Lunz am See, Austria (47°15'N, 15°04'E). The setup consists of 6 experimental flumes, see Fig. 1, that are 40 m long, 40 cm wide and 40 cm high and fed with natural stream water of the nearby "Oberer Seebach", a third-order subalpine gravel stream that drains a pristine calcareous 20 $km^2$ large catchment with elevations ranging from 600 m to 1878 m above sea level [3].

The stream is summer-cold (6.6–15.0 °C), saturated in oxygen, nutrient poor ($PO_4$-P: <3 µg $L^{-1}$; $NH_4$-N: 4.4 µg $L^{-1}$; $NO_3$-N: 0.57 mg $L^{-1}$), clear (5.4 ± 36.2 nephelometric turbidity unit (NTU)), low in dissolved organic carbon (DOC) concentrations (1–5 mg $L^{-1}$), pH (8.3 ± 0.2) and electrical conductivity of 232.4 ± 13.9 µS $cm^{-1}$ [12].

Water flow in the flumes was adjusted so that three flumes had an approximate discharge of ~0.7 L/s (hereafter referred as to $Q_{Low}$), while the other three had ~2.75 L/s ($Q_{High}$, hereafter), see Fig. 2. These flows resulted in an approximate doubling of the flow velocities $v$ [m/s] of $Q_{High}$ as compared to $Q_{Low}$. Water levels were set to 15 cm due to practical constraints. Channel slope was set to 0.0025 m $m^{-1}$, which would be typical for a slow flowing lowland river.

**Fig. 1.** Image of the Lunzer:::Rinnen experimental flumes during the cleaning and experiment set-up process.

The flume sides and bottom were covered with black ethylene propylene diene monomer rubber (EPDM) liner. The liner was cleaned thoroughly before the experiment so that minimal biofilm on the surfaces inside the flumes were present when the textiles were submerged. The first 2–3 m of all flumes were used as a sedimentation chamber. Water from this chamber was led through a medium-sized mesh (mesh size = 1.2 mm) and a flow equilibrator, consisting of 2 × 1 cm and 40 cm long straight tubes over the full width and height of the flume, to ensure stable conditions. Despite these measures, it was noted that there were some differences in flow velocities and some turbulent flows within the first 1–2 m downstream of the flow equilibrators.

#### 2.1.1. Discharge

Discharge was quantified using salt slug injections and the bucket method. For each flume, we carried out one to two slug injections at the end of the experiment, while 5–10 bucket measurements were performed during the ongoing experiment. For the bucket method, the time needed to fill a 11.8 L bucket was tracked. For the slug injection, the protocols suggested by Moore [23] were followed. This included adding a diluted salt tracer (100–300 g NaCl, dissolved in ~1 L of water) at the flume inlet, and logging electrical conductivity and water temperature at intervals of 10 s or 30 s using conductivity meters (WTW Cond 3210, Weilheim, Germany) placed ~0.5 m above the flume outflow. Slug injections were performed ~2 m from the inlet to ensure stable flow and good mixing. Minimum travel time was calculated as the time between the injection and the time when a first significant increase in electric conductivity occurred; mean travel time was calculated as the time when 50% of the salt mass had passed the outlet logger. Maximum and mean flow velocities were computed as the distance between the injection point and outlet loggers (~37 m) divided by the respective minimum and mean travel time.

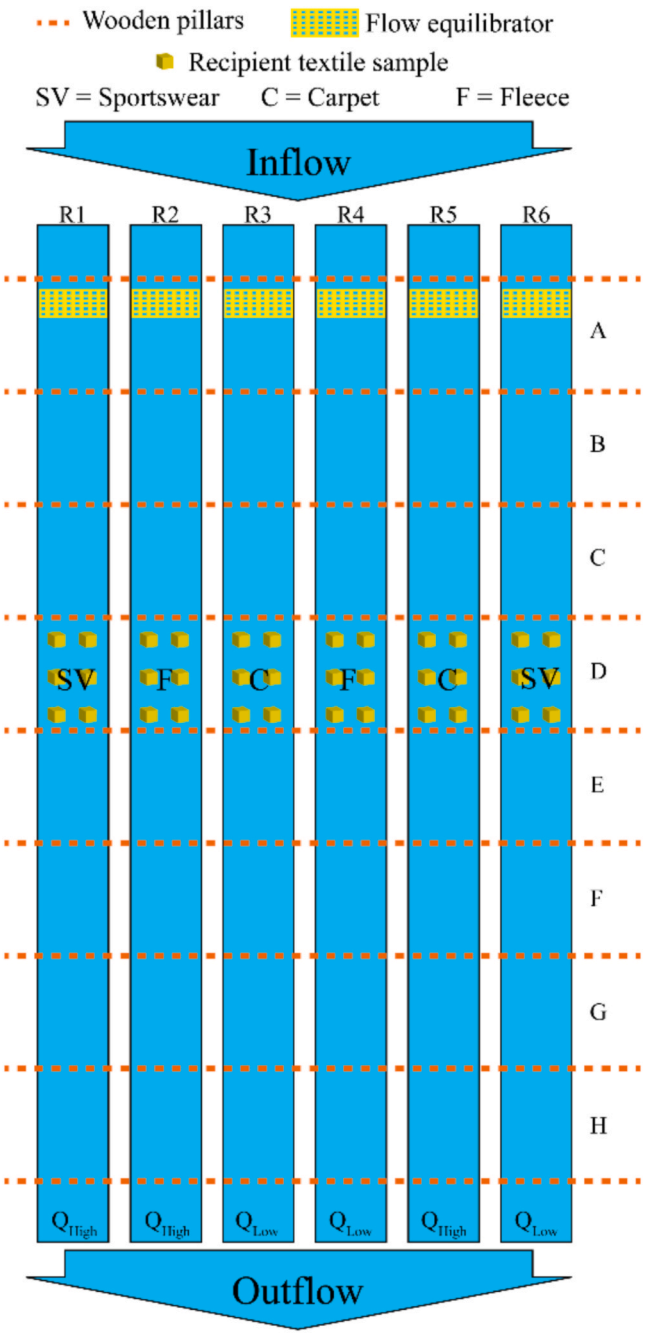



**Fig. 2.** Diagram showing the experimental flumes setup. Stream water was pumped from a header tank through the six experimental flumes.

### 2.2. Experimental set-up: Fibre evidence

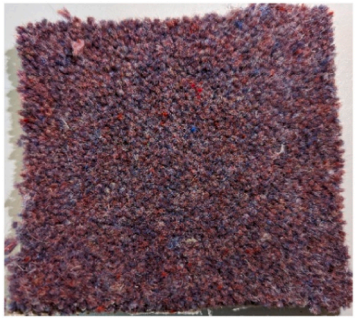
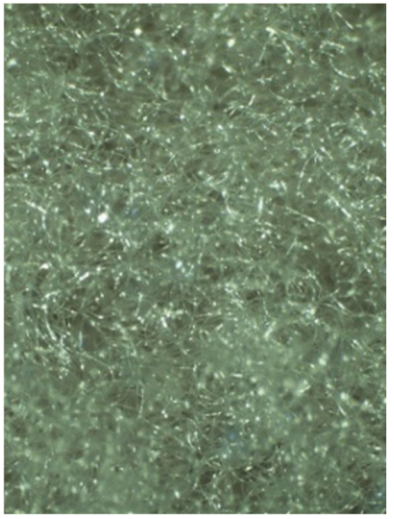
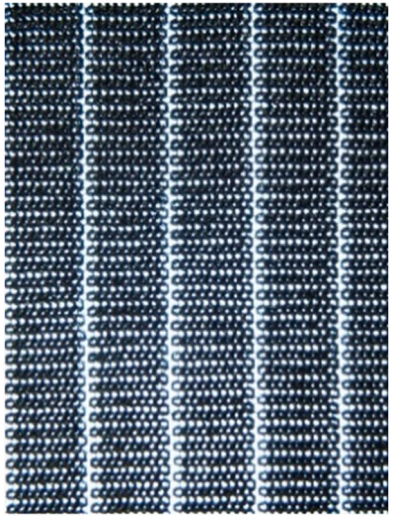
#### 2.2.1. Recipient textiles

Three recipient textiles were chosen which varied in surface texture, weave pattern and sheddability; see Table 1 for details. The textiles were chosen as they displayed a variety of morphological characteristics whilst also being representative of common everyday household and garment fabrics, as these would frequently be present in criminal investigations [20,35,5,7]. Ten control fibre samples were removed from each of the textiles using metal tweezers, mounted on a glass microscope slide in Depex (Refractive Index = 1.52) and analysed using a calibrated Microtec polarized light microscope to record morphological (diameter and cross-sectional shape) and optical properties (birefringence and sign of elongation) and confirm fibre type. Mean diameter of the fibres were calculated by measuring 10 control fibres in five locations along their length. For carpet, 5 of those fibres were wool and 5 were nylon and for sports vest, 4 were polyester and 6 were elastane. All measurements were measured using the Leica DM2700P polarizing light microscope with the DMC600 camera and the measurement tool on the LAS X software. The results of these examinations can be found in Table 1.

#### 2.2.2. Recipient textile preparation

Each of the three recipient textiles were cut into six 10 × 10 cm squares. The size of the textile squares was deemed optimum for transferring and quantifying the donor fibres, placement in the flumes (allowing enough space between samples) and also for the transportation boxes used (plastic boxes sized length = 17 cm, width = 12 cm and depth = 5 cm). Pilot testing showed that if the textile squares were

**Table 1**
Description and Properties of recipient textiles.

| Textile | Carpet | Fleece | Sports Vest |
|---|---|---|---|
| **Fibre type** | Wool/nylon mix | 100% polyester | 95% polyester/5% elastane |
| **Textile description** | Cut pile, rough texture | Knitted, rough texture | Fine mesh microfibre, smooth texture |
| **Mean diameter (μm)** | Wool – 29.7 (n = 5)<br>Nylon – 35.2 (n = 5) | 9.5<br>(n = 10) | Polyester – 10.4 (n = 4)<br>Elastane – 9.1 (n = 6) |
| **Cross-sectional shape** | Cylindrical (wool)/Trilobal and cylindrical (nylon) | Polygonal* | Polygonal* |
| **Sourced from** | Carpet provided by Staffordshire University, UK | Bolt of fabric bought from the Abakhan Haberdashery, UK | Vest tops bought from Primark, UK |
| **Images: Front (seeded side)** |  |  |  |
| **Images: Back** |  |  |  |
| **Images: Close-up (magnification = x40)** |  |  |  |

*identified using the study by Lunstroot et al. [22]

smaller it would encourage the fibres to clump together decreasing accuracy and ease when counting.

#### 2.2.3. Donor fibres

Yellow 100% polyester high visibility fluorescent vests were selected as the donor textile. These fibres fluoresced yellow when illuminated with a hand-held LED torch that emits light at 395 nm. Ten control fibres from the donor garment were analysed using the Microtec polarized light microscope to identify its morphological and optical properties in the same manner as the fibres from the recipient textiles described in Section 2.2.1. The mean diameter and associated standard deviation of these fibres were 14.8 μm and 3.8 (n = 50) and the mean fibre length was 3672.7 μm. The polyester fibres were cylindrical in cross sectional shape. All measurements were measured using the Leica DM2700P polarizing light microscope with the DMC600 camera and the measurement tool on the LAS X software.

#### 2.2.4. Fibre transfer

Fibre transfer and quantification were conducted in an on-site field laboratory (cabin). This room provided a space to safely quantify the donor fibres, protecting them from outdoor conditions that could result in fibre loss, while also creating a darker environment to aid in the visualisation of the fluorescent donor fibres. This also enabled the fibres to be counted on site, minimising the time the textile samples were out of the flumes. The use of fluorescent donor fibres and the availability of a field laboratory on site greatly minimised the risk of contamination during the transferring and quantifying stages.

Prior to donor fibre transfer, the front and back of each recipient textile sample were taped using J-Lar ™ tape and the surface of each of the recipient textiles were checked for the presence of any fluorescent contaminant fibres using the 395 nm torch.

The surface of the donor fabric was roughened using a wooden block covered by fine grade sandpaper, in order to fragment the fibres on the surface of the fabric so they would easily transfer upon contact with the recipient textile. Holding the donor fabric in one hand, front side up, and the recipient textile in the other, while applying constant firm force, the donor fabric was rubbed from one edge of the recipient to the other, to ensure equal contact was made between the entire front side of the recipient textile and the donor fabric. Using the 395 nm torch, the samples were checked to confirm sufficient transfer had occurred (between approximately 100 – 800 fibres). If the number of transferred fibres were insufficient, the contact was repeated. Once fibre transfer was completed, the textile samples were placed in clear clean plastic containers for transportation. Prior to use, the plastic containers were washed and dried with blue paper towel to remove any contaminating fibres.

#### 2.2.5. Quantifying the donor fibres

The donor fibres were quantified using the 395 nm hand held torch and a cell counter. An A4 clear glass sheet, with a 12 × 12 cm grid marked on and labelled horizontally 1–6 and vertically A-F, was placed over the sample in order to improve accuracy of the count. The gridded glass was placed on top of the sample's plastic container with the sample inside to prevent contamination or disturbance of the donor fibres from the glass itself. As an added measure each side of the gridded glass was wiped with blue paper towel before use and between each sample to ensure no contamination occurred. The final count was recorded before the plastic container was sealed and labelled with the textile type, sample number, flume number and fibre count.

#### 2.2.6. Submersion of samples in flumes

The three textile types were split across the three $Q_{Low}$ flumes and the three $Q_{High}$ flumes, see Fig. 2, to limit any cross contamination or redistribution of fibres.The six replicas for each textile type were pegged onto three handmade 'wire fences', made by bending cage style wire fencing at each end to make it stable in the flumes. Each 'wire fence' held two replicates, pegged using plastic laundry pegs on each corner of the sample, that were spaced approx. 10 cm apart, see Fig. 3. Each of the three 'wire fences' were placed approx. 1 m apart in each flume. These 'wire fences' were created so they could stand securely in the flumes, hold the samples at a suitable height to completely submerge them and allow the water to continue to flow evenly through the flumes. Each replicate was secured so that the front of the textile with the tranferred fibres faced downstream and away from the water flow. It is worth noting that the backing material on the carpet samples meant that the water did not pass directly through the sample and instead the water flowed onto the backing and around the textile. This was also true for the other textiles but to a lesser extent as some water would be able to pass through the weave of the textiles.

The six samples in their plastic transport containers were first laid out next to the flumes in numerical order. The samples were then taken out of the container one by one and pegged onto the 'wire fences' whilst wearing blue nitrile gloves, which were changed between each new sample. Once each pair of samples were securely pegged, the 'wire fence' was then carefully submerged in the flume and the time was recorded. This was repeated for all textile types. The attachment process was done as quickly and as carefully as possible so as to prevent disturbance to the donor fibres and limit exposure to the outdoor environment. Following submersion, and subsequent re-submersions of the samples, any fluorescent fibres remaining in the containers were quantified and recorded as the 'fibres lost during transportation' count. See Tables S1-S2 in the Supplementary Materials for these results.

#### 2.2.7. Recovery of samples for quantification

The samples were retrieved at 1 hr, 8 hrs, 24 hrs, 48 hrs (2 days), 120 hrs (5 days), 168 hrs (1 week), 264 hrs (11 days), 336 hrs (2 weeks), 504 hrs (3 weeks) and 672 hrs (4 weeks). At each of the sampling times, the wire fences were removed from the flumes and placed onto wood planks. Each textile sample was then carefully removed and placed into its corresponding plastic transport container. The samples were retrieved following the same order they were immersed. The samples were then moved to the field laboratory and quantified following the same method detailed in Section 2.2.5. The 'total number of fibres persisted' count was determined by counting the number of remaining fibres on the front side of the textile, which the fibres were originally transferred onto. Once all counts were recorded, the samples were re-submerged following the same process detailed in Section 2.2.6. A time limit of 1 hr was set to count the samples in order to limit exposure and prevent any contamination from airborne sources; the exact time when each sample was retrieved (emersion) and re-submerged (immersion) was recorded. See Tables S3-S8 in the Supplementary Materials for these results.

#### 2.2.8. Environmental conditions

Over the 4 weeks, the weather was mainly sunny with rainfall occurring on 50% of the days, with a high of 4.4 mm and a low of 0.1 mm. A total of 72 mm of rainfall occurred, with light rainfall reported during the first half of the experiment and moderate rainfall recorded towards the end of the experiment. The average wind speed over the 4 weeks was 1.08 m/s, with a minimum of 0.2 m/s and a maximum of 5.3 m/s. Weather data can be found in Fig. S9 in the Supplementary Materials.

#### 2.2.9. Data analysis

Fibre counts for each exposure time were converted into percentage persistence values of the original fibre transfer count (at time zero). Outliers were identified in the datasets which were thought to be due to the redistribution of the donor fibres between samples within each flume. Persistence values were determined as outliers when they showed an increase of over 10% since the previous exposure time. A maximum of a 10% increase between each exposure time was agreed to ensure extreme values that may bias the data were removed, while

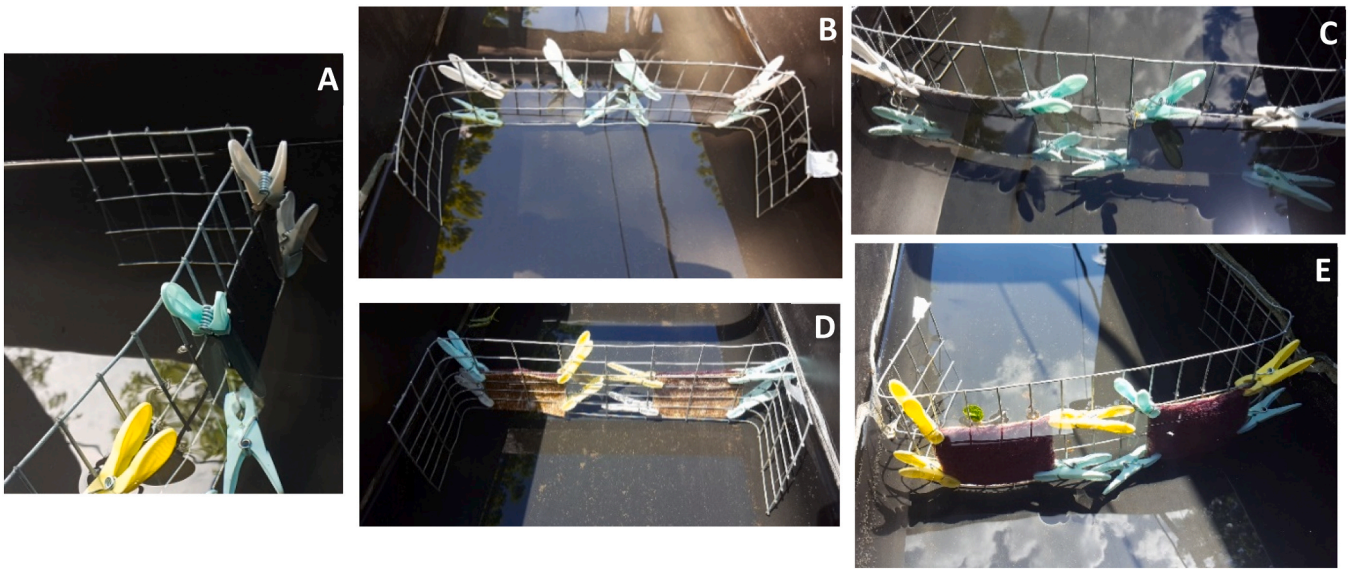



**Fig. 3.** Photographs of the textile samples pegged on the wire fences submerged in the flumes. A – sports vest squares, B & C – fleece squares, D & E - carpet squares.

**Table 2**
Minimum persistence %, maximum persistence %, mean persistence % and standard deviation of fibres including n-values (excluding outliers) for low flow rate ($Q_{Low}$).

| Exposure Time (Hours) | Textile Type | N | Minimum Persistence (%) | Maximum Persistence (%) | Mean (%) | Standard Deviation |
|---|---|---|---|---|---|---|
| 1 | *Carpet* | 5 | 60.8 | 97.1 | 75.7 | 13.8 |
| | *Fleece* | 6 | 53.5 | 96.0 | 80.7 | 15.0 |
| | *Sports Vest* | 5 | 61.7 | 89.2 | 74.8 | 11.0 |
| 8 | *Carpet* | 5 | 61.7 | 86.3 | 69.9 | 9.6 |
| | *Fleece* | 6 | 49.6 | 83.1 | 65.2 | 11.2 |
| | *Sports Vest* | 5 | 38.3 | 71.0 | 58.3 | 12.7 |
| 24 | *Carpet* | 5 | 45.9 | 80.5 | 56.9 | 13.7 |
| | *Fleece* | 6 | 42.5 | 66.8 | 51.1 | 9.9 |
| | *Sports Vest* | 5 | 34.6 | 65.9 | 47.7 | 12.2 |
| 48 | *Carpet* | 3 | 48.2 | 78.1 | 60.5 | 15.6 |
| | *Fleece* | 6 | 41.2 | 64.4 | 51.2 | 9.3 |
| | *Sports Vest* | 5 | 30.4 | 48.9 | 41.1 | 9.1 |
| 120 | *Carpet* | 4 | 46.5 | 75.6 | 57.1 | 12.8 |
| | *Fleece* | 6 | 34.1 | 60.0 | 47.1 | 9.2 |
| | *Sports Vest* | 5 | 23.6 | 51.1 | 37.4 | 10.0 |
| 168 | *Carpet* | 4 | 47.0 | 73.2 | 56.1 | 11.7 |
| | *Fleece* | 3 | 40.3 | 52.9 | 45.0 | 6.9 |
| | *Sports Vest* | 4 | 25.1 | 49.8 | 35.8 | 10.5 |
| 264 | *Carpet* | 4 | 54.6 | 58.5 | 56.8 | 1.9 |
| | *Fleece* | 5 | 27.0 | 62.6 | 45.1 | 13.0 |
| | *Sports Vest* | 3 | 27.8 | 40.7 | 35.7 | 6.9 |
| 336 | *Carpet* | 5 | 49.7 | 82.9 | 61.5 | 13.6 |
| | *Fleece* | 5 | 23.9 | 65.7 | 46.4 | 15.3 |
| | *Sports Vest* | 3 | 35.4 | 50.2 | 40.5 | 8.4 |
| 504 | *Carpet* | 4 | 47.7 | 81.5 | 56.9 | 16.4 |
| | *Fleece* | 5 | 23.3 | 72.6 | 42.5 | 18.5 |
| | *Sports Vest* | 5 | 23.2 | 39.8 | 29.9 | 7.5 |
| 672 | *Carpet* | 4 | 45.5 | 79.5 | 57.3 | 16.0 |
| | *Fleece* | 4 | 22.4 | 71.9 | 46.9 | 20.7 |
| | *Sports Vest* | 4 | 22.8 | 49.8 | 34.1 | 11.4 |

**Table 3**
Minimum persistence %, maximum persistence %, mean persistence % and standard deviation of fibres including n-values (excluding outliers) for high flow rate ($Q_{High}$).

| Exposure Time (Hours) | Textile Type | N | Minimum Persistence (%) | Maximum Persistence (%) | Mean (%) | Standard Deviation |
|---|---|---|---|---|---|---|
| 1 | *Carpet* | 4 | 60.1 | 80.2 | 69.5 | 8.5 |
| | *Fleece* | 5 | 28.9 | 63.2 | 52.8 | 13.8 |
| | *Sports Vest* | 3 | 59.7 | 72.9 | 65.3 | 6.8 |
| 8 | *Carpet* | 4 | 55.8 | 69.5 | 63.8 | 5.9 |
| | *Fleece* | 4 | 45.0 | 63.2 | 55.3 | 7.7 |
| | *Sports Vest* | 3 | 36.6 | 48.6 | 44.1 | 6.5 |
| 24 | *Carpet* | 4 | 54.3 | 67.9 | 60.5 | 7.2 |
| | *Fleece* | 4 | 32.5 | 47.5 | 39.7 | 6.1 |
| | *Sports Vest* | 3 | 36.4 | 39.0 | 37.9 | 1.3 |
| 48 | *Carpet* | 4 | 44.4 | 64.1 | 51.0 | 9.3 |
| | *Fleece* | 4 | 31.4 | 56.7 | 43.2 | 10.9 |
| | *Sports Vest* | 3 | 33.0 | 41.4 | 37.2 | 4.2 |
| 120 | *Carpet* | 4 | 43.8 | 62.6 | 52.1 | 8.0 |
| | *Fleece* | 4 | 31.4 | 53.2 | 41.2 | 9.6 |
| | *Sports Vest* | 3 | 31.8 | 40.7 | 35.8 | 4.5 |
| 168 | *Carpet* | 4 | 50.3 | 61.1 | 55.4 | 4.8 |
| | *Fleece* | 4 | 31.4 | 51.8 | 39.7 | 9.6 |
| | *Sports Vest* | 3 | 25.4 | 38.4 | 33.9 | 7.4 |
| 264 | *Carpet* | 3 | 45.1 | 50.9 | 48.5 | 3.0 |
| | *Fleece* | 3 | 41.6 | 48.8 | 45.0 | 3.6 |
| | *Sports Vest* | 3 | 28.3 | 33.1 | 30.2 | 2.6 |
| 336 | *Carpet* | 4 | 40.5 | 67.2 | 50.9 | 11.5 |
| | *Fleece* | 4 | 27.8 | 51.1 | 37.6 | 9.7 |
| | *Sports Vest* | - | - | - | - | - |
| 504 | *Carpet* | 3 | 33.3 | 55.0 | 44.3 | 10.8 |
| | *Fleece* | 5 | 28.4 | 53.2 | 38.6 | 9.5 |
| | *Sports Vest* | 3 | 21.9 | 29.7 | 25.3 | 4.0 |
| 672 | *Carpet* | 4 | 30.9 | 46.6 | 39.1 | 6.7 |
| | *Fleece* | 4 | 27.2 | 40.6 | 33.4 | 6.7 |
| | *Sports Vest* | - | - | - | - | - |

simultaneously allowing for natural variation and movement of the fibres during the experiment. Please see Tables 2 and 3 for the minimum persistence (%), maximum persistence (%), mean persistence (%) and standard deviation with outliers removed, for each exposure time and recipient textile type for $Q_{Low}$ and $Q_{High}$ respectively. See Figs. 4, 5 and 6 for mean fibre persistence (%) (and standard deviation bars) at all exposure times for each recipient textile for $Q_{Low}$ and $Q_{High}$ respectively. Graph points have been slightly staggered around each exposure time so that the standard deviation bars can be easily viewed.

A series of Kruskal-Wallis tests were conducted using SPSS version 28 to compare recipient textile types for each exposure time and flow rate (a total of 20 tests). To compare the fibre persistence between $Q_{Low}$ and $Q_{High}$ for each recipient textile and exposure time, a series of Wilcoxon sign rank tests using SPSS version 28 were conducted. A significance level of 0.05 was used for all tests.

## 3. Results and discussion

This study investigated the persistence of polyester fibres on three recipient textiles (carpet, fleece, and sports vest) when submerged in an experimental riverine environment, referred to as 'flumes'. Two flow rates were tested ($Q_{Low}$ and $Q_{High}$) at 1, 8, 24, 48, 120, 168, 264, 336, 504 and 672 hrs. This is the first study to use a mesocosm to test the persistence of fibres evidence and its benefits and limitations are discussed later in this section. Experiments were conducted without any major incidents or change in environmental conditions (e.g. extreme weather, Fig. S9 in the Supplementary Materials). No obvious degradation was observed on the recipient textiles even after 4 weeks with the textiles maintaining their integrity and consistency throughout. For both $Q_{Low}$ and $Q_{High}$, there was a high initial loss of fibres in the first 24 hrs, with mean persistences of 75.7%, 80.7% and 74.8% for low flow rate and 69.5%, 52.8% and 65.3% for high flow rate for carpet, fleece and sports vest respectively. This high initial loss is typically found in many persistence studies [13,25,31,4,48] including those that submerged the fabrics in water [19,20]. This can be explained by the loss of loosly bound fibres as described by Pounds and Smalldon [32]. These loosly bound fibres will be washed off during initial submergence and then further as the fabric is exposed to the dynamic flow of water. After 24hrs, the effect of the more medium bound and strongly bound fibres was seen with the number of fibres lost reducing. Persistence rates in most instances did not decrease in a smooth linear way and instead appeared as a sawtooth pattern, which was also seen by Lepot and Vanden Driessche [19] in their medium flow experiment in a canal. This sawtooth pattern, which indicates an increase in the percentage of fibres compared to the previous exposure time for that particular fabric, can partly be explained by the redistribution of the fibres from one sample to another and the large variance seen between replicates, as indicated by the maximum and minimum values, which will have affected the mean persistence values. The high variance seen between replicates in some samples is to be expected due to the realistic conditions being used. It would be expected that variance in persistence values would be lower for these textiles in controlled laboratory environments.

Redistribution of donor fibres was not the focus of this study, therefore the exact movements of transferred fibres from one recipient fabric to another was not monitored; to do this, different coloured donor fibres would be needed, to allow their movement to be tracked. Although not specifically monitored, the increase of fibres seen between exposure times may indicate redistribution has occurred and it is this increase this study has used to note the presence or absence of redistributing fibres. In this study, redistribution occurred after 48 hrs of exposure in $Q_{Low}$ for carpet and fleece and after 120 hrs, 168 hrs and 336 hrs of exposure in $Q_{High}$ for carpet. This redistribution primarily occurred after 24 hrs of exposure (apart from the 8 hrs in $Q_{High}$ for carpet). Excluding the 336 hrs in $Q_{Low}$, where all three textiles exhibited redistribution, there were no other obvious points in time where this occurred more. Flow rate did not appear to substantially affect the number of instances of redistribution with 9 instances for $Q_{Low}$ and 7 instances for $Q_{High}$. The carpet and the fleece showed a greater number of instances of redistribution than the sports vest; with 7, 8 and 2 instances being seen respectively, which could be explained due to the difference in surface textures; the rougher upright fibres of the carpet and fleece are more likely to catch the redistributing fibres than the smoother fibres of the sports vest. Due to the lower number of instances of redistribution, the sports vest exhibited a more traditional exponential profile of fibres loss seen in previous studies. Very few persistence studies discuss or highlight redistribution. Studies, such as Robertson et al. [36] investigated how redistribution affects the specific location of the donor fibres and if their location can subsequently provide accurate context to the crime committed rather than on the effect redistribution between recipient garments or replicates might have on the persistence rate itself. Robertson and Lloyd [37] observed that between 13% and 38% of wool/nylon donor fibres redistributed after 225 min of activity

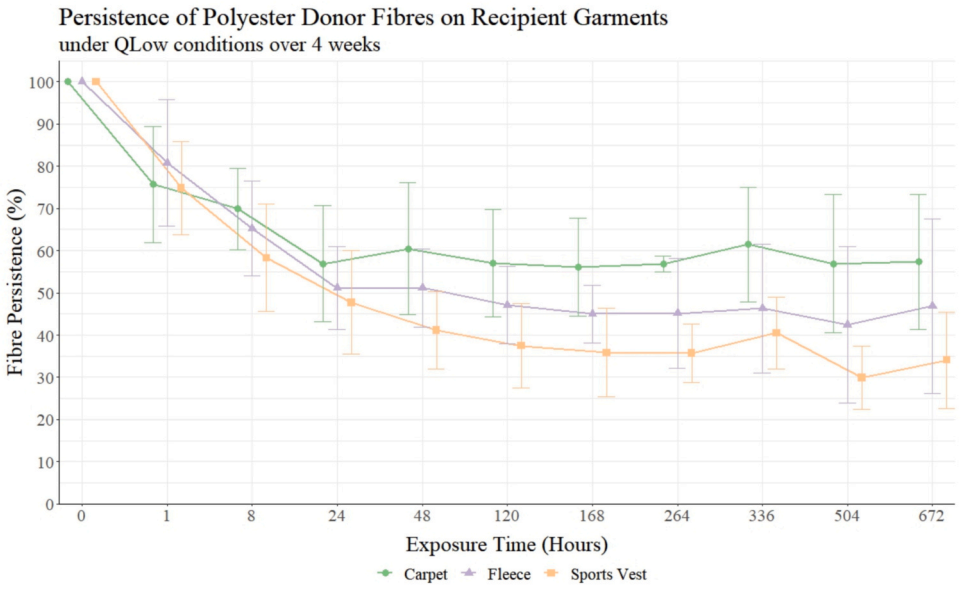



**Fig. 4.** Mean percentage persistence of polyester donor fibres on the three recipient textiles exposed to low flow rate ($Q_{Low}$), including standard deviation bars (please note that these have been slightly staggered to allow ease of viewing).

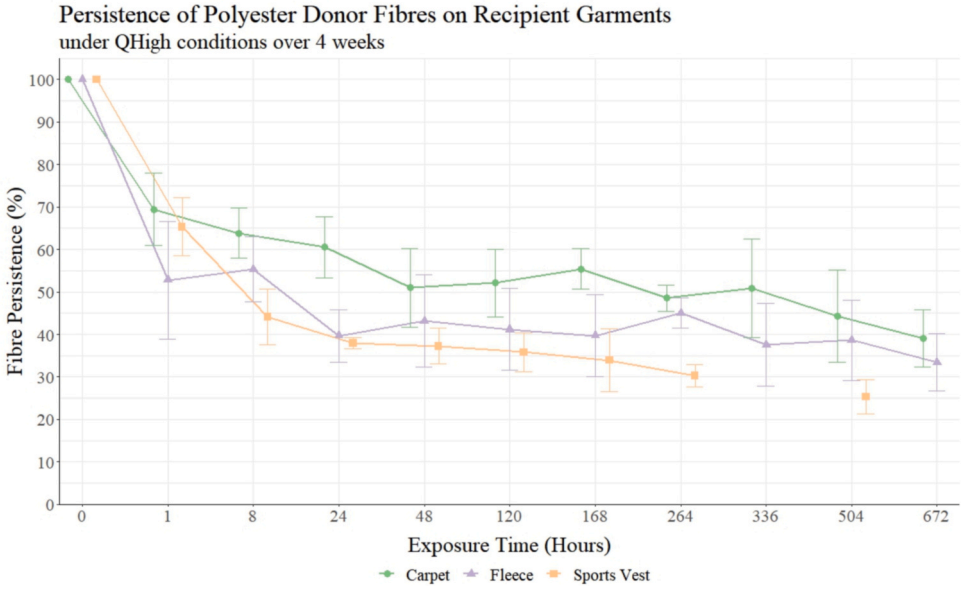



**Fig. 5.** Mean percentage persistence of polyester donor fibres on the three recipient textiles exposed to high flow rate ($Q_{High}$), including standard deviation bars (please note that these have been slightly staggered to allow ease of viewing).

after being transferred to fabric squares that were attached to volunteer's clothing. Szewcow et al. [45] showed that the introduction of water greatly increases this redistribution percentage, with 50–100% of persisting fibres (acrylic, wool and viscose donor) being redistributed away from the initial target area following the washing of garments, in a washing machine. Both Palmer and Polwarth [27] and Lepot et al. [20] visually observed minimal redistribution of fibres but did not quantify or detail this. It appears in this study, that the redistribution happens at a local level, as the dislodged fibres are lost from one recipient sample into the water, a few directly 'contaminate' to another sample while the rest of them are swept away. The amount of fibres transferred to the water could be analysed in further studies by taking water samples at different points along the flumes and filtering them using a filtration system, as used in microplastic studies [11]. Irrespective of the differences in flow rate in this study, the movement of water evidently facilitates the redistribution of the fibres once they have been lost.

This study investigated persistence for a greater exposure time than many other studies; typically studies have maximum time frames of 8 hrs [31,33,41], to 12 or 14 days [5,27] respectively), with the longest exposure to an aquatic environment being 7 hrs [19]. Even after 4 weeks (672 hrs), the lowest percentage of remaining fibres was 33.4% (fleece in $Q_{High}$ conditions). This clearly indicates that it is extremely valuable to search for fibre evidence even after a long exposure time.

### 3.1. *Effect of textile type on the persistence of fibres*

At $Q_{Low}$ (Fig. 4), the three recipient textiles showed a high initial loss of fibres with fairly similar decreases in fibre persistence at 1 hr, 8 hrs and 24 hrs. After 48 hrs, the decrease in fibre persistence begins to plateau but the effect of the textile type becomes clear with persistence being highest on carpet and lowest on the sports vest, correlating with their respective roughness of surface texture. These textiles continued to demonstrate this same hierarchy of persistence for the remaining exposure times. Fig. 5 shows that the same initial loss occurred for all three textiles for $Q_{High}$ as with $Q_{Low}$, with the loss highest for the fleece textile. Similar to $Q_{Low}$, the textiles demonstrated differences after the initial loss; with the sports vest exhibiting the highest loss followed by fleece and carpet. Two data points are missing for the sports vest (336 hrs and 672 hrs), this was unfortunately caused by the loss of these data points during the quantification process.

For $Q_{Low}$, there was a significant difference in fibre persistence between textile types at only one exposure time (504 hrs, $p = 0.032$). All other exposure times showed no significant difference ($p > 0.05$). For $Q_{High}$, significant differences in fibre persistence between recipient textiles were seen at 8 hrs ($p = 0.041$), 24 hrs ($p = 0.024$), 168 hrs ($p = 0.042$) and 264 hrs ($p = 0.039$). This indicates that textile type only has a significant effect when subjected to the higher flow rate, albeit it not at every exposure time. The differences seen in the construction of the carpet compared to the sports vest, where the upright course carpet fibres can easily trap transferred fibres, is likely to be the reason for the significant difference seen between the textiles at these exposure times. This effect of fabric construction is regularly seen in other persistence studies [1,14,16,17,20,31,4] with rougher surfaces retaining a higher percentage of fibres as the texture enables more fibres to bind strongly to the fabric. While the smoother surfaces, in this case the sports vest, create a more difficult environment for the fibres to bind to, resulting in lower fibre retention. The presence of the backing on the carpet could also contribute to the high fibre persistence due to the differences in the way the water flows through or around the different textiles. Regardless of flow rate, the textile types keep the same order of highest to lowest persistence over the 672 hrs, illustrating the overarching effect of fabric construction.

### 3.2. *Effect of flow rate on the persistence of fibres*

From Fig. 6, it is clear across all textile types that a higher flow rate does result in decreased persistence, with the highest initial loss for $Q_{High}$ reaching ~48% (in fleece) compared to ~25% for $Q_{Low}$ (in carpet and sports vest). Research from Lepot and Vanden Driessche [19] also showed a higher intial loss of fibres during the immersion in medium (~2000 L/s) flow water conditions (~25% loss), compared to gentle (~0.4 L/s) flow water conditons (~15% loss). They explain that the immersion stage has the greatest effect on the fibre persistence due to the loss of the loosely bound fibres. After an exposure time of 24 hrs, $Q_{High}$ and $Q_{Low}$ persistence rates plateaued and showed similar persistence ranges (~40–65% for $Q_{High}$ and ~45–55% for $Q_{Low}$.) After the first hour of submergence, there was an average loss per hour of ~1% for $Q_{Low}$ and ~1.5% for $Q_{High}$, which is similar to those reported by Lepot & Vanden Driessche [19], who noted 1 ± 2% and 1.5% loss per hour for gentle and medium flowing water respectively. At 672 hrs, the textiles under $Q_{Low}$ conditions retained ~ 10–20% more fibres than those under $Q_{High}$ conditions, with an mean of ~8% more fibres persisting on $Q_{Low}$

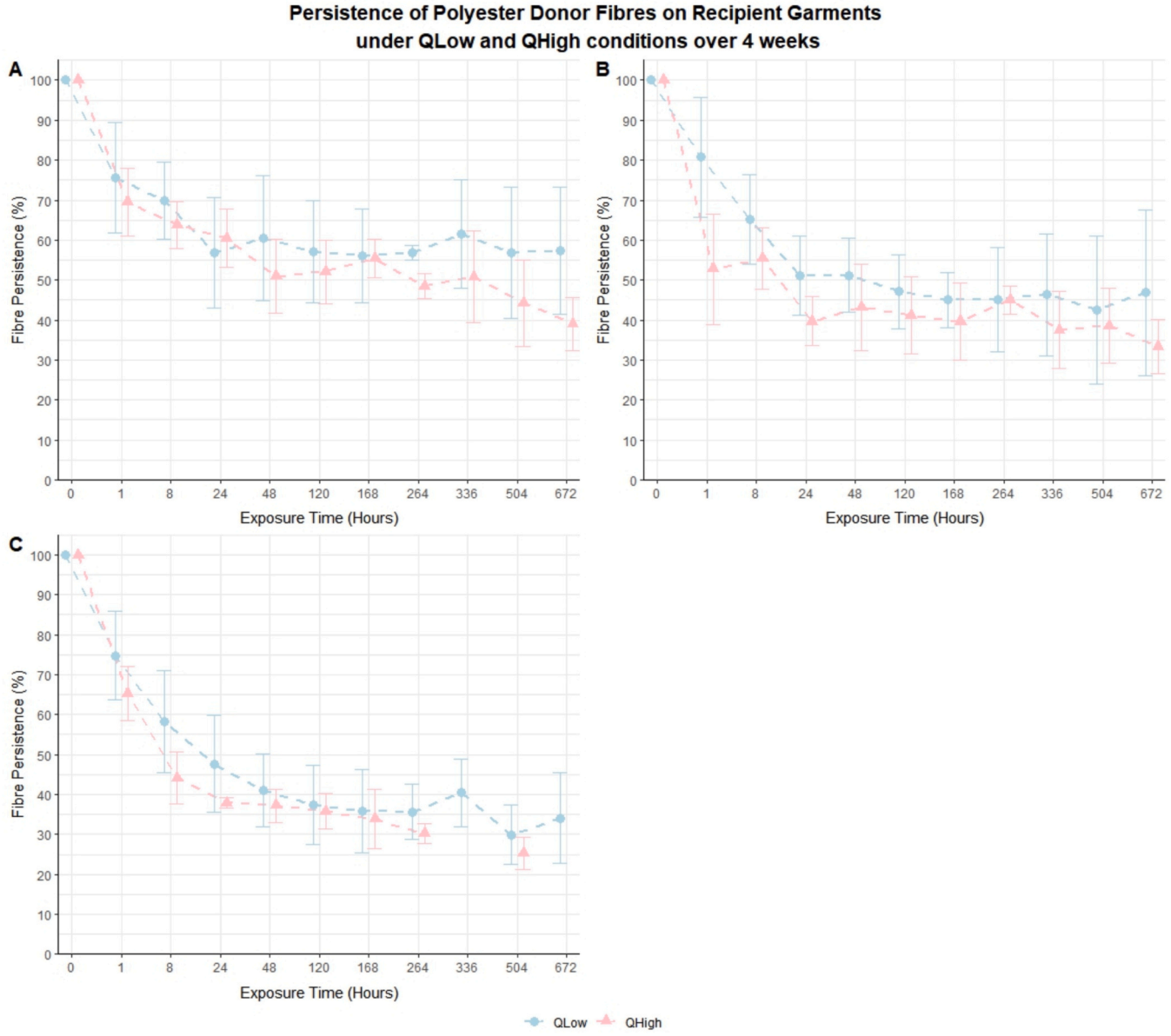



**Fig. 6.** Graphs depicting the mean percentage persistence of polyester donor fibres on the three recipient textiles when exposed to low flow rate ($Q_{Low}$) and high flow rate ($Q_{High}$), including standard deviation bars (please note that these have been slightly staggered to allow ease of viewing). A = Carpet, B = Fleece, C = Sports vest.

garments throughout the total exposure period.

It would be expected that a higher flow rate would have a lower number of retained fibres compared to a lower flow rate yet no significant difference was seen in all but one condition. There was no significant difference in fibre percentage persistence between $Q_{Low}$ and $Q_{High}$ at any exposure time for carpet or sports vest ($p > 0.05$ in all cases) but there was a significant difference in fibre persistence between $Q_{Low}$ and $Q_{High}$ for the fleece textile after 1 hr of exposure only ($p = 0.043$); all other exposure times resulted in no significant difference for this textile. Due to this, there is no clear evidence to demonstrate whether the flow rates used in this study had a significant effect on fibre persistence. It is possible that with a greater differential between flow rates, a significant difference may be seen.

### 3.3. *Use of mesocosms in persistence studies and limitations of experiment*

Lepot and Vanden Driessche's [19] study compares a greater difference between their 'gentle' and 'medium' flow rates, in contrast to this study's $Q_{Low}$ and $Q_{High}$, but they note that the realistic environment of the medium water conditions created difficulty when attempting to consistently monitor the fibre persistence, due to variables such as boat activity and fish interference, which produced large variations in the results. In comparison, this study has shown that mesocosms hold potential for conducting water based persistence studies. The ability to control and monitor flow velocity of the water has obvious benefits over submergence in real rivers, where controlling flow is not possible and monitoring of flow velocity is thought to be more problematic. Animal interactions in real environments has been noted as potentially affecting fibre persistence and is a disadvantage of using real environments as these interactions are difficult to monitor [19,27]. The absence of boats and aquatic organisms in the mesocosms is likely to have affected the persistence rates and as such, can not be thought of as a completely realistic environment. The potential differences between mesocosms and real rivers is worthy of further investigation.

Although mesocosms allow detailed and controlled monitoring of the water conditions, the ability to gain similar information about real river conditions is still possible, albeit not controllable. In other disciplines, specifically hydrology, the measurement of stream flow and availability

of the data are essential and are therefore widely available. This data also informs local authorities about flood risks and supports flood forecasts. Hydrometric measurements of water level surface elevation and/or volumetric discharge are routinely carried out, and automated equipment for assessing water level is cheap and easily accessible. The data can usually be downloaded free of charge from online data portals. The national hydrological services in Austria (e.g., for streams in Lower Austria: https://www.noe.gv.at/wasserstand/#/en/Messstellen) provide discharge observations and forecasts for most major streams and rivers in the country. Handheld probes are also standard equipment and easy to use to measure the flow velocity in any given stream. Their use could be implemented, when an aquatic crime scene is established, to record this data to aid in the intepretation of recovered trace evidence.

The use of mesocosms is a safer alternative to real bodies of water, where access may be difficult and dynamic changes in the water level can lead to dangerous conditions. The mesocosms in this study had a field based laboratory next to it, which provides researchers with a protected location which can be used for counting the donor fibres at each exposure time. Having access to such an environment reduces the chance of fibre loss during quantification and provides an opportunity to have a fully darkened room to better view the fluorescent fibres.

No substrate was used in the base of the flumes nor any plants introduced to the mesocosms for this particular study which may have affected results. For example, in real river environments, plant material and riverbeds may trap fibres which have not persisted and prevent further redistribution. Fortunately, the flumes in this study allow for different set-ups including the presence of different riverbeds; this is beneficial for future studies where riverbed substrate could be an additional variable tested.

The method chosen to transfer donor fibres from a donor garment, by roughening the surface of the donor garment to ensure fibres are fragmented and available for transfer, has been commonly used in fibre persistence studies; [30,31], Kidd and Robertson [14], Robertson et al. [36], Robertson and Llyod [37], Scott [41], Akulova et al. [1], Palmer and Burch [26], DeBattista et al. [5], Skokan et al. [42] & Prod'Hom et al. [33]. This approach has the potential to weaken the fibres in a less realistic way when compared to a natural direct contact between clothing. This weakening could potentially cause the fibres to continue to fragment throughout the study, whilst on the recipient textiles, possibly increased by the pressure of the waterflow. This may also contribute to the sawtooth pattern seen in the persistence profiles of the recipients. The potential effect of weakening and fragmentation of the donor fibres has not been investigated in this study but would be useful to examine in future studies.

Further research into the use of other types of mesocosms, such as those that mimic still freshwater and marine environments, for fibre transfer and persistence studies, would also be useful. Fibres were the focus of this study, yet mesocosms could also be an appropriate approach for investigating the persistence of other evidence types, such as hair, gun shot residue, glass and DNA.

## 4. Conclusion

This study investigated the persistence of fibres on different recipient textiles in an aquatic environment through the novel use of mesocosms that mimic riverine ecosystems. An initial loss of fibres was seen with all three textile types (carpet, fleece and sports vest) in both low flow ($Q_{Low}$) and high flow ($Q_{High}$) conditions. Fibre persistence for each textile is similar at 1 hr, 8 hrs and 24 hrs of exposure but textile type began to have an effect at 48 hrs.

Mesocosms have shown to have specific benefits for forensic transfer and persistence studies. This includes being a safer alternative to real waterways and allowing for variables such as flow velocity to be controlled whilst still creating a realistic environment including limited biological activity. Previous studies in this area [19], noted the difficulty in using real-water environments and that assumptions had to be made about what is happening within the water environment. This study uses an innovative approach to investigate fibre persistence on different recipient textiles submerged in flowing water continously for 4 weeks and has observed that fibres do in fact persist in this environment for this length of time, with a high possibility of them persisting longer than this. This indictates the importance of searching for fibre evidence even after a long exposure time in aquatic environments contrary to current beliefs held by forensic practitioners, according to the ENFSI European Fibres Group survey [8]. Additionally, this is the first study to use mesocosms for any forensic persistence study and has demonstrated the potential for this experimental set-up for future persistence studies.

## CRediT authorship contribution statement

**Afsané Kruszelnicki:** Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualisation, Project administration, Funding acquisition. **Jakob Schelker:** Investigation, Resources, Writing – original draft, Writing – review & editing, Project administration. **Barbara Leoni:** Investigation, Writing – review & editing. **Veronica Nava:** Investigation, Writing – review & editing. **Jovan Kalem:** Investigation. **Katrin Attermeyer:** Investigation, Resources, Writing – original draft, Writing – review & editing, Project administration. **Claire Gwinnett:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualisation, Supervision, Project administration, Funding acquisition.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.forsciint.2023.111818.

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