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Predicting flushed wet wipe emissions into rivers

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ABSTRACT

Flushed wet wipes pose a significant pollution risk to river systems at both macro and micro levels. However, the link between their emissions and environmental contamination remains unclear. Here we integrated emissions-based modelling with existing data on wet wipe disposal and microfibre generation to predict the quantity of emissions entering river systems and the transport pathways involved. Results indicate that wastewater pathways, including sewer overflows, wastewater treatment plants, and agricultural runoff, are major conduits for these pollutants. Despite advanced wastewater treatment, substantial microfibre emissions still enter the environment. Extrapolating to larger scales reveals wet wipe pollution as an international issue requiring urgent attention. This research offers a comprehensive modelling framework applicable to various wastewater pollutants, providing valuable insights for policymakers and the water industry. Improved data on wet wipe disposal, fate, and spatially distributed wastewater systems are necessary to pinpoint their environmental risks more accurately.

1. Introduction

Driven by current hygiene standards and consumer convenience (Shruti et al., 2021), the prevalence of wet wipes and their improper disposal threatens river systems (Ó Briain et al., 2020). When flushed down the toilet, these wipes navigate wastewater systems, either resisting degradation due to their material strength and aggregation properties, or physically breaking down into large volumes of microfibres (Pantoja-Munoz et al., 2018; Durukan and Karadagli, 2019; Atasagun and Bhat, 2020). Undegraded or partly degraded ‘solid’ wet wipes are notorious for blocking sewers and causing overflow, which lead to raw sewage spilling into rivers (Drinkwater and Moy, 2017; Giakoumis and Voulvoulis, 2023). Furthermore, wet wipe microfibres, mainly composed of plastic or cellulose, can be ingested by aquatic wildlife, act as vectors for surrounding pollutants, or release harmful chemical additives (McCoy et al., 2020; Ó Briain et al., 2020; Allison et al., 2023).

Despite widespread public knowledge and regulatory advisories against the flushing of wet wipes, improper disposal remains a persistent issue. To thoroughly assess the environmental risks created by these flushed wipes, we first need to know the quantities likely to enter river systems. Studies estimating solid wet wipe emissions to wastewaters and microfibre generation under wastewater conditions provide valuable first insights to understanding the environmental fate of wet wipes (Lee et al., 2021; Kwon et al., 2022; UKWIR, 2022). However, they focus on the initial disposal stage of wipes into wastewaters. Lack of quantified understanding of the ‘journey’ of each wet wipe flushed down the toilet precludes any quantification of wet wipes emissions to rivers, and ultimately to seas and oceans. Preventing the flushing of wet wipes is a key mitigation strategy, but understanding their transport through wastewater systems is essential for developing further targeted solutions. This study aims to contribute to that effort.

Emission-based mathematical models, which estimate the input, output, and transport pathways of specific pollutants within a system, have proven effective in quantifying plastic emissions to rivers from wastewaters (Nizzetto et al., 2016; Siegfried et al., 2017; van Wijnen et al., 2019; Kawecki and Nowack, 2020). However, no models have specifically focused on wet wipes or their microfibres, despite significant numbers entering wastewaters and their potential environmental impacts.

Here, we present the first comprehensive model to quantify likely wet wipe emissions to rivers by integrating available data on flushed wet wipe disposal and their microfibre generation behaviour with emission-based mathematical modelling. In turn, we: 1) parameterise an emission model that traces the entire ‘journey’ of flushed wet wipes from

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wastewater systems to rivers, 2) identify the main entry points of flushed wet wipe into rivers and quantify their predicted contributions, 3) apply our modelling framework to estimate wet wipe emissions across both UK and EU rivers, and 4) contextualise the impact of wet wipe pollution by comparing their river emissions with those of laundry microfibres. This work provides the first large-scale quantification of wet wipe pollution, revealing the key pathways and the environmental hazards associated with both solid and microfibre forms of wet wipes.

2. Materials and methods

2.1. Overview of the emission model

We developed our wet wipe model by integrating microplastic emissions modelling with experimental models of wet wipe microfibre generation in wastewater systems. The emissions approach identifies point-source mass inputs of micropollutants through a system into the environment, while the experimental models simulate how different wet wipe materials behave in simulated wastewater systems, focusing on their disposal, microfibre shedding, and transport dynamics. This integrated model allowed us to identify likely wastewater transport pathways and controlling parameters for two emissions scenarios: flushed solid wet wipes and fragmented wet wipe microfibres (Fig. 1). In both scenarios, we focused on wet wipes made with either plastic-based or cellulose-based fibres to understand the broader impacts created by commonly flushed wet wipes.

2.2. Study catchments

Wastewater systems in our modelling study were based on local sewer overflow (SO) data. SOs refer to any spills from the sewer system and wastewater treatment plants (WWTPs) when capacity is exceeded. As visualised in Fig. 2, we analysed SO operational data from two UK river sub-catchments with varying urbanisation levels: a semi-urban sub-catchment (Taff; 83 km^2 area; 1223 inhabitants/km^2, calculated using a weighted average of SO catchment areas; 26 SOs) and a rural sub-catchment (Wye; 392 km^2 area; 311 inhabitants/km^2; 18 SOs).

Due to the lack of data directly connecting populations to SOs, we developed a method to delineate SO drainage areas using local elevation data (SRTM, 2013) and flow direction modelling in QGIS version 3.26.0 (See Fig. 2). This approach was essential for estimating wet wipe emissions from connected populations into wastewater systems. We assumed SO drainage areas corresponded to the natural wastewater catchments, and this was validated using topographical data in QGIS.

Population data for the catchments was sourced from Lower-layer Super Output Areas (LSOAs), which provide local demographic statistics (Ministry of Housing, 2019), while urban areas within these boundaries were identified using Corine Land Cover geospatial data (Copernicus, 2018).

2.3. Point source inputs to wastewater

Wet wipe inputs to rivers via wastewater systems in our model

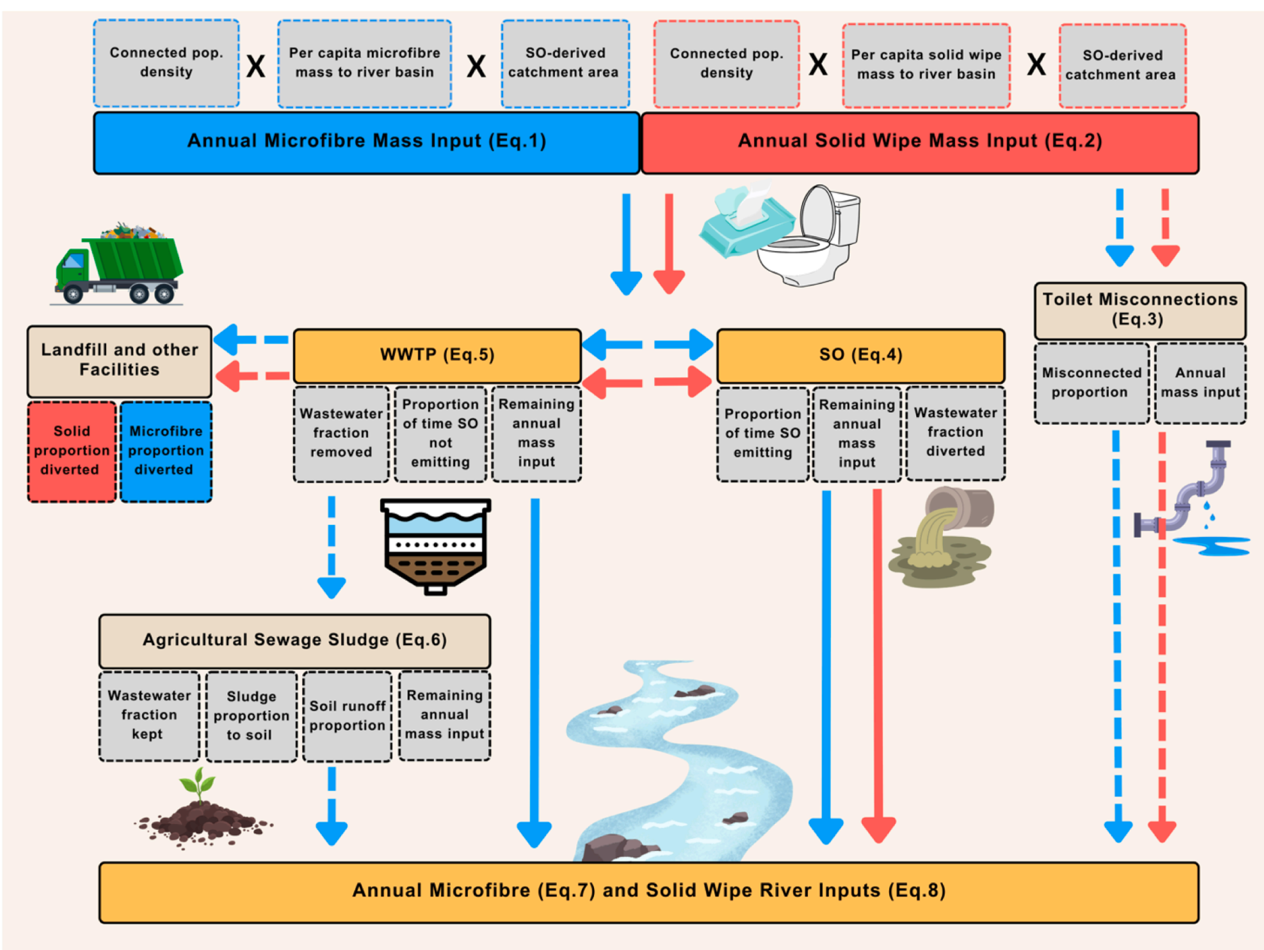

Fig. 1. Wastewater Emission Pathways and Parameter Inputs. Colour schemes represent modelled microfibre (blue) and solid wipe (red) emissions, with pathways categorised by lowest (orange; solid arrows) and greatest (beige; dashed arrows) uncertainty. Parameter inputs for each pathway are shown in grey and detailed in the methods, with corresponding equations attached to their respective pathways.

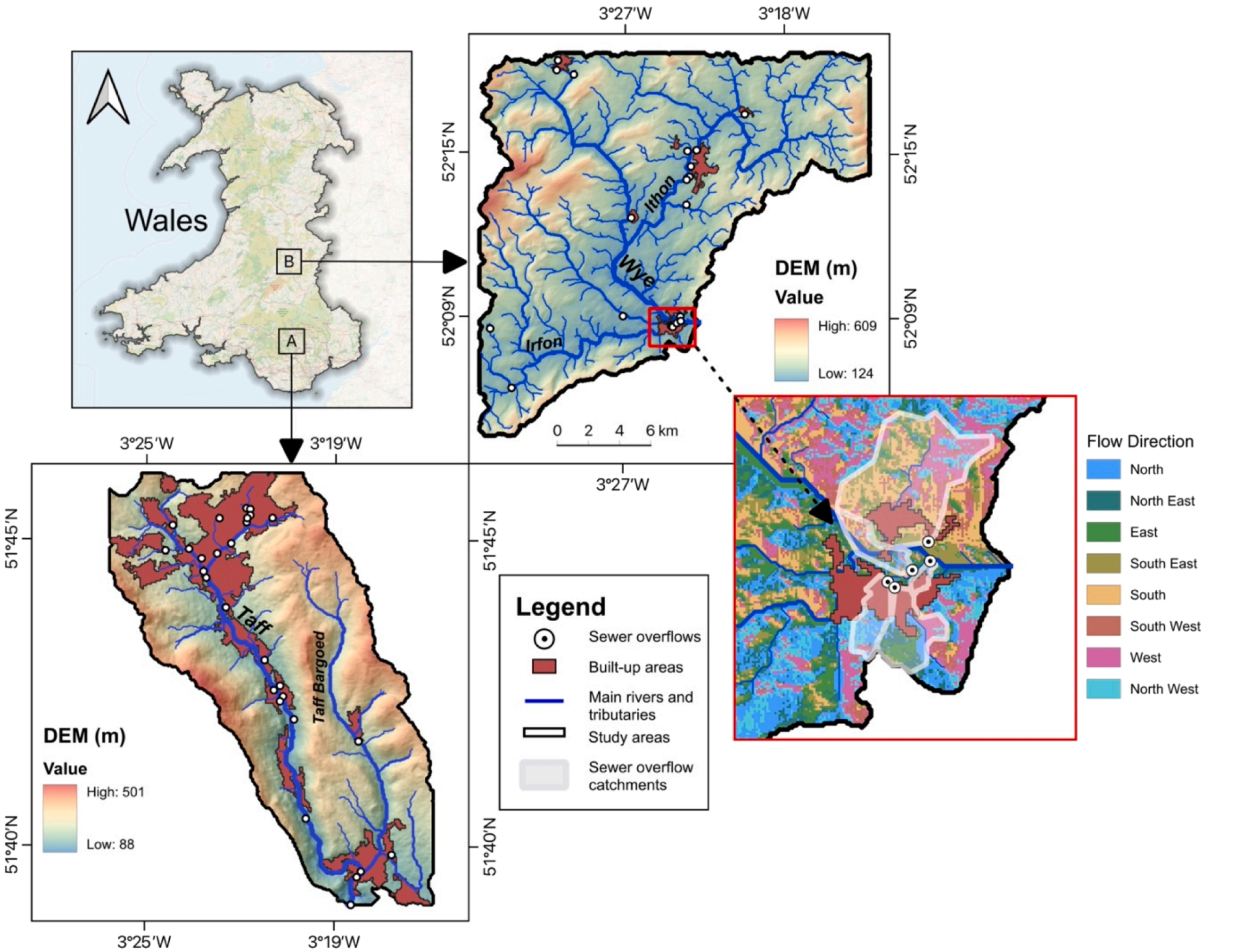

Fig. 2. Our two sub-catchment study sites: A) Taff sub-catchment, B) Wye sub-catchment, showing publicly available sewer overflow locations, an example of delineated overflow drainage areas, surrounding built-up areas, and main rivers and tributaries. Delineated drainage areas were essential for applying our emissions model to any geographical area by identifying populations connected to each overflow. Map generated using the QGIS 3.36 software. OSM data provided by © OpenStreetMap contributors URL: https://www.openstreetmap.org/.

depend on several wastewater parameters, including per capita input of solid wet wipes and microfibres, SO catchment area size, and population density. We assumed full population connectivity to wastewater systems while accounting for sewer misconnections. The input of wet wipe microfibres into wastewater systems via toilet flushing is calculated as:

$$WWi_{wmf} = PDenCon \times MFG_{cap} \times SOA \quad (1)$$

where WWi_{wmf} is the total mass of wet wipe microfibres entering wastewater systems from each sub-catchment (g/y); *PDenCon* is the population density connected to the sewage system within the SO catchments (capita/km^2); MFG_{cap} is the estimated annual mass release of wet wipe microfibres in wastewater systems per person (g/capita/y); and *SOA* is the wastewater catchment area derived from SOs (km^2).

Similarly, the input of solid wet wipes is calculated as:

$$WWi_{ws} = PDenCon \times SG_{cap} \times SOA \quad (2)$$

where WWi_{ws} is the total mass of solid wet wipes entering wastewater systems from each sub-catchment (g/y); and SG_{cap} is the estimated annual mass input of solid wet wipes in wastewater systems per person (g/capita/y).

To calculate *PDenCon*, we delineated geomorphological catchments for each SO and estimated population using several methods. In straightforward cases, we multiplied the LSOA population by the SO catchment area (*SOA*). For more complex regions with overlapping built-up areas or varied population densities, adjustments were made as follows for accuracy. If large catchments inflated LSOA estimates, we used the portion of built-up area around each SO to refine the population estimate. Where no built-up area existed, we used the default LSOA density. In catchments entirely within built-up areas, the LSOA population density was applied. When SO catchments overlapped multiple LSOAs, the population density was averaged.

2.4. Estimation of wet wipe mass inputs

UK annual mass inputs for plastic and cellulosic solid wet wipes (SG_{cap}) and their microfibres (MFG_{cap}) were estimated based on several assumptions. Annual UK wet wipe consumption is 11 billion, with 90 % plastic and 10 % assumed cellulosic (Water UK, 2022; BBC, 2023). Of these, about 2.5 billion wipes (23 %) are flushed annually (UKWIR, 2022), equating to an average 33.2 plastic wipes and 3.69 cellulosic wipes flushed per person, based on the 2023 UK population of 67.78 million (United Nations, 2023).

For microfibre generation (MFG_{cap}), we used three case scenarios – best, worst, and average – based on mass ranges from Kwon et al. (2022). The best-case represents the lower bound, worst-case the upper bound, and average-case the mean (Table 1). Wet wipes were categorised into three types: 1) natural cellulosic fibres, 2) regenerated cellulosic fibres,

Table 1
Microfibre generation data for wet wipes under wastewater conditions adapted into our modelling system from existing literature. Values not in brackets represent mean (average-case) scenarios, while the lower bound and upper bound values in brackets represent best- and worst-case scenarios, respectively.

Fibre type	Microfibre generation (#/g wipe)[a]	Mass generation (mg/g wipe) [a]	Total microfibre generation (#/wipe)[*]	Total mass generation (g/wipe)[*]
Natural	548,000 (163,000 – 933,000)	28 (16–40)	2603,000 (774,250 – 4431,750)	0.133 (0.076 – 0.19)
Regenerated[†]	27,800 (15,000 – 40,600)	3.6 (0.4 – 6.8)	132,050 (71,250 – 192,850)	0.0171 (0.0019 – 0.0323)
Plastic	2940 (710 – 5170)	0.73 (0.24 – 1.22)	13,965 (3373 – 24,558)	0.0034 (0.0011 – 0.0058)

[a] Values derived from Kwon et al. (2022).
[*] Average wipe mass when wet of 4.75 g derived from Durukan and Karadagli (2019).
[†] Originally non-natural but relabelled as regenerated based on Zambrano et al. (2020).

and 3) plastic fibres, ranked by their shedding potential in simulated wastewaters (Kwon et al., 2022). We treated 'non-natural' fibres as regenerated cellulosic fibres based on Zambrano et al.'s (2020) similar findings.

With the growing use and frequent misclassification of regenerated cellulose in wet wipes (Allison et al. 2023), we also added a 10 % share for regenerated fibres beyond the current 90:10 split to account for likely overlap or underrepresentation in existing estimates while preserving plastic and assumed natural fibre proportions. All microfibres were assumed to be released upon initial wastewater entry, simplifying the model to focus on estimating total microfibre load without modelling degradation during transport.

Microfibre inputs were based on an average wet wipe mass of 4.75 g (Durukan and Karadagli, 2019) (Table 1). Solid wet wipe mass inputs (SG_{cap}) were calculated by multiplying the number (#) of flushed wet wipes by their average mass. Using these experimental datasets (Durukan and Karadagli, 2019; Kwon et al., 2022), we also converted microfibre masses into counts, yielding an average of 2603,000 microfibres per natural wipe, 132,050 per regenerated wipe, and 13,965 per plastic wipe released into wastewater.

2.5. Wastewater pathways into rivers

Our emissions model parameterised three primary wastewater point sources to rivers: toilet misconnections, SOs, and WWTPs, along with diffuse sources through agricultural sewage sludge and soil runoff, and landfills as environmental sinks

Toilet misconnection inputs to rivers ($MISC_i$) were adapted from Ellis and Butler (2015), who identified an annual misconnection rate of 3 % in England and Wales, of which 8 % were linked to toilets. The annual mass input of wet wipes and microfibres entering rivers via misconnected toilets from each sub-catchment (g/y) was calculated as:

$$MISC_i = PMisc \times \ WWi_{wmf} \ or \ WWI_{wws} \tag{3}$$

where *PMisc* is the annual UK toilet misconnection proportion (0.0024).

Annual river input from SOs during their periods of activity (SO_i) was proportionally modelled using 2021 UK wastewater monitoring data on SO operation hours. We assumed a constant flow of wet wipes during SO activity and 50 % diversion rate to rivers, with the remainder sent to WWTPs, in line with Jones et al. (2024, preprint). Therefore, the SO input to rivers in each sub-catchment was calculated as:

$$SO_i = \frac{WWi_{wmf} \ \ or \ WWI_{wws} \ \times \ PTime_{ON}}{2} \tag{4}$$

where, $Ptime_{ON}$ is the yearly operational proportion of a SO (0–1).

To estimate wet wipe microfibres entering rivers in each sub-catchment after wastewater treatment ($WWTP_{ti}$), we used average removal rates for microplastic and microfibres reported in the literature (Supplementary Table 1). This allowed us to model the fraction of microfibres that escape removal under different levels of treatment. For solid wet wipes, we assumed complete removal by mesh screens or blockage maintenance, with the waste diverted to landfills. Microfibre input to rivers post-treatment (g/y) was calculated as:

$$WWTP_{ti} \ = \ \left(WWi_{wmf} - SO_i\right) \ \times \ 1 - Ptime_{ON} \times \ WWrem_{ti} \tag{5}$$

where, SO_i, in this case, represents wet wipes bypassing treatment during SO operation, and $WWrem_{ti}$ represents the inefficiency of microfibre removal for different treatment levels (0–1).

$WWrem_{ti}$ categorises three wastewater treatment types based on microplastics research: 1) Primary treatment, including basic physical processes like screening, sedimentation, and skimming (AEAL, 2009); 2) Secondary treatment, involving biological treatment and solid clarification (Michielssen et al., 2016; Murphy et al., 2016); and 3) Tertiary treatment, using advanced filtration technologies such as bioreactors and sand filtration. These treatment types were applied to our best-case (tertiary), worst-case (primary) and average-case (secondary) emission scenarios, with the latter based on its common usage in the UK and EU (Kawecki and Nowack 2020; See Supplementary Table 1). Average treatment efficiencies derived from the literature – 88.48 % for primary, 94.58 % for secondary, and 97.7 % for tertiary – were converted into fractional inefficiencies (0–1) for calculations.

Based on the existing literature (Gies et al., 2018; Lares et al., 2018; Schell et al., 2022; Zhang et al., 2022), we assumed that most fibres removed during treatment are eventually directed to sewage sludge facilities. Based on UK data (Lofty et al., 2022), an average 68 % of sludge was applied to agricultural soils in our model, with the remaining 32 % sent to landfills.

The model estimated microfibre transport from agricultural land as sewage sludge to rivers via soil runoff ($AgrSS_i$), assuming 25 % soil retention for microfibres, and 75 % transported to rivers. This was based on theory regarding heavier than water particle runoff from rivers and estimated microplastic retention in agricultural soils, reported to range from 10 to 40 % (Nizzetto et al., 2016; Norling et al., 2024). Therefore, agricultural runoff to rivers was calculated as:

$$AgrSS_i = WWi_{wmf} \times \ WWrem \ \times \ P_{SS} \ \times \ P_{SR} \tag{6}$$

Where, P_{SS} is the proportion of microfibres in sewage sludge exported to agricultural soils (0–1); and P_{SR} is the proportion of microfibre soil runoff to rivers (0–1).

2.6. River input from wastewater pathways

Our model calculates the total annual mass of solid wet wipes (Ri_{WS}) and microfibres (Ri_{WMF}) entering rivers from our two study sub-catchments (g/y). We express this input for our microfibre and solid wet wipe scenarios, respectively, as:

$$Ri_{wmf} = \ \Sigma(MISC_i \ + \ WWTP_{ti} + CSO_i + AgrSS_i \ ) \tag{7}$$

$$Ri_{ws} = \ \Sigma(MISC_i + CSO_i) \tag{8}$$

2.7. Model limitations

This study represents an initial attempt to model wet wipe emissions through wastewater systems, and thus, has inherent uncertainties. Due to the limited data on wet wipe disposal and fate in wastewater and river systems, conservative assumptions were used to construct parameters, acknowledging the inability to fully capture all variations and complexities. Confounding factors in microfibre scenarios were partly mitigated by using likely case-scenarios as upper and lower confidence bounds. Further limitations discussed in the results and discussion sections. Other key limitations are discussed here.

We assumed that all flushed wet wipe emissions enter the wastewater system. However, wipes that cause blockages are removed during maintenance and reallocated to the landfills. Our framework only considers fragmentation processes due to limited data on biochemical and biophysical degradation processes in wet wipes (but see Allison et al. 2023 for a review). While the model provides insight into flushed wet wipe transport to rivers, downstream factors beyond the study's scope may influence the fate of emissions in rivers and other ecosystems (Besseling et al., 2017; Siegfried et al., 2017; van Wijnen et al., 2019; Kawecki and Nowack, 2020).

2.8. Applying our model to laundry microfibres

To validate our wet wipe emission model, we extended it to assess laundry microfibres, a better-studied wastewater pollutant, to benchmark and enhance the robustness of our estimates. Using data from Vassilenko et al. (2021) on plastic (0.161 ± 0.173 g/kg/wash) and cellulosic (0.165 ± 0.44 g/kg/wash) fibres, we introduced new parameters to estimate annual inputs to wastewater systems per UK individual. These included an average household size of 2.36 individuals (Office for National Statistics, 2023), 260 laundry loads per household per year (Office for National Statistics, 2016), and a standard 6 kg wash load. All other parameters remained consistent with our wet wipe microfibre scenarios. The large standard deviation for plastic fibres reflects high variability in shedding across different textile types.

3. Results

3.1. Emission pathways and transport dynamics of wet wipes

To inform transport mechanisms, we first modelled the scenarios from individual inputs to wastewater systems, through interconnected pathways, to their fate in rivers (See Fig. 1). Emission pathways and parameters were assigned based on prior studies of wastewater pollutants and emissions modelling (Murphy et al., 2016; Nizzetto et al., 2016; Siegfried et al., 2017; van Wijnen et al., 2019; Van den Berg et al., 2020; Di Nunno et al., 2021; Schell et al., 2022). Three sets of pathways emerged: 1) point sources directly transporting wet wipe materials to rivers (toilet-derived sewer misconnections, sewer overflows (SOs), and wastewater treatment plant (WWTP) effluents); 2) diffuse sources to rivers (agriculturally applied sewage sludge and soil runoff); and 3) terrestrial sinks, including landfill facilities and the retention of pollutants in agricultural soils (Fig. 3). The transport of wet wipe materials through these pathways are assumed to be size-dependant, with microfibres traversing all pathways due to their small size, and solid wipes being completely removed before or at the WWTP entry stage and directed to landfill and other facilities.

3.2. Contributions from wastewater pathways

Per capita contributions of wet wipe materials to wastewater systems in the UK are substantial. Plastic wipes dominate solid emissions, with individuals contributing an estimated average of 33 plastic wipes annually, compared to 4 cellulosic wipes. This translates to 157.7 g and 17.53 g of plastic and cellulosic wipes per person, respectively. In the case of microfibre emissions, a countertrend is observed. Based on the fibre generation findings of Kwon et al. (2022), natural microfibres are predominant, with an average UK individual contributing 0.49 g [mean] (0.28 - 0.7 g [range]) of natural fibres, 0.06 g (0.03 – 0.12 g) of regenerated fibres, and 0.11 g (0.04 – 0.19 g) of plastic fibres annually to

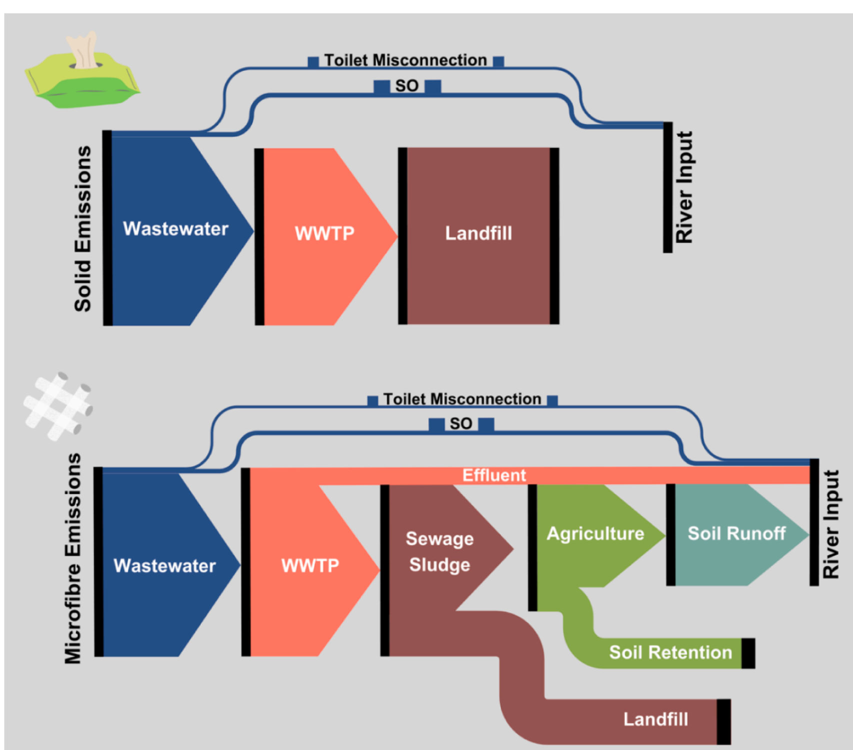

Fig. 3. Conceptual framework for wet wipe emissions through wastewater systems illustrating likely wastewater transport and comparative quantities through each pathway.

wastewaters. On average, this equates to 268,520 natural fibres, 1668 regenerated fibres, and 323 plastic fibres per person annually.

Scaled up to the Taff, representing our densely populated sub-catchment (78–3042 capita/km^2), we see a substantial wastewater input of 7054 kg and 784 kg of solid plastic and cellulosic wipes. This is equal to approximately 1.5 million plastic and 165,000 cellulosic wipes flushed annually. For microfibre emissions, natural fibres constitute the highest annual wastewater input, ranging between 12.5 kg and 31.4 kg (mean = 21.9 kg) in the Taff (Supplementary Fig. 1).

WWTPs emerge as the primary recipients of solid wet wipes and microfibres from wastewater systems, playing a crucial role in their environmental fate. Almost 99 % of solid wet wipe emissions are transported to WWTPs, then directed to landfill and other facilities, serving as environmental sinks. This flow also accounts for potential wet wipe sewer blockage maintenance. For example, in the Taff, plastic and cellulosic wipes annually contribute 6963,579 g and 774,074 g to environmental sinks.

The entry of microfibre emissions into WWTPs and their release as effluent varies greatly based on the different scenarios of filtration treatment (See Methods for details). These various treatment-based scenarios for annual microfibre emissions to effluent are shown in Supplementary Fig. 2. Despite all-round high treatment efficiency, the significant microfibre input to effluent highlights the importance of enhancing treatment strategies to mitigate microfibre pollution in rivers.

Toilet misconnections and SOs both contribute to solid wet wipe and microfibre emissions in rivers but are often overlooked in wastewater pollution analyses. Toilet misconnections in our model divert about 0.24 % of wastewater emissions to rivers annually. While modest, this diversion is substantial for solid wipe pollution, with estimated annual emissions of 14,813 g of plastic and 1647 g of cellulosic wipes to the Taff through this pathway. However, misconnections are the least important pathway for microfibre transport in our model (Supplementary Fig. 3).

In comparison, SOs are more significant contributors, particularly for solid wipes, where they input 5.1 times more emissions directly to rivers. Interestingly, the active duration of SO spills has little effect on emissions. Even with less variability in operational hours in the Taff sub-catchment (0–584 h per year) compared to the Wye sub-catchment (0–2027 h per year), river emissions from both wet wipe scenarios are considerably higher in the former study site, underscoring emissions volume as the key factor influencing input. Microfibre emissions to rivers via SOs, though more than from toilet misconnections, are still marginal compared to other pathways (Supplementary Fig. 4).

Sewage sludge filtered out of WWTPs is the primary pathway for transporting wet wipe microfibres in our model. These microfibres are directed to agricultural soils or landfill sites, depending on wastewater filtration levels and average UK sewage sludge diversion percentages, outlined in the Methods section. Microfibre emissions are highest in the post-tertiary treatment scenario, accounting for about 66 % to agricultural soils and 31 % to landfill facilities of the total average emissions entering the wastewater system (Supplementary Fig. 5).

We find soil runoff to be the main transport pathway for microfibre emissions to enter rivers in our model (Supplementary Fig. 6). This pathway is distinguished from the average proportions of microfibres retained in the soil, which we conservatively assume to hold a quarter of all emissions within agricultural soils. However, in reality, we expect soil retention to be a temporary environmental sink, and therefore, annual microfibre emissions from agricultural soils into rivers may be even greater.

To further illustrate the annual emission contributions through each of the wastewater pathways discussed here for both the Taff and Wye sub-catchments, conceptual frameworks for solid wet wipes (Supplementary Fig. 7 and 8) and microfibres (Supplementary Fig. 9 and 10) have been provided. These figures represent average-case scenarios (mean emission input with secondary treatment) and outline the key transport pathways and their respective contributions to river inputs.

3.3. Emission scenarios to rivers

Modelling wet wipe and microfibre emissions into rivers provides crucial insights into their potential environmental risks. In solid emissions scenarios, plastic wipes significantly outweigh cellulosic wipes in river influx, constituting a small fraction (1.28 %) of total emissions into the wastewater model system but raising concerns for freshwater ecosystems. For example, annual plastic wipe input to rivers in the Taff sub-catchment total approximately 90 kg (equivalent to 19,020 wipes), while cellulosic wipes contribute 10 kg (equivalent to 2114 wipes), roughly translating to 2 g of plastic wipes and 0.23 g of cellulosic wipes per person annually.

Table 2 details the wet wipe microfibre export to the Taff and Wye sub-catchments, where natural microfibres account for 74 % of total mass emissions to rivers (See Supplementary Fig. 11 for a full breakdown by microfibre type). The combined annual microfibre input to rivers is around 16 kg for the Taff and 1.8 kg for the Wye, assuming average microfibre production and secondary treatment. Across all scenarios, combined inputs could range from 8.5 to 25.7 kg for the Taff and 0.9 to 2.9 kg for the Wye. The breakdown of this river input and contributions from each pathway for the average-case scenario is visualised in Fig. 4. Converted to volume of microfibres (see Methods), the combined river input equates to approximately 6.57×10^9 and 7.39×10^8 microfibres per year on average, with substantial variability, depending on available wastewater treatment and microfibre generation rates (See Table 2).

3.4. Scaling up the modelling framework

Scaling up our model from the local (our study sites) to the national and international scales reveals important insights for wet wipe pollution to rivers (Fig. 5). Extended to the UK national level, our model predicts annual inputs of 10,816 t (0.16 kg per person) from solid plastic wipes and 1202 t (0.018 kg per person) from cellulosic wipes to wastewater systems. With refined parameters, including an average UK SO spill rate of 2.6 % (Giakoumis and Voulvoulis, 2023), and a population of 67.78 million, we estimate the annual solid mass input to rivers as approximately 163.3 t (2.4 g per person) for plastic wipes and 18.2 t (0.27 g per person) for cellulosic wipes.

Table 2
Emission export of wet wipe microfibres to our two study sub-catchments. Mean values represent mean microfibre generation and secondary treatment scenarios. Predicted lower and upper ranges are derived from emission scenarios with low microfibre generation (L) and tertiary treatment (T) to high microfibre generation (H) with primary treatment (P).

Site	Wet wipe microfibre type	Mean mass microfibre input (g/y)	Microfibre mass range (g/y)	Mean microfibre input (#/y)	Microfibre range (#/y)
Taff	Natural	11,912	6718 (L;T) – 17,942 (H;P)	6.53×10^9	1.10×10^9 (L;T) – 1.67×10^{10} (H;P)
Taff	Regenerated	1531	827 (L;T) – 3050 (H;P)	4.26×10^7	1.24×10^7 (L;T) – 1.24×10^8 (H;P)
Taff	Plastic	2670	944 (L;T) – 4862 (H;P)	7.85×10^6	6.7×10^5 (L;T) – 2.51×10^7 (H;P)
Wye	Natural	1339	744 (L;T) – 2018 (H;P)	7.34×10^8	1.21×10^8 (L;T) – 1.88×10^9 (H;P)
Wye	Regenerated	172	93 (L;T) – 343 (H;P)	4.78×10^6	1.4×10^6 (L;T) – 1.39×10^7 (H;P)
Wye	Plastic	300	106 (L;T) – 547 (H;P)	8.82×10^5	7.53×10^4 (L;T) – 2.83×10^6 (H;P)

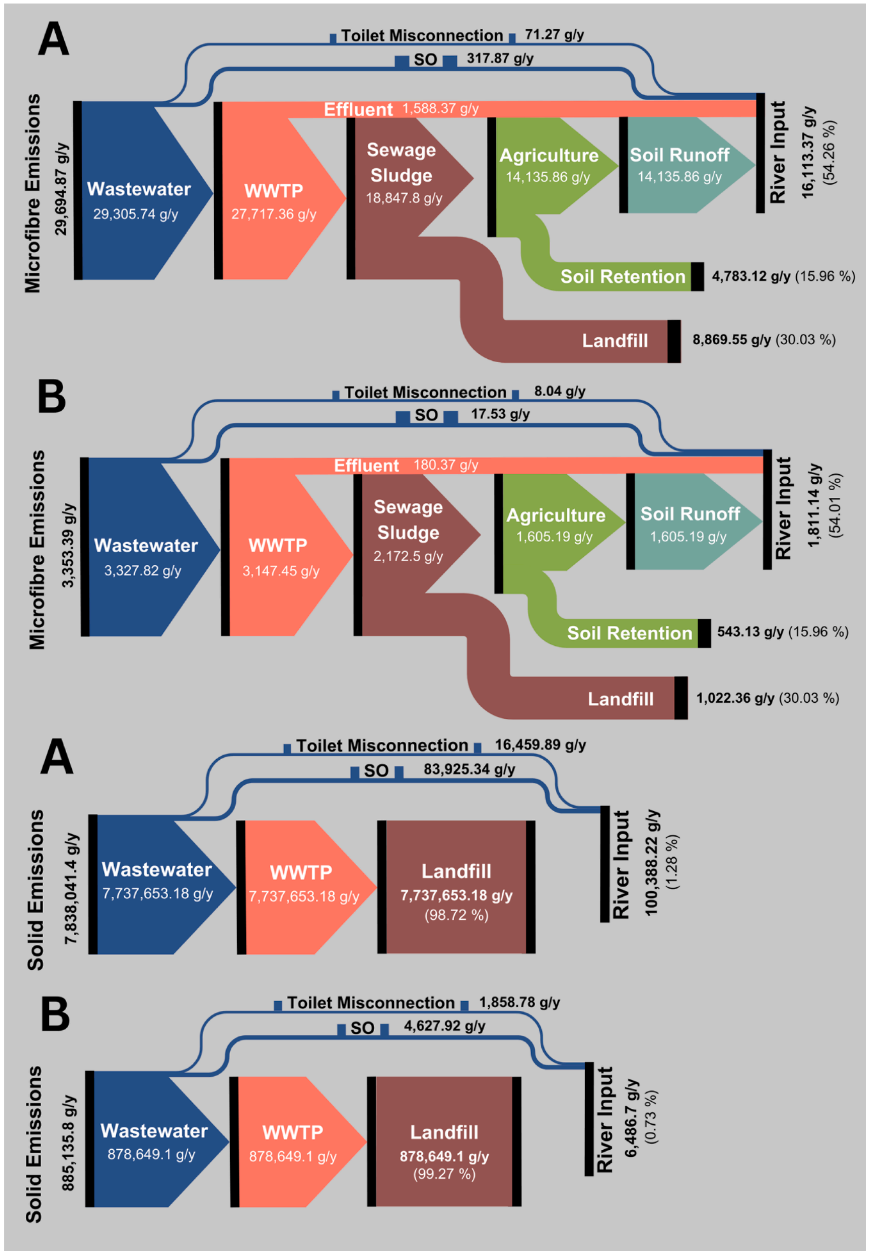

Fig. 4. Conceptual framework of annual wet wipe emissions through wastewater systems in the Taff (A) and Wye (B) sub-catchments based on average case scenarios (mean emission input, secondary treatment). Percentages represent each pathway's share of total emissions. Unit = g/y.

Expanding to the EU-28 level, our model projects yearly contributions of up to 85,757 t (168 g per person) from solid plastic wipes and 9529 t (18.6 g per person) from cellulosic wipes to wastewater systems. Within this, we estimate 1085 t of plastic wipes (2.12 g per person) and 121 t (0.24 g per person) of non-plastic wipes to enter European rivers annually. EU-level estimates were based on updated parameters such as an annual consumption of 68 billion wet wipes in the EU-28 from a population of 511 million (Cabrera and Garcia, 2019), an average flushing probability of 29.5 % (Kawecki and Nowack, 2019), an average EU-28 SO spill rate of 1.97 % (Quaranta et al., 2022), and a toilet misconnection rate of 0.28 % (Ellis and Butler, 2015).

3.5. Model comparisons with laundry microfibres

Applying laundry microfibre generation data from Vassilenko et al. (2021) into our model reveals important comparisons that help to validate the modelling system. Model input values for natural and plastic laundry microfibres show considerable but variable annual emission rates, with per individual wastewater inputs of 109.1 g (± 29.08) and 106 g (± 114.35), respectively. Mean laundry input rates to wastewater vastly exceed all wet wipe microfibre scenarios but are somewhat lower than solid plastic wipes. For instance, projected over the Taff sub-catchment, natural and plastic laundry microfibres could annually contribute 4878 (± 1300) kg and 4760 (± 5115) kg to wastewaters, compared to 7054 kg from solid plastic wipes annually. As total mass emissions to wastewater, our modelled wet wipe inputs (solid and fibres) were slightly less than those from laundry (natural and plastic), representing around 82 % of their annual emissions.

In rivers, emissions from each laundry fibre scenario are roughly 28 times greater than solid plastic wipes on average. For instance, modelled natural and plastic laundry microfibres annually contribute an average 2570 kg and 2510 kg to rivers in the Taff sub-catchment, equating to 101.13 g and 98.77 g per person, respectively. Combined wet wipe mass emissions to rivers are approximately 2.3 % of those contributed by total

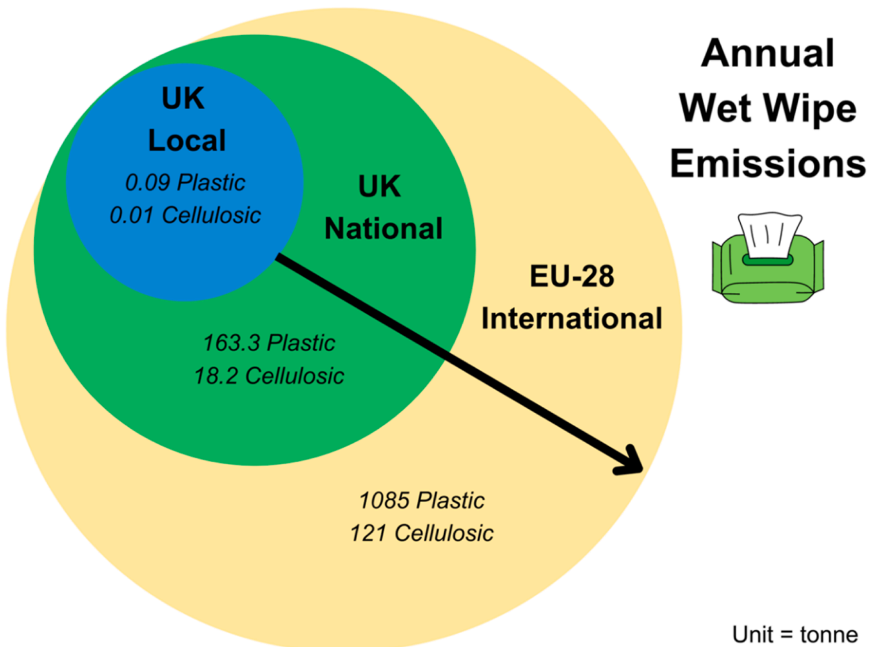

Fig. 5. Annual solid wet wipe emissions to rivers modelled across spatial scales. UK Local emissions represent the Taff sub-catchment. UK National and EU-28 International are based on refined model parameters highlighted in the results. Emission inputs are based on mean values, with unit measurements in tonnes.

laundry fibres. These river input values and comparisons are based on average-case scenarios with secondary treatment. From our model assumptions, annual river inputs to the Taff sub-catchment for laundry microfibres could range between 1850 kg (best-case scenario; tertiary treatment) and 3450 kg (worst-case; primary treatment) for natural laundry fibres, and between zero (due to variability that results in a negative lower bound) and 5510 kg (worst-case scenario; primary treatment) for plastic laundry fibres.

4. Discussion

4.1. A comprehensive framework for wet wipe emissions

This study sought to unravel the complex dynamics of flushed wet wipes in wastewater systems. By integrating microplastic modelling with experimental microfibre generation data, we developed a framework to reveal and quantify the pathways of wet wipe emissions into rivers. Our model identified nine pathways through which wet wipe emissions, both solid and microfibre, are transported, categorised into point sources, diffuse sources, and terrestrial sinks. These pathways include: 1) wastewater to WWTP, 2) WWTP to effluent, 3) WWTP to sewage sludge, 4) sewage sludge to landfill, 5) sewage sludge to agriculture, 6) soil retention in agriculture, 7) agricultural soil runoff to rivers, 8) toilet misconnections to rivers, and 9) SOs to rivers (Fig. 3).

The model accounted for size-dependant transport behaviour: microfibres traverse all pathways, while solid wet wipes are largely removed or enter rivers at earlier stages. By parameterising these pathways using real-world data and assumptions justified by surrounding literature, the model ensured practical and relevant emission scenarios, allowing us to better capture the complexity of wet wipe transport in wastewater systems.

4.2. Challenges and uncertainties in data and model validation

The lack of comprehensive national data on wet wipe pollutants limited direct model validation. As detailed in the Methods section, we used empirical data for parameters such as wet wipe consumption, flushing rates, microfibre generation, and transport pathways when available. Where empirical data were unavailable, we used reasonable assumptions based on analogous pollutants and conservative estimates. Scenario modelling with best, worst, and average cases helped account for variability in wastewater systems and from spatio-temporal and environmental conditions (Kooi et al., 2018). Although this provides a strong baseline, improving accuracy will require future regional and temporal data collection to reduce reliance on assumptions, as well as greater market share insights for wet wipe consumption.

4.3. Key emission pathways to rivers and the role of wastewater systems

Our findings highlight WWTPs, SOs, and agricultural runoff as the main pathways for wet wipe emissions into rivers, with overlooked contributors such as toilet misconnections also playing a role. Agricultural runoff was the dominant pathway for microfibre emissions, accounting for 83–93 % in the Taff sub-catchment. This aligns with prior studies (Nizzetto et al., 2016; Norling et al., 2024) but may be more on the conservative side, as reported runoff values have exceeded 99 % elsewhere (Crossman et al., 2020). This is possibly due to the unique morphology of microfibres which increases their retention in soils (Zubris and Richards, 2005; Schell et al., 2022).

WWTPs also play a crucial role in wet wipe transport. Despite significant microfibre removal, large quantities still enter effluent and agricultural sludge. Natural microfibres contributed an average of 643 million fibres (14,375 per person) annually through effluent in the Taff and 73 million (14,452 per person) in the Wye, consistent with previous findings (Mason et al., 2016; Murphy et al., 2016). Solid wet wipes are directed to landfills, with an estimated 10,708 t of plastic and 1190 t of cellulosic wipes entering UK landfills annually. This contribution does not account for solid wet wipes disposed through municipal waste streams. Given this scale, the findings underscore the need for effective waste management strategies at these environmental sinks to prevent remobilisation and further pollution risks from solid wet wipes (Shruti et al., 2021; Zhang et al., 2021; Hu et al., 2022).

SOs contribute significantly to solid wet wipes in rivers, accounting for 77.5 % of total emissions on average. This aligns with Kawecki and Nowack's (2020) findings on macro and microplastic emissions (80–95 %), when also considering our toilet misconnection pathway. However, unlike studies that report higher SO contributions for microplastics (Schernewski et al., 2020, 2021), our model showed SOs contributing only 1–2 % of annual microfibre river emissions on average, consistent with Baresel and Olshammar (2019). These discrepancies may stem from regional differences in rainfall, wastewater infrastructure, urbanisation, and microplastic sources. Seasonal variation also affects SO activity (Schernewski et al., 2020), with higher overflow frequencies during wetter months likely increasing wet wipe emissions. We applied a fixed 50 % diversion rule for SOs based on limited data (Jones et al., 2024, in print), potentially simplifying spatio-temporal overflow dynamics compared to the higher-resolution methods of Schernewski et al. (2021). Nonetheless, our findings align with broader pollution analyses and highlight the need for more region-specific data to better understand SO impacts and spill rates.

Toilet misconnections are often overlooked as transport pathways for pollutants, yet our findings show that they can contribute up to 16 % of all solid wet wipe emissions to rivers. Future studies should further explore this pathway to better understand its role in pollutant transport.

Per capita input estimates for plastic wipes indicate a significant risk to wastewater and river systems. Our estimates are roughly four times lower than those in Spence et al. (2016), possibly explained by the unspecified materials compositions also considered in their study. Conversely, our plastic estimates exceed those from Swiss river systems (Kawecki and Nowack, 2019), which suggest an annual 0.45 g per person based on an assumed population of 8.8 million (Worldometer, 2023). While their study assumes a flushing probability between 0.6 % and 46 %, aligning with our average assumption of 23 %, discrepancies in river inputs may result from variations in wipe mass, their exclusive focus on SO pathways, and differences in SO infrastructure and operational periods.

Our model also highlights the potential environmental risks posed by solid wipes and their microfibres in river systems. Despite accounting for a smaller fraction of total mass inputs, plastic wipes are the dominant solid wipe material and still present a significant risk to aquatic environments. Once in rivers, plastic wipes may resist chemical degradation but fragment due to material defects and physical interactions (Enfrin et al., 2020; Ó Briain et al., 2020), contributing to persistent microfibre loads (Hu et al., 2022).

The high-volume of solid wipes are also expected to correlate with global occurrences of sewer blockages, which have serious operational and ecological consequences (Durukan and Karadagli, 2019; Lee et al., 2021; Allison et al., 2023). Wet wipes are responsible for up to 90 % of sewer blockages (Drinkwater and Moy, 2017), increasing the likelihood of sewer overflows and the release of untreated wastewater and associated pollutants into rivers. However, the extent of this relationship remains debated (Giakoumis and Voulvoulis, 2023).

4.4. Extrapolating wet wipe emissions to wider spatial scales

Refining model parameters enabled us to extend the analysis of solid wet wipe emissions to both national and international scales, focusing specifically on the UK and EU-28. Quantifications revealed substantial solid inputs to wastewater systems, particularly from plastic wipes, driven by factors such as annual wet wipe consumption rates and flushing probabilities at each scale. Updated parameters for average SO spills further highlight their critical role as transport pathways for solid wet wipes into rivers.

These EU-level extrapolations are intended to illustrate the potential scale of solid wet wipe emissions to rivers rather than provide precise fibre quantifications. Variability in wastewater treatment and sludge disposal to agricultural land across Europe, ranging from 0.3 % to 89 % (Lofty et al. 2022), highlights the challenge of applying uniform modelling to such a diverse region. Although this extrapolation focuses on solid wipes entering rivers via SOs and misconnections, these findings underscore the broad environmental impact of wet wipe emissions across multiple regions.

4.5. Comparing wet wipe emissions with laundry microfibres

To contextualise and validate our model, we compared wet wipe emissions with laundry-derived microfibres using wastewater release data from Vassilenko et al. (2021). Laundry emissions contributed more microfibres to rivers, especially natural fibres, consistent with previous studies (Zambrano et al., 2019). Finnish data also supports our findings on natural fibre emissions, although their plastic fibre emissions were significantly lower than our projections (Sillanpää and Sainio, 2017). Despite the lower proportion of cellulosic textiles in Vassilenko et al.'s (2021) study, they showed similar fibre shedding to plastic textiles, indicating a higher shedding propensity for cellulosic materials - a pattern also observed for wet wipes (Kwon et al. 2022). The high variability in plastic fibre shedding across different textile types suggests that, in worst-case scenarios, plastic laundry fibres could be the greatest contributors to river pollution in our modelling system.

Solid plastic wipes contribute more mass to wastewaters than either natural or plastic laundry fibres individually. However, this contrasts for their river emissions, as laundry microfibres can bypass wastewater treatment and enter rivers (Miller et al., 2017; Talvitie et al., 2017). Detailed comparisons of laundry microfibres are limited due to a lack of mass quantification. However, our per capita laundry microfibre inputs to wastewater are approximately 30 times higher than those reported by Hartline et al. (2016) for synthetic laundry microfibres, while their estimates align more closely with our wet wipe emission rates.

While laundry fibres contribute substantially more microfibre mass to rivers annually, the environmental implications of wet wipe pollution are equally important to consider. Intact wet wipes reaching waterbodies can degrade into vast amounts of microfibres (Ó Briain et al., 2020; Lee et al., 2021; Hu et al., 2022), exacerbating existing microfibre pollution and increasing ecological risks. Furthermore, our conservative assumptions regarding laundry emissions, particularly for plastic microfibres, may lead to overestimation, potentially underrepresenting their comparability to wet wipes. The shift by manufacturers and consumers towards 'biodegradable' wet wipes is also likely to intensify cellulosic (both natural and regenerated) microfibre pollution in aquatic environments (Hadley et al., 2023).

5. Conclusion

This study presents the first comprehensive quantification of wet wipe emissions and microfibre release through wastewater systems into rivers. By integrating experimental microfibre generation data with microplastic modelling approaches, we developed a model that tracks the transport dynamics of both solid wet wipes and their microfibres. Applied to two sub-catchments with varying degrees of urbanisation - the Taff and the Wye - we estimate annual emissions of solid wet wipes to these rivers at approximately 100 kg and 6.49 kg, respectively. Across all modelled microfibre scenarios, total annual river emissions may range from 9.4 – 28.8 kg between the Taff and Wye sub-catchments, or approximately 1.23×10^9 – 1.89×10^{10} microfibres per year.

A key innovation of this study is the development of a geo-spatial method to delineate SO drainage areas using geomorphological and hydrological data. This approach allowed us to connect local populations to wastewater systems, enabling more precise, and spatially-specific estimates of emissions to wastewater systems.

Our model identifies SOs, WWTPs, and, particularly agricultural runoff from sewage sludge as critical pathways through which wet wipe microfibres enter rivers. Despite generally advanced wastewater treatment technologies in place, substantial volumes of flushed microfibres could still reach agricultural land via sewage sludge. Combined with emissions from undegraded wipes during SO periods, this poses a significant pollution risk to aquatic ecosystems.

Additionally, our model demonstrates adaptability to other pollutant types, such as laundry microfibres, and across various geographical scales, providing insights into the environmental impact of wet wipes.

While this study establishes a strong foundation, we encourage future work that focuses on empirical data collection and region-specific modelling to refine our parameters and emission estimates, and to develop targeted strategies to mitigate wet wipe pollution in aquatic systems.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2024.122733.

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