Rapid ‘fingerprinting’ of potential sources of plastics in river systems: an example from the River Wye, UK

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Abstract

Literature review identified seven principal pathways of plastic debris entry into river systems: waste water treatment plants; combined sewer overflows; on-site wastewater treatment systems; road and rail transport systems; agriculture; industrial sources; and diffuse litter. A further category of ‘microplastics’ reflects their multiple potential sources, including microplastic breakdown within rivers. Regulatory and management bodies necessarily make operational decisions based on resource limitations and significant uncertainty due to sparse or missing data, requiring a substantial degree of inference. To support this need, we develop a rapid, desk-based approach based on risk criteria to ‘fingerprint’ likely pathways of plastic pollution based on catchment characteristics.

Characteristics of the River Wye system in the UK are reviewed identifying a risk-based ‘fingerprint’ of potential pathways of plastic entry or accumulation of plastic debris, represented graphically as a colour-coded ‘traffic lights’ classification. This ‘fingerprinting’ approach is based on desk-based inference from published materials as a rapid and resource-efficient alternative to intensive data collection, supporting prioritisation of further investigation or response measures. We recommend replication of this ‘fingerprinting’ approach in other river catchments to support operational management of plastic pollution. Where feasible, it may also be down-scaled where sub-catchment or major river reach properties differ significantly.

Highlights

- Unique catchment characteristics influence likely sources of plastics in rivers
- 7 potential plastic sources were identified, with a residual microplastics category
- Literature, interviews and surveys can rapidly ‘fingerprint’ likely plastic sources
- Fingerprinting can prioritise management and investigations in specific catchments

Keywords

Macroplastic; microplastic; River Wye; fingerprinting; management response options; risk-based

1. Introduction

Plastic pollution is receiving growing global attention as a major environmental, human health and economic issue (UNEP, 2014). Global plastic production in 2018 was estimated at 359 million tonnes (PlasticsEurope, 2019). Initially mainly used in durable items, a growing proportion of plastic is now used for single-use purposes (Andrady & McNeal, 2009; Geyer, Jambeck, & Law, 2017). The ubiquity and durability of plastic presents a problem if inappropriately disposed at end-of-life, as most plastics do not biodegrade (Andrady, 2003; Sigler, 2014).

Marine plastic debris presents a complex challenge to communities globally (Wessel *et al*., 2019), as well as to wildlife, through issues such as entanglement, contaminant transfer and ingestion (Consoli *et al*., 2019; Thompson *et al*., 2009). However, relatively little attention has been paid to accumulation of plastics in river systems (Blettler *et al.*, 2018) and their role as debris pathways from land to sea (Mani *et al*., 2015). The complex and significant contribution of plastic debris transport by rivers is still an emerging science (van Emmerik and Schwarz, 2020).

Studies on the effects of plastics in fresh waters have largely been undertaken in developed countries, with most attention paid to microplastics (particle size <5 mm) (Blettler *et al*., 2018). Larger plastic pieces and plastic pellets are aesthetically unattractive, can block free exchange between sediment and the overlying water column, may facilitate transfer of adsorbed pollutants when ingested and passed up food chains (Zbyszewski and Corcoran, 2011) and can promote the spread of potentially invasive attached species (Miralles *et al*., 2018). Primary microplastics, from sources including 'microbeads' in cosmetics (Crawford and Quinn, 2017), may cause physical damage when ingested by organisms, can leach constituent contaminants and adsorb inorganic and organic chemicals (Bayo *et al*., 2017). Fibres released when artificial fabrics are washed (microfibres) are also environmentally problematic (Horton *et al*., 2017). Microfibre densities in wastewater flowing into Swedish wastewater treatment plants were in excess of 20,000 m^{-3}, with treated effluent still containing 150-3,300 microplastic fibres m^{-3} (Magnusson and Wahlberg, 2014). Secondary sources of microplastics include the breakdown of larger plastic items in freshwater ecosystems through photo-degradation, physical, chemical and biological interactions (Thompson *et al*., 2009; Zbyszewski and Corcoran, 2011; Galgani *et al*., 2013). The majority of microplastics found in the American Great Lakes were found to be secondary microplastics (Eriksen *et al*., 2013). Estimates of microplastic concentrations in freshwater systems in Europe, Asia, and north and south America range from greater than 1 million m^{-3} to less than 0.01 m^{-3} (Li *et al*., 2018). There is growing evidence of potential health impacts from microplastics in the food chain (Hurley *et al*., 2018) which absorb and release toxic chemicals (Li *et al*., 2018), carry invasive species (Sigler, 2014; Blettler et al., *et al*., 2017) and may provide novel substrates for selection and dispersal of microbial assemblages (McCormick *et al*., 2016). The diversity of impacts of plastics in rivers is reviewed by van Emmerik and Schwarz (2020), however, a wide range of knowledge gaps remain regarding the sources, impacts and environmental fate of plastics in in freshwater systems (Wagner *et al*., 2014) and about factors which determine plastic transport from land to aquatic systems (van Emmerik and Schwarz, 2020).

This study is based on a specific British river system: the River Wye catchment traversing through Wales and England. The Wye was selected as there: (a) are relatively few urban centres all of which are discretely identifiable; (b) are few major industries; (c) is potential for visual blight to have a negative impact on the river's significant aesthetic and tourism value; (d) is evidence of the presence of microplastics in multiple species of invertebrates (Windsor *et al*., 2018); and (e) is a prior study of different types of pollution measures needed to improve operational sub-catchments of the Wye system (Environment Agency, 2014). The Wye catchment does not have an associated rich resource of plastic litter research. However, this is representative of the generic situation in many rivers as, despite global acknowledgement of the emerging threat of plastic pollution in aquatic ecosystems, useful data on plastic debris in rivers remains generally scarce (van Emmerik and Schwarz, 2020). In common with other river systems, resources for monitoring and responses are also limited, meaning that a risk-based approach supporting prioritisation of regulatory effort is required. Recognising that understanding and managing plastic pollution is increasingly important for policy-makers, Winton *et al*. (2020), drew upon European literature to identify a macroplastic 'top ten' of litter types in fresh waters, cumulatively accounting for 58% of identifiable plastic litter; 33% of identifiable plastic was accounted for by the top three items (food wrappers, bottles and lids, and bags). Five of the 'top ten' were food-related, 2 were sanitary/cosmetic, 2 were smoking-related and 1 was cotton buds. Our study complements these findings by focusing not on plastic types but on likely routes of entry of plastics into rivers, taking a rapid, risk-based 'fingerprinting' approach based on existing evidence at catchment scale. We acknowledge the complexity of plastic types but also the lack of data enabling disaggregation by polymer and finished plastic type, and so necessarily address all plastic types collectively.

The objectives of this study are to: (1) assess likely sources of plastics entering river systems based on literature review; (2) using the Wye system as a pilot, rank likely sources of plastic waste entering the river as a basis for prioritising investigations and control measures; and (3) develop from this a scalable model framework for the rapid, risk-based ‘fingerprinting’ of likely sources of plastic debris entering river systems to help prioritise management measures.

2. Methods

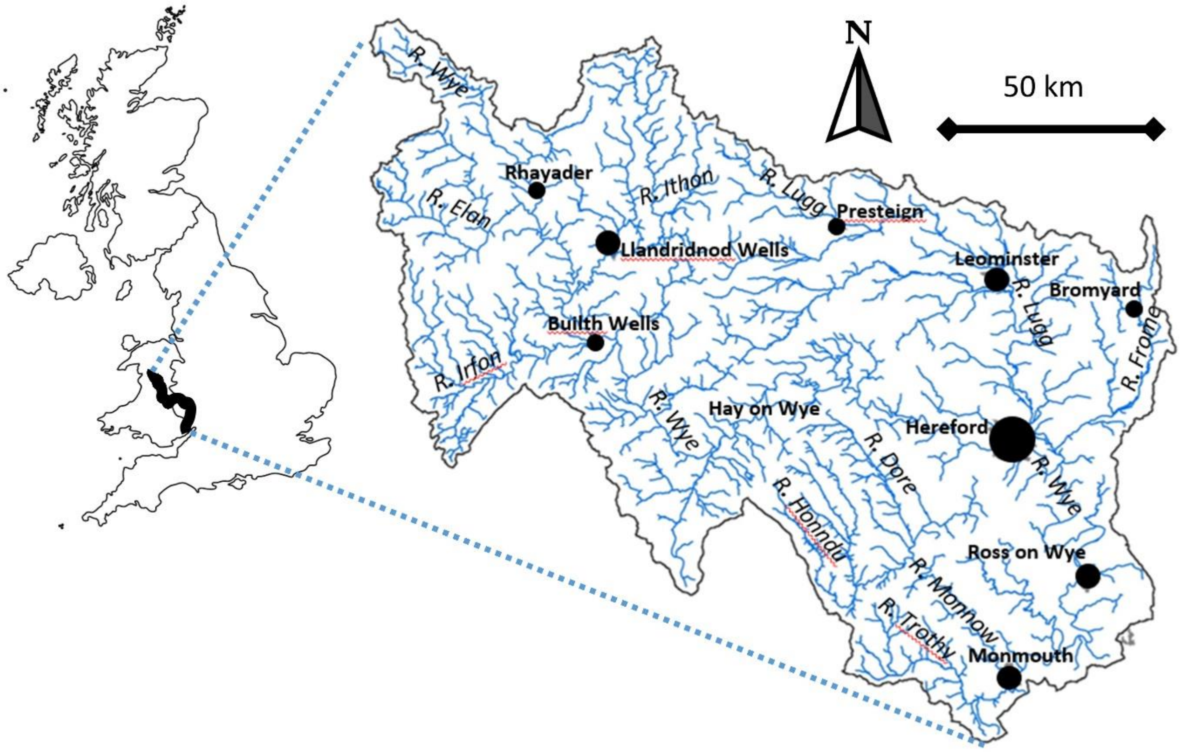
2.1 Fingerprinting likely sources of plastic entering the Wye

Development of a ‘fingerprinting’ approach, recognising significant limitations on investigative and regulatory resources, makes use of existing evidence through rapid and mainly desk-based study to characterise potential plastic pollution sources, helping prioritise further investigatons and management responses. This risk-based fingerprinting approach, developed on the Wye in this study, is intended to be of generic relevance for assessment and direction of management attention in other river systems that are overwhelmingly subject to the same scarcity of data and limited management resources.

2.2 The study site

The River Wye is the fifth longest river in the United Kingdom, flowing for approximately 215 km from its sources in the Cambrian Mountains in Wales. The main stem of the river forms part of the border between Wales and England before crossing over into England near the town of Hay-on-Wye in the English county of Herefordshire (Encyclopedia Britannica, 2013; PrimaryFacts, 2019). The Wye flows down through the town of Ross-on-Wye and the Forest of Dean before discharging into the Severn Estuary near the English town of Chepstow (Figure 1). Hereford is the only city and the largest conurbation (population approximately 55,800 in 2018) located along the river, with smaller centres of population at Chepstow, Leominster, Ross-on-Wye, Llandrindod Wells and Monmouth (Edwards *et al*., 1982). The 300 km^2 catchment of the Wye system, encompassing a number of major tributaries including the Irfon, Ithon, Lugg, Arrow, Frome, Monnow and Trothy, is predominantly rural with pastoral farming dominating in the hilly upper catchment and mixed farming more common in the lower reaches. Industrial development is sparse and generally low-impact, and the larger factories in the Wye valley including the H.P. Bulmer cider-making plant (using apples produced across the catchment for cider-making since 1887) are located in Hereford. A 72 km section of the lower stem of the main river between Hereford and Chepstow is designated as the Wye Valley Area of Outstanding Natural Beauty (AONB), an internationally important and scenic protected landscape straddling the border between England and Wales encompassing an area of 326 km^2 (Wye Valley AONB Office, 2015). The Wye system also supports nationally significant angling, particularly as an Atlantic salmon (*Salmo salar*) fishery (Environment Agency, 2014) but also high-quality mixed game and coarse fishing (Wye and Usk Foundation, 2019). A high tourism value is consequently associated with the Wye Valley, which has been regarded as the birthplace of the British tourism industry in the 18th century (Bloomfield, 1811). Environmentally based tourism is potentially negatively impacted by aesthetic and other forms of pollution (Yao *et al*., 2016), making it of particular concern in the Wye alongside other plastic pollution issues which have impacts that are temporally and spacially more distant.

Figure 1. Map of the Wye catchment showing rivers, brooks and major settlements



From an environmental management perspective, the Wye catchment is part of the Severn River Basin District (RBD) under the EU Water Framework Directive (WFD) (Environment Agency, 2015). The WFD sets out a catchment approach to managing water quality leading towards the end-goal of achieving Good Ecological Status (European Commission, 2019a). For environmental management and reporting purposes, the Environment Agency (2014) divides the Wye catchment into 10 ‘operational catchments’ (identified in Table 3 in the Results section).

2.3 Literature review of sources of plastics entering river

Establishing sources, movement and impacts of plastics, as with all pollutants, is crucial to inform effective management. Different types of plastic enter freshwater systems from a variety of point and non-point sources and in diverse ways (Horton *et al*., 2017). This study drew upon the scientific literature to assess potential sources of plastic waste entering rivers, using search terms and library resources of the University of the West of England as described in Table 1. Returns from these searches, in addition to less formal searches, were used to identify principal sources and types of plastic pollution in river systems

Table 1. Structured literature search using the library facilities of the University of the West of England

Library search term	Number of results (21st January 2019)	Comments
(river) AND (plastic) AND (pollution) AND (UK)	29,470	Few relevant papers: abstracts from only the first 100 results were read, as no relevance was found after item 53.
(UK) AND (rivers) AND (pollution) AND (water quality) AND (testing)	29,756	Led to refined search syntax below
(UK) AND (rivers) AND (pollution) AND (water quality) AND (testing) AND ((plastic) OR (microplastic))	8,166	Few relevant papers as many on accumulation in organisms, sediments, marine and other environments, transport of organisms and ecological effects. Abstracts from only the first 100 results were read, as no relevance was found after item 42.
A further search on macroplastics run in April 2020 used the string ((UK) AND (rivers) AND (pollution) AND (water quality) AND (testing) AND ((plastic) OR (macroplastic))) returned 4,318 results, with no additional relevant references in the first 150. However, a search on the string ((rivers) AND (microplastic)) located the Winton *et al*. (2020) and Vriend *et al*. (2020) references.		
Databases searched		

A subset of the databases accessed by www.uwe.ac.uk library resources include: BCIS (Building Cost Information Service), BCIS Online Rates Database, BioMed Central, Cambridge Journals Online, Box of Broadcasts (BoB), British Humanities Index, BSOL (British Standards Online), Building Design Online, Building Types Online, Building.co.uk, Business Source Complete, CIB (International Council for Research and Innovation in Building and Construction), COMPASS Online, Constructing Excellence, Construction Information Service, CoStar Suite, Credo Reference, CumInCAD (Cumulative Index of Computer Aided Design), Data Archive, DETAIL Inspiration, Digimap, DOAJ (Directory of Open Access Journals), EBSCO eBook Collection, ECONLIT, EGi News/Radius Data Exchange, EMBASE, Emerald, ENDS Report, Environmental Management, EThOS, FAME, Food and Drink Safety, FreeMedicalJournals.com, GreenFILE, Historic England (formerly English Heritage), ICE (Institution of Civil Engineers) Virtual Library, IEEE Xplore, IJ Global, i-Law, Index to Theses, InformationBridge, isurv, Journals@OVID, JSTOR, Knovel, Landmap, Lexis PSL, LexisLibrary, LexisLibrary International, LexisLibrary News, Marketline Advantage, MaterialDistrict, MEDLINE, Mintel, National Statistics, Nexis, Nexis Company Dossier, Occupational Health and Safety Information Service, PANGAEA, Passport, PILOTS, Practical Law, Property Week Magazine, ProQuest Dissertations & Theses: A&I, PubMed, RefWorks, RIBA (Royal Institute of British Architects) On-Line, Royal Society of Chemistry Journals, SAGE Journals Online, SAGE Research Methods, ScienceDirect, Scopus, Specify-it, SpringerLink, Sustainable Organization Library, Taylor and Francis, Taylor and Francis eBook Collection, TRILT (Television and Radio Index for Learning and Teaching), UK Data Service, UKBORDERS, Westlaw UK, Wiley Online Library, Zetoc

2.4 Determining the ‘fingerprint’ of plastic debris sources entering the Wye system

In order to assess likely sources of plastic debris entering the Wye system, additional terms were added to the literature search. These included (((wye river) OR (river wye)) AND (pollution) AND (plastic) NOT (maryland)). This search syntax returned 78 items, but only 2 references were relevant to this study; the exclusion of Maryland related to a River Wye tributary of Chesapeake Bay in the US. The structured literature review was augmented by wider-scale and less formal searches linking the terms ‘plastics’, ‘macroplastics’, ‘microplastics’ and ‘aesthetics’ to the terms ‘river wye’ or ‘wye’ using the same search online databases as noted in Table 1. This broad approach, interrogating a wide spectrum of databases encluding for example newspaper coverage, was undertaken in recognition that relevant sources of information may lie outside the peer-reviewed literature. The search also located regulatory reports, such as Environment Agency (2014), though publications from regulatory bodies were also searched directly.

2.5 Model framework for rapid ‘fingerprinting’ of likely risks of plastic debris

Results from both literature searches, categorising types of plastic debris sources entering rivers and the Wye-specific search, were consequently collated into three broad categories of high risk (good evidence of likely impact), medium risk (pollution measures indicate a likely source) and low risk (no evidence or measures found) across the River Wye as a whole. The purpose of doing this specifically for the River Wye was two-fold: firstly, to develop a ‘fingerprint’ of likely sources of plastic entering the river system that might be useful for prioritisation of limited resources for further investigation or other regulatory action; and, secondly, as an example of a transferrable, rapid approach to ‘fingerprinting’ risks in river systems using readily available published sources.

3. Results

3.1 Sources of plastics in rivers

Rivers constitute major transport pathways for microplastics and macroplastic particles (>5 mm), both positively related to mismanaged plastic waste (MMPW) generated in river catchments (Schmidt *et al.*, 2017). Conclusions about volumes and also the episodic nature of plastics entering the sea from land-based source via rivers are summarised in Table 2. There nevertheless remain significant knowledge gaps about the extent of plastic pollution in river systems relative to the amount of studies of marine accumulation (Blettler *et al.,* 2017).

Table 2: Quantification and variability of plastic loads entering the sea from rivers

Literature source	**Findings**
Lebreton *et al*. (2017)	Modelling based on waste management, population density and hydrological information evidence in the literature, suggest that between 1.15 and 2.41 million tonnes of plastic waste currently enter the ocean annually from global rivers.
Schmidt *et al*. (2017)	Modelling, though subject to high uncertainties due to data limitations, found that global plastic debris inputs from rivers into the sea to range between 0.41 and 4×10^6 tonnes yr^{-1} of marine microplastic and macroplastic debris entered the sea from land-based sources via river transport, positively related to MMPW.
Vriend et al. (2020)	Visual observations with passive sampling led to estimates that 10–75 macroplastic items per hour and 1.3–9.7 kg per day are transported in the River Rhine.
Simon-Sanchéz *et al*. (2019)	The River Ebro, Spain, was estimated as representing an input of 2.14×10^9 microplastic particles per year into the Mediterranean Sea, with estuarine sediments constituting a potential important sink for microplastics.

Mani *et al*. (2015)	Relatively little attention has been paid to the role of rivers as pathways of microplastics entering the sea.
Lebreton *et al*. (2017)	Modelled global plastic inputs from rivers predicted that 74% of oceanic inputs occur between May and October
van Emmerik *et al*. (2019a, 2019b)	Long-term measurements in rivers such as the Seine and Saigon, an order of magnitude difference was observed in plastic transport within a year
Chen *et al*. (2014)	The majority of the annual river transport is caused by a single events
Castro-Jiménez *et al*. (2019)	Riverine plastic volumes fluctuate by up to a factor 10 between months

It is commonly reported that: 80% of marine plastic pollution comes from land (Jambeck et al., 2015); 90% of the total riverine plastic entering oceans derives from just 10 rivers (Schmidt et al., 2017) or that; 67% of global total plastic pollution derives from the top 20 polluting rivers, mostly located in Asia (Lebreton *et al*., 2017), all studies based on assumption-based models. However, van Emmerik and Schwarz (2020) note that the current state of science is too limited to support these broad claims. Recent global observations (van Calcar & van Emmerik, 2019) and modelling (Meijer et al., 2019) shows that plastic emissions from rivers are significantly more distributed than indicated by these reports.

An understanding of riverine transport is further complicated by the diversity of types and applications of plastic: the term ‘plastic’ spanning not only multiple synthetic polymers but also a wide range of formulations incorporating multiple additives (Jasso-Gastinel and Kenny, 2016). Furthermore, the tendency for plastics to be transported in aquatic environments varies with density and shape (Schwarz et al., 2019): plastics with a density greater than 1.0 g cm^{-3}, such as polyvinyl chloride (PVC) polymer with a density of 1.38 g cm^{-3} (BPF, 2019a), tend to sink; whereas lighter plastics, such as polyolefins (polyethylene has a density of 0.917-0.930 g cm^{-3}: BPF, 2019b), tend to float. Larger modelling studies on river transport (for example Lebreton et al., 2017; Schmidt et al., 2017) do not make these distinctions (van Emmerik and Schwarz, 2020). Differential durability between polymer types also influences propensity to degrade (Webb *et al*., 2013). Geographical variations in societal attitudes and infrastructure for take-back and recycling further affect the likelihood of entry into rivers (Schmidt *et al*., 2017); only some 9.4 million tonnes (15%) of the total plastic production of 61.8 million tonnes in Europe (EU28 + Norway and Switzerland) in 2018 were collected for recycling (inside and outside the EU) (PlasticEurope, 2019).

Based on the reviewed literature sources, seven principal categories of pathway of plastic inputs to rivers were identified: 1) waste water treatment plants; 2) combined sewer overflows; 3) on-site wastewater treatment systems; 4) road and rail transport systems; 5) agriculture; 6) industry; and 7) diffuse litter. A residual category of microplastics is considered separately, as attribution of source, including inputs from land but also breakdown of macroplastics in the river, is highly uncertain. Each category is outlined below and then used to inform an evaluation of their potential impacts on the study site.

3.1.1 Waste water treatment plants (WWTPs)

Waste water treatment plants (WWTPs) represent a source of plastic entering freshwater systems (Okoffo *et al*., 2019). A proportion of influent materials eventually exit WWTPs in treated effluent and sewage sludge though the lack of standardised methods and robust analytical sampling techniques means that this pathway remains a major research gap. The paucity of studies which have attempted to identify nano-sized plastics potentially results in an underestimation of total plastic emissions (Okoffo *et al*., 2019). (Nanoplastics in ecotoxicological settings, primarily formed by bulk degredation, are defined as plastic materials less than 1,000 nm: Gigault *et al*., 2018). However, respectively based on field sites in the UK and on a global review, Kay *et al*. (2018) and Li *et al*. (2018) found that WWTPs are the main source of microplastics in rivers. This view is supported by Nordic studies, which found that between 5.3% and 28% of microplastics were not removed during waste water treatment (Kole *et al*., 2017). This contrasts with studies suggesting that more than 98% of microplastics are efficiently removed during treatment (Magnusson and Noren, 2014; Carr *et al*., 2016; Murphy *et al*., 2016). However, the high volume of treated effluent discharged into rivers means that even the small percentage identified in the "best case" findings above may represent a significant load (Talvitie *et al*., 2017).

Although macroplastic items tend to be removed by the use of screens, studies of litter in rivers have shown a high proportion of macroplastic waste in rivers direct results from inappropriate items being flushed down toilets, some of which may enter rivers through incomplete capture in WWTPs. In a study of sub-surface 'rubbish' items trapped using fyke nets in the upper Thames estuary in 2012, Morritt *et al*. (2014) found that most contaminated sites were near WWTPs and that most of the 8,490 items trapped were plastic, respectively comprising 'Food wrappers/containers'(25%), 'general plastics'(24%), 'sanitary towel components' (21%), 'tobacco packaging/wrappers'(19%), 'cups, plates, forks, knives and spoons'(5%), 'other' (4%) and 'plastic bags'(2%). This concurs with an older study of a South Wales river that found that feminine hygiene products accounted for 22% of all waste recorded (Williams and Simmons, 1999), although Winton et al. (2020) found that only 5.2% of identifiable plastic waste in Euroepan rivers comprised 'sanitary items'. Other studies have also found an increase in litter items found in UK rivers following flood events, directly attributable to sewage outfalls (Williams and Simmons, 1997).

3.1.2 Combined sewer overflows

Williams and Simmons (1999) cite the conclusions of a study by Davies and Boden (1991) that litter from sewage does not enter freshwater primarily via WWTPs, but rather from combined sewer overflows (CSOs). In practice, it may not be possible to distinguish the role of CSOs in the transportation of macroplastics into rivers from transit through WWTPs. Combined sewage systems convey domestic and industrial sewage in the same pipes as rain water (from gutters, drains and roads), with CSOs overflowing directly into watercourses or the sea to relieve pressure on combined wastewater treatment system at times of high rainfall when volumes of water exceed the carrying capacity of the sewerage system. Consequently, the role of WWTPs in treating contamination and removing litter from wastewater from surface, domestic and industrial premises is bypassed during heavy rainfall, leading to direct inputs of litter and microplastics into rivers without the benefit of screening or settlement during the wastewater treatment process.

3.1.3 On-site wastewater treatment systems

Septic tanks or small package sewage treatment plants, collectively called on-site wastewater treatment systems (OSWwTS), can legally discharge directly into surface water. However, there are growing concerns about the negative impact of inefficient or poorly maintained septic tank systems on water quality (Withers *et al.*, 2013). Microplastics released from synthetic textiles are a significant and growing source of microplastic pollution (Henry *et al.*, 2019) with domestic washing machine effluent identified as the major pollution pathway. Due to the discharge of wastewater from OSWwTs without filters to remove microplastics contained in washing machine effluent, OSWwTPs may therefore represent a potentially significant source of microplastics in the form of textile microfibres. However, while there have been numerous studies on the effectiveness of WWTPs in removing microplastics, there are gaps in the analysis of volumes of microplastics entering rivers through surface run-off fed by OSWwTSs (Seigfried *et al.*, 2017).

3.1.4 Road and rail transport systems

Transport systems in this context refer principally to road networks, for which some literature is available, and to railways that are less well represented in the literature. Globally, approximately one-third of car tyre wear ends up in the sewerage systems (Boucher and Friot, 2017), though this generality may represent a substantial underestimate in drainage basins where road drainage is discharged directly into surface waters or the seas (Van Wijnen *et al*., 2019). Kole *et al*. (2017) concluded that microplastics produced from the wear and tear of car tyres have been vastly underestimated and should be considered a major microplastic source. Magnusson *et al*. (2016) concluded that the most important emissions of microplastics in Sweden were from wear in the road network totalling 13,519 tons per year (15 from polymer-modified bitumen, 13,000 from car tyres and 504 from road markings), though it is uncertain how much of these particles are transported into aquatic environments. The lack of data on releases from railway networks discoverable through literature searches suggests that this is an under-researched issue.

3.1.5 Agriculture

Catchments that include agricultural areas have been identified as an important source of microplastics in freshwater due to run-off from fields to which sewage sludge has been applied as a fertiliser, or from the breakdown of agricultural plastics (Kay *et al*., 2018).

Synthetic fibres from laundry have been found in agricultural soil up to 15 years after application of sludge from WWTPs (Zubris and Richards, 2005). A three-year study of French rivers in an agricultural area found that agricultural tarpaulin and packaging was the highest component of inland plastic waste (Bruge *et al.*, 2018).

3.1.6 Industrial sources

Synthetic materials by definition arise from the outputs of manufacturing sites. Field observations along the shoreline of Lake Huron, Canada, Zbyszewski and Corcoran (2011) ascertained that plastics in pellet form comprised 94% of plastic debris. The majority of the pellets were found proximally to an industrial sector along the south-eastern margin of Lake Huron, abundance steadily decreasing northward following the dominant lake current patterns. In a study aimed at identifying and assessing sources of litter in four large European rivers, Van der Wal *et al* (2015) found that, notwithstanding difficulties in assessing sources of litter from their appearance, industrial packaging was a likely major source of pollution. However, manufacturing industries themselves, at least in the UK, are considered less of a problem in terms of releases to the environment than societal habitats and associated resource recovery or disposal infrastructure (HM Government, 2018). Globally, particularly in regions where resource and waste management is far less tightly controlled than in Europe, the contributions from industrial sources may be significantly higher. However, the sparse literature specifically addressing the scale of direct industrial inputs of plastics to rivers frustrates attempts at quantification

3.1.7 Diffuse litter

It is accepted that the term ‘diffuse litter’ is broad, and can also span a range of sources that may include or overlap with identifiable sources above. Litter sources vary from public littering (either released directly into the rivers or indirectly via storm drains), improper waste management, landfills and litter spread via sewage (JRC, 2016) . The industrial sector appears to be the main source of European riverine litter, particularly industrial packaging with additional potentially significant inputs from urban areas, households, agriculture, fisheries, medical waste and wastewater treatment (Van der Wal *et al*., 2015). Some litter may enter from direct inputs, but also by diffuse inputs including as wind-blown materials (Faure *et al*., 2015). In the Rhône, a peak in plastic transport was measured several days after rainfall events (Castro-Jiménez *et al*., 2019). Observations support the hypothesis that wind and surface run-off are the main drivers of plastic transport from land to rivers (Bruge *et al*., 2018; Castro-Jiménez *et al*., 2019; Crosti *et al*., 2019; Moore *et al*., 2011), potentially vectored by surface run-off, drainage system discharge, atmospheric deposition or other means.

Studies analysing litter in rivers have shown that plastics were nearly always the most abundant material in litter samples (Van der Wal *et al*., 2015; Bruge *et al*., 2018; Morritt *et al*., 2014), though the mobile nature of litter compounds difficulties in identifying exact sources (Williams and Simmons, 1999). Crosti *et al*. (2018) and Emmerik *et al*. (2018) concur that land-based activities are the main source of marine litter, with rivers acting as pathways of mismanaged waste entering the sea.

Potential routes of entry of plastic debris into rivers include food packaging waste moved by the wind or collected in rainwater systems, litter left by visitors, sanitary products disposed of in toilets, discarded fishing tackle, fly tipping and other forms of illegal waste disposal, agricultural, industrial discharges, boat discharges, and urban/rural runoff (Van der Wal *et al*., 2015; Bruge *et al*., 2018; Morritt *et al*., 2014; Williams and Simmons, 1999). Studies aimed at identifying the predominant types of litter include the EU RIMMEL (RIverine and Marine floating macro litter Monitoring and Modelling of Environmental Loading) project, which coordinated a network of several research bodies monitoring floating litter (> 2.5 cm) from fixed observation points located on rivers near the sea. The study included the River Tiber in Italy, where it was found that 82% of floating items were plastic and belong to the food and cosmetic sector with 30% of this already fragmented (Crosti *et al*., 2018). Casto-Jiménez *et al*. (2019) estimate that plastic represents 77% of identified floating macro-litter in surface waters from the Rhone River, France, confirming its predominance in riverine floating litter, with fragments (2.5–50 cm) and single-use plastics (such as bags, bottles and cover/packaging) among the most abundant items. Casto-Jiménez *et al*. (2019) present a lower-end estimate of ~223,000 plastic items (~0.7 tonnes of plastic) transported annually by the Rhone surface waters to the Gulf of Lion (north-west Mediterranean Sea). Floating macroplastics are only a fraction of the total plastic export by the Rhone. Applying a standardised methodology to determine the weight, size and composition of riverine macroplastics (>5 cm) in the Saigon River, Vietnam, van Emmerik *et al*. (2018 and 2019) suggest that plastic emissions from the Saigon River may be 4-5 times greater than previously estimated, and by implication that emissions from other global river systems may also be significantly under-estimated.

3.1.8 Microplastics

Mani *et al*. (2015) report that surface microplastics loads had not been studied on any single major river globally throughout their length, their study reporting on the abundance and composition of microplastics at the surface of the Rhine (central Europe). Measurements taken by Mani *et al*. (2015) from 11 locations over a stretch of 820 km found microplastics in all samples at an average density of 892,777 particles km^{-2} peaking in the Rhine-Ruhr metropolitan area at 3.9 million particles km^{-2}. Early investigations of freshwater systems in Europe, North America and Asia reviewed by Eerkes-Medrano *et al*. (2015) suggest that freshwater microplastic presence and interactions are as far-reaching as those observed in marine systems in which microplastics reached densities as high as 100,000 items m^{-3} in waters and sediments, with numerous recorded organism and environment interactions. However, a study of the quantity and composition of floating plastic debris entering and leaving the Tamar Estuary in south-west England found that, although microplastics comprised 82% of the debris, the largely rural River Tamar was not identified as a net source or sink (Sandri *et al*., 2014). Rodrigues *et al*. (2018) found that a Portuguese river was severely affected by microplastics, showing pronounced spatial and temporal abundance particularly in the water column at sampling locations adjacent to intensive anthropogenic activities, emphasising the importance of rivers as carriage systems of microplastics. The presence and impacts of freshwater microplastics is at present under-researched, though inferences drawn from studies in the marine environment suggest similar problems with the compounding factor of closer proximity to point sources in freshwater systems.

The routes by which microplastics enter river systems are not always clear, some arriving in identifiable pollution sources and other, currently unquantified, loads likely to result from breakdown of larger plastic items in the river environment. In regions with combined sewerage systems, microplastics entering rivers can derive from WWTPs or CSOs deriving from household and/or industrial sources along with storm water run-off.

Hurley *et al*. (2018) found one of the highest global levels of microplastic in river sediments in a catchment in Manchester (north-west England). However, there have been very few studies of microplastics specifically on rivers (Blettler *et al*., 2018). These exceptionally high readings may be due to the robustness of testing and a lack of comparable data and agreed common testing frameworks, but this is still a significant finding.

Additional microplastic sources may be many and varied, and also largely under-researched and quantified. For example, Magnusson *et al*. (2016) estimated that 2,300-3,900 tons of microplastics were generated by wear of artificial turfs in Sweden per year, though the quantity entering aquatic systems was uncertain.

3.2 Sources of plastic debris in the River Wye

The sparse peer-reviewed and informal literature on plastics in the River Wye system is compounded by a lack of routine monitoring of plastic pollution. EU freshwater legislation, particularly the WFD, does not specifically include litter or plastic pollution in assessments of water quality (Van der Wal *et al*., 2015; Water News Europe, 2019) although the EU Marine Strategy Framework Directive (2008/56/EC) does require Member States to take action to quantify plastic fluxes entering the oceans. There is consequently no mention of plastic pollution in the Environment Agency (2014) Wye catchment WFD report. However, quantities of plastic in rivers are highly correlated with population density, urbanization, wastewater treatment and waste management (Best, 2019; Schwarz *et al*., 2019).
Consequently, the Environment Agency (2014) assessment undertaken for WFD purposes forms an initial basis for consideration of the most likely plastic debris inputs to the Wye system. The Environment Agency (2014) assessment identified diffuse pollution as the most significant contributing factor in the failure to attain Good Ecological Status across the Wye catchment, with point source sewage discharges identified as significant contributing factors.
Agriculture and the water industry were identified as "…key sectors where further collaboration is required" (Environment Agency, 2014, p.11). A breakdown of confirmed

reasons for not achieving good status shown in Table 3, with pollution-related issues by type discussed further below. It was also noted that the number of water bodies in the Wye catchment classified as of ‘Good Ecological Quality’ under the WFD had declined between assessments in 2009 and 2013 (Environment Agency, 2014).

Table 3. Numbers of confirmed reasons for not achieving good status of water bodies in the Wye catchment, relating source sector to nature of source or impact (Environment Agency, 2014).

Impacts	**Source sectors**					
	Water Industry	**Urban and transport**	**Unknown (not ascertainable)**	**Unable to assign a sector**	**Industry, manufacturing and other business**	**Agriculture and rural land management**
Changes to the natural flow and levels of water	2	-	-	14	-	2
Negative effects of non-native species	-	-	-		-	-
Physical modification	1	2	10		1	-
Pollution from rural areas	-	-	-		-	26
Pollution from waste water	2	-	-		-	-
Other pressures	-	-	-		-	1
Pollution from mines	-	-	-		-	-
Pollution from towns, cities and transport	-	19	-		-	-

A summary of the identified measures to improve the water environment specifically related to pollution sources in each operational catchment shown at Table 4.

Table 4. Operational Catchments within the wider Wye catchment including types of pollution measures needed to improve the water as identified by the Environment Agency (2014)

Surface water 'Operational Catchment'	**Pollution-related measures required**		
	Rural areas	Waste water	Towns, Cities and Transport
Wye upstream of Ithon (River Wye on the slopes of Plynlimon in Powys, Mid-Wales to the confluence of the River Ithon just below Newbridge on Wye)			✓ (Diffuse pollution at source and diffuse pollution pathways)
Irfon (the River Irfon rises on the slopes of Bryn Garw in the Cambrian Mountains, Powys, Mid-Wales)			✓ (Diffuse pollution and diffuse pollution pathways)
Ithon (the River Ithon rises between the slopes of Glog and Kerry Hill in Powys, mid-Wales. The Ithon flows in a southerly direction through Llandrindod Wells to join the main River Wye just downstream of Newbridge on Wye)	✓ (Diffuse pollution at source and diffuse pollution pathways)		

Lugg (Wales) (covers the upper Lugg above Presteigne and the upper Hindwell Brook, both of which are within Wales)		✓ (Diffuse pollution at source and point source pollution pathways)	
Wye: from confluence of the River Ithon to Hay (the main River Wye from its confluence with the Ithon just below Newbridge on Wye, to the confluence of the Sgithwen Brook below Llanstephen Bridge)	✓ (Diffuse pollution at source and diffuse pollution pathways)	✓ (Diffuse pollution at source and point source pollution pathways)	
Arrow, Lugg and Frome (the Arrow and Lugg originate in Wales and, with the Frome, join the Wye below Hereford)	✓ (Diffuse pollution at source and diffuse pollution pathways)	✓ (Point source)	
Monnow (the Monnow and its tributaries drain the Black Mountains and join the River Wye at Monmouth)	✓ (Diffuse pollution at source and	✓ (Point source)	✓ (Diffuse pollution at source)

	diffuse pollution pathways)		
Trothy (The River Trothy rises on Campston Hill around 250 masl in Monmouthshire, South Wales, flowing in a south-easterly direction to join the main River Wye just below Monmouth)	✓ (Diffuse pollution at source and diffuse pollution pathways)	✓ (Diffuse pollution at source and point source pollution pathways)	
Wye OC (Lower River Wye from Glasbury in Wales down through to Herefordshire, Monmouthshire and Gloucestershire and joins the Severn Estuary at Chepstow)	✓ (Diffuse pollution at source)	✓ (Point source)	✓ (Diffuse pollution at source)
Wye, downstream of River Lugg (below the confluence with the Lugg but outside of the Monnow and Trothy operational catchments)			

The Hurley *et al*. (2018) study also showed that rural rivers in the North of England are contaminated with microplastics, suggesting that the Wye may have high, albeit currently unassessed, significant microplastic levels. Out of the ten OCs for which the need for pollution control measures were recognised by the Environment Agency (2014): five were identified as requiring improved management of point and diffuse sources; six required improved management of rural sources; four required better manage inputs from towns, cities and transport; six required measures to address waste water. Two OCs required measures to deal with pollution from all three categories (wastewater, rural and towns, cities and transport) and, diffuse and point source pollution was specifically been identified as the main type of measure needed to improve water quality in three OCs.

3.2.1 WWTPs inputs to the River Wye

An indicator that WWTPs or CSOs are a likely source of plastic pollution in the Wye can be taken from the recommendation that actions are required in six of the ten OCs to mitigate/remediate point source impacts on receptors by managing pollution from waste water (Environment Agency, 2014). An EU (2014) report on the Wye catchment in connection with the Urban Waste Water Directive listed six 'Linked treatment plants' distributed across the catchment: 'Eign STW Outfall Works Road HFD STW'; 'Rotherwas STW Fir Tree Lane HFD STW'; 'Lydbrook Sewage Treatment Works STW'; 'Coleford STW'; 'Ross Lower Cleeve WWTW Ross on Wye STW'; and 'Monmouth STW'

3.2.2 CSO inputs to the River Wye

As noted above, plastic pollution emanating from WWTPs and CSOs may in practice be hard or impossible to distinguish. As most WWTPs in the region are fed by combined sewaergage systems, it is highly likely that that issues related to CSOs observed on other rivers also represent sources of plastic pollution in the River Wye. A study of riverine litter in a South Wales river noted that many CSOs in that area were unscreened (Williams and Simmons, 1999); if similar unscreened CSOs exist on the Wye, this increases the potential for plastic waste to enter via this route. Some local newspapers report on plastic sewage waste being seen in the Wye (Miles, 2018; Monmouthshire Beacon, 2016). Welsh Water (n.d.)

documents releases and their duration per annum for overflows of CSOs under the company's control in 2018 (Table 5), though the extent of screening and screen maintenance of CSOs is not documented. These figures reveal that, for monitored CSOs only, there were 1,220 discharges totalling 6,168.25 hours in 2018. From this evidence, a significant contribution from CSOs across the catchment can be surmised.

Table 5. Extracts from Welsh Water combined sewer overflow monitoring in 2018 (Welsh Water, n.d.)

Area	**Name of Wye catchment area**	**Releases per annum**	**Duration**	
			Hours	**Minutes**
Hereford	Hereford – Fownhope	0	0	0
	Ross on Wye – Weir End	0	0	0
	Lower Lydbrook – River Wye	0	0	0
	Bromyard	1	0	15
	Hereford – Seaton Avenue	1	1	30
	Hereford – Whitecross Road	1	2	30
	Newland	2	4	45
	Bridge Street Kington	4	1	15
	Cannop Rd	6	9	45
	Newland - Lane Newland	11	37	45
	Hereford – Belmont Roundabout	12	30	15
	Lydbrook – Great Hough	13	52	15
	Kington	14	9	15
	Moccas	14	87	15

	Porth House Industrial Estate	15	4	45
	Three Elms Rd Hereford	15	5	45
	Tarrington Hereford	15	149	30
	New Court Lugwardine Hereford	17	87	0
	Tanyard Lane Kington	18	11	15
	Eign	19	14	30
	Wyebank Road Chepstow	20	9	45
	Ross on Wye – Ross Lower Cleeve	28	57	15
	St Briavels Lydney	30	144	45
	Beneath Greyfriars Bridge Hereford	32	69	45
	Hereford - St Martins Allotments	33	76	0
	Joyford Mill	45	748	15
	Cawdor Arch	53	15	45
	Grandstand Road Hereford	55	66	15
	Sherford Street Bromyard	55	66	30
	Weobley	55	137	0
	New Road Pettybridge	61	78	30
	Ruardean	70	741	0
	Eardisley	71	1248	15
	Ross on Wye – Hope and Anchor	74	277	45
	Sedbury Chepstow	74	526	45
	Shobdon Hereford	246	1241	15
	Lydbrook	-	-	-

Mid Wales	There are currently no Combined Sewer Overflows with monitors in this area	-	-	-
Valleys and south east Wales	Monmouth / Trefynwy 1	40	9,240 (154 hours)	

3.2.3 OSWwTS inputs to the River Wye

Due to its predominantly rural nature, a high number of properties in the Wye catchment use OSWwTSs (septic tanks or small package sewage treatment plants) to manage their wastewater (Allaway, 2014). This then represents a potentially pervasive source principally of microplastics across both urban and rural areas of the Wye catchment. However, there was no documented evidence of actual impacts.

3.2.4 Road and rail transport system inputs to the River Wye

There is no readily transferrable knowledge to assess implications for the Wye Catchment. However, information in the Wye Management Catchment Plan (Environment Agency, 2012) includes an assessment that two OCs receive significant pollution from “towns, cities and transport”. Details in the report, corroborated by the conclusion of Natural Resources Wales (2019), confirm that these entries relate to acidification from acid grassland and coniferous woodland in the upper catchment. However, phosphate reduction studies in Herefordshire, covering large parts of the Wye catchment, identify roads as a source of diffuse pollution (Read *et al*., 2015) and hence there is a likelihood of microplastic tyre wear entering the Wye as in other areas where road drainage is discharged to surface waters (Van Wijnen *et al*. 2019), although this remains a research gap.

3.2.5 Agricultural inputs to the River Wye

The Wye and Usk Foundation (n.d.) report the results of an 11-year volunteer-based clean-up campaign on the upper River Wye completed in 2015, clearing litter from over 1,100 miles of river bank and collecting 4,171 sacks of litter and other items. 61% of items were identified as of agricultural origin, representing approximately 90% of total litter cleared by volume and weight. This quantification mirrors the finding of Bruge *et al*. (2018) from a three-year study of French rivers in an agricultural area, observing that agricultural tarpaulin and packaging was the highest component of inland plastic waste. No information on sewage sludge use in the Wye catchment area has been found though literature review. However, pollution from agriculture and rural land management is reflected in the status of the parts of the Wye catchment as being at risk of nitrate water pollution from agriculture and the formation of the River Wye SAC Nutrient Management Plan which focusses on phosphate reduction (Allaway, 2014), so its use can't be ruled out.

3.2.6 Industrial source inputs to the River Wye

In terms specifically of the River Wye, the paucity of larger industrial sites and the tighter regulatory controls on industrial processing and waste management means that industry is not perceived to be a major direct source of plastics entering the river system.

3.2.7 Diffuse litter inputs to the River Wye

Williams and Simmons (1999) concluded that fly tipping was one of the two main routes of entry of litter in the river Taff, South Wales, and it is likely that illegal waste disposal is not isolated to this geographical area. The presence of large amounts of litter and plastic pollution is highlighted in a report on microplastic ingestion by riverine micro-invertebrates carried out on three South Wales rivers, including the Wye (Windsor *et al*., 2018), although the results did not show clear evidence of their likely sources. Given the high visitor numbers that the Wye system attracts, it possible that recreational use could constitute a significant source of litter, a view supported by a Herefordshire newspaper article reporting on community participation to clear up litter from the banks of the River Wye in June 2017 (Scrivin, 2017).

3.2.8 Microplastics in the River Wye

No quantified levels of residual microplastics could be determined form the Wye system. However, by inference from the pervasion of WWTPs, CSOs, OSWwTSs and agricultural activities, it is reasonable to assume that microplastics are a pervasive problem in rural and urban areas alike, with additional potential inputs from transport infrastructure. This could also be due to the high level of transfer of microplastics due to flooding (Hurley *et al*., 2018). Quantification of microplastic inputs to and generation within the river remains a research gap

3.3 Risk-based 'fingerprinting' of plastic sources entering the River Wye

A summary of the likely sources of plastic pollution in the Wye is shown in Table 6. Entries are coded using a 'traffic lights' scheme ranging from red for high risk, amber for medium risk and green for low risk, based on a combination of (E) good evidence of impact in the target river system, (R) clear response options that may or may not be implemented, and/or (?) knowledge gaps considered significant and needing further research. This breakdown highlights that principal likely sources of plastic pollution in the Wye are identified as:

- macroplastics from agriculture and also inappropriate disposal via domestic toilets, transferred into the aquatic environment via CSOs, OSWwTs and direct diffuse litter inputs. Although there is evidence of large amounts of macroplastic litter in the Wye, the only confirmed source is from agriculture. Other studies would suggest that packaging litter is present, but more information is needed to confirm if this is from recreational activities on and around the river or from urban areas near the river; and

- microplastics from fibres in washing effluent, tyre and road network wear and tear, and degradation of local macroplastics, transferred via WWTP, CSOs, OSWwT and run-off into streams. The presence of microfibres in the Wye has been confirmed in an invertebrate study, but source apportionment is far from clear.

Table 6. Summary of possible sources of pollution in the Wye, including (E) evidence for the Wye, (R) responses, and (?) Knowledge gaps/research needs. 'Traffic lights' colour coding signifies (green) low priority, (amber) medium priority, and (red) high priority for investigation and/or control measures

Pathway	Plastic type	Route	Activity source	Priority based on (E:) Evidence, (R:) Responses and/or (?:) Significant knowledge gaps
WWTPs - point source pollution identified as issue in 6 OCs	Macroplastics	Passage though WWTPs	Inputs from multiple wastewater inputs to WWTP	**R:** Check-up required on effectiveness of WWTP screening procedures
	Microplastics	Domestic combined waste water	Fibres resulting from washing of fabrics	**E/?:** Macroinvertebrate study in the Wye and studies in other rivers highlight issue with microplastics but not attributing them to specific sources
			Cosmetics	**E:** Banned in UK since June 2018
		Industrial combined waste water	Processes using microbeads	**E:** No evidence found of use in industries in the Wye catchment
		Storm run-off entering wastewater stream	Multiple sources potentially significantly including road network wear	**E/R/?:** Identified as a priority in 3 OCs in the Wye system
CSOs - point source pollution identified issue in 6 OCs and evidence of use. No information on screening	Macroplastics	Flushing	Inappropriate waste disposed in toilets	**E:** Studies in similar areas and media reports suggest this may be an issue in the Wye. **R:** More monitoring is required to assess problem. **?:** Contribution of CSOs to riverine macroplastics is a knowledge gap
	Macroplastics leading to microplastics	In river	Degradation of macroplastics in of before treatment system	**E:** Microinvertebrate study in the Wye and studies in other rivers highlight issue with microplastics but not attributing them to specific sources. **?:** This is a significant knowledge gap.
	Microplastics	Domestic combined waste water	Fibres resulting from washing of fabrics	**E/?:** Macroinvertebrate study in the Wye and studies in other rivers highlight issue with microplastics but not attributing them to specific sources
			Cosmetics	Banned in UK since June 2.18

		Industrial combined waste water	Processes - microbeads	**E:** No evidence found of use in industries in the Wye catchment. **R:** Maintain surveillance for potential problems
		Storm run off	Multiple sources potentially significantly including road network wear	**E/R/?:** Identified as a priority in 3 OCs in the Wye system
OSWwTS - diffuse source pollution identified as priority in 6 areas	Macroplastics	Flushing	Inappropriate waste disposed of in toilets	Macroplastics are unlikely to transit OSWwTSs intact
	Macroplastics leading to microplastics	In river	Degradation of macroplastics in of before treatment system	**E:** Microinvertebrate study in the Wye and studies in other rivers highlight issue with microplastics but not attributing them to specific sources. **?:** This is a knowledge gap.
	Microplastics	Domestic combined waste water	Fibres resulting from washing of fabrics	**E/?:** Microinvertebrate study in the Wye and studies in other rivers highlight issue with microplastics but not attributing them to specific sources
			Cosmetics	Banned in UK since June 2.18
Transport Systems	Microplastics	Direct input from catchment	Potentially highly significant inputs from tyre and road network wear	**E/R:** Identified as a priority in 1 OC in the Wye system. **?:** remains a significant knowledge gap given indicative scale of the source
Agriculture	Macroplastics	Storm run-off and wind-blown	Litter from agricultural activities	**E/R:** Agricultural litter main was component of litter cleared from banks, requiring more enforcement
	Macroplastics leading to microplastics	In river	Degradation of macroplastics during or after use in agriculture	**E:** Microinvertebrate study in the Wye and studies in other rivers highlight issue with microplastics but not attributing them to specific sources. **?:** This is a significant knowledge gap.
	Microplastics	Storm run off	Inputs with sewage sludge	**E:** Evidence in other agricultural areas, requiring **R:** further monitoring, and **?:** research to address a potentially significant knowledge gap

Industry	Macroplastics	Direct disposal	Industrial process wastes	**E:** Likely to be a low priority in the Wye due to paucity of industry and stringent regulatory controls
	Microplastics	Direct release or breakdown	Industrial process wastes	**E:** Likely to be a low priority in the Wye due to paucity of industry and stringent regulatory controls, with most effluent directed through WWTPs
Diffuse litter	Macroplastics	Wind-blown, agriculture, recreation, run-off, etc.	Multiple sources that are not otherwise characterised	**?:** Source apportionment of microplastics is a research priority to determine scale of inputs and necessary management responses
Residual category of microplastics	Microplastics	Run-off, agriculture, breakdown in situ, transport infrastructure, etc.	Multiple sources that are not otherwise characterised	**?:** Source apportionment of microplastics is a research priority to determine scale of inputs and necessary management responses

Though a far from complete inventory of sources and lacking quantification, the analysis of the River Wye nonetheless provides a ‘fingerprint’ of likely sources of plastics that can be used by regulatory organisations to inform priorities for further studies or direction of regulatory, education and other management responses. This fingerprint is unique to the River Wye based on currrently-available evidence, reflective of the particular balance of industries, settlements, farming, wastewater treatment systems, stringency of resource and waste management, and other factors peculiar to any specific river systems.

Research gaps identified as priorities for further understanding of plastic inputs to the Wye include: the contribution of industries in the catchment, particularly those using plastic pellets; the role of OSWwTS; the make-up of plastic litter to determine likely sources; and research on microplastic entry through the use of sewage sludge by agriculture.

4. Discussion

As rivers accumulate plastic from multiple sources, actions to reduce the presence of macroplastics in rivers is fundamental to conserving both freshwater and marine environments (Winton *et al*., 2020). The structured review of peer-reviewed, regulatory and other reports provides an overview of seven identified sources: waste water treatment plants (WWTPs); combined sewer overflows (CSOs); on-site wastewater treatment systems (OSWwTS); transport systems; agriculture; industrial sources; and diffuse litter. An additional generic category of microplastics reflects difficulty of attributing to specific sources. Potentially influencing all categories, unsoundly disposed plastic waste, defined as mismanaged plastic waste (MMPW), is of major, growing global concern (Lebreton and Andrady, 2019). Lebreton and Andrady (2019) estimate that between 60 and 99 million metric tonnes (Mt) of MMPW were produced globally in 2015, a figure that could triple to 155–265 Mt y^{-1} by 2060 under current trends with the majority of MMPW (91%) transported via rivers in watersheds larger than 100 km^2 into the world's oceans. Knowing precisely where litter is generated is important to target priority areas for the implementation of mitigation policies, so improvements in source attribution are a key research need.

Further research gaps to better inform understanding and management of pathways of plastics into river systems and response options to control plastic pollution include: the behaviour of different types of plastics, including different polymer types and their many alternative formulations (including for example their tendency to float or fragment); apportionment of plastic in rivers from different applications, particularly durable versus short-life; the efficacy of the regionally variable implementation of take-back and recycling infrastructure; and better characterisation of the routes by which microplastics enter rivers, including evidence of their residence time and rates of breakdown in rivers.

Analysis of likely sources of plastics in the River Wye has developed a distinctive 'fingerprint' of likely sources based on rapid, desk-based review of published information. This 'fingerprinting' approach, apportioning inputs from seven potential sources – WWTPs, CSOs; OSWwTS; transport systems; agriculture; industrial sources; and diffuse litter – and a residual 'hard to apportion' microplastics fraction, is helpful to regulatory bodies with limited resources for investigation and response, and is relevant to other rivers both nationally and globally. We accept that data supporting this approach is sparse, and therefore is significant amount of inference is required. However, this does reflect operational realities for regulatory bodies with limited resources, and necessarily making decisions about allocation of constrained resources to further investigatory and regulatory responses in the face of a high degree of uncertainty. This justifies the need for a rapid, fingerprinting approach addressing potential sources of plastics in rivers based on available, primarily desk-based evidence, informing likely catchment-specific risk presented here using an intuitive and transparent ‘traffic lights’ colour coding system. We recognise that this is a coarse assessment extrapolating knowledge to the whole of a heterogeneous catchment. Here and in other catchments, particularly larger river systems, investigations and fingerprinting could be downscaled to address sub-catchments with widely differing properties.

A key recommendation from this analysis is therefore that this fingerprinting approach is generically applied to other river systems. By using an accessible range of literature, potentially backed up by interviews with key stakeholders (such as regulatory agencies) and limited field surveys, it serves as a rapid and highly cost-effective screening method to identify the particular catchment-specific ‘fingerprint’ of likely sources contributing to plastic pollution. Catchment-specific fingerprinting can in turn be of significant value for informing a strategic approach to the targeting and prioritisation of regulatory or enforcement action, advice and wider education, possible inducements, taxes or other financial instruments, amongst wide range of potential management response options. This can inform management responses at anything from local to regional or national scales, to address the growing and internationally variable problem of plastic pollution into and downstream of rivers.

Ultimately, ceasing to emit, or reducing releases of, plastics at source would stem the current high volumes of plastics entering river systems and transported onwards to marine environments. The EU strategy to work towards a circular economy (European Commission, 2018) and the UK government's Resources and Waste Strategy (HM Government, 2018) both lay particular emphasis on recovery of plastics and other materials for recycling, phase-out in applications where they might accumulate in natural systems, and additional options such as increasing biodegradability. More complete recovery of plastics would avert at least a proportion of the entry of plastic materials into rivers and other ecosystems.

5. Conclusions

- Literature review and field observations identify seven potential sources of plastics entering river systems – waste water treatment plants (WWTPs); combined sewer overflows (CSOs); on-site wastewater treatment systems (OSWwTS); transport systems; agriculture; industrial sources; and diffuse litter – with a further residual microplastics category recognising unclear sources.

- Review of peer-reviewed, regulatory and other literature support rapid, desk-based assessment of a risk-based 'fingerprint' of likely plastic entry from different sources in the River Wye system.

- This rapid 'fingerprinting' approach can be a helpful in prioritisation of limited enforcement and management actions and further investigations, also averting potential wastage of resources in taking a more generic approach to catchments.

- A more granular scale of investigation could usefully be carried out in larger catchments, and in those river systems comprising sub-catchments with widely differing properties.

- This ‘fingerprinting’ approach is transferrable to other river systems, serving as a first phase of desk-based investigation to prioritise further action.

- Sources, environmental behaviours, potential impacts and potential control measures for some types plastics in rivers are substantially under-researched, in particular microplastics.

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7. References

Allaway, C., 2014. *River Wye SAC: Nutrient Management Plan*. Atkins, Epsom. (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/361793/River_Wye_NMP_final_report_v3_14052014.pdf, accessed 14th February 2019.)

Andrady, A.L. (Ed.). (2003). Plastics and the environment. New York: John Wiley & Sons.

Wiley Online Library Google Scholar

Andrady, A. L., & Neal, M. A. (2009). Applications and societal benefits of plastics. Philosophical Transactions of the Royal Society B: Biological Sciences, 364(1526), 1977–1984.

Bayo, J., Martínez, A., Guillén, M., Olmos, S., Roca, M-J., Alcolea, A., 2017. Microbeads in Commercial Facial Cleansers: Threatening the Environment. *CLEAN – Soil, Air, Water*, 45(7). DOI: https://doi-org.ezproxy.uwe.ac.uk/10.1002/clen.201600683.

Best, J. (2019). Anthropogenic stresses on the world's big rivers. *Nature Geoscience*, 12(1), 7–21.

Boucher, J. and Friot, D. (2017). *Primary microplastics in the oceans: a global evaluation of sources*. IUCN, Gland, Switzerland, 43pp.

BPF, 2019a. *Polyvinyl Chloride PVC*. British Plastics Federation (BPF), London. (https://www.bpf.co.uk/plastipedia/polymers/pvc.aspx, accessed 21st December 2019.)

BPF, 2019b. *Polyethylene (Low Density) LDPE, LLDPE*. British Plastics Federation (BPF), London. (https://www.bpf.co.uk/plastipedia/polymers/LDPE.aspx, accessed 21st December 2019.)

Blettler, M.C.M., Abrial, E., Khan, F.R., Sivri, N., Espinola, L.A., 2018. Freshwater plastic pollution: Recognizing research biases and identifying knowledge gaps. *Water Research*, 143 pp.416-424.

Blettler, M.C.M., Ulla, M.A., Rabuffetti, A.P., Garello, N., 2017. Plastic pollution in freshwater ecosystems: macro-, meso-, and microplastic debris in a floodplain lake. *Environmental Monitoring and Assessment*. 189 (11), pp.1-13.

Bloomfield, R., 1811. *The Banks of Wye; A Poem in Four Books*. Vernor, Hood and Sharpe, London.

Bruge, A., Barreau, C., Carlot, J., Collin, H., Moreno, C., Maison, P., Maison, P., Carlot, J., Moreno, C., Collin, H., Bruge, A., Barreau, C., 2018. Monitoring Litter Inputs from the Adour River (Southwest France) to the Marine Environment. *Journal of Marine Science and Engineering*, 6 (1), pp.24.

Carr, S., Liu, J. and Tesoro, A. (2016). Transport and fate of microplastic particles in wastewater treatment plants. *Water Research*, 91, pp.174-182.

Castro-Jiménez, J., González-Fernández, D., Fornier, M., Schmidt, N. and Sempere, R. (2019). Macro-litter in surface waters from the Rhone River: Plastic pollution and loading to the NW Mediterranean Sea. *Marine Pollution Bulletin*, 146, pp.60-66.

Chen, J., Bouchez, J., Gaillardet, J., & Louvat, P. (2014). Behaviors of major and trace elements during single flood event in the Seine River, France. Procedia Earth and Planetary Science, 10, 343–348.

Consoli, P., Romeo, T., Angiolillo, M., Canese, S., Esposito, V., Salvati, E., Cotti, G., Andaloro, F. and Tunesi, L. (2019). Marine litter from fishery activities in the Western Mediterranean Sea: The impact of entanglement on marine animal forests. *Environmental Pollution*, 249, pp.472-481.

Crosti, R., Arcangeli, A., Campana, I., Paraboschi, M. and Fernández, D.G. (2019). 'Down to the river': amount, composition, and economic sector of litter entering the marine compartment, through the Tiber river in the Western Mediterranean Sea. *Rendiconti Lincei. Scienze Fisiche e Naturali*, 29, pp.859–866. DOI: 10.1007/s12210-018-0747-y.

Crawford, C.B., Quinn, B., 2017. *Microplastic Pollutants*. Amsterdam: Elsevier.

Edwards, R.W., Brooker, M.P., Illies, J., 1982. *The Ecology of the Wye*. Dordrecht: Springer Netherlands.

Eerkes-Medrano, D., Thompson, R.C., Aldridge, D.C., 2015. Microplastics in freshwater systems: A review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. *Water Research*, 75, pp.63-82.

Encyclopedia Britannica, 2013. *River Wye*. (https://www.britannica.com/place/River-Wye, accessed 14th February 2019.)

Environment Agency, 2014. *The Wye Management Catchment: A Summary of Information about the Water Environment in the Wye Management Catchment.* (https://circabc.europa.eu/webdav/CircaBC/env/wfd/Library/framework_directive/implementation_documents_1/2012-2014%20WFD%20public%20information%20and%20consultation%20documents/UK/UK09%20Severn/Wye.pdf, accessed 14th February 2019.)

Environment Agency, 2015. *Water for Life and Livelihoods: Part 1: Severn River Basin District River Basin Management Plan.* (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/718336/Severn_RBD_Part_1_river_basin_management_plan.pdf, accessed 14th February 2019.)

Eriksen, M., Mason, S., Wilson, S., Box, C., Zellers, A., Edwards, W., Farley, H. and Amato, S. (2013). Microplastic pollution in the surface waters of the Laurentian great lakes. *Marine Pollution Bulletin*, 77(1-2), pp.177-182.

EU. (2014). *European Commission urban waste water website: United Kingdom*. European Union. [Online.] (https://uwwtd.eu/United-Kingdom/receiving-area/ukwari11/2014, accessed 28th December 2019.)

European Commission, 2018. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A European Strategy for Plastics in a Circular Economy COM/2018/028* *final*. European Commission, Brussels. (https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1516265440535&uri=COM:2018:28:FIN, accessed 14th February 2019.)

European Commission, 2019a. *The EU Water Framework Directive - integrated river basin management for Europe*. European Commission, Brussels. (http://ec.europa.eu/environment/water/water-framework/index_en.html, accessed 14th February 2019.)

European Commission, 2019b. *The Habitats Directive*. European Commission, Brussels. (http://ec.europa.eu/environment/nature/legislation/habitatsdirective/index_en.htm, accessed 14th February 2019.)

European Commission, 2019c. *The Nitrates Directive*. European Commission, Brussels. (http://ec.europa.eu/environment/water/water-nitrates/index_en.html, accessed 14th February 2019.)

Faure, F., Demars, C., Wieser, O., Kunz, M., de Alencastro, L.F., 2015. Plastic pollution in Swiss surface waters: nature and concentrations, interaction with pollutants. *Environmental Chemistry*, 12(5), pp.582-591.

Galgani, F., Hanke, G., Werner, S. and De Vrees, L. (2013). Marine litter within the European Marine Strategy Framework Directive. *ICES Journal of Marine Science*, 70(6), pp.1055-1064. DOI: 10.1093/icesjms/fst122.

Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. Science Advances, 3(7), e1700782.

Gigault, J., Halle, A.T., Baudrimont, M., Pascal, P.Y., Gauffre, F., Phi, T.L., El Hadri, H., Grassl, B. and Reynaud, S. (2018) Current opinion: What is a nanoplastic? *Environmental Pollution*, 235, pp.1030–1034.

Henry, B., Laitala, K., Klepp, I.G., 2019. Microfibres from apparel and home textiles: Prospects for including microplastics in environmental sustainability assessment. *Science of the Total Environment*, 652 pp.483-494.

HM Government, 2018. *Our waste, our resources: a strategy for England*. HM Government, London. (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/765914/resources-waste-strategy-dec-2018.pdf, accessed 14th February 2019.)

Horton, A.A., Svendsen, C., Williams, R.J., Spurgeon, D.J., Lahive, E., 2017, Large microplastic particles in sediments of tributaries of the River Thames, UK – Abundance, sources and methods for effective quantification. *Marine Pollution Bulletin*, 114 (1), pp.218-226.

Hurley, R., Woodward, J., Rothwell, J., 2018. Microplastic contamination of river beds significantly reduced by catchment-wide flooding. *Nature Geoscience*, 11 pp.251-257.

Jambeck, J. R., Geyer, R., Wilcox, C., Siegler, T. R., Perryman, M., Andrady, A., … Law, K. L. (2015). Plastic waste inputs from land into the ocean. Science, 347(6223), 768– 771.

Jarvie, H.P., Neal, C., Withers, P.J.A., Robinson, A., Salter, N. (2003) Nutrient water quality of the Wye catchment, UK: exploring patterns and fluxes using the Environment Agency data archives. *Hydrology and Earth System Sciences*, 7(5), pp.722-743.

Jasso-Gastinel, C.F. and Kenny, J.M. (2016). Modification of Polymer Properties (Plastics Design Library) 1st Edition. William Andrew Publishers.

JRC, 2016. *Riverine Litter Monitoring - Options and Recommendations*. (https://ec.europa.eu/jrc/en/publication/riverine-litter-monitoring-options-and-recommendations, 14th February 2019.)

Kay, P., Hiscoe, R., Moberley, I., Bajic, L., McKenna, N., 2018. Wastewater treatment plants as a source of microplastics in river catchments. *Environmental Science and Pollution Research*, 25(20), pp.20264-20267.

Kole, P.J., Löhr, A.J., Belleghem, F.G.A.J., Ragas, A., 2017. Wear and tear of tyres: a stealthy source of microplastics in the environment. *International Journal of Environmental Research and Public Health*, 14 pp.1-31.

Lebreton, L. and Andrady. A. (2019). Future scenarios of global plastic waste generation and disposal. Palgrave Communications, 5.1, article No.6. (https://www.nature.com/articles/s41599-018-0212-7, accessed 2019.12-24.)

Lebreton, L.C.M., van der Zwet, J., Damsteeg, J-M., Slat, B., Andrady, A. and Reisser, J. (2017). River plastic emissions to the world's oceans, *Nature Communications*, 8, 15611. https://www.nature.com/articles/ncomms15611.

Li, J., Liu, H., Chen, J.P., 2018. Microplastics in freshwater systems: A review on occurrence, environmental effects, and methods for microplastics detection. *Water Research*, 137, pp.362-374.

Magnusson, K., 2014. *Mikroskräp i avloppsvatten från tre norska avloppsreningsverk*. IVL Swedish Environmental Research Institute. Rapport C71.

Magnusson, K., Eliasson, K., Fråne, A., Haikonen, K., Hultén, J., Olshammar, M., Stadmark, J., Voisin, A., IVL Svenska Miljöinstitutet, 2016. *Swedish sources and pathways for microplastics to the marine environment: A review of existing data*. Study for the Swedish Environmental Protection Agency. IVL Swedish Environmental Research Institute, Stockholm. (http://www.ivl.se/download/18.7e136029152c7d48c205d8/1457342560947/C183+Sources+of+microplastic_160307_D.pdf, accessed 14th February 2019.)

Magnusson, K. and Norén, F. (2014). Screening of Microplastic Particles in and Down-stream a Wastewater Treatment Plant. Report Number C55, IVL Swedish Environmental Research Institute, Stockholm.

Magnusson, K., Wahlberg, C., 2014. *Mikroskopiska skräppartiklar i vatten från avloppsreningsverk* (Microscopic litter particles in water from WWTPs). IVL Swedish Environmental Research Institute. Report B 2208: 30.

Mani, T., Hauk. A., Walter, U., Burkhardt-Holm, P., 2015. Microplastics profile along the Rhine River. *Nature: Scientific Reports*, 5:17988. DOI: https://doi.org/10.1038/srep17988.

McCormick, A.R., Hoellein, T.J., London, M.G., Hittie, J., Scott, J.W., Kelly, J.J., 2016. Microplastic in surface waters of urban rivers: concentration, sources, and associated bacterial assemblages. Ecosphere, 7(11), e01556. DOI: https://doi.org/10.1002/ecs2.1556.

McKinsey & Company, Ocean Conservancy, 2015. *Stemming the Tide: Land-based strategies for a plastic-free ocean*. McKinsey & Company and Ocean Conservancy. (https://oceanconservancy.org/wp-content/uploads/2017/04/full-report-stemming-the.pdf, accessed 20th December 2019.)

Meijer, L. J. J., van Emmerik, T., Lebreton, L., Schmidt, C., & van der Ent, R. (2019). Over 1000 rivers accountable for 80% of global riverine plastic emissions into the ocean. *Science Advances*. https://doi.org/10.31223/osf.io/zjgty.

Miao, L., Wang, P., Hou, J., Yao, Y., Liu, Z., Liu, S. and Li, T. (2019). Distinct community structure and microbial functions of biofilms colonizing microplastics. *Science of The Total Environment*, 650(2), pp.2395-2402.

Miles, R., 2018. Resident's Shock at Sewage in River Wye. *Hereford Times*, 22nd August 2018. (https://www.herefordtimes.com/news/16591889.residents-shock-at-sewage-in-river-wye/, accessed 14th February 2019.)

Miralles, L., Gomez-Agenjo, M., Rayon-Viña, F., Gyraitė, G. and Garcia-Vazquez, E. (2018). Alert calling in port areas: Marine litter as possible secondary dispersal vector for hitchhiking invasive species. *Journal for Nature Conservation*, 42, pp.12-19. DOI: https://doi.org/10.1016/j.jnc.2018.01.005.

Monmouthshire Beacon, 2016. High Sewage Levels Cause River Fears. Monmouthshire Beacon, 22nd June 2016. (http://www.monmouthshirebeacon.co.uk/article.cfm?id=105297&headline=High%20sewage%20levels%20cause%20river%20fears&sectionIs=news&searchyear=2016, accessed 14th February 2019.)

Moore, C. J., Lattin, G. L., & Zellers, A. F. (2011). Quantity and type of plastic debris flowing from two urban rivers to coastal waters and beaches of Southern California. Revista de Gestão Costeira Integrada-Journal of Integrated Coastal Zone Management, 11(1), 65–73.

Morritt, D., Stefanoudis, P.V., Pearce, D., Crimmen, O.A., Clark, P.F., 2014, Plastic in the Thames: A river runs through it. *Marine Pollution Bulletin*, 78 (1-2), pp.196-200.

Murphy, F., Ewins, C., Carbonnier, F. and Quinn, B. (2016). Wastewater treatment works (WwTW) as a source of microplastics in the aquatic environment. *Environmental Science and Technology*, 50(11), pp.5800-5808.

Natural Resources Wales, 2018. *Water Management: Information about how we Manage and Monitor Water Resources in Wales*. (https://naturalresources.wales/guidance-and-advice/environmental-topics/water-management-and-quality/resources/water-management/?lang=en, accessed 14th February 2019.)

Natural Resources Wales. (2019). *Challenges and Choice: Consultation on the summary of significant water management issues for Wales, Western Wales River Basin District and Dee River Basin District*, Natural Resources Wales, Cardiff. (https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=9&ved=2ahUKEwjPjLax6ufmAhVEQEEAHWJzCGkQFjAIegQIBRAC&url=https%3A%2F%2Fcdn.naturalresources.wales%2Fmedia%2F689924%2Fchallenges-and-choices-2019_final-1.pdf%3Fmode%3Dpad%26rnd%3D132115634850000000&usg=AOvVaw2R0rYA5aGwq-8ES9xB6fqW, accessed 4th January 2020.)

Okoffo, E.D., O'Brien, S., O'Brien, J.W., Tscharke, B.J. and Thomas, K.V. (2019). Wastewater treatment plants as a source of plastics in the environment: a review of occurrence, methods for identification, quantification and fate. *Environ. Sci.: Water Res. Technol.*, 5, pp.1908-1931. DOI: 10.1039/C9EW00428A.

PlasticsEurope. (2019). *Plastics – the Facts 2019: An analysis of European plastics production, demand and waste data*. PlasticsEurope, Brussels. (https://www.plasticseurope.org/application/files/9715/7129/9584/FINAL_web_version_Plastics_the_facts2019_14102019.pdf, accessed 14th April 2020.)

PrimaryFacts, 2016. *River Wye: Primary facts and information*. [Online.] (http://primaryfacts.com/7006/river-wye-facts-and-information/, accessed 20th December 2019.)

Read, N., Oakes, N. and Meredith, C. (2015). *Phosphate Reduction Feasibility Study: A Report to Natural England on behalf of the Herefordshire Local Nature Partnership*. [Online]. Report Number 2015/02. The Bulmer Foundation, Hereford (https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&cad=rja&uact=8&ved=2ahUKEwiP0ca49enmAhUHJsAKHRtQC90QFjAAegQIBRAC&url=https%3A%2F%2Fwww.brightspacefoundation.org.uk%2Fsites%2Fdefault%2Ffiles%2Fimce%2F2015-02-Phosphate%2520Reduction%2520Feasibility%2520Study.pdf&usg=AOvVaw3fdBZw6bLz9iiKYRuuSLXv, accessed 4th January 2020.)

Rodrigues, M.O., Abrantes, N., Gonçalves, F.J.M., Nogueira, H., Marques, J.C., Gonçalves, A.M.M., 2018. Spatial and temporal distribution of microplastics in water and sediments of a freshwater system (Antuã River, Portugal). *Science of The Total Environment*, 633, pp.1549-1559.

Sandri, S.S., Thompson, R.C., 2014. On the quantity and composition of floating plastic debris entering and leaving the Tamar Estuary, Southwest England. *Marine Pollution Bulletin*, 81(1), pp.55-60.

Schmidt, C., Krauth, T., Wagner, S., 2017. Export of Plastic Debris by Rivers into the Sea. *Environmental Science and Technology*, 51(21), pp.12246-12253. DOI: 10.1021/acs.est.7b02368.

Schwarz, A.E., Ligthart, T.N., Boukris, E., van Harmelen, T. (2019). Sources, transport, and accumulation of different types of plastic litter in aquatic environments: A review study. *Marine Pollution Bulletin*, 143, pp.92-100.

Schmidt, C., Krauth, T. and Wagner, S. (2017). Export of plastic debris by rivers into the sea. *Environmental Science and Technology*, 51(21), pp.12246-12253. DOI: https://doi.org/10.1021/acs.est.7b02368.

Scrivin, J., 2017, Dog Walkers Help Clear Litter Left at the River Side in Ross on Wye. *The Ross Gazette*, 28th June 2017. (http://www.rossgazette.com/article.cfm?id=109454&headline=Dog%20walkers%20help%20clear%20litter%20left%20at%20the%20river%20side%20in%20Ross-on-Wye&sectionIs=news&searchyear=2017, accessed 14th February 2019.)

Siegfried, M., Koelmans, A.A., Besseling, E., Kroeze, C., 2017. Export of microplastics from land to sea. A modelling approach. *Water Research*, 127, pp.249-257.

Sigler, M., 2014. The Effects of Plastic Pollution on Aquatic Wildlife: Current Situations and Future Solutions. *Water, Air, & Soil Pollution*, 225 (11), pp.1-9.

Simon-Sánchez, L., Grelaud, M., Garcia-Orellana, J. and Ziveria, P. (2019). River Deltas as hotspots of microplastic accumulation: The case study of the Ebro River (NW Mediterranean). *Science of the Total Environment*, 687, pp.1186-1196. DOI: https://doi.org/10.1016/j.scitotenv.2019.06.168.

Talvitie, J., Mikola, A., Setälä, O., Heinonen, M., Koistinen, A., 2017. How well is microlitter purified from wastewater? – A detailed study on the stepwise removal of microlitter in a tertiary level wastewater treatment plant. *Water Research*, 109, pp.164-172.

Thompson, R.C., Moore, C.J., vom Saal, F.S., Swan, S.H., 2009. Plastics, the environment and human health: current consensus and future trends. *Philosophical Transactions of the Royal Society B – Biological Sciences*, 364(1526). DOI: https://doi.org/10.1098/rstb.2009.0053.

Tramoy, R., Gasperi, J., Dris, R., Colasse, L., Fisson, C., Sananes, S., Rocher, V. and Tassin, B. (2019). Assessment of the plastic inputs from the Seine Basin to the sea using statistical and field approaches. *Frontiers in Marine Science*, 10. DOI: https://doi.org/10.3389/fmars.2019.00151.

UNEP, 2014. *United Nations Environment Programme Year Book 2014: Emerging Issues in our Global Environment.* (http://wedocs.unep.org/handle/20.500.11822/9240, accessed 14th February 2019.)

van Calcar, C.J. and van Emmerik, T. H. M. (2019). Abundance of plastic debris across European and Asian rivers. *Environmental Research Letters*, 14(12), 124051.

Van der Wal, M., Van der Meulen, M., Tweehuijsen, G., Peterlin, M., Palatinus, A., Kovac, M., Coscia, L., Krzan, A., 2015. *Identification and Assessment of Riverine Input of (Marine) Litter* [online]. Report number: SFRA0025. Bristol. European Commission.

(http://ec.europa.eu/environment/marine/good-environmental-status/descriptor-10/pdf/iasFinal%20Report.pdf, accessed 14th February 2019.)

van Emmerik, T, Kieu-Le, T-C., Loozen, M., van Oeveren, K., Strady, E., Bui, X-T., Egger, M., Gasperi, J., Lebreton, L., Nguyen, P-D., Schwarz, A., Slat, B. and Tassin, B. (2018). A methodology to characterize riverine macroplastic emission into the ocean. *Frontiers in Marine Science*, 5: 372. DOI: https://doi.org/10.3389/fmars.2018.00372.

van Emmerik, T., Strady, E., Kieu-Le, T-C., Nguyen, L. and Gratiot, N. (2019a). Seasonality of riverine macroplastic transport. *Scientific Reports*, 9, Article number: 13549

van Emmerik, T., Tramoy, R., van Calcar, C., Alligant, S., Treilles, R., Tassin, B., & Gasperi, J. (2019b). Seine plastic debris transport tenfolded during increased river discharge. *Frontiers in Marine Science*, 6, 642.

van Wijnen, J., Ragas, A.M.J. and Kroeze, C. (2019). Modelling global river export of microplastics to the marine environment: sources and future trends. *Science of the Total Environment*, 673, pp.392-401. DOI: 10.1016/j.scitotenv.2019.04.078.

Vriend, P., van Calcar, C., Kooi, M., Landman, H., Pikaar, R. and van Emmerik, T. (2020). Rapid Assessment of Floating Macroplastic Transport in the Rhine. *Frontiers in Marine Science*. DOI: https://doi.org/10.3389/fmars.2020.00010.

Wagner, M., Scherer, C., Alvarez-Muñoz, D., Brennholt, N., Bourrain, X., Buchinger, S., Fries, E., Grosbois, C., Klasmeier, J., Marti, T., Rodriguez-Mozaz, S., Urbatzka, R., Vethaak, A.D., Winther-Nielsen, M., Reifferscheid, G., 2014. Microplastics in freshwater ecosystems: what we know and what we need to know. *Environmental Sciences Europe*, 26(12). DOI: https://doi.org/10.1186/s12302-014-0012-7.

Water News Europe, 2019. WFD: European river basin organisations plea for revision 'One out all out' principle. *Water News Europe*, 30th June 2019. [Online.] (https://www.waternewseurope.com/wfd-european-river-basin-organisations-plea-for-revision-one-out-all-out-principle/, accessed 20th December 2019.)

Webb, H.K., Arnott, J., Crawford, R.J., Ivanova, E.P., 2013. Plastic Degradation and Its Environmental Implications with Special Reference to Poly(ethylene terephthalate). *Polymers*, 5(1), pp.1-18. DOI: https://doi.org/10.3390/polym5010001.

Welsh Water. (n.d.) *Combined Sewer Overflow Monitoring: Hereford* (https://www.dwrcymru.com/en/devmap/CSO-Monitoring/Hereford.aspx, accessed 23rd December 2019.)

Wessel, C., Swanson, K., Weatherall, T. and Cebriana, J. (2019). Accumulation and distribution of marine debris on barrier islands across the northern Gulf of Mexico. *Marine Pollution Bulletin*, 139, pp.14-22. DOI: https://doi.org/10.1016/j.marpolbul.2018.12.023.

Williams, A.T., Simmons, S.L., 1999. Sources of Riverine Litter: The River Taff, South Wales, UK. *Water, Air, and Soil Pollution*,112 (1), pp.197-216.

Williams, A.T., Simmons, S.L., 1997. Movement patterns of riverine litter. Water, Air, and Soil Pollution [online]. 98 (1), pp.119-139.

Windsor, F.M., Tilley, R.M., Tyler, C.R., Ormerod, S.J., 2018. Microplastic ingestion by riverine macroinvertebrates. *Science of the Total Environment*, 646, pp.68-74.

Winton, D.J., Anderson, L.G., Rocliffe, S., Loiselle, S., 2020. Macroplastic pollution in freshwater environments: Focusing public and policy action. *Science of The Total Environment*, 704, 135242. DOI: https://doi.org/10.1016/j.scitotenv.2019.135242.

Withers, P.J., Jordan, P., May, L., Jarvie, H.P., Deal, N.E., 2014. Do septic tank systems pose a hidden threat to water quality? *Frontiers in Ecology and the Environment,* 12(2), pp.123-130.

WWF. (2010) *Revealed: The Best and Worst Rivers in England and Wales*. World Wildlife Fund. [Online.] (https://www.wwf.org.uk/updates/revealed-best-and-worst-rivers-england-and-wales, accessed 20th January 2019.)

Wye and Usk Foundation. (n.d.). *Clearing litter*. Wye and Usk Foundation, Talgarth. [Online.] (https://www.wyeuskfoundation.org/clearing-litter, accessed 24th December 2019.)

Wye and Usk Foundation, 2019. *The Fishing Passport: River Wye*. (https://www.fishingpassport.co.uk/fishing/wye, accessed 14th February 2019.)

Wye Valley AONB Office, 2015. *Wye Valley Area of Outstanding Natural Beauty (AONB) Management Plan 2015-2020*. Wye Valley AONB Office, Monmouth. (http://www.wyevalleyaonb.org.uk/index.php/about-us/management-and-guidance/management-plan-2015-2020/, accessed 14th February 2019.)

Yao, H., You, Z., Liu, B., 2016. Economic estimation of the losses caused by surface water pollution accidents in China from the perspective of water bodies' functions. *International Journal of Environmental Research and Public Health*. 13(2), 154. DOI: 10.3390/ijerph13020154.

Zbyszewski, M. and Corcoran, P. (2011). distribution and degradation of fresh water plastic particles along the beaches of Lake Huron, Canada. *Water Air and Soil Pollution*, 220(1), pp.365-372. DOI: 10.1007/s11270-011-0760-6.

Zubris, K.A.V., B.K. Richards., 2005. Synthetic fibres as an indicator of land application of sludge. *Environmental Pollution*, 138, pp.201-211.