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Review

Addressing the challenges of combined sewer overflows☆

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A B S T R A C T

Europe's ageing wastewater system often combines domestic sewage with surface runoff and industrial wastewaters. To reduce the associated risk of overloading wastewater treatment works during storms, and to prevent wastewater backing-up into properties, Combined Sewer Overflows (CSOs) are designed into wastewater networks to release excess discharge into rivers or coastal waters without treatment. In view of growing regulatory scrutiny and increasing public concern about their excessive discharge frequencies and potential impacts on environments and people, there is a need to better understand these impacts to allow prioritisation of cost-effective solutions.We review: i) the chemical, physical and biological composition of CSOs discharges; ii) spatio-temporal variations in the quantity, quality and load of overflows spilling into receiving waters; iii) the potential impacts on people, ecosystems and economies. Despite investigations illustrating the discharge frequency of CSOs, data on spill composition and loading of pollutants are too few to reach representative conclusions, particularly for emerging contaminants. Studies appraising impacts are also scarce, especially in contexts where there are multiple stressors affecting receiving waters. Given the costs of addressing CSOs problems, but also the likely long-term gains (e.g. economic stimulation as well as improvements to biodiversity, ecosystem services, public health and wellbeing), we highlight here the need to bolster these evidence gaps. We also advocate no-regrets options to alleviate CSO problems taking into consideration economic costs, carbon neutrality, ecosystem benefit and community well-being. Besides pragmatic, risk-based investment by utilities and local authorities to modernise wastewater systems, these include i) more systemic thinking, linking policy makers, consumers, utilities and regulators, to shift from local CSO issues to integrated catchment solutions with the aim of reducing contributions to wastewater from surface drainage and water consumption; ii) broader societal responsibilities for CSOs, for example through improved regulation, behavioural changes in water consumption and disposal of waste into wastewater networks, and iii) greater cost-sharing of wastewater use.

1. Introduction

Despite the implementation of a range of EU Directives spanning Wastewater Treatment (91/271/EEC) Bathing Water (76/160/EEC) and general water quality (2000/60/EC), European surface waters are still extensively challenged by pollution from both point and diffuse sources (Birk et al., 2020; Whelan et al., 2022). These stem from an array of human activities such as agriculture, forestry, mining, and industry, but also from untreated or not 'sufficiently treated' wastewater discharged into water bodies (Acteson, 2022; BBC, 2021; Laville, 2021; Petrie, 2021). While past emphasis on sanitary discharges has focussed on wastewater treatment works (WWTW), more recent concerns have focussed on Combined Sewer Overflows (CSOs). CSOs are structures, installed as release valves in combined sewer systems, that spill into the environment to simultaneously reduce overloading WWTWs while also reducing the risk of backed-up discharge flooding homes, businesses and other properties upstream (Zhao et al., 2019). The conceptual basis of their design and environmental permitting is that they operate as the result of heavy rainfall which both increases discharge through wastewater networks but also increases dilution once CSOs discharge to

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surface waters (Quijano et al., 2017). In practice, however, CSO spills are also caused by lack of hydraulic capacity outside of heavy rainfall events, in addition to operational faults, blockages and unplanned water infiltration into wastewater systems (Giakoumis and Voulvoulis, 2023). Across the ageing wastewater infrastructure of Europe, such problems have increased as a result of urban expansion, population growth and modern consumption behaviours that increase domestic flow into wastewater networks initially designed for much smaller populations (Mahaut and Andrieu, 2019). In addition to domestic flow, increases in surface runoff caused by climate change (Liu et al., 2010; Mohammed et al., 2021; Nie et al., 2009) and expansion of impermeable urban surfaces (Salerno et al., 2018), have also increased wastewater volumes, and thus CSO spill volumes. In the UK, where much of the basic wastewater network is of Victorian age and there are thousands of CSOs, pressures on combined sewers are acute (Wilde et al., 2022), and the issue has received considerable public attention, media interest and government scrutiny (House of Commons Environmental Audit Committee, 2022). More generally across Europe, CSO regulation has been heterogeneous triggering an ongoing review of the Urban Wastewater Treatment Directive bringing renewed emphasis on wastewater problems and their solutions (Pistocchi et al., 2019).

The discharge of pollutants from CSOs into receiving waters has the potential for an array of impacts on freshwater ecosystems, human health, and local amenity, with economic and societal consequences. For water companies, negative effects on consumer satisfaction and risks of regulatory penalties are large. Detriment to the economy can also arise through reduced tourism or impact on livestock. In all these cases, the magnitude of the risk depends on factors such as the frequency and timing of the spills relative to water flow; the location of the spills relative to the ecological status and sensitivity of receiving waterbodies; human activities such as water-based recreation that bring people in contact with contaminated freshwaters; and interactions with other stressors such climate change and land use change.

Resolving the challenge posed by large numbers of active CSOs across Europe, probably in excess of 650,000 (EurEau, 2020), will require time and major investments. Given the scale of investment required, especially in countries like the UK where infrastructure investment has been neglected (Ofwat, 2022), prioritisation will be needed. This will require solutions that: i) deliver the best cost-to-benefit ratios; ii) are pragmatic and favour the most straightforward and effective interventions, and iii) adopt whole systems approaches where reductions in CSO volumes are considered alongside conventional engineering solutions. Besides technological feasibility, and economic cost, trade-offs will need to consider customer needs, regulatory demands, public perception, net zero priorities (i.e. "cutting greenhouse gas emissions to as close to zero as possible, with any remaining emissions re-absorbed from the atmosphere" (United Nations, 2023)) and the long-term health of people and ecosystems. Recent advances in attribution of potential risk through meta-analyses of occurrence and critical concentration levels have proved valuable in prioritisation of pollutants (Mutzner et al., 2022), however, overall, the literature and evidence on which to guide these decisions is fragmented. Moreover, there is limited literature on the impact that spills of untreated wastewater may pose to river water quality and ecosystems (Hammond et al., 2021; Woodward et al., 2021). This is partly explained by data availability: in many countries CSO monitoring is scant, and typically not recording key characteristics such as volumes or pollutant composition (Moreira et al., 2016). This limits capacity to quantify impacts on the receiving bodies, or on the health of those who encounter these waters. The lack of quantitative data also impacts the ability to model fate and transport of pollutants in the receiving waters which in turn affects capacity to estimate risk to people or ecosystems (King et al., 2021).

In the face of these challenges, we review the latest knowledge on the impacts of CSO spills on ecosystems, people and economies, considering the complex array of variables that are important when estimating or modelling CSO risk. The review focuses on CSOs reaching freshwater bodies and consider CSOs as systems that release untreated wastewater from the combined sewer network through safety relief valves. The approach adopted (Fig. 1) consists of investigating: i) the potential risk to ecosystems and people associated with the pollutants found in wastewaters; ii) the actual risk to people and ecosystems associated with the pollutant load in the receiving body; iii) the evidence of impact of these pollutant loads on freshwater ecosystems and people; iv) the social, economic and environmental considerations involved in addressing the CSO challenge.

2. Pollutant composition in CSO discharges and associated potential risks to people and ecosystems

Pollutant composition in CSO discharges plays a key role in the potential risk to people and ecosystems. Wastewater is highly variable in composition, and has multiple inputs that can vary in both time (McCall et al., 2016) and space (Rule et al., 2006). To better understand the composition of wastewater releases and their associated risks, the review focuses on the physical, chemical and biological qualities (Fig. 2).

2.1. Physical attributes

The most visible component of wastewater is 'litter' i.e. solid macroscopic waste which does not fully degrade within the wastewater network. Plastic is a key component, with wet wipes being an important contributor to the macroscopic fractions (Mitchell, 2019) (Fig. 2c), as well as cotton bud sticks (Metcalf et al., 2022), sanitary products (Williams and Simmons, 1999), condoms (Ehiri and Birley, 2002) and plastic litter that may enter from roadside drains. WWTW increasingly remove large quantities of these plastics (Rasmussen et al., 2021). In addition, the degradation of macroplastics in the wastewater network can lead to the release of meso, micro and nanoplastics (Di Nunno et al., 2021) (Fig. 2d). Microplastics are also generated by activities such as the washing of synthetic clothes (Sun et al., 2019), surface runoff from roads with materials such as tyre dust (Jan Kole et al., 2017) and road marking paint (Horton et al., 2017).

The second physical attribute of wastewater spills is heat which could affect the thermal regime of a receiving river. Wastewater from buildings has a higher temperature than the water entering the building because 60% of the water used is heated before discharge to sewers (Cipolla and Maglionico, 2014). Wastewater that reaches a WWTW can be as much as 18 °C warmer than the ambient air temperature in colder climates (Golzar et al., 2020).

Wastewater contains high concentrations of inert suspended matter which largely occurs from the resuspension of sediments from the wastewater system during high flow events, and these can contribute as much as 75% of the total suspended matter in a river (Viviano et al., 2017) (Fig. 2a), increasing the turbidity of the receiving waters, and resulting subsequently in sedimentation (Fig. 2b).

Finally, wastewater contains a range of charged ions, such as chloride or potassium (see section 2.2.). When these charged wastewaters enter freshwater systems, the subsequent changes in electrical conductivity are clear enough to be used to trace spills (de Sousa et al., 2014).

2.2. Chemical attributes

In combined sewers, domestic wastewater is combined with multiple inputs, containing potentially hazardous chemicals (Gardner et al., 2012) (Fig. 2e), with sources including industry, roads and a complex cocktail of domestic waste. Chemicals of known toxicity originate from industry and households, and include biocides such as tributyltin (TBT) (used in wood preservative, agrochemicals, materials, textiles processing, detergents, and sponges (Montigny et al., 2022; Scrimshaw et al., 2013)) and Triclosan (used in shampoos, soaps, deodorants, cosmetics, skin-care lotions, mouth rinses and toothpastes (Guerra et al., 2019)). The overlap between industrial and domestic production of these and

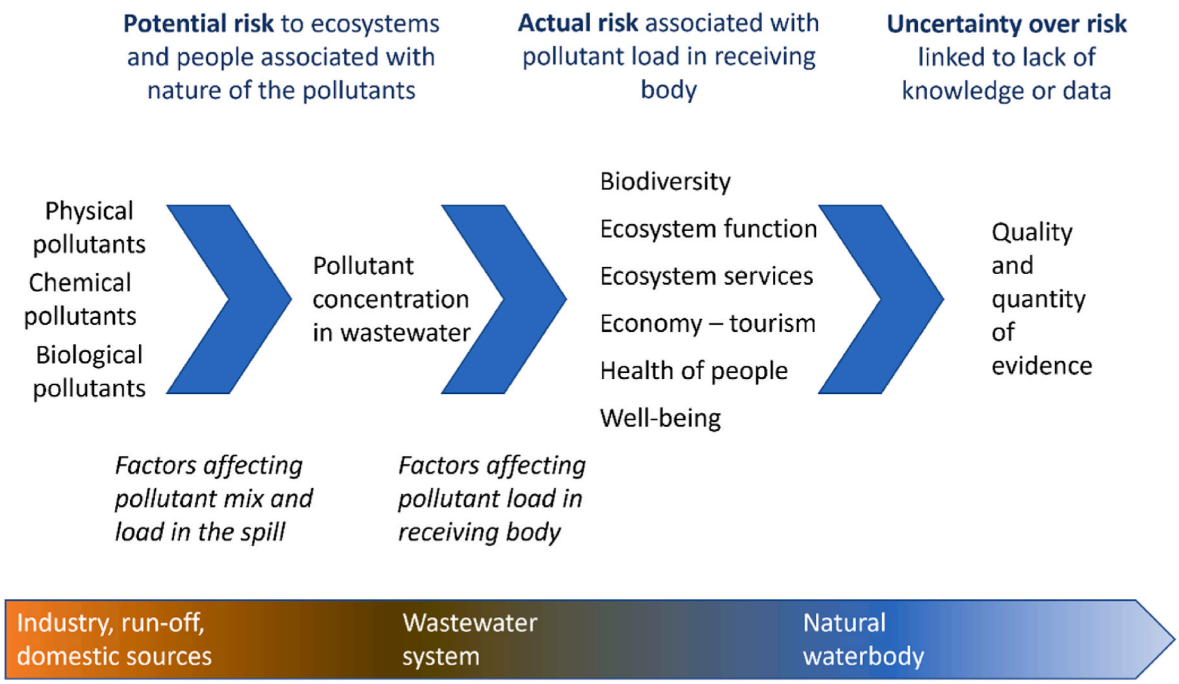

Fig. 1. Approach adopted in this review for assessing the risks posed by each CSO to people and ecosystems.

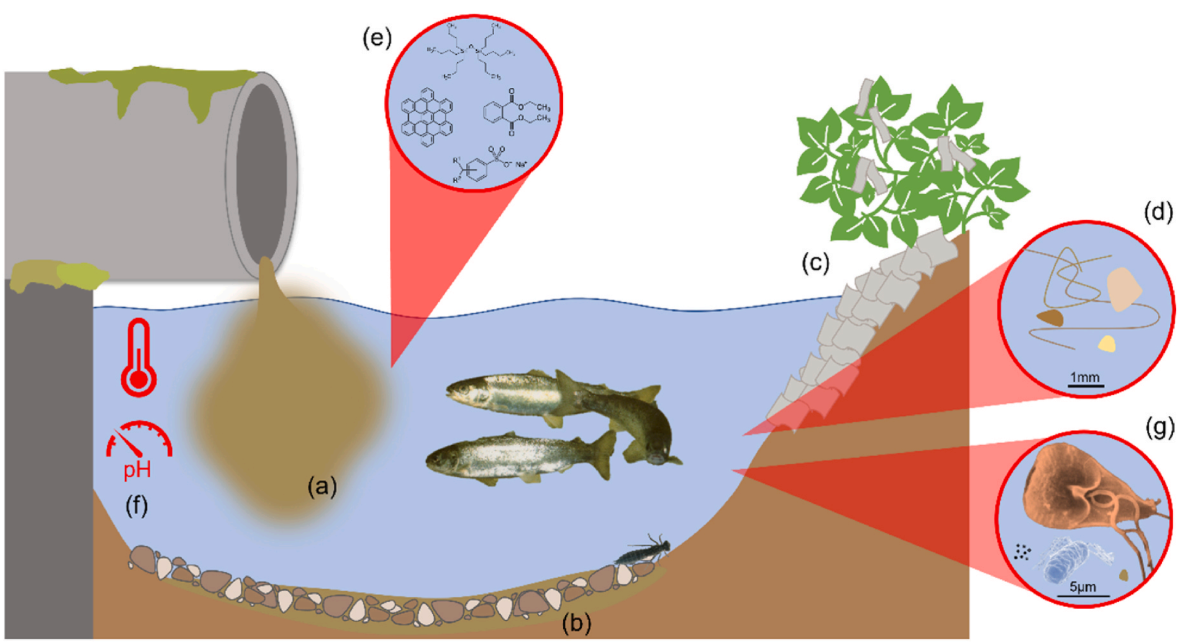

Fig. 2. Illustration of a CSO spill and its attributes. Physical attributes can include for example (a) increased turbidity and (b) corresponding sedimentation, plastic litter in the form of (c) wet wipes or (d) microplastics. Besides (e) chemical contaminants, physiochemical characteristics such as (f) temperature and pH of the receiving water body may also be impacted. Finally, there are a range of (g) biological attributes that include contamination by protozoa, bacteria, viruses, and also included in this magnification are nanoplastics, which, like microplastics, can promote the propagation of antimicrobial resistant bacteria.

similar contaminants such as linear alkylbenzene sulphonates (LAS) and polyfluoroalkyl and perfluoroalkyl substances (PFAS used in a range of products including cookware, paints and polishes) means the sources of these contaminants in wastewater are uncertain. Runoff in urban environments is another source of chemical contaminants, capturing persistent organic pollutants (POPs) like polyaromatic hydrocarbons (PAHs) that originate from incomplete combustion by vehicle traffic (Nas et al., 2020), as well as emerging contaminants such as 6PPD, an antiozonant used in the manufacture of rubber vehicle tires shed during their erosion (Cao et al., 2022). Heavy metal pollution can also originate from multiple sources, including traffic, heating and building materials (Gounou et al., 2011) which can enter the network through surface run-off (Thornton et al., 2001). For example, heavy metals such as cadmium, chromium and nickel can be released from automobile brake dust (Leng et al., 2021). Particulate-bound metals are mostly caused by the erosion of sediments within the wastewater network (Gasperi et al., 2012). Indeed, of a recent meta-analysis of micropollutants demonstrated that 50% of the top 10 micropollutants, ranked by number of sites found, was occupied by heavy metals (Mutzner et al., 2022).

Chemical inputs from domestic wastewater have diversified over recent decades. Increasingly, domestic down-the-drain disposal and excretion of both human and veterinary pharmaceuticals and their metabolites are another source of chemical contaminants (Kasprzyk-Hordern et al., 2021). Problem pharmaceuticals in UK wastewater include antimicrobial compounds such as erythromycin and oxytetracycline, as well as ibuprofen, propranolol, fluoxetine and diclofenac (Gardner et al., 2013). Illicit drugs such as cocaine are also commonly found in wastewaters and are so ubiquitous that they can be used as a marker for CSO spills (Munro et al., 2019). However, assessments on concentrations in CSO discharge are limited. Chemicals from domestic sources also stem from the polyvinyl chloride (PVC) piping used to connect to the main sewers which tend to leach Diethylhexyl phthalate (DEHP) (Rule et al., 2006).

Pesticides and nutrients from gardens and parks leach into sewers from surface run-off (Rule et al., 2006). Wastewater can contain elevated levels of nutrients with nitrogen and phosphorus being the two main nutrients released through CSOs (Aslan and Kapdan, 2006; House et al., 1994). Up to 50% of the total phosphorous loads in a river have been attributed to CSO discharges (Viviano et al., 2017).

Finally, wastewaters can also alter the physiochemistry of receiving water bodies. While wastewaters can have relatively high or low pH conditions, only small changes to river pH (less than 0.25 pH units) have been recorded (Munro et al., 2019) (Fig. 2f). However, significant changes to river dissolved oxygen (DO) have been recorded at the outfall of CSOs (Daniel et al., 2002; Miskewitz and Uchrin, 2013) reflecting both biochemical and chemical oxygen demand (Piro et al., 2012).

2.3. Biological attributes

While chemical and physical attributes of wastewater discharged through CSOs will affect biological communities in receiving waters, biological communities associated with wastewater will also be discharged through CSOs. Communities that contain combinations of microorganisms such as viruses, protozoa, fungi and bacteria, many of which can be found mentioned as microbial hazards in the World Health Organization's Guidelines for drinking-water quality (World Health Organization, 2017). This community can pose risks to human health and possibly freshwater ecosystems. Wastewater can carry bacteria that are a risk to human health, such as *Aeromonas* spp.*, Campylobacter*, Enterohemorrhagic *Escherichia coli*, *Salmonella* sp., *Streptococcus* sp., *Pseudomonas aeruginosa* and *Enterococcus* sp. (McGinnis et al., 2018; Tondera et al., 2015) as well as from protozoan parasites such as *Giardia* and *Cryptosporidium* (Donovan et al., 2008) (Fig. 2g). Monitoring programs usually focus on indicator organisms such as *Escherichia coli* and intestinal enterococci, which are also relevant for the EU revised Bathing Water Directive (European Comission, 2006). Jalliffier-Verne et al. (2016) showed that high *E. coli* concentrations at raw water collection points for drinking water production correlate with the discharged concentrations from CSOs, the location of overflows, dispersion processes in the surface waterbody, and season. Infectious viruses are also present in the wastewater released by CSOs such as are Norovirus, Hepatitis A/E viruses and Adenovirus (Robins et al., 2019) (Fig. 2g). A resource base of biological attributes associated with wastewater which are relevant to public health has been developed by the Global Water Pathogen Project (GWPP) (Global Water Pathogen Project, 2018).

2.4. Factors affecting pollutant mix

Storm events are a key factor affecting pollutant composition in CSOs, having been shown to cause increases in pollutants from runoff such as heavy metals, biocides and PAH, but due to their transient nature, are often not captured in temporally coarse water monitoring surveys (Dittmer et al., 2020). In some instances, the concentration of pollutants from runoff found in CSOs are similar to those found in storm overflows, demonstrating the large influence of storms (Gasperi et al., 2012). The composition of wastewater from CSO spills also depends on characteristics of the wider wastewater network (e.g. demography, land use and hydrology), its age and condition (Nickel and Fuchs, 2019), and even then, due to the complexity of the system, it is not always possible to characterise variation in pollutants (Mutzner et al., 2020). Fig. 3 illustrates how characteristics of the drainage catchment affects pollutant mix. For example, wastewaters draining mainly rural areas (a) will carry more pesticides and nutrients than urban areas (c,e). Within drainage catchments mainly localised in urban areas, the type of housing, transport infrastructure, level of industrialisation (d) and road traffic will also affect the nature of pollutant mix (Nickel and Fuchs, 2019).

3. Pollutant concentrations in receiving bodies – assessing the actual risk to people and ecosystems

The level of risks from CSO spills to people and ecosystems is not only determined by the pollutant mix, but also by the way that this combines with pollutant loads in the receiving body. Here, in turn, pollutant loads depend on load from other wastewater sources (3.1), dilution by the receiving waterbody (3.2) and marginal risk caused by the CSO spilling (3.3).

3.1. Factors affecting pollutant load in wastewaters

The concentration of pollutants varies with the characteristics of the wastewater system, the location of the overflows, and changes in overall flow, mainly linked to rainfall events, but drainage basins vary in size and in their proportion of domestic, industrial and extraneous (e.g. accidental infiltration) wastewater inputs. For example, more recently built areas are likely to collect less surface run-off due to improved building regulations separating rainwater runoff from entering the wastewater network and thus wastewater is less likely to be diluted during storm events. During dry weather periods the concentration of pollutants in wastewater tends to be higher because of the limited dilution from rainfall events (Montserrat et al., 2013; Willems et al., 2012). Prolonged periods of dry weather may also lead to the accumulation of pollutants on land, as well as sedimentation of solids in wastewater systems, which can contribute towards increased 'first flush' pollutant loads in wastewater released from CSO (Campos and Darch, 2015) when it does rain. These spills will be characterised by high concentration and high volume. Conversely, the dilution caused by high precipitation can decrease the concentrations of wastewater contaminants (Botturi et al., 2020). Rainfall is therefore a key driver, not only of spill frequency and volume, but also spill load, with the impact of rainfall also being dependent on sewer hydrology and surface topography.

3.2. Factors affecting pollutant load in the receiving body

Changes in river flow will mitigate or exacerbate the impact of spills on river quality, through their influence on pollutant load dilution. High flows are more likely to lead to increase dilution (Botturi et al., 2020). Changes in river flow can also affect the distances over which pollutants are transported. For example, wet wipes tend to be retained by riparian vegetation at high flow (Besley and Cassidy, 2022)(Fig. 2c). The transport of pollutants also depends on the particulate or dissolved state of the pollutant. In surface waters, particulates such as microplastics will be carried in the water column and by rolling or saltating downstream like sediment particles (Horton and Dixon, 2018). This transport depends on flow, turbulence, river morphology and vegetation, as well as on the characteristics of the particles such as material, grain size, shape, and density. Pesticides, flame retardants and POPs tend to accumulate in sediments downstream from CSOs (Schertzinger et al., 2019) in accordance with the magnitude of sorption to geosolids, where stronger binding to solids makes chemical pollutants more retentive in streams

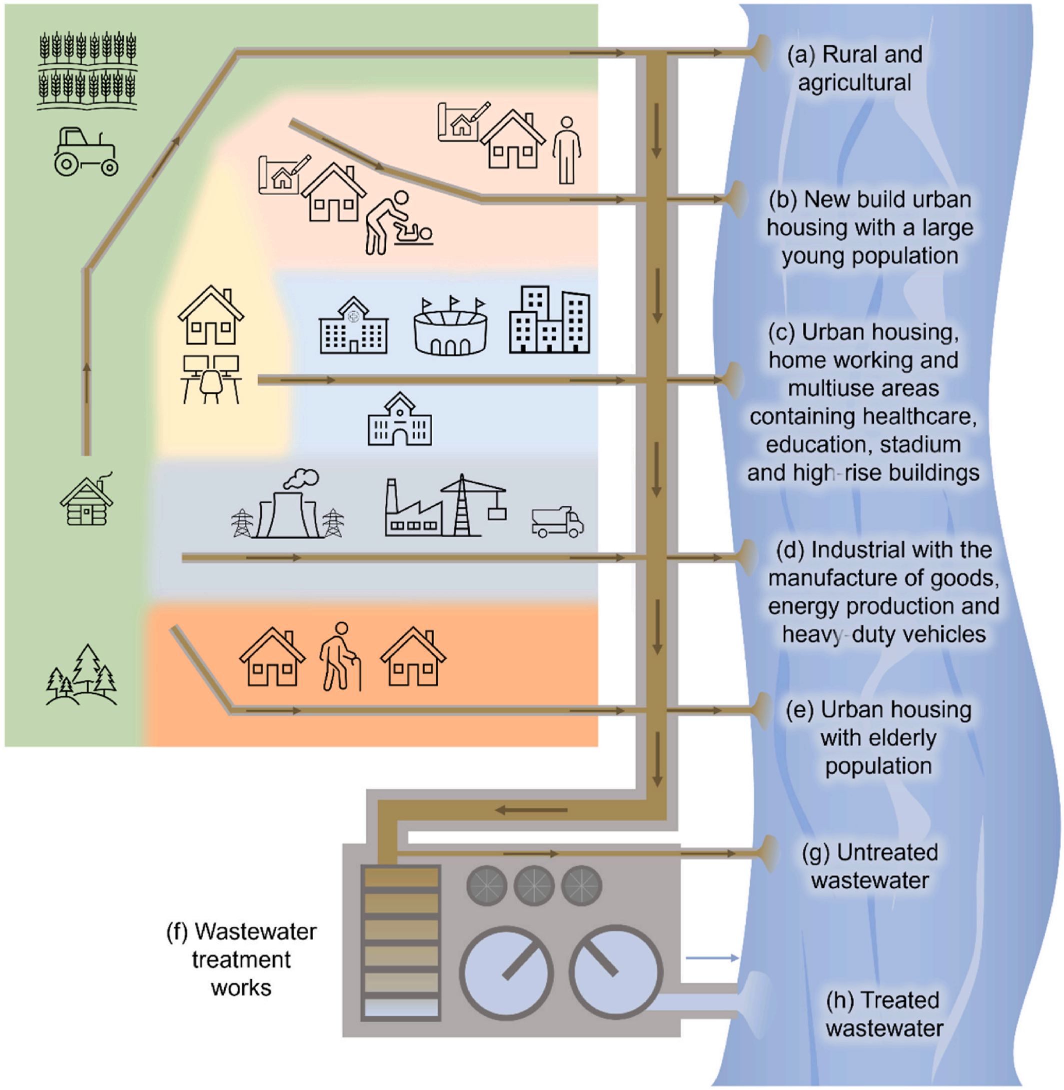

Fig. 3. Example of how catchment characteristics can affect pollutants.

near discharge sources (Foster et al., 2022).

3.3. *Relative contribution of spills to pollutant loads in water bodies*

Understanding how much of the impact on ecosystems or people is driven by CSOs is challenging as pollutants from a spill join the existing pollutant load in the receiving waterbody. CSOs are thought to contribute to between 30 and 95% of the annual load of rivers for 'domestic' pollutants such as caffeine, ibuprofen, polycyclic aromatic hydrocarbons (PAHs), phenolic xenoestrogens, hormones, and urban pesticides (Launay et al., 2016; Phillips et al., 2012). Besides wastewater effluents, CSO discharges are also thought to be the main contributors for endocrine-disrupting compounds and personal care products (Benotti and Brownawell, 2007; Ryu et al., 2014) as well as volatile organic compounds (Botturi et al., 2020). While these data exemplify potential areas of concern, there are few studies that have explored the loads of pollutants entering waterbodies from CSOs, their behaviour and interaction with the existing mix of pollutants, and the modifying effects of the physical, chemical and biological character of the receiving water body.

The complex relationship between rainfall, pollutant load and the receiving waterbody makes assessment challenging. Pollutant load is not only complex in terms of its composition and inputs, but it also differs in dilution due to intrinsic characteristics of the wastewater system, hydrological processes and receiving water body. Better field data, experiments and models – for example to apportion pollutant sources - are therefore needed to measure variations in pollutant loads under different scenarios before it is possible to start to understand the impact spills may have.

4. Evidence of ecological impact from CSO spills

Over the last decade, there has only been a small proportion of CSO studies examining the impact of spills on ecology (Fig. 4c) with many of the few studies focusing on microbial ecology and ecotoxicology. Of those studies, there is also a primary focus on chemical and bacterial attributes of a spill, and often independently (Fig. 4a).

4.1. *Evidence of ecological impact from physical attributes of spills*

Among the emerging risks associated with CSOs, the potential effects of plastic have gained attention. The ecological risks caused by plastic litter include visible structural change to habitat, entanglement of wildlife and ingestion (Fig. 5). Indeed, high densities of wet wipes have been seen to alter habitats so drastically that some species are unable to colonise areas of a river (McCoy et al., 2020).

An important but less visible risk to ecosystems comes from the discharge of meso-, micro- and nanoplastics from CSOs (Woodward

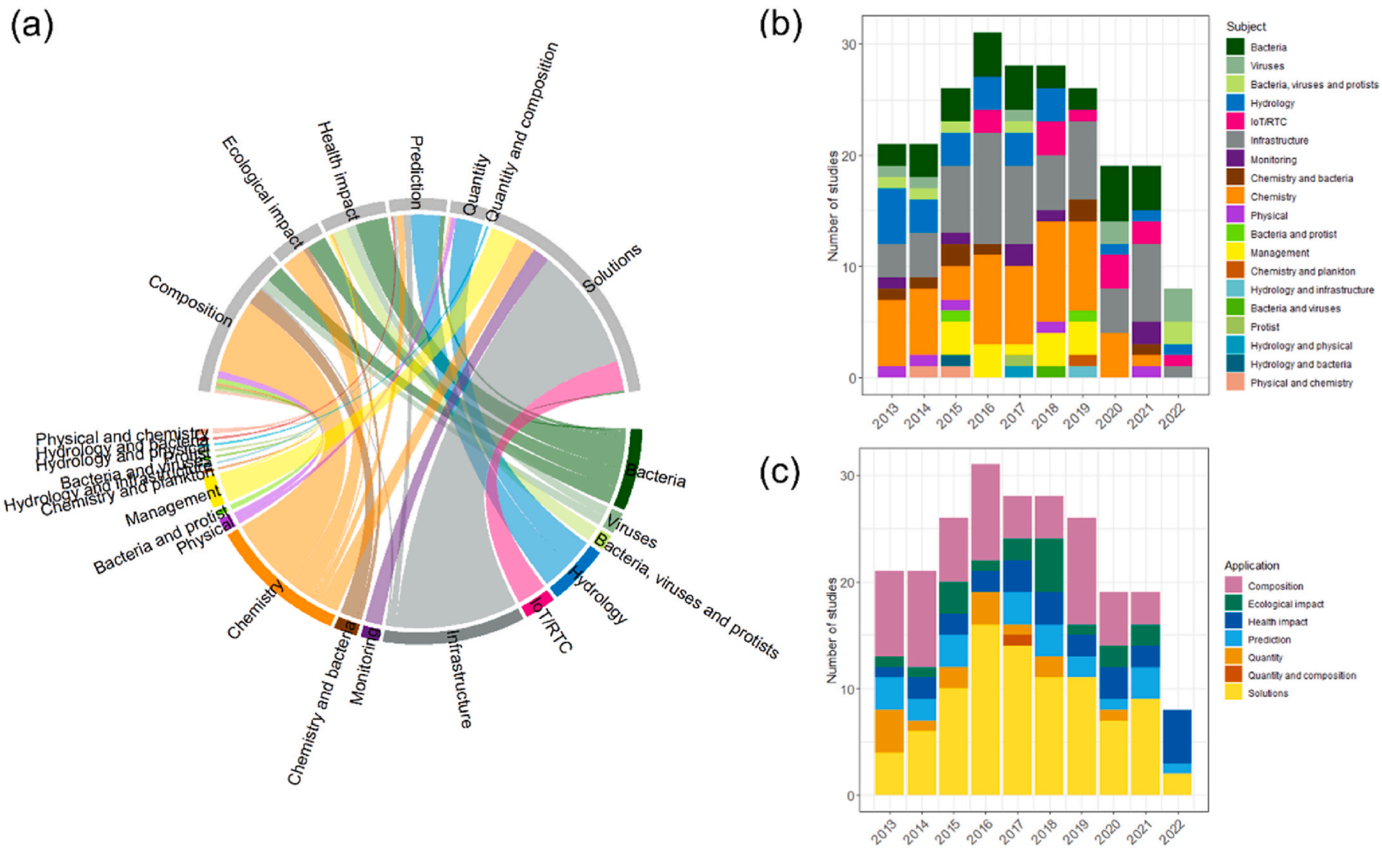

Fig. 4. Systematic review of the last decade of CSO research, with each article having been assigned a subject and an application. Links between subjects and their application are displayed in a (a) chord diagram. Also shown is the change in CSO research (b) subject and (c) application over time, along with absolute change in study number over time. The methodology used to compile this data can be found in the supplementary materials.

et al., 2021). For example, microplastics have been found in half of the invertebrates in the River Taff (Windsor et al., 2019), a highly urbanised river catchment, as well as further up the food web in fish and riverine birds like the dipper (*Cinclus cinclus*) (D'Souza et al., 2020). Although data illustrating impacts on populations and ecological communities are still scarce, data from individual organisms shows that these particles can impact growth rate, hatchability, food ingestion, gut morphology, inflammatory response and liver lipid accumulation (Sarijan et al., 2021) (Fig. 5). The risk of smaller plastic particles to ecological health are compounded when combined with other stressors within wastewaters as microplastics can act as a carrier for complex organic pollutants (Sarijan et al., 2021), like PAHs, as well as antimicrobial resistance (AMR)(Dong et al., 2021).

There is evidence that an increase in water temperature in the receiving body caused by CSO spills could also pose risks to river ecosystems, as even small changes in temperature can impact aquatic organisms (Pander et al., 2022). Effects are particularly likely where increased temperature and increased organic loading combine to decrease oxygen concentrations while also increasing metabolic demand (Riechel et al., 2016; Verberk et al., 2016). Therefore, changes in thermal regime caused by CSO spills and climate change could pose a risk to biodiversity. In addition, the risks associated with increased oxygen demand of aquatic organisms could also be exacerbated by the oxygen depletion associated with CSO spills (Miskewitz and Uchrin, 2013). There have been no investigations, to our knowledge, appraising how CSO spills might impact river thermal dynamics and ecology. However, studies investigating WWTW discharges suggest that they can cause significant long-term increases in river temperature (up to 9.3 °C), especially in winter months (Xin and Kinouchi, 2013), while also changing thermal diurnal temperature rhythms (Bae et al., 2016).

Increased turbidity comes with a risk to freshwater ecosystems, as it can reduce light penetration into the water column, reducing photosynthesis (e.g. aquatic plants, diatoms and other algae), and thus primary production, which will have a cascading effect on food webs (Henley et al., 2000). The change in light regime may also impact the behaviour and morphology of organisms. For example, fish in highly turbid environments increase the brightness of their colours to maintain communication (Kelley et al., 2012), demonstrating a risk to the ecology and evolution of species. Much like microplastics, there is also a risk of suspended sediments binding with chemical contaminants (Dunlop et al., 2005), which could pose a greater risk to organisms. In deeper rivers, temperature profiles may also be impacted, increasing the risk of temperature stratification, as solar heat cannot reach deeper waters (Ryan, 2010). This may have a contrasting effect on the thermal changes already discussed, but will likely pose a less localised risk, and may alter the thermal profile of a river with more complexities than just heating or cooling.

Sediments caused by high turbid water can pose a mechanical risk to organisms, damaging fish (Sutherland and Meyer, 2007) and invertebrate gills, filling pores in the river bed which destroys microhabitat for invertebrates (Karna et al., 2014), reduce the feeding activities of visual or filter feeders (Relyea et al., 2000), and reducing the survival of salmon eggs (Julien and Bergeron, 2006). While increases in sediment deposition elsewhere have been linked to alteration in community composition in stony-bedded rivers, there is little published evidence appraising the impacts of CSO on suspended or deposited sediments (Larsen and Ormerod, 2010).

Finally, while significant changes in stream conductivity, namely from increased chloride linked to road salt run-off, have sometimes been linked to fish condition, it seems that any ecological impact arises from

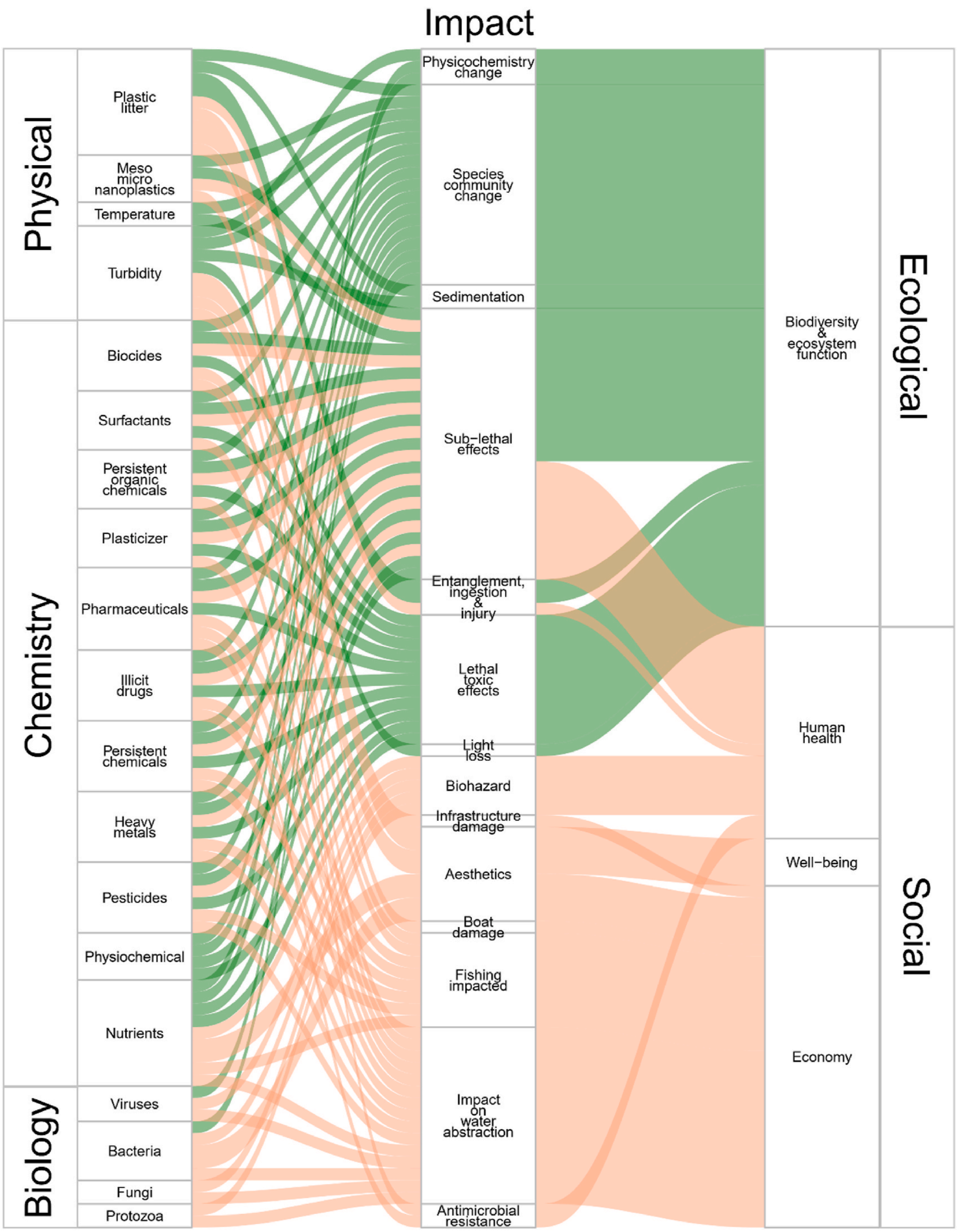

Fig. 5. Flow diagram showing characteristics of CSO spills (column 1), followed by their potential impacts (column 2) and the overall impact they have on people and ecosystems (column 3). Colours indicate ecological (green) and social interactions (red). Not included are the feedback loops which also exist between different dimensions of this diagram.

the specific chemicals that contribute to electrical conductivity (see section 4.2), rather than conductivity per se (Coop, 2003).

4.2. Evidence of ecological impact from chemical composition

Although many of the experiments looking at the impact of chemicals on ecology are laboratory based, effect concentrations used in those experiments are within the ranges of those found in wastewater, and can, therefore, provide some insight into what might occur under a spill scenario (Table 1).

These examples are just some of the ecologically hazardous chemicals found in wastewater. It must be stressed that impacts can vary within the broad categories given here. For example, the impact of the pesticide will be compound specific, as insecticides will have a greater impact on aquatic invertebrate species than the trifluralin herbicide example given in Table 1.

Interactions between chemicals, either antagonistic, synergistic or additive, will impact organisms in a receiving water body. For example, increased river pH could increase the degradation of pesticides (Relyea, 2006), but also make their affects more acute (Capkin et al., 2006), while also increasing the toxic effect of another CSO contaminants, like ammonia (Randall and Tsui, 2002). Indeed, some of the chemical

Table 1
Data on the ecological impact of different characteristics of chemical spills.

Chemical characteristics of spill	Reproduction	Non-reproductive physiology	Bioaccumulation	Acute toxicity	Molecular change	Abundance and diversity	Effect concentration range	Concentration in wastewater or CSO effected area
Biocides - TBT	[1]	[2]	[3]	4]	[5]	[6]	0.0002–0.1 mg L-1	0.0002–0.014 mg L-1 [7–8]
Surfactants - alkylbenzene sulphonates	[9]	[10]	[11]	[12]		[13]	0.293–115 mg L-1	0.0003–16.9 mg L-1 [14–15]
POPs - PAH	[16]	[17]	[18]	[19]	[20]	[21]	0.05–16.3 mg L-1	0.0007–0.012 mg L-1 [14, 22]
Plasticizer - DEHP	[23]	[23]	[24]	[23]	[23]		0.0002–58.51 mg L-1	0.006–0.057 mg L-1 [14,25–26]
Pharmaceuticals – fluoxetine	[27]	[28]	[28]		[28]		0.00035–5 mg L-1	0.000009–0.003465 mg L-1 [29–30]
Illicit drugs - cocaine	[31]	[32]	[33]		[34]		0.00002–5 mg L-1	0.00000018–0.000286 mg L-1 [35–36]
Persistent chemicals - PFAS	[37]	[37]	[38]	[37]	[39]	[40]	0.0001–195 mg L-1	0.000009–0.00052 mg L-1 [41]
Heavy metals - cadmium	[42]	[43]	[44]	[45]	[46]	[47]	0.025–13.6 mg L-1	0.00011–0.13 mg L-1 [48–49]
Pesticides – trifluralin	[50]	[51]	[52]	[53]	[54]		0.25–50 mg L−1	0.000002–8.3 mg L-1 [55]
Nutrients - ammonia	[56]	[57]		[58]	[59]	[60]	5–163 mg L−1	0.07–155.14 1 mg L−1 [61]
pH **- acidity**	[62]	[63]				[64]	5.2–7	6.5–9.5 [61]
DO - anoxic	[65]	[66]		[67]	[68]	[69]	0.25–5 mg L−1	1–9 mg L−1 [70–71]

1 = (Guo et al., 2010), *2* = *(Widdows and Page, 1993)*, *3* = (Fernández-Alba et al., 2002), *4* = (Dong et al., 2006), *5* = (Hanaoka et al., 2018), *6* = (Dowson et al., 1996), *7* = (Voulvoulis et al., 2010), *8* = (Scrimshaw et al., 2013), *9* = (Trivedi et al., 2001), *10* = (Gouda et al., 2022), *11* = (Tolls et al., 2003), *12* = *(Shukla and Trivedi, 2018)*, *13* = (Belanger et al., 2002), *14* = (Rule et al., 2006), *15* = (Terzić et al., 2008), *16* = (Xu et al., 2009), *17* = (Peters et al., 2007), *18* = (Li et al., 2023), *19* = (Black et al., 1983), *20* = (Mirbahai et al., 2011), *21* = *(Beasley and Kneale, 2016)*, *22* = (Terzakis et al., 2008), *23* = (Liu et al., 2016), *24* = (Wofford et al., 1981), *25* = (Oliver et al., 2005), *26* = (Dargnat et al., 2009), *27* = (Fursdon et al., 2019), *28* = (Salahinejad et al., 2022), *29* = (Salgado et al., 2011), *30* = (Lajeunesse et al., 2012), *31* = (Fontes et al., 2022), *32* = (Mersereau et al., 2015), *33* = (Capaldo et al., 2012), *34* = (Parolini et al., 2018), *35* = (Kumar et al., 2019), *36* = (Deng et al., 2020), *37* = (Ankley et al., 2021), *38* = (Windsor et al., 2020), *39* = (Blanc et al., 2019), *40* = (Zhang et al., 2022), *41* = (Coggan et al., 2019), *42* = *(Gomot, 1998)*, *43* = (EL-Gazzar et al., 2014), *44* = (Jia et al., 2017), *45* = (Pantung et al., 2008), *46* = (Kim et al., 2010), *47* = (Xu et al., 2018), *48* = (Hosseinipour Dizgah et al., 2017), *49* = (Agoro et al., 2020), *50* = (Song et al., 2017), *51* = (Vanderlé Merlini et al., 2012), *52* = *(Specie and Hamelink Eli Lilly, 1979)*, *53* = *(Sanders, 1970)*, *54* = (Yuk et al., 2011), *55* = *(OSPAR Commission, 2005)*, *56* = (Armstrong et al., 2012), *57* = (Zhang et al., 2019), *58* = (Parvathy et al., 2022), *59* = (Ding et al., 2021), *60* = *(Beketov, 2004)*, *61* = *unpublished data from* 47 WWTW *across Wales*, *62* = (Ormerod et al., 1991), *63* = (Magee et al., 2001), *64* = *(Fryer, 1980)*, *65* = (Sun et al., 2020), *66* = *(Timmerman and Chapman, 2004)*, *67* = (Small et al., 2014), *68* = (Léger et al., 2021), *69* = (Keister et al., 2000), *70* = (Riechel et al., 2020), *71* = (Alp et al., 2007).

components of a spill may not pose a risk directly, but can cause ecological damage, such as elevated nutrient levels resulting in eutrophication and blooms of toxic cyanobacteria. Yet, even with a well understood perturbation such as eutrophication, the outcome is likely caused by multiple interacting factors, making it difficult to assign causation.

4.3. Evidence of ecological impact from biological attributes

Bacterial pathogens can persist in the environment after a CSO spill (Byappanahalli et al., 2003). Indeed, perturbations to natural microbial communities caused by heavy metals and pharmaceuticals like antibiotics, lead to pathogen-dominated microbial communities (Mao-Jones et al., 2010)(Fig. 5). Pharmaceutical antimicrobial compounds are chemical components which can also contribute changes to the biological attributes of a CSO spill, which can restructure natural microbial communities (Qiu et al., 2019) and promote AMR (see later section 5.2). Current understanding of how microbial communities found in a CSO can directly impact the ecosystem structure and functioning of receiving rivers is limited. Much of the literature focuses on the impact that these microorganisms may have on human health. In addition, separating the ecological impacts of these microorganisms from the array of other components in CSO spills is experimentally difficult.

4.4. Evidence of risks linked to the nature of the receiving body

Functioning, healthy ecosystems are more likely to be resilient to spill disturbances. However, continued degradation of an ecosystem through removal of ecological redundancy, functional groups, trophic levels, as well as altering the magnitude, frequency and duration of disturbances, can cause an ecosystem to rapidly shift to a less desired state (Folke et al., 2004). Some aquatic ecosystems may also have characteristics which make them less resilient, such a reduced niche differentiation, inhibited recolonisation potential due to poor connectivity and inherently low functional redundancy caused by resource/refugia homogeneity (Van Looy et al., 2019). An example of this would be an urban tributary whose connectivity has been reduced through in-river barriers (e.g. weirs, sluices or culverts) and impermeable surfaces preventing connection with neighbouring tributaries during period of high water. Add to this induced habitat homogeneity (e.g. channelisation, heavily engineered flood prevention, sedimentation), which reduces niche differentiation and functional redundancy (DeBoer et al., 2020; Latli et al., 2019), and it results in a river ecosystem vulnerable to perturbations caused by CSO spills.

Some river ecosystems may naturally also be less resilient to CSO spills. For example, ecosystems such as chalk streams which can contain species that have complex life histories, are highly specialised or pollutant sensitive (Durance and Ormerod, 2009). Conversely, highly 'modified' rivers, such as lowland eutrophic rivers, will be more resilient to CSO spills as they have already entered a degraded state which facilitates generalist species with larger ecological tolerances.

5. Evidence of socioeconomic impact from CSOs

Over the last decade, there has only been a small proportion of CSO studies examining the socioeconomic impact of spills, which are focused on health (Fig. 4c). Of those studies, the pathogenic bacterial, viral and protist attributes of a spill are focused on (Fig. 4a), often under the broad label of 'gastrointestinal illness', and mainly in recreational areas.

5.1. Evidence of socio-economic impact from physical attributes

The effect of plastic litter on the aesthetics of freshwater bodies, and its ability to undermine well-being, has gained much attention, especially as rivers are often tourism hotspots. While evidence on plastic litter and its impact on people's use of rivers is not well characterised, studies on beaches have demonstrated the detrimental impact of visual litter pollution on utilisation of the natural environment (Ballance et al., 2000; Williams et al., 2016). This could cause economic loses from temporary and permanent damage to tourism. There is also evidence to show that the degradation of large plastics and the production of meso/micro and nanoplastics can impact human health through ingestion, which will have subsequent health costs. Besides the contaminants that microplastics can capture, the microplastics themselves can cause inflammation of the gut lining and impact gut microbial communities (Forte et al., 2016; Li et al., 2020).

The other physical attributes that can directly impact human activity on rivers are turbidity and other visible organic matter caused by CSO spills. The primary risk here is aesthetic (Pflüger et al., 2010) linked to visible sewage litter, grease, and scum spilling into recipient rivers (Munro et al., 2019). The ecological impacts of turbidity will also directly influence other human activities, such as angling (Jónsson et al., 2008), wild swimming or water abstraction. Records of public complaints also highlight associated odours at CSO outlets (Morgan et al., 2017; Mulrow et al., 2020).

5.2. Evidence of socio-economic impact from chemical attributes

Many of the socio-economic impacts from CSO spill chemical attributes relate to human health (Table 2) and range from carcinogens to physiological disrupters that may affect individuals in contact with wastewater polluted waterbodies. While human and ecosystem health have been split here as there is a clear divide in the experimental designs utilised to assess each in the literature, it should be highlighted that the impacts on human health are embedded in ecosystem health (Table 1). However, some characteristics of CSO spills have the potential to have a more widespread impact on health. One example is the release of antimicrobial compounds, such as erythromycin and oxytetracycline

Table 2
Data on the human health impact of different characteristics of chemical spills.

Chemical characteristic of spill	Health outcome	Animal system	Dose	Reference	Concentration in wastewater or CSO effect area
Biocides **- TBT**	Testosterone decrease. Increased body weight & fat deposits. Hepatic inflammation.	Rat Rat	Ingesting 15 mg/kg/day for 30 days Ingesting 0.1 μg/kg/day, for 15 days	[1] [2]	0.2–14 μg L-1 [3–4]
Surfactants e- alkylbenzene sulphonates	No effect A limit value for LAS in wastewater sludge cannot be substantiated.	Rat Risk assessment	0.5–0.02% LAS in feed for 2 years NA	[5] [6]	0.0003–16.9 mg L-1 [7–8]
POPs **- PAH**	Lifetime Average Daily Intake of PAHs for carcinogenic effects. Increased CYP1A1 expression with links to mutagenic metabolites.	Human survey Rat	Ingesting 3.22 ng/kg/day Ingesting contaminated mussels 7.48 μg/kg for 2 days	[9] [10]	0.7–12 μg L-1 [7,11]
Plasticizer **- DEHP**	Disrupts insulin signal transduction. Downregulation of sperm quality genes.	Rat Mouse	Ingesting 10–100 mg/kg for 30 days Injecting 5 μg/kg/day for 42 days	[12] [13]	0.006–0.057 mg L-1 [7,14–15]
Pharmaceuticals **- fluoxetine**	No evidence				0.009–3.465 μg L-1 [16,17]
Illicit drugs - cocaine	No evidence				0.00018–0.286 μg L-1 [18–19]
Persistent chemicals **- PFAS**	Liver hypertrophy with signs of cell injury	Mouse	Ingestion 0.1–5 mg/kg for 35 days	[20]	0.009–0.52 μg L-1 [21]
Heavy metals - cadmium	Development of pancreatic cancer	Human patient, rat, cell culture	15–30 mg/kg (rat experiment)	[22]	0.11–130 μg L-1 [23–24]
Pesticides **- trifluralin**	Possible link between trifluralin exposure and colon cancer in agricultural workers. Disturbance of liver mitochondria respiration	Human survey Rat	NA On extracellular organelle 22.8 mg/L	[25] [26]	0.002–830 μg L-1 [27]
Nutrients **- ammonia**	No evidence				0.07–155.14 mg L−1 [28]
pH **- acidity**	No evidence				6.5 to 9.5 [28]
DO - anoxic	No evidence				1–9 mg L−1 [29–30]

1 = (Grote et al., 2004), 2 = (Bertuloso et al., 2015), 3 = (Voulvoulis et al., 2010), 4 = (Scrimshaw et al., 2013), 5 = (Buehler et al., 1971), 6 = (Schowanek et al., 2007), 7 = (Rule et al., 2006), 8 = (Terzić et al., 2008), 9 = (Yoon et al., 2007), 10 = (Chaty et al., 2008), 11 = (Terzakis et al., 2008), 12 = (Rajesh et al., 2013), 13 = (Zhang et al., 2013), 14 = (Oliver et al., 2005), 15 = (Dargnat et al., 2009), 16 = (Salgado et al., 2011), 17 = (Lajeunesse et al., 2012), 18 = (Kumar et al., 2019), 19 = (Deng et al., 2020), 20 = (Crebelli et al., 2019), 21 = (Coggan et al., 2019), 22 = (Djordjevic et al., 2019), 23 = (Hosseinipour Dizgah et al., 2017), 24 = (Agoro et al., 2020), 25 = (Kang et al., 2008), 26 = (de Oliveira et al., 2020), 27 = (OSPAR Commission, 2005), 28 = unpublished data from 47 WWTW across Wales, 29 = (Riechel et al., 2020), 30 = (Alp et al., 2007).

highlighted in section 2.2, which contributes to the risk of AMR (Aydin et al., 2015). Low levels of antimicrobial agents in wastewater as biproducts from healthcare applications and farming provide a selective pressure for bacteria that are resistant to these agents. AMR is expected to be the cause of 10 million deaths by 2050, and cost US$100 trillion between 2016 and 2050 (Strange et al., 2021). Small urban streams have been identified as reservoirs of Antimicrobial Resistance Genes (ARGs) because of inputs from CSOs, and are therefore contributing to the AMR risk to global health (Reynolds et al., 2020).

Chemical characteristics can affect people in ways other than health. For example, increased nutrient levels which cause eutrophication and cyanobacteria blooms can damage the aesthetics of a river, cause loss of livestock and pets, not to mention the loss of ecosystem services, such as the impact of hypoxia-induced fish kills on recreational fishing. These impacts are still poorly evidenced, however, reduction in the value of waterside dwellings caused by eutrophication has been evidenced, as well as the additional water processing costs, loss in amenity and biodiversity and negative impacts to tourism, which are estimated to cost £75.0–114.3m a year in England and Wales (UK) alone (Withers et al., 2014). Increased nutrients such as proteins, like that released from dairy production, in wastewater can also be broken down into ammonium, ammonia, and finally, nitrite, whose levels can be toxic to humans and livestock (Wang and Serventi, 2019).

5.3. Evidence of socio-economic impact from biological attributes

There is clear evidence to show that the biological communities released by CSOs pose a risk to human health, especially when there are significant human interactions with the receiving waterbody, including recreation, water abstraction (Taghipour et al., 2019) or aquaculture activities (Abu-Bakar et al., 2017). CSO spills introduce infectious pathogens not only originating from human faeces and organic waste in wastewater, but also from animal faeces in run-off originating from wildlife or domestic animals (Botturi et al., 2020; Bunt and Jacobson, 2021; Schares et al., 2005). One of the largest human risks to human health is gastrointestinal disease by water ingestion. There is even evidence in people who interact with biologically contaminated waterbodies for activities such as wild swimming (Hall et al., 2017). Enteric viruses are another source of risk to human health in rivers contaminated by CSOs (Fong et al., 2010). These can also render rivers unsuitable for recreational activities, and there is evidence that the highest risks for swimmers derive from noro- and rotaviruses which cause infections and sequelae, some of which are chronic (Pond, 2005). The evidence demonstrating the link between CSOs, pathogens and risk to human health is so robust that there are a plethora of quantitative microbial risk assessments designed to mitigate that risk (Eregno et al., 2016; Fewtrell et al., 2011; McGinnis et al., 2022).

6. Tackling the challenge of CSOs

From the perspective of water utilities, investment to address the challenge of CSO spills needs to reflect: i) the risks (and uncertainties) that a CSO may pose to people – for example health and amenity - and ecosystems and ii) the legislative, technological and socio-economic context in which a given CSO may function and iii) the pragmatic opportunities to address CSOs where straightforward and feasible. The challenge to address is whether to target quantity or quality of the spill or both, while considering cost-benefit in the short and long term given that it will impact the public now and in future generations.

6.1. Risk to ecosystems and people

This review has identified a range of potential risks posed by the components of wastewaters (section 2), the factors that modulate the risk (section 3) and the quality of the limited evidence that links CSO spills to impact on ecosystems, human health and the economy (sections 4 and 5), thus providing the necessary context to discuss and prioritise solutions and to mitigate risk. The review of evidence highlights the paucity of field-based knowledge on the impacts of wastewater on receiving water bodies and potential further impact to people. The review also highlights that.

i) the risks to freshwater ecosystems are geographically extensive across the UK, Europe and beyond, due to the abundance of CSOs;
ii) the risks to people depend largely on individual interaction with waterbodies;
iii) many risks to ecosystems and people are not well covered by regulation, even in highly regulated regions such as the EU;
iv) some risks to the ecology of freshwaters are relatively well documented, such as the risks posed by nutrients, while other emerging risks such as the impacts of pharmaceuticals or plastics do not have such a comprehensive evidence base;
v) some risks to people using freshwaters are relatively well documented, too, such as the risks associated with pathogens, while other risks such as the impact on wellbeing or local economies do not have such as comprehensive evidence base.

Overall, the review calls for a better understanding of the impact of wastewater spills on freshwater ecosystems and people. Given the uncertainty over the actual impact of wastewater spills, and the technological challenge in dealing with many of the risks highlighted, knowledge of the sources of these risks provides a direct means to better manage them (see Fig. 6).

6.2. The importance of legislative and social context – risks to wastewater utilities

Besides potential ecological and social impacts, the legislative, technological and socio-economic context in which a given CSO may function, significantly influences prioritisation. Legislative responsibilities of utilities for CSO spills are governed by permits that define, for each CSO, the sewer volume above which it may spill. The volumes are calculated when the CSO is installed and based on the dry weather volumes of wastewater generated by the drainage catchment at the time of installation. In many instances, water utilities have legal environmental responsibilities, and river stretches that come under environmental protection legislation are of particular concern when prioritising CSO investment.

In European legislation, for example, two types of Directives apply to CSOs: Directives aimed at protecting receiving waterbodies and Directives aimed at controlling CSO discharges. The Urban Waste Water Treatment Directive 91/271/EEC (UWWTD) highlights that the collecting systems shall be constructed and managed to limit the quantity of pollution entering receiving waters due to storm water overflows and that all wastewater discharges, including CSOs, should be preauthorized (Morgan et al., 2017). The current evaluation of the UWWTD has highlighted the importance of better managing CSOs. New developments proposed for a revised UWWTD now suggest more control at source rather than end of pipe action, putting the onus on the polluters to find the resources to deal with the waste before it reaches the wastewater system. The Bathing Water Directive 2006/7/EC (BWD) and the Habitats Directive 92/43/EEC assess the bathing waters affected by CSOs as "subject to short-term pollution". In the EU Regulation No. 166/2006 (2006) "concerning the establishment of a European Pollutant Release and Transfer Register", EU member states are also obligated to report pollutant loads to water and to consider threshold values. In this context, the pollutant loads from CSO discharges should also be estimated, but CSO structures are not designed for monitoring purposes (Morgan et al., 2017).

The social context of a CSO is also an important factor to consider. Customer perceptions of pollution are an important consideration for a water utility (see for example, Gill et al. (2021)). Additionally, given the

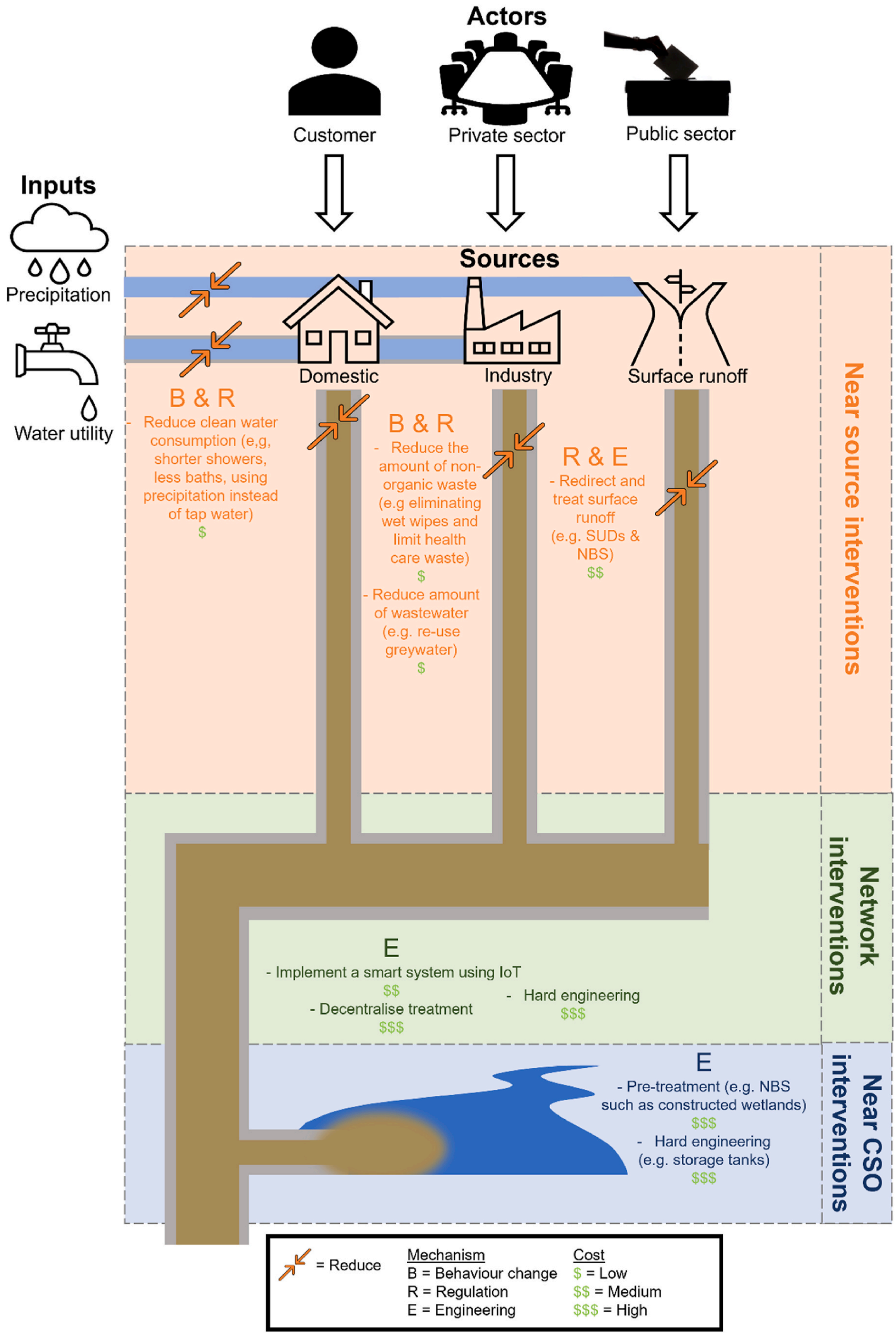

Fig. 6. Mechanisms and costs involved in different interventions from source to end of pipe.

rising levels of water poverty in countries such as the UK (Lobo and Kenzie, 2022), there needs to be consideration as to the financial resources invested in CSO spill remediation given the potential knock-on effects on water bills for the most vulnerable. Solutions that provide multiple benefits and engage collaboration across sectors (eg. with local authorities, government) are clearly key to ensure long term socio-economic benefits.

6.3. Innovative approaches to the CSO challenge: targeting quantity, quality, or both

Investment to tackle CSO spills can aim to: i) reduce or eliminate the spill, ii) reduce or eliminate high risk attributes of the spill that bear unacceptable cost to ecosystems, people or the water utilities. The solutions focused approach to CSOs is also visible in the last decade of research and is often linked with infrastructure (Fig. 4a&c). Conventional solutions to reducing CSO spill quantity are hard engineered including diverting spill volumes (for example in storage tanks), improving capacity of the network through installation of larger piping, or fixing broken pipes to reduce infiltration. Other solutions can avoid the high cost, high carbon approach of hard engineering (Fig. 6).

Thinking further 'upstream', changing customer behaviour is a promising approach. Customers misusing sewers not only impacts the quality of the wastewater, but also the quantity of CSO spills through blockages. Changing behaviours to reduce water consumption would reduce domestic inputs into the wastewater network while also reducing the energy expenditure associated with supplying water. Additionally, behavioural changes relating to the disposal of waste would also be beneficial, including the prevention of pharmaceutical disposal and wet wipe usage, both of which generate unique risks when released through CSOs. Other risks would require changes in the pharmaceutical and health industry to alter the composition of products that are likely to end in wastewater, such as the liquid plastics used to structure toothpaste and shampoos. Likewise, understanding and controlling direct industry sources based on CSO priorities should also be feasible given that wastewater utilities often grant licences based on the composition of the wastewater input. Changing upstream behaviours therefore requires concerted efforts from utilities, regulators, retailers and manufacturers. The benefit of implementing these solutions would be the reduction of risks to freshwater ecosystems from physical and chemical characteristics of wastewater, while also reducing the risk of CSOs spilling through blockages, particularly wet wipes.

Managing extraneous inputs such as surface run-off (not the responsibility of utilities) is another approach. Rechannelling surface-runoff into a nearby waterbody and not the combined sewer system could reduce CSO spills, but it would also introduce polluted stormwater to the waterbody. Transport and urban pollutants that mix with surface run-off during rain events are well documented, although their impact on freshwater ecosystems is still poorly quantified. In these scenarios, solutions such as SUDS (Sustainable Urban Drainage Systems) which can slow and filter these run-off waters before they reach combined sewer drainage systems or watercourses, can yield notable benefits, including in terms of reducing flooding risk, improving water quality and amenity, education, and biodiversity (Johnson and Geisendorf, 2019) all while being a low carbon solution (Quaranta et al., 2022). However, large scale reduction of urban, transport and agricultural surface run-off into wastewater systems at source would require integrated catchment management and collaborations between utilities and local stakeholders such as landowners or local authorities, which has so far been lacking (Fu et al., 2019).

Innovations that deliver more accurate and real-time monitoring of the wastewater system can also provide useful solutions to utilise the system most effectively, while also addressing issues such as blockages or unwanted inputs in a more efficient way (Fig. 6). The Internet of Things (IoT) and real time control (RTC) is a potential approach to reducing CSO spill volume, whereby sensors, modelling, software and internet connectivity allow for real time control of combined sewer systems (Van Der Werf et al., 2022), and therefore timely interventions further upstream to remove the cause of a spill. A potential that is reflected in the last decade of research (Fig. 4a), with studies into these approaches increasing in frequency over the last five years (Fig. 4b).

Treating CSO spills before they enter a receiving water body is also an end of line option, and often relies on soft engineering, or nature-based solutions. Constructed wetlands are a successful method of spill treatment, however, they can struggle to remove important contaminants such as phosphorus (Vymazal, 2011) and require significant land areas which may be challenging to carve out in many urban areas. In addition to this, they may prevent contaminants such as plastics and heavy metals from entering a river, but those contaminants can build-up in the wetland (Vymazal and Březinová, 2016), shifting the problem from one freshwater environment to another.

More generally the blueprints for wastewater systems in urban areas often revolve around the collection of large amounts of wastewater from a catchment and piping it to large, centralised WWTWs. Replacing these with a more modular decentralised system of smaller WWTW might allow more tailored treatments to tackle the unique mixes of contaminants within a smaller catchment – for example focusing on nature-based solutions for rural catchments that carry few pollutants other than nutrients, and more costly targeted treatments for catchments draining high risk or more specific pollutants. As well as tackling the composition of CSO spills, small scale, inexpensive decentralisation of wastewater treatment can be made in the first instance with increased rainwater water storage at the local level used for toilets, garden irrigation and washing machines, all of which would reduce wastewater volume.

6.4. Challenges in measuring cost benefit potential of CSO investments

Addressing the CSO challenge in countries with a dependency on aging infrastructure would require unprecedented investment via hard engineering solutions such as augmenting drainage capacity. Yet the public in many countries have shown willingness to pay for effective wastewater infrastructure (Ahn et al., 2020; Mourato et al., 2009). An evaluation framework for considering what type of additional work to wastewater infrastructure might be justified, in terms of a wider socio-economic return on investment, is therefore urgent.

Initial economic assessments of hard or soft engineered CSO solutions are relatively straightforward. Costs include land purchases/rents, the development costs of the infrastructure, and lifecycle costs linked to the efficient operation of the system. Benefits include local/regional employment, skills development supported by the investment and local/regional supply chain effects from construction spending. Indirect economic effects can also be assessed using simple economic models, where secondary effects of spending are monitored in different sectors of the economy, a methodology which has been applied to other large infrastructure assessments (Dimitriou et al., 2015).

However, in evaluation terms, expected solutions need to be understood beyond the strictly economic. More innovative engineered solutions such as nature-based solutions might require an approach that embraces the social and environmental returns on investment (Nicholls et al., 2012). For example, improvements to biodiversity and ecosystem services could improve the aesthetics of an area, instil pride in place, reduce insurance premiums, reduce flood incidence as well as improve tourism, leisure, and business access. Innovative infrastructure can also result in improvements to local land and housing values which can be easily monitored, or in value added to industries such as fisheries or tourism. Moreover, other social effects could include improvement to public health, be that due to a reduced exposure to pollutants or through improved wellbeing associated with aesthetics and new leisure opportunities, environmental security, educational effects of signature infrastructure to communities and firms, as well as a sense of community cohesion.

A real challenge with CSOs is embracing the varied social, economic and environmental consequences and framing them with respect to an initial investment (Munday et al., 2020). This is not an easy exercise, with a danger that business decisions may be reliant on case evidence of effects from other studies, and then coming to conclusions on whether 'conditions' are similar in the reference project case to lever similar benefits. Going forward there should be value in following the principles of developing a Social Return on Investment. There is also value in examining approaches in other sectors. For example, overall modelling of the economic impact of CSO spills could be achieved using similar modelling to that of COCO-2, a model used to assess the economic impacts of nuclear accidents (Higgins et al., 2008) given that this approach considers direct and indirect economic impacts, including changes to tourism and a systematic approach to health. Similarly, in major road investments, contractors regularly report socio-economic returns to government through a 'dashboard' style approach which tracks how projects have local direct and indirect economic consequences, but also how schemes meet wider social and community objectives (Nicholls et al., 2012). Such an approach might be adopted for wastewater and CSO schemes, as this would add to the evidence base of effects to inform future investment. Establishing the wider social and economic benefits of CSO schemes is not easy and there is need for careful consideration of the additional costs in developing the evidence base against its usefulness for informing investment decisions.

Besides hard and soft engineering options, which require significant capital investment, interventions based on behaviour change and regulation that are more typical of near source interventions (Fig. 6), provide lower costs solutions. These options are not without cost as they require preliminary behavioural studies followed by concerted information and education campaigns, and the cost of implementation of policy measures. Initiating changes in customer behaviour through regulatory measures also needs careful consideration as to potential unintended consequences, for example a switch to alternative options with more negative environmental consequences when the whole life cycle of the product is considered. However, all considered, near source interventions still present a low-cost option with potentially longer term and more sustainable impact.

7. Conclusion

Under pressure from increasing water use and climate change, and in the context of climate, biodiversity and pollution emergencies, combined sewers are struggling to contain their wastewater volumes. In countries across Europe and in some parts of the USA, these systems have often received little investment or innovation since they were first built over a century ago. Waste from human activities is also increasingly finding its way to combined sewers, so that the relief valves, designed initially to cope for extreme rainfall events, are too often spilling a complex mix of physical, chemical and biological pollutants, including plastics, biocides and bacteria into waterbodies. Theoretically, the risk posed to the wildlife and people who interact with the receiving water body depends on the pollutant load concentration, the volume of wastewater spilled and the state or nature of the receiving waterbody. This review shows that evidence to inform risk assessment and new investment decisions is still scarce (Fig. 4), and that the complexity of the challenge requires systemic change.

A significant challenge lies in that the composition and volume of combined sewer wastewater are highly variable. Combined sewer wastewaters transport a broad array of waste material from urban areas with varying demographics but also from a wide array of sectors. The ensuing array of pollutants and the variability of pollutant loads means that every CSO spill is different. Lack of monitoring means that it is difficult to estimate the actual risk CSO spills may have on ecosystems and people.

Once spills reach waterbodies, the actual risk they pose to ecosystems and people is modulated by the nature and state of the receiving body. Field evidence is challenging because freshwater bodies can vary in volume rapidly, and because pollutant loads, even when measured directly downstream of CSOs, reflect various pollutant sources. Data are also scarce because regulatory measurements still only concern some water pollutants, and many pollutants are still costly or difficult to measure. The task of measuring direct CSO spill impact is further challenged by the variable sensitivities of freshwater organisms and ecosystems to pollutants at different times of the year.

Lack of knowledge and evidence on the actual risk and thus impact of CSO spills limits the capacity to properly prioritise investment in CSOs. In the short term, filling these gaps in data, evidence, and knowledge is important. Emerging pollutants are a prime example where investments will need to future-proof against currently unknown risks. Areas which require immediate attention include widespread monitoring of quantity and quality of CSO spills across both space and time as well as understanding and monitoring the outcomes of those spills for ecosystems and people. In the meantime, the fall-back prioritisation principles are likely to be based on considerations around existing data and knowledge, with some that are quantifiable and rational such as frequency and timing of spills or the Water Framework Directive status of the receiving water body, and others of a more subjective nature such as customer perception of visible litter.

However, despite current knowledge gaps, investments likely to reduce the amount of spill or the potential hazard that the spill represent useful solutions for all CSOs. The challenge here is often in terms of monetising costs and benefits such as ecosystem services and social benefits. Whilst climate emergencies are pushing in favour of further utilisation of low carbon, nature-based solutions, these remain constrained by the difficulties in assessing their benefits, and by the fact these usually large-scale endeavours require collaborative efforts from a range of stakeholders (utilities, regulators, landowners) who are rarely organised to achieve this.

Approaches that involve upstream thinking such as behavioural change and/or regulation to reduce the amount of waste and/or used water that enters sewers also offer inexpensive solutions. However, changing social norms to alleviate CSO spills are also unlikely to be effective in the short term, as has been seen with responses to other challenges such as climate change, where concern for others and self-interest against an intangible gradual risk have proven to be ill-equipped to motivate behavioural change (Sparkman et al., 2021).

In the long-term, as extreme climatic events increase and water availability decreases, fundamental shifts in waste disposal and wastewater management are required. Increasing capacity to process more complex and voluminous wastewaters is not economically feasible nor is it sustainable. It is clear a step-change is necessary. Our conclusions point towards adopting a systems perspective that considers the water cycle holistically, and also highlight the opportunities of 'upstream' thinking that focuses efforts on the root cause of the issue. Over the past decades there has been significant changes in solid waste disposal, spurred by regulation, information, and behaviour change. It is also time to rethink wastewater systems and explore alternative smaller scale decentralised options.

CRediT authorship contribution statement

William Bernard Perry: Investigation, Visualization, Writing - original draft, Writing - review & editing. **Reza Ahmadian:** Conceptualization, Investigation, Writing - review & editing. **Max Munday:** Conceptualization, Investigation, Writing - review & editing. **Owen Jones:** Conceptualization, Investigation, Writing - review & editing. **Steve J. Ormerod:** Conceptualization, Investigation, Writing - original draft, Writing - review & editing. **Isabelle Durance:** Conceptualization, Funding acquisition, Investigation, Supervision, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: William Bernard Perry, Reza Ahmadian, Max Munday, Owen Jones, Steve J. Ormerod and Isabelle Durance reports financial support was provided by Dwr Cymru Welsh Water.

Data availability

No data was used for the research described in the article.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2023.123225.

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