National Engineering Policy Centre

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Testing the waters

Priorities for mitigating health risks from wastewater pollution

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Contents

Foreword

Managing the threat of cholera epidemics, typhoid and many other water-borne diarrhoeal diseases was central to the birth of scientific public health in the UK, and has remained central to it since. The remarkable feats of engineering which separated human faeces from water we come into contact with, and in particular from contaminating drinking water, broke the chain of transmission of the major faecal-oral diseases which were previously a major cause of mortality in children and adults. It was one of the greatest public health triumphs of the last 200 years, responsible for saving millions of lives globally. The principal reason for the existence of the sewerage system is to protect public health.

Minimising ingestion of human faecal pathogens- bacteria, viruses and parasites- remains a public health priority. Whilst we continue to have safe drinking water, ensuring both fresh and sea water people regularly come into contact with through leisure or other activities has a minimum number of viable human faecal organisms is one of the many contributions engineering makes to public health.

There are two principal routes of human faecal-oral organisms into public waterways in the UK, both of which have potential engineering solutions. The first is raw sewage entering rivers or the sea via storm overflows which has received extensive attention over recent months. The second is via continuous effluent discharge from routine sewage works operations. Whilst sewage effluent has undergone treatment processes which significantly reduce the risk, it still can contain viable human bacteria and viruses which have the potential to cause serious disease if ingested.

I therefore welcome this report from the National Engineering Policy Centre, which demonstrates the many possible solutions available for use across sewage systems and treatment works of varying sizes and settings. It clearly sets out that to reduce the public health risk significantly, a combination of practical solutions can be implemented and tailored to each context.

Public waterways are a great resource enjoyed by many children and adults and can have a significant positive impact on our health. Whilst there will always be challenges with the efficient management of sewers and sewage treatment works, minimising the entry of human organisms that can cause harmful infection should be a major priority. This report provides clear options for how this can realistically be achieved.

Professor Sir Chris Whitty FRS FMedSci
Chief Medical Officer for England

Executive Summary

In this report we examine the interventions available to reduce the public health risks to people using public waters for recreation that may be polluted with faecal organisms from human waste.

Public health definition: Organised measures (whether public or private) taken to reduce risk to tolerable levels to prevent disease, promote health, and prolong life among the population as a whole.

Our wastewater system is, at its core, an asset for the protection of public health, and it has been remarkably successful, including interrupting the transmission of major epidemics and protecting the environment by treating wastewater before it is returned to our rivers and seas.

However, the deterioration of wastewater assets, growing urbanisation and forecasts for more frequent and intense rainfall events due to climate change will mean increasing pressure is put on our ageing wastewater system. In addition, the growing popularity of open water recreation activities across the UK (including swimming, water sports, and angling) has increased the exposure of the public to pollution. Furthermore, greater public awareness of water pollution and the greater availability of water quality data have changed public expectations of water quality. Together, these have opened questions about the standards we expect from UK waters and the acceptability of risk.

Significant attention has been paid to pollution from storm overflows (also known as 'combined sewer overflows'), including concern about the implications for the health of recreational users, as set out in chapter 1. For sewage passed through to wastewater treatment works, the concentration of faecal organisms will be substantially reduced through treatment. However, the final treated effluent discharged continuously into waterbodies still contains high numbers of faecal organisms. We know that public health risks are increased by exposure to high concentrations of faecal organisms even though the causal link between specific wastewater discharges, the sources of faecal organisms we measure, and reported incidents of diseases such as gastroenteritis is rarely firmly established.

Even mild cases of illness can have broader impacts beyond the direct health effects, for example, economic impacts from increased number of sickness absences from work or losses for tourism-based businesses near waters used for recreational activities.

In addition to these short-term public health risks, the wastewater system is also a source of antimicrobial resistance. The exposure of recreational water users to human faecal organisms resistant to known antibiotics poses a longer-term risk to public health.

There are numerous sources of faecal organisms including agricultural run-off, livestock, wild animals, septic tank discharges, storm overflows, and treated final effluent from wastewater treatment works, and the contribution of any one of these sources to any one body of water will vary significantly depending on multiple factors including catchment geography, land use, and weather. In this report, we focus on the role of wastewater infrastructure as a source for, principally, human faecal organisms through storm overflows and the discharge of treated final effluent, as described in chapter 2.

Public health risks may be addressed by reducing either the hazard itself – the type or concentration of pollutants – or by limiting public exposure to that hazard. In chapter 3 we examine a range of interventions, each with varied impacts on reducing public health risks, which can be grouped into four broad categories set out in Table 1. Through workshops with engineers, wastewater experts, water service providers, campaign organisations, and policymakers as well as reviewing the published evidence, we have made risk-based assessments of the suitability of interventions

Category	Public health impact	Advantages	Limiting factors
Water management Interventions examined: 1. Sewer separation 2. Sustainable drainage 3. Storage tanks 4. Water efficiency	Technologies to reduce the volume of water that enters combined sewers will reduce the volume spilled through overflows, reducing exposure to untreated sewage. This includes measures such as storage tanks, separate sewers, and sustainable drainage systems (stormwater) and water efficiency (wastewater).	Multiple benefits for storm water management and other aspects of urban design. Can be part of urban greening projects. Water efficiency gives reduced potable water demand.	Significant land footprint and need for large-scale retrofit of impermeable surfaces. Limited effect on treated effluent quality.
Wastewater treatment Interventions examined: 5. Capacity for treatment 6. Effluent disinfection 7. Constructed wetlands 8. Overflow disinfection	Improving wastewater treatment to increase the removal of microorganisms would reduce exposure to human faecal organisms in treated effluent. This includes technologies such as ultraviolet disinfection and constructed wetlands.	Some technologies are highly effective at reducing microorganism numbers, and alternative treatment processes can increase resource and energy recovery.	Effluent disinfection is expensive, carbon intensive, and requires extra space at treatment works. It is difficult to provide at small or remote storm overflows.
Monitoring and communicating risk to the public Interventions examined: 9. Water quality monitoring 10. Pollution forecasting 11. Risk communication	Increased frequency, accuracy, and reliability of monitoring will create a better understanding of the level of faecal organisms present in waterways; allow for better information to be given to the public on the risk at given locations and times; and better inform the selection and targeting of interventions.	Can be effective at reducing public health risks by preventing public exposure to pollution incidents.	Risk is challenging to communicate well, and communications can be missed. Effective targeting of messages and trust in the messenger are needed.
Maintenance and operations Interventions examined: 12 Addressing misconnections 13. Resolution of blockages 14. Addressing sewer infiltration 15. Treatment works maintenance 16. Automation and digitisation	Maintaining and optimising sewers and wastewater treatment assets to reduce overflows and ensure treatment levels. This includes addressing blockages, infiltration, cross connections, and digitisation of assets for proactive maintenance.	Effective at reducing frequency of overflows, and has benefits for asset longevity and quality of treatment	Challenging to identify sources in sewers. Lack of access to private sewers.

Table 1 | Categories of intervention, their impact, advantages and limitations

Capital expenditure \ Relative risk reduction	Low	Low - medium	Medium	Medium - high	High
High		14	3	1, 2	8
Medium - high			16		
Medium	4	5		7	6
Low - Medium		12, 13, 15			
Low		9, 10	11		

Water management
1. Sewer separation
2. Sustainable drainage
3. Storage tanks
4. Water efficiency

Wastewater treatment

5. Capacity for treatment
6. Effluent disinfection
7. Constructed wetlands
8. Overflow disinfection

Monitoring and engagement

9. Water quality monitoring
10. Pollution forecasting
11. Risk communication

Maintenance and operations

12. Addressing misconnections
13. Resolution of blockages
14. Addressing sewer infiltration
15. Treatment works maintenance
16. Automation and digitisation

Figure 1 | shows a summary of the relative risk reduction effectiveness and indicative capital expenditure scores of all the interventions considered

for reducing public health risks. We recognise that there are other key policy priorities such as flood mitigation, water supply resilience, net zero, ecological recovery, the need for development, and affordability. The balance of priorities and applicability of any one intervention will vary depending on factors such as geography, governance arrangements, energy use, and resource availability.

Recommendations

A portfolio of interventions is needed to create multiple barriers of protection to minimise public health risks from treated effluent and storm overflows. Our collaborative approach identified the need to take a risk-based methodology to the deployment of interventions and to target those actions at sites where public health risks are greatest, while balancing the need for action against other policy priorities, as explained in chapter four. These recommendations identify those actions that need to be addressed collectively by water service providers, UK government, devolved administrations and public bodies to reduce public health risks while also supporting a more effective and resilient wastewater system across the UK.

Immediate actions to reduce the public health risks

1. **Maintenance and rehabilitation**: Water service providers should further prioritise maintenance and rehabilitation of assets, informed by regulatory frameworks that require the demonstration of asset resilience including the reduction in sewer infiltration, and supported by enforcement measures.
2. **Monitoring and forecasting**: Department for Environment, Food & Rural Affairs (Defra) should revise targets to accelerate the roll-out

of Continuous Water Quality Monitoring in England and extend the scope so environmental regulators monitor the microbiological quality of treated effluent. This includes accelerating the public availability of near-live data to inform improved pollution forecasting and provide clear public communications to reduce the public's exposure to poor water quality. Comparable data should be made available across the UK.

3. **Bathing standards**: Defra should initiate a review of the designation and protection of bathing waters, working with academic experts, regulators and devolved administrations to develop agreed methods to better quantify microbiological water quality, and ensure the standards that are applied are proportionate to the public health risks.
4. **Asset monitoring and modelling**: Water service providers should work in partnership with experts and researchers to develop models of catchments, supported by agreed standards for data sharing, to enable a better understanding of infrastructure asset health, to aid proactive management of its performance and to protect water quality.
5. **Storage tanks**: UK government's calls for short-term relief of overflows based on storage tank construction should be weighed against sustainability considerations and opportunities for longer-term plans for capacity management across the whole system, only sanctioning storage tanks where environmental and public health risks are greatest and there are no acceptable alternative actions.
6. **Managing surface water**: To reduce the number of overflows, local authorities, regulators, and property owners should identify and implement mechanisms to reduce surface run-off. These may include incentivising the removal of impermeable surfaces as well as the diversion or slowing of surface run-off from private properties with sustainable drainage systems (SuDS) and other urban greening initiatives.
7. **Risk communication**: Health protection authorities, environmental regulators, and local authorities should engage stakeholders and the public through educational campaigns and community involvement to increase public understanding of the health risk, promote responsible behaviour, and improve the effectiveness of signage and information at designated bathing sites.
8. **Disinfection**: Water service providers and environmental regulators should assess the need for the wider deployment of disinfection processes at priority sites as part of a public health risk-based approach to improving the UK's wastewater infrastructure.

Opportunities to seize now for long-term transformational change:

9. **Joined-up vision**: A vision for the UK's wastewater system should be developed by Defra and the devolved administrations, involving the public and diverse perspectives across the water sector. The vision should balance human health and wellbeing, protection of nature, security of supply, flood resilience, economic sustainability, and customer satisfaction and be supported by measurable targets to monitor delivery.
10. **Sustainable drainage**: Defra, devolved administrations, and local authorities should coordinate a national scale deployment strategy for sustainable drainage systems to future proof our wastewater infrastructure in a changing climate. These interventions must be supported with clear guidance and responsibilities for maintenance and evaluation to ensure long-term performance.
11. **Public, trade, and industry engagement**: Defra and devolved administrations should revisit their strategies for water efficiency and blockage prevention measures, which would be supported by other policy initiatives such as a ban on the flushing of nonbiodegradable items. This should be part of wider engagement to support a culture shift around our use of and shared responsibility for the water system.
12. **Demonstrator programmes**: Water service providers, regulators, and UK Research and Innovation should dedicate funding to pilot large-scale demonstrator programmes

for the development and deployment of new treatment approaches for improved performance and pollutant removal, to support operational optimisation, and the development of real-time monitoring of faecal organisms.

Enabling actions:

13. **Understanding**: UK Research and Innovation and other funders should support multidisciplinary research to better understand faecal microbial behaviour and antimicrobial resistance in inland and coastal waters and develop better monitoring technology for near-real-time monitoring of faecal organisms and other microorganisms of human concern in waterbodies used for recreation. This should support policymakers and water service providers to take a risk-based approach, identifying priority sites for improvement and informing where certain interventions should be targeted.
14. **Skills and capacity**: An increase in the capacity of regulatory and engineering skills will be required to enable the delivery of the interventions and resource the monitoring and enforcement of water quality targets. Collaborative efforts between government bodies, regulators, and water service providers should allocate resources towards recruiting and developing skilled staff.
15. **Strategic oversight**: Defra, with the support of the devolved administrations, should appoint a wastewater champion to enable effective collaboration across different stakeholder groups to deliver these recommendations and coordinate action to reduce these public health risks across the UK.

In conclusion, we propose that public health risks for users of waterbodies, and the reduction of those risks, should be explicitly accounted for by reference to statutory standards within all current and future wastewater infrastructure improvement schemes whether they are intended to address flood risk, ecological health or support urban development.

Chapter 1
Introduction

Bathing and recreational use of rivers, lakes, and coastal waters has become increasingly popular over the last few years with strong public interest in formally designating more sites under the Bathing Water Regulations.[1] In the Chartered Institution of Water and Environmental Management's recent publication, *A Fresh Water Future*, most respondents to a public survey said that they engaged with local waters weekly for recreation or reflection, and 84% were concerned about water pollution.[2] Furthermore, the availability of data on storm overflows and concerns about the underperformance of overloaded sewers and treatment works[3] has reopened questions about risk, and risk acceptability.

Recent media coverage of pollution of rivers and beaches has brought attention to the role of storm overflows (also known as 'combined sewer overflows'). However, intermittent storm overflows are not the only source of faecal organisms as treated effluent still contains significant levels of faecal organisms and is discharged continuously. Furthermore, agriculture and wild animals can also be significant sources of faecal pollution. In this report, we focus explicitly on exposure to faecal organisms of human origin from wastewater discharges, transmitted through recreation on or in open water.

This report explores the potential of a range of interventions to mitigate the public health risks posed by the discharge of treated and untreated sewage to rivers, lakes, and coastal waters used for recreation. In addition to considering interventions that specifically address public health risks, we consider the opportunities for longer-term transformational change to our wastewater infrastructure to reduce public health risks and build a more resilient wastewater system. A summary of the project methodology is outlined on page 10, with further details set out in Annex A.

In this chapter, we will explore what public health concerns exist around exposure to human faecal organisms, how a risk-based approach can help to mitigate those risks and examine the other policy priorities facing the water system.

1.1 Public health and wastewater

Our sewerage system is, at its core, an asset for the protection of public health, and it has been remarkably successful including interrupting the transmission of major epidemics including cholera and typhoid.[4,5] Its primary role is to remove human excreta and other domestic and industrial wastewater, for example from population centres and to protect water quality by providing sufficient treatment before returning the treated wastewater to the environment.

The growing demand for bathing and recreational use of open waters (in designated and non-designated bathing waters), coupled with the evidence of the underperformance of overloaded sewers and treatment works[3], may raise the relative risk of human exposure to faecal

Project methodology

This project took a systems-based approach in exploring the portfolios of interventions to the engineered wastewater system that could reduce public health risks while minimising other negative environmental and economic impacts. Collaborative workshops attended by water company personnel, public health engineers, environmental campaign groups, water experts, policymakers, and regulators ensured different perspectives could be heard. The initial scoping workshop sought feedback on leverage points in the wastewater system and potential interventions to reduce public health risks. Indicative impacts, costs, and scalability of these interventions were considered and compared at a second workshop. Intervention choices were considered against two scenarios: the maximum reduction in public health risks in the shortest time versus the maximum reduction considering long-term resilience. These discussions highlighted the limitations and co-benefits of individual interventions, which inform our recommendations.

Given the specific focus on mitigating the public health risks from human faecal pathogens, the following topics are outside of the scope of this report:

- **A detailed assessment of the applicability of different interventions across different catchments and geographies, or within different administrations.**
- **Supply and treatment of drinking water.**
- **The application of sewage sludge (biosolids) to agricultural land or its wider disposal.**
- **Agricultural pollution, animal waste, and diffuse pollution sources.**
- **A detailed discussion of specific treatment products**
- **An assessment of industry structure or specific policies and targets across devolved administrations, though an overview of the policy context is included to highlight where any recommendations are in addition to ongoing work.**

organisms. Furthermore, the growing availability of water quality information and changing public expectations have opened questions of risk acceptability.

We know that public health risks are increased by exposure to high concentrations of faecal organisms (which include faecal pathogens) even though the causal link between specific wastewater discharges (overflows and treated effluent), the sources of faecal organisms we measure, and reported incidents of diseases such as gastroenteritis, is rarely firmly established. Faecal pathogens – microorganisms that cause disease – are challenging to identify and measure directly in the water environment. Instead, a small set of faecal indicator organisms (which are not necessarily pathogenic) are used as proxies to indicate the presence of faecal pollution and to inform water quality assessments. In this report, we will principally use the term faecal organisms to include disease-causing faecal pathogens and those faecal organisms that are measured and used to assess the performance of wastewater treatment technologies.

Faecal organisms of animal origin may be present in large quantities in waterways from agricultural run-off, road run-off, livestock, and wild animals depending on the nature of the catchment and its land use.[6,7] While these organisms can present a health risk, because of species barriers and the more diffuse nature of this pollution these will typically be a less significant risk to human health than human-derived infections.[8,9] The nutrient content of sewage pollution and agricultural run-off can also lead to blooms of blue–green algae which produce toxins harmful to people and animals.[10,11] There is emerging evidence of public health harms from chemical pollutants that can enter waterbodies through surface run-off and industrial effluent (including fertilisers, pesticides, heavy metals, chemicals, oils, and microplastics), however, the public health impacts are less established.[12,13] This report focuses exclusively on faecal organisms of human origin, and on wastewater discharges as a source.

In the UK, the risk of exposure to faecal organisms (of both human and animal origin) is currently mitigated within designated bathing waters via the Bathing Water Regulations.[14] These regulations require that designated bathing waters are subject to monitoring of faecal indicator organisms – which are used as a proxy measurement for the presence of faecal pathogens – up to twenty times throughout the bathing season (May–September), and that the public is provided with pollution warnings to reduce exposure to pollution.

The quality of a bathing water is classified as ‘poor’, ‘sufficient’, ‘good’ or ‘excellent’ based on the measured concentration of faecal indicator organisms, averaged over the previous four years. These classifications are based on a set of standards from the World Health Organization research on the frequency of gastrointestinal illness in people bathing in differing water quality.[15,8] Undesignated waters do not receive any microbiological monitoring, nor are they covered by any microbiological standards.

In 2023, 380 of 423 (90%) designated bathing waters in England were classed as ‘good’ or ‘excellent’,[16] 100 out of 109 (91%) in Wales,[17] 75 of 89 (84%) in Scotland,[18] and 24 of 26 (92%) in Northern Ireland.[19] This is a significant increase from the 1990s, when 28% of bathing waters in England met the highest standards in force at the time. The improvement of these sites can be attributed to the investment that has been made over the past three decades.[20]

The evidence base behind these quality standards is largely based on randomised control trials in marine environments, however, the evidence in freshwater environments and outside of the bathing season is limited. Recent evidence suggests that same-day variation of faecal indicator organisms can be substantial, suggesting that current weekly monitoring regimes may be insufficient. Furthermore, evidence suggests that current bacterial faecal indicator organisms are unreliable indicators of the presence of enteric viruses, which are a significant cause of recreationally associated waterborne disease.[21]

Human faecal pathogens

There are broadly five routes by which major transmission of infections can occur: faecal–oral (this report), respiratory, sexual/bloodborne, touch, and vector (insects). Faecal–oral transmission of pathogens – microorganisms that can cause disease – is a significant cause of individual disease and is a route by which diseases can spread within a population, with many of the major epidemics in history transmitted via this route.[22] This prompted concerns (fortunately unrealised) at the outbreak of SARS-CoV-2 of a possibility of a viral transmission pathway through exposure to wastewater in the environment; although this was not a major route of transmission in the COVID-19 pandemic it could be a risk in future pandemics and epidemics.[23]

Human excreta contains significant numbers of microorganisms,[24,25] some of which are pathogenic and can cause a range of morbidities to people exposed through contact or ingestion, including via water.[26]

- Bacteria such as salmonella, campylobacter, and some strains of E. coli can lead to gastrointestinal illnesses characterised by symptoms such as diarrhoea, vomiting, abdominal cramps, and fever.

- Viruses such as noroviruses and adenoviruses are highly contagious and resilient in water environments and can cause acute gastroenteritis. Similarly, hepatitis A, a virus that can be transmitted through contaminated

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water sources, can lead to acute liver infections and systemic illness.

- Protozoan parasites such as giardia and cryptosporidium are resistant to traditional disinfection methods and can cause diarrheal diseases and gastrointestinal infections upon ingestion or exposure.

While acute gastrointestinal illnesses and skin infections are well-documented outcomes of exposure to contaminated water, establishing a link with a source of pollution is challenging. For example, in 2023, an outbreak of gastrointestinal illness following a triathlon event in Sunderland prompted public concerns about sewage pollution.[27,28] However, a UK Heath Security Agency investigation was unable to identify the exact source of the infection beyond finding that swimming in the sea had been the "most likely source of infection."[29]

Alongside acute illnesses, the potential for chronic health effects, particularly in vulnerable populations such as children, the elderly, immune-compromised people, and individuals with pre-existing health conditions, remains less understood.[30] There is also a lack of understanding of how to predict and model the impact of overflows and discharges on bathing waters. More comprehensive studies examining the transmission dynamics of waterborne pathogens in designated bathing water settings, including the role of environmental factors, human behaviour, and microbial interactions are needed.[26]

Antimicrobial resistance

Significant concern also exists about the development of antimicrobial resistance (AMR), particularly in human faecal pathogens.[31] Faecal organisms with resistance to known antibiotics are abundant within wastewater as a direct result

Antimicrobial resistance

Antimicrobial resistance genes (ARGs) found in sewage originate from bacteria found in human faeces and other bodily fluids that enter wastewater. They can also stem from biofilms found in the sewer system, including within storage tanks, which peel off naturally and under high flow. While the ARGs are not a direct threat, bacteria can transfer and take up genes that could give pathogens the capacity to resist treatment with antibiotic drugs.

Sewage treatment can reduce the quantity of ARGs by a factor of 10 to 1,000,[38,39] however, some ARGs have been shown to increase in prevalence through treatment. This suggests concentrations of AMR-driving chemicals[40] are sufficiently high within wastewater treatment works to encourage the survival of microorganisms that harbour the ARGs.[41]

The chemicals discharged in treated effluent are sometimes met with very low levels of dilution in the receiving river.[42] High concentrations of known ARGs downstream of the treatment works may drive the evolution of novel ARGs in the water environment.

The continuous release of microorganisms from treated sewage poses a human health risk to those exposed to sewage-impacted environmental waters. However, thresholds of safe human exposure levels to individual pathogens harbouring ARGs have not yet been characterised. Such thresholds would be driven by the susceptibility of the most vulnerable groups, such as the very young, the immunocompromised, and the elderly. Human gut colonisation with environmentally derived ARGs is likely to have a different threshold of safe exposure.

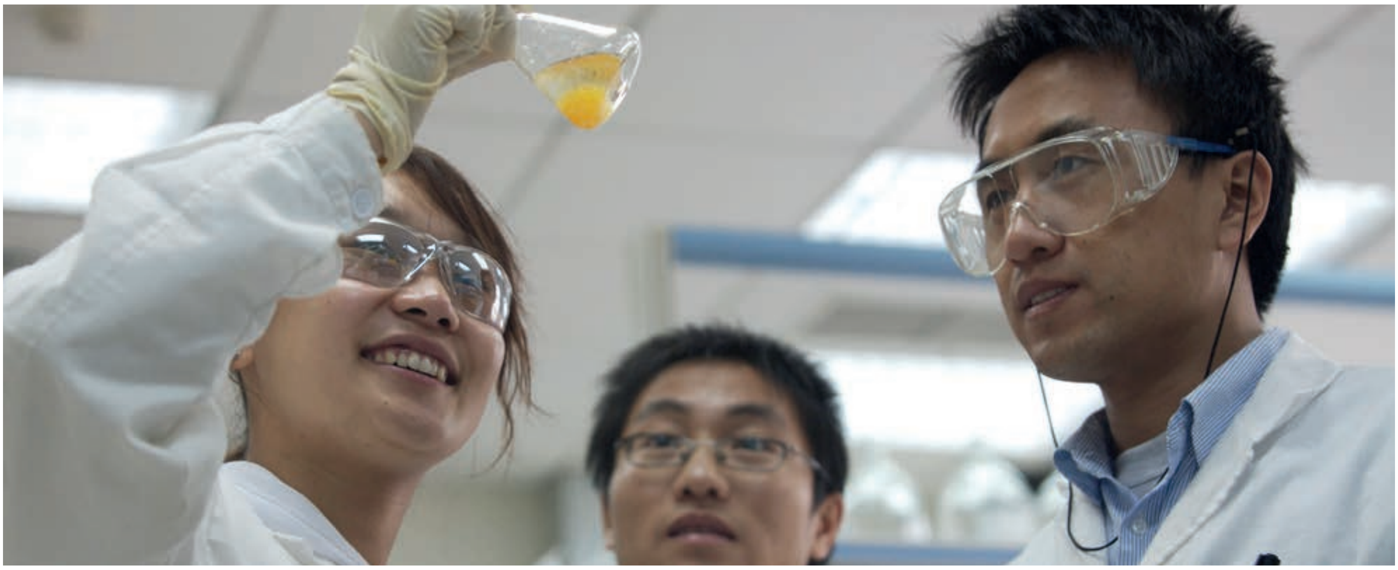
The risk is significantly increased when the sewage that is discharged is untreated, as is the case in storm overflows. Although it is already known that the risk of acquiring a pathogen from exposure to sewage-impacted water is greatly elevated during heavy rainfall,[43] it remains largely unexamined how this relates to ARG acquisition, especially from locations downstream of wastewater treatment works and storm overflows where ARGs might be retained in the environment long-term.

of human consumption of antibiotics which are then excreted into the wastewater system.[32] Water users are disproportionately exposed to AMR[33] as sewers are a primary source of the release of resistant faecal organisms into the environment.[34] The public health risks posed by AMR from the wastewater system have not been explicitly considered in this report, however, reducing exposure to faecal organisms from wastewater discharges is expected to correlate with a reduction in environmental exposure to AMR. Exposure to human faecal organisms may also occur through consumption where polluted water is used for irrigation of crops,[35] where sludge is used as a soil conditioner or crop fertiliser,[36] and through the contamination of shellfish waters.[37] However, we have not examined these exposure routes in this report.

Sources of human faecal organisms

Two of the primary sources of human faecal organisms reaching natural waterbodies are storm overflows and the treated wastewater discharged from wastewater treatment works.[44]

Storm overflows are designed to sporadically discharge diluted sewage directly to the environment during high-flow conditions (such as storms) when downstream dilution is expected to be high to prevent sewer flooding of homes and protect the performance of downstream wastewater treatment works. However, growing



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urbanisation and forecasts for more frequent and intense rainfall events due to climate change will mean increasing pressure is put on our ageing wastewater system. This presents public health risks to those who may be using waterways downstream of overflows. Furthermore, standard wastewater treatment processes are designed to remove nutrients, not microorganisms, and treated effluent still contains high numbers of faecal organisms.[45]

Discharges from septic tank systems can also be locally significant sources of pollution,[46] however, there is no monitoring or comprehensive records of the number of septic tank systems, making their impact on faecal pathogen levels difficult to assess[47,48] and they have not been considered in this report. Misconnections of (typically household) separate foul sewers to separate surface water sewers can also be a direct route of faecal pollution.

The relative risks posed by overflows versus treated effluent at any one time will depend on the treatment processes deployed, the river catchment, the recent weather, and the distance of the user from the source of pollution. Storm overflows will operate more frequently during or immediately after heavy rain, which might limit the exposure of some recreational water users to untreated sewage. Treated wastewater is discharged continuously, and during the drier summer months there may be less flow within the river to dilute the wastewater.[49,50] However, short bursts of precipitation during the summer can still overwhelm a sewer network leading to overflow discharges.

1.2 Managing risk

In this report, we have used a high-level, risk-based framework for the assessment and selection of interventions to mitigate public health risks from human faecal pollution. This builds on recommendations made by the World Health Organization.[51]

Taking such an approach means first understanding the range of public health risks relating to the wastewater system and recognising that negative health outcomes arise at the intersection of three things: a hazard, an exposure, and a vulnerability (Figure 2).

- **Hazard**: the type and level of pollutants – for example, high concentrations of faecal organisms in recreational waters.
- **Exposure**: how people come into contact with the hazard – for example, through ingestion or contact.
- **Vulnerability**: this is relative to the person who is exposed to the hazard – for example, in general, children will be more vulnerable to infection than adults.

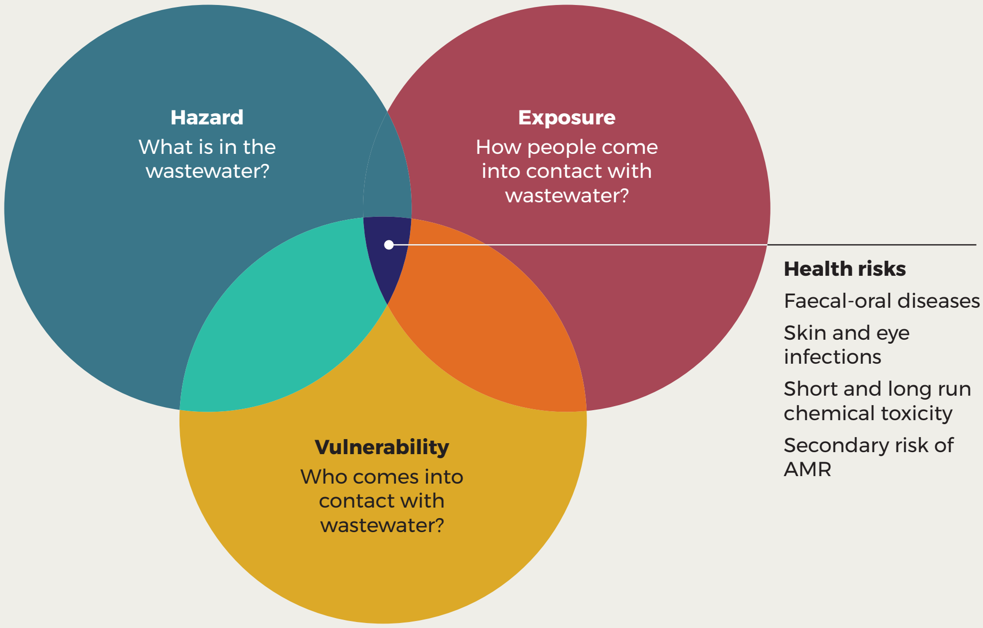


Figure 2 | Framework for the assessment and selection of interventions to mitigate public health risks from human faecal pollution

Relevant health risks include faecal–oral diseases, skin and eye infections, short- and long-term chemical toxicity, and the secondary effects of AMR. For each risk, we need to identify health protection interventions that, used singly or in combination, can achieve desired outcomes.

In Chapter 3, we will use this framework to consider interventions that can either reduce the hazard (for example, improved treatment processes) or reduce exposure (for example, better risk communication). We also extend this approach to consider the opportunities and trade-offs of any one intervention against a range of other key policy priorities.

1.3 Policy priorities

The wastewater system has been designed to address different challenges, including risks to public health and natural environments, and has evolved over time. Water service providers (all providers of water and sewerage services, publicly or privately owned) have been set various aims for multiple issues, led by policy priorities from regulators and customer needs, and are trying to balance these in current strategies and asset management plans.

This report outlines key interventions for reducing public health risks and comments on potential impacts on other areas of operation or responsibilities. However, the competing policy priorities for the wider water system need to be taken into consideration when planning for asset management. As health considerations are brought forward, decision-makers need to be fully aware of how they will influence change in the wastewater system and where any trade-offs exist.

Various priorities will have their own demands for resources and/or infrastructure which will also introduce considerations for cost and financing. In a fully privatised system, such as in England and Wales, service providers and the economic regulator are also concerned with consumer bills, which are used to fund provision of services, and the extra strain on the population.

Key policy areas considered in the context of this report include:

Resilience of water supply: Many water service providers across the UK provide both clean drinking water and wastewater services and must manage demands for freshwater to prevent disruption to services. However, many waterbodies are unsustainably abstracted and there are increasing challenges from more regular droughts and hot weather in summer months consistent with the predicted impact of climate change. Water service providers need to consider opportunities for efficiency to ensure resilience of water supplies. The UK government *Plan for Water* considers the importance for both a clean environment and resource security.[52]

Reaching net zero: The UK has established legal targets to achieve net zero emissions (relative to the 1990 level) by 2050. The water industry is estimated to contribute 1% of national greenhouse gas emissions, in terms of electricity consumption and associated emissions, accounting for nearly a third of UK industrial and waste process emissions.[53] Many water service providers across the UK have committed to achieving net zero emissions between 2030 and 2050 (this differs across the devolved nations), prioritising actions such as integrating nature-based solutions, adopting renewable energy sources, and implementing water conservation measures.[54]

Need to improve ecology: Treated wastewater is discharged back into natural water bodies, including designated bathing waters. The quality of discharged water will have a direct impact on local habitats. An assessment in 2019 highlighted that most rivers, lakes, and coastal waters in England are not meeting 'good' ecological status[55] and there are legal targets within the Environment Act, the storm overflow reduction plan, and the Water Framework Directive for improving biodiversity and water quality. The government has set strategic priorities for the economic regulator, Ofwat, and the water sector that include protecting and enhancing the environment. As such water service providers are being challenged to improve environmental performance.

Need for development: In 2019, the UK government pledged to continue increasing the number of houses being built and set targets to build 300,000 homes per year by the mid-2020s. Developers have a right to connect new homes to an existing public sewer as well as connecting surface water drainage in the development to sewers where discharging to a watercourse is not feasible, increasing the demand on sewerage systems. However, there may be changes under Schedule 3 of the Flood and Water Management Act 2010 which sets out a framework for national standards for sustainable drainage systems and an approving body who would need to sign-off the proposed drainage before construction could start or the property is connected to a public sewer. Schedule 3 is to be implemented in 2024 in England and already in force in Wales. Additionally, new housing developments within protected habitat sites must ensure they are not adding new sources of nutrient pollution, including sewage, to the water catchment under nutrient neutrality requirements.[56]

Mitigation of flooding: Water service providers must ensure their systems are resilient to flooding. Individual companies are one of the flood risk management authorities and so have a role in advising lead local flood authorities about how assets and systems could affect flood risks and prevent infrastructure failures. Impacts from climate change on flooding may also affect local drainage. The increasing frequency and severity of storms, as well as increasing risks of compound flooding (where a second flooding event occurs before a previous event has receded), which could potentially increase stress on assets that water service providers will need to consider in their asset management plans. The National Infrastructure Commission advised that water service providers work with local authorities and the Environment Agency to develop plans for managing surface water flooding from 2025.[57] Improving resilience for flooding is included in the government strategic priorities for the water industry in England and Wales.[58]

In the following chapters, this report will set out the existing structure and operation of the wastewater system to explain the context for change and explore interventions that could be taken, outlining key interdependencies with the challenges noted above that will need to be carefully considered by decision-makers.

Chapter 2
Our wastewater system

Any interventions made to the wastewater system to reduce public health risks must consider the context of existing infrastructure and working practices. This chapter will consider the design and workings of the sewerage system, wastewater treatment process, the effect they have on faecal organisms, and the governance of the system, so that the opportunities for public health mitigations can be identified.

2.1 Sewers and drainage

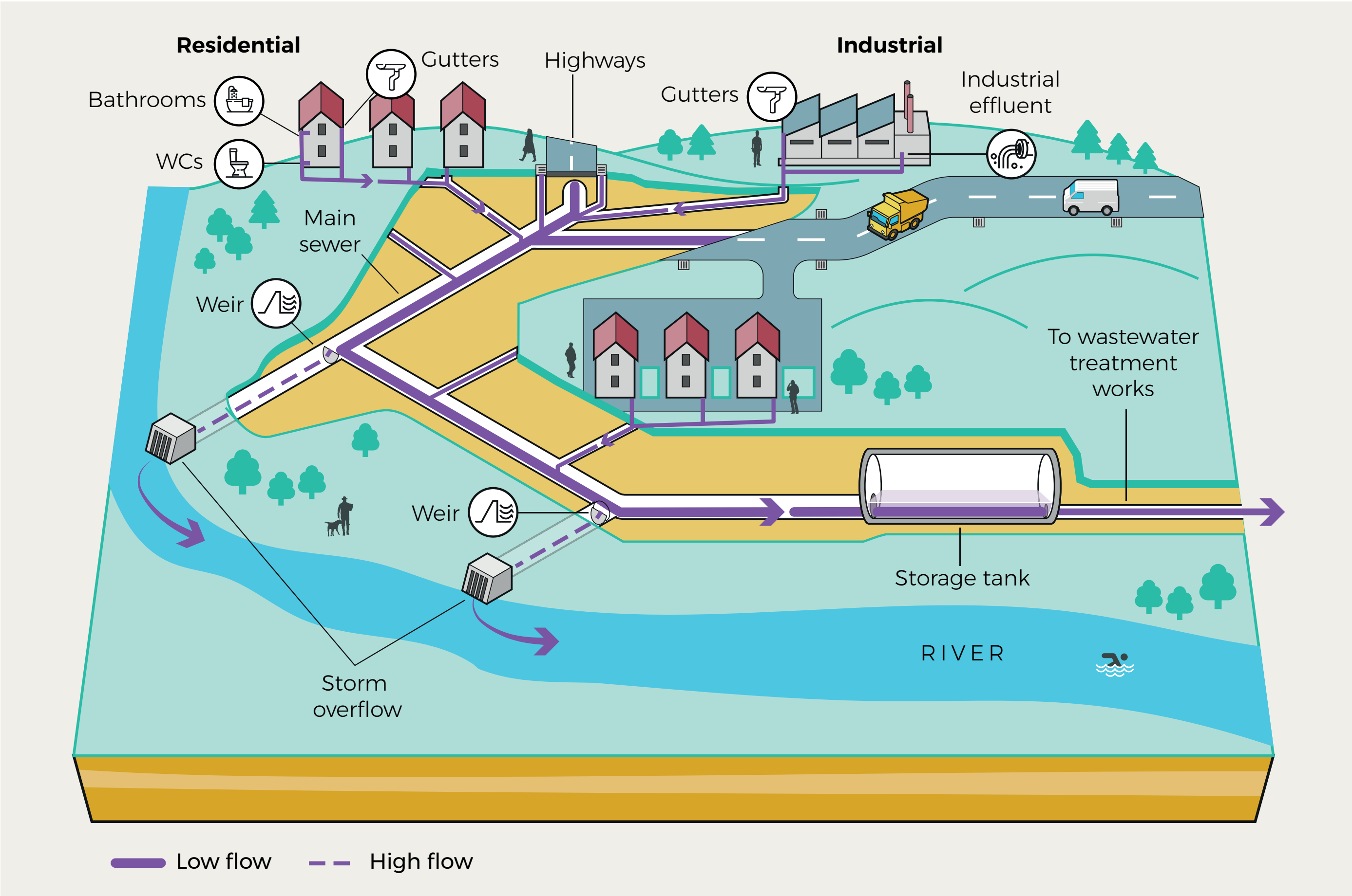
Our sewerage system's primary role is to remove human excreta and other domestic and industrial wastewaters from properties to protect public health. Sewers collect and convey wastewater to wastewater treatment works where pollutants are removed to protect water quality before the water is returned to a natural body of water.

In our homes, drains collect human waste as well as water from toilets, bathrooms, kitchens, laundry, and household cleaning, and these drains connect to larger sewers underneath our streets. Over 90% of the water we consume in our homes is discharged to the sewers. Sewers also collect wastewater from businesses and industry. During dry weather, the total amount of wastewater fluctuates substantially throughout the day, but in relatively predictable patterns. This is referred to as dry weather flow.

However, wastewater is not the only thing that our sewers are expected to collect. We collect rainfall from roofs to protect our buildings, and paved roads have drains to minimise surface flooding. Historically, and still for many properties in the UK, this 'surface run-off' is also directed into the same sewer – known as a combined sewer. The surface run-off carried in combined sewers is instrumental in removing blockages and keeping sewers operating – the design of combined sewers relies specifically on this cleaning action of rainwater.

Combined sewers need to be able to effectively transport variable flows of wastewater from the population they serve during dry weather, but also be able to handle variable surges of surface run-off during storms.[59] Larger sewer pipes have more capacity for surface run-off, but if the pipes are too big, flow during dry weather will be too slow, causing settlement of solids and blockages within the network, placing an upper limit on their size.

Today, new properties are built with separate sewers, one pipe system (surface water sewers) carrying surface runoff and the other sewage (foul sewers). In large new developments the foul sewers may be taken directly to a dedicated wastewater treatment works but in smaller developments, particularly in or adjacent to established urban areas, they are connected into older combined sewers. Surface water ideally is either discharged into a local body of water or stored, treated or infiltrated locally using sustainable drainage systems. However, in many established urban areas that is not feasible, and the surface water sewers are also ultimately connected to existing



■ **Figure 3 | A representation of the workings of a typical combined sewer system, where gravity-assisted flow collects water from buildings and surface run-off into main sewers. During heavy rainfall, high flows in the sewer will over-top weirs and excess wastewater will be discharged into nearby water bodies through storm overflows to prevent flooding and overwhelming the treatment works. Storage tanks can provide temporary storage during peak flows and capture the most polluted 'first flush' of stormwater**

combined sewers. So, much of our surface water and wastewater still passes through combined sewers at some point.

The size limit for sewers means that under very heavy rainfall surface run-off can quickly exceed the capacity of the pipes – storm flows can be many times greater than dry weather flow. Without emergency relief routes, overburdened sewers under pressure from surface run-off would back up into homes and cause flooding along the network. These relief routes are called storm overflows. There are approximately 20,000 storm overflows in the UK (including storm tank overflows and emergency overflows).[60]

Storm overflows are designed to pass forward flows up to a permitted limit,[61] above which they will overflow and discharge excess into the adjacent body of water. Storm overflows help to stabilise the flow within the sewer, prevent the downstream wastewater treatment works from being overloaded and minimise surface flooding. Well-designed storm overflows retain most floating and large insoluble solids (for example, plastics, sanitary products), but their effectiveness in retaining dissolved pollutants and microorganisms is very limited.

Sewers typically take advantage of catchment geography and gravity to transport their contents towards central sewers and on to wastewater treatment works and, as a consequence, often follow the paths of rivers. Over long distances or in hilly terrain wastewater needs to be periodically pumped upwards closer to the surface so that

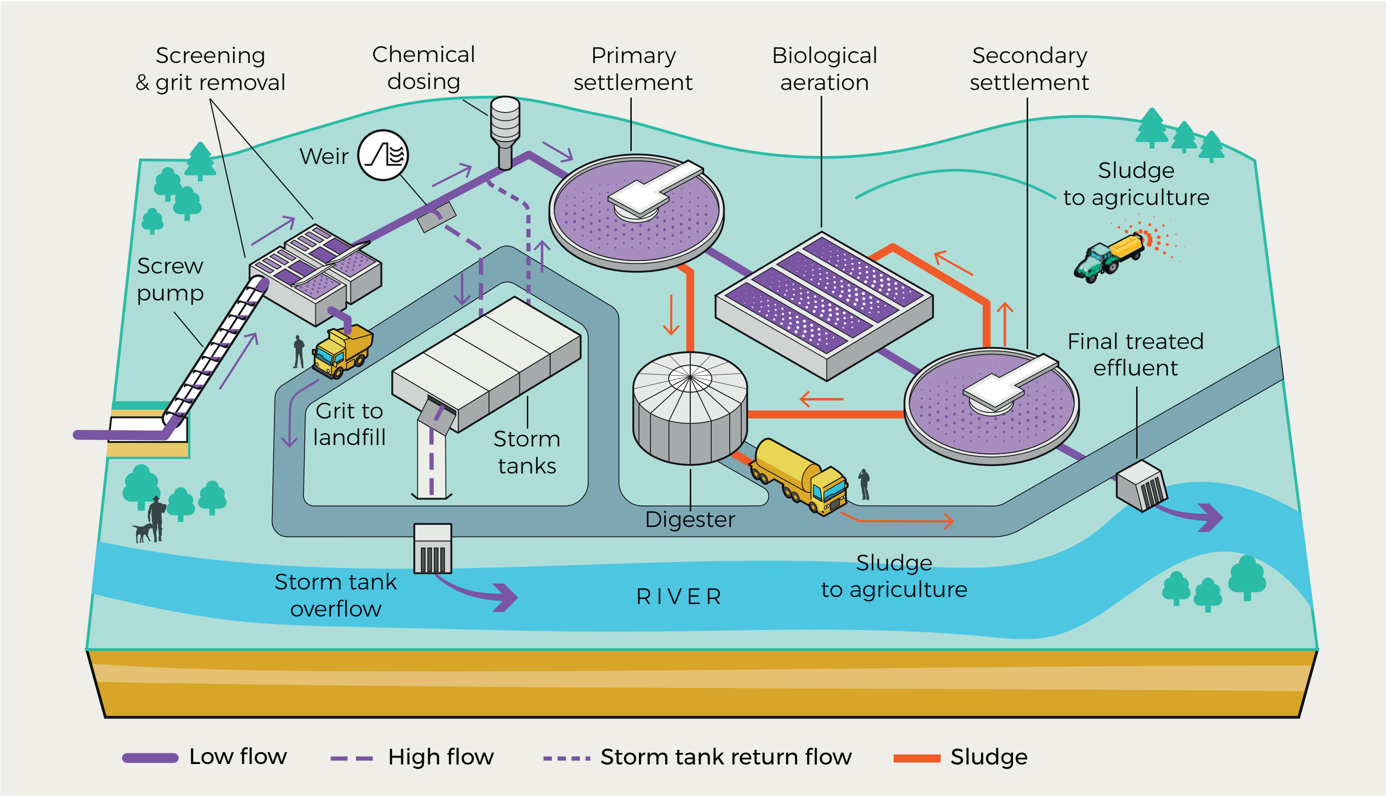


Figure 4 | A representation of the main stages of wastewater treatment commonly used in the UK, including screening and grit removal, primary settlement, biological aeration, and secondary settlement. Sewage sludge collected in settlement steps is digested and dried before it is used in agriculture. During heavy rainfall storm tanks capture high flows beyond the treatment works capacity for a duration of time determined by the size of the tank

gravity can continue to transport it along its path. These pumping stations have dedicated emergency overflows in case of pump failure or loss of power.

Through the combined action of gravity and pumps, wastewater is transported towards a central site where it can be treated – a wastewater treatment works. (Figure 3).

2.2 Sewage treatment

There are around 9,000 wastewater treatment works in the UK.[63] The size of the treatment works depends on the size of population it serves. Simplistically, wastewater treatment works are designed to accept up to three times the dry weather flow within their network for treatment – this is called the Flow to Full Treatment. If flows exceed this level, some treatment works, and also some pumping stations, have storm tanks into which excess flows, up to approximately six times the dry weather flow, can be diverted. If high flows persist, these storm tanks will overflow into the adjacent body of water, however the storm tanks provide some settlement of solids and delay to the overflow, which may also mean that the river flow has increased and can provide more dilution. Once sewer flows subside below Flow to Full Treatment, the contents of the storm tanks can be pumped back to the treatment works for full treatment. Extra storage may be provided if the available dilution in the receiving water body is limited. Treatment works without storm tanks will overflow excess flows directly into the adjacent body of water.

The treatment processes that are deployed depend on the size of the works as well as factors such as the contents of the wastewater, the sensitivities of the catchment that treated effluent is discharged into, and how that catchment is used. However, the base technology is broadly the same, with a primary step where larger solids are settled out

of suspension and a secondary step of biological treatment where microorganisms are grown and used to remove a fraction of the remaining organic material from the wastewater. Wastewater treatment steps include:

1 **Screening and grit removal** – designed to remove rags, grit, and plastic waste. This waste stream is sent to landfill.

2 **Primary settlement** – larger suspended solids and organic material are settled out of the wastewater and are collected and sent for sludge digestion.

3 **Biological treatment** – cultures of microorganisms are used to the biodegrade remaining organic material and nutrients. In smaller sites, trickling filters are used where the microorganisms live on fixed media, whereas in large sites large, aerated tanks with suspended microorganism cultures are used in an activated sludge process.

4 **Secondary settlement** – settlement of any remaining suspended solids and microorganism culture. In activated sludge processes, this sludge is returned to the biological treatment step to maintain the active microorganism culture, with excess sent for sludge digestion.

5 **Sludge digestion** – The sludge collected in primary and secondary settlement is typically thickened, sent to an anaerobic digester, producing methane, which is used as for power generation, and the sludge is then dried. Most of the final biosolids are used in agriculture as a soil conditioner.

Following secondary settlement, effluent is typically directly discharged into rivers or the sea. However, further treatment steps such as nutrient removal are required where the treatment works are located near sensitive areas.[64] Designated bathing waters are an example of one such sensitive area.

Treatment stage	Base flow conditions (eg dry weather)		High flow conditions (eg following storms)	
	Total coliforms (CFU/100ml)	Reduction against untreated (%)	Total coliforms (CFU/100ml)	Reduction (%)
Untreated	$3.9x10^7$	n/a	$8.2x10^6$	n/a **
Primary settlement	$3.8x10^7$	2%	$2.2x10^7$	n/a ***
Secondary treatment (activated sludge)	$7.8x10^5$	98%	$1.4x10^6$	89%
Secondary treatment (trickling filter)	$1.4x10^6$	95%	$1.4x10^6$	88%

Table 2 | Concentrations of total coliforms (a type of faecal organism, colony forming units per 100ml water) at different stages of wastewater treatment processes under base-flow (dry weather) and high-flow (wet weather) conditions, and indicative reductions between steps. Data taken from Kay et al. (2008).45). *A reduction of total coliforms of 70–80% is seen between base-flow and high-flow conditions in untreated sewage representing the dilution by storm water. **Not enough data was available for this comparison with significant variance seen under high-flow conditions

For treatment works serving population equivalents of more than 2,000 (inland) or 10,000 (coastal), the principal compliance limit is a 70–90% overall reduction in biochemical oxygen demand – the amount of oxygen used by microorganisms to break down organic material (which would otherwise be stripped from natural waterbodies).

Secondary treatment is not specifically designed to remove faecal organisms. While a significant reduction of faecal organisms does occur as wastewater passes through the treatment works, high concentrations of faecal organisms are still found in secondary treated effluents.[65] Table 2 shows how the faecal organism concentration of changes as wastewater passes through primary and secondary treatment stages in both base-flow (dry weather) and high-flow (wet weather) conditions. Viruses are also present in wastewater and small-scale studies have shown that similar reduction levels of norovirus concentration can be achieved after secondary treatment.[66]

Wastewater treatment works discharging into designated bathing waters may be required to provide a tertiary process of disinfection, such as ultraviolet treatment, to reduce the concentration of faecal organisms that reach the sensitive area. Similar restrictions are also placed on discharges to designated shellfish waters.

2.3 System governance

Policy oversight for management of the water and sewerage system is devolved across UK administrations. Governments set the policy framework, including the establishment of water quality or treatment standards and drafting of legislation. National legislation for water and sewerage services is set by the devolved administrations, and service providers can also be affected by legislation for issues including environmental standards, and flood and drought protection.

Dedicated regulators then set targets and grant permits for key areas of operation and governance. They monitor performance of water service providers to ensure compliance with standards and to ensure that water service providers properly carry out and finance their operations. Regulation of the water sector is a devolved matter, with different regulators in each devolved administration, and oversight is further split between economic regulators and environmental regulators. Economic regulators include: Ofwat (England and Wales), the Water Industry Commission for Scotland and the Northern Ireland Authority for Utility Regulation. Environmental regulators include: the Environment Agency (England), Natural England, Natural Resources Wales, the Scottish Environmental

Protection Agency, and the Northern Ireland Environment Agency. Separate regulators exist with responsibility for drinking water, which is beyond the scope of this report.

Most sewers, distribution pipes, and treatment works are owned by dedicated water service providers, either publicly owned in Scotland and Northern Ireland or privately owned in England and Wales. Wastewater assets are financed and maintained through private investment, public funding and consumer bills for services provided to households and commercial buildings. Service providers are responsible for ensuring proper maintenance of public sewers and treatment works to keep the infrastructure in working order. Where regulations require regular sampling and reporting against performance measures, in most cases water service providers will self-report and regulators will assess for compliance, only investigating cases of noncompliance.

Water service providers are also responsible for the removal of rainwater that falls on properties and drains into public sewers. Where there are drainage connections that serve individual private properties or connections are made across publicly owned land maintenance of drainage assets are the responsibility of the landowner, which can include private homeowners, local councils, and the highways authority.

Further information on water governance, including a discussion on key aspects of regulations for public health, is set out in Annex B.

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Chapter 3
Interventions

There are various leverage points in the system, upstream, downstream, and within sewerage and treatment works that affect public health risks. This chapter outlines the range of interventions that could be deployed across the wastewater system to reduce the public health risks for recreational water users. Policymakers and decision-makers need to consider how a portfolio of interventions could interact within the local context and where trade-offs or synergies exist with other policy priorities.

We have looked at interventions in four broad categories:

- **Water management**. These interventions seek to reduce the volume of water entering combined sewers to reduce the number of overflows and therefore the exposure to the hazard.
- **Wastewater treatment**. Improving the quality of pathogen removal to reduce the hazard of treated effluent or overflows.
- **Monitoring and communicating risk to the public**. Reducing exposure by providing better information to the public.
- **Maintenance and operations**. Improving performance of assets to reduce both the number of overflows and improve the quality of treatment.

In considering what interventions would impact public health, a risk-based framework was used (see Section 1.2). Only those interventions which either reduce the hazard (the concentration of human faecal organisms in open waters used for recreation, designated bathing waters or otherwise) or the exposure of people to that hazard (the use of these open waters), are considered. Furthermore, two sources of hazard are considered: overflows of raw sewage and the continuous discharge of treated effluent to highlight where each intervention could have an impact. These four factors, and how they interact, will be presented in this chapter as shown in Table 3.

Each identified intervention is presented in turn in the remainder of this chapter. For each intervention an explanation of the working principles is given alongside any key considerations and limitations for deployment.

In addition, to aid comparison of the different interventions, each has been given an indicative score against its effectiveness in reducing public health risks relative to current levels, the indicative associated capital costs (CapEx) for deployment UK-wide, and the indicative operational costs (OpEx) for its maintenance. UK-wide deployment is used for comparison, it is not suggested that any of these interventions should be applied everywhere. Specific costs on interventions at individual sites will vary. An overview of the scoring scales used is given in Table 4.

Risk component	Exposure	Hazard
Risk Source		
Overflows	Measures to reduce the number of spills or provide advanced warning	Measures to reduce the concentration of faecal organisms n sewage overflows
Effluent	Measures to provide public information on pathogen levels and public health risk	Measures to reduce the concentration of faecal organisms in treated effluent

Table 3 | Intervention routes to risk reduction. Intervention considered in this report target one of two sources of risk (overflows and treated effluent) by considering the two components of risk (exposure and hazard, see Section 1.2)

Reduction in risk	●○○○○ Low	●●○○○ Low – medium	●●●○○ Medium	●●●●○ Medium – high	●●●●● High
Capital expenditure	●○○○○ less than £100m	●●○○○ between £100m–1b	●●●○○ between £1–10b	●●●●○ between £10–100b	●●●●● more than £100b
Operational expenditure	●○○○○ less than £100k per year	●●○○○ between £100k–1m per year	●●●○○ between £1–10m per year	●●●●○ between £10–100m per year	●●●●● more than £100m per year

Table 4 | The scales used for scoring each intervention's effectiveness in reducing risk (relative to current levels), the scale of indicative capital expenditure for nationwide deployment (£) and the indicative operational expenditure required to maintain it
(£ per year)

Assumption	**Cost**		**Risk reduction**		
	CapEx	**OpEx**		**Hazard reduction**	**Exposure reduction**
The complete separation of all combined sewers	●●●●● *(high confidence)*	●●●○○ *(low confidence)*	Overflows	n/a	●●●●○ *(low confidence)*
			Treated effluent	n/a	n/a

Table 5 | An example of the scoring information given for each intervention. Any assumptions that sit behind the scores are listed. The scores for capital expenditure (CapEx), operational expenditure (OpEx), and risk reduction are given alongside confidence ratings and references to sources where available. Risk reduction scores are also shown relative to risk source and component as explained in Table 3

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These scores were based on a combination of reported values in the literature, where available, and expert opinion from our working group. Confidence ratings have been given to each score to reflect the availability of evidence behind the scores: *(high confidence)* denotes that scores are taken from published literature, *(med. confidence)* is used where scores are extrapolated from published literature, and *(low confidence)* is used where scores are obtained solely through expert evaluation.

Table 5 shows how the scoring information is presented for each intervention.

A summary of the capital expenditure and operational expenditure, and risk reduction scores of all the interventions considered in shown in Figure 5 and 6 respectively at the end of this chapter.

In selecting promising and resilient interventions, consideration must be given to the wider water system and the impacts that any one intervention would have across different policy priorities. The need for a systems approach to water management has long been recognised.[67] As such, we have attempted to situate public health interventions within the wider system, considering the trade-offs and co-benefits of each intervention with the policy priorities identified in Chapter 1, and this has informed our findings in the following chapter.

1 Sewer separation

Public Health Impact

Sewer separation would leave more capacity for stormwater in combined sewers, reducing or even eliminating overflows.

Sewer separation refers to reconfiguring an existing single-pipe combined sewer system into a two-pipe system of separate foul and surface water sewers. The separate foul sewers handle wastewater (from homes and businesses) and the surface sewers convey the stormwater run-off (from roofs, roads, and paved areas) separately. While the wastewater is conveyed to treatment works, the surface run-off is discharged into the environment.

Storm overflows would be eliminated, but the number of surface water outfalls would increase. The separated foul water would remain undiluted by surface run-off and its flow would be more predictable, improving the quality of treatment.

While many newer developments have separate sewers, they tend to connect to older, combined sewers further down the network. Retrofitting separate sewers can be achieved by constructing another foul sewer network alongside an existing combined sewer or by building a completely new two-pipe system to meet capacity requirements and connecting existing properties to the new system.

The separation of existing combined sewer systems is not common as it is costly, time-consuming, and causes extensive disruption in urban areas. While this solution may eliminate or reduce the need for storm overflows and their discharges of human faecal organisms, this is done at the expense of more surface water discharges to local watercourses, which will still contain faecal indicator organisms. In addition, illicit misconnections of foul water into the separate surface water sewer may, in time, nullify potential benefits.

Assumption	**Cost**		**Risk reduction**		
	CapEx	OpEx		Hazard reduction	Exposure reduction
The complete separation of all combined sewers	●●●●● *(high confidence)*[68]	●●●○○ *(low confidence)*	Overflows	n/a	●●●●○ *(low confidence)*
			Treated effluent	n/a	n/a

Policy priorities	**Interaction with intervention**
Resilience of water supply	
Reaching net zero	New systems will have high embodied carbon. However, reduced wastewater volumes would reduce demand for pumping and therefore reduce operational carbon.
Need to improve ecology	Broadly positive in the short term because of reduction of storm overflows, but less certain longer term because of risk of misconnections and contaminants in surface run-off, particularly from roads.
Need for development	New schemes assumed to have full sustainable drainage systems (SuDS) provision.
Mitigation of flooding	Could help reduce surface water flooding if scheme is designed for pollution and flood control purposes.

2 **Sustainable drainage**

Public Health Impact

Sustainable drainage systems (SuDS) divert surface run-off away from entering combined sewers, thereby reducing overflow frequency.

SuDS are typically surface-based features used to manage the flow of surface run-off by using and mimicking natural drainage processes.

SuDS can be used in combination with combined or separate sewers. SuDS aim to divert much of the surface run-off from entering the sewers, filtering it, and conveying it to watercourses or encouraging infiltration into the ground. They can also be used to temporarily store surface run-off before entering sewers so to reduce peak flows during storms. SuDS techniques can provide a range of services, and many provide a range of benefits, including:

- **Source control** – using green roofs to slow run-off, rainwater harvesting to store run-off, and permeable surfaces to temporarily store or infiltrate run-off at its source. Stored water can be reused or be slowly released into the sewer at a rate which the infrastructure can cope with.
- **Conveyance** – divert, slow, and filter surface run-off using vegetated channels and swales.
- **Filtration** – using vegetation, soil, and aggregates to capture and degrade pollutants within surface run-off. Technologies include filter drains, vegetated filter strips, and constructed wetlands.
- **Infiltration** – surface run-off can be encouraged to infiltrate into the soil and recharge groundwater using soakaways and shallow infiltration basins. Their suitability depends on the permeability of the soil and depth of the water table.
- **Detention** – surface run-off can be detained at a larger scale using detention basins and ponds, which also allow for some settlement.

Impact on flow varies across different interventions but some studies have shown that retention and exfiltration to soil can have a considerable impact to reduce overflows. Current best practice, especially in terms of water quality improvement, is for multiple components to be used in series, creating a 'SuDS train'. SuDS can be included in new housing areas or retrofitted into existing urban areas.

To substantially reduce storm overflows, widespread retrofit would be needed in urban areas to reduce the number and extent of impermeable surfaces. However, SuDS alone would not be able to achieve very substantial reductions in overflow frequency, and schemes that combine SuDS and storage are predicted to be more expensive than storage alone in the short term.

Assumption	**Cost**		**Risk reduction**		
	CapEx	**OpEx**		**Hazard reduction**	**Exposure reduction**
Preventing 50% of surface run-off from entering combined sewers with retrofitted SuDS. Storage tanks are still needed to achieve zero overflows.	●●●●● *(high confidence)*[68]	●●●●● *(high confidence)*[68]	Overflows	n/a	●●●●○ *(low confidence)*
			Treated effluent	n/a	n/a

Policy priorities	**Interaction with intervention**
Resilience of water supply	If rainwater harvesting is specified, this will generate extra non-potable water supplies.
Reaching net zero	There will be some embodied carbon, but relatively small. Reducing the volume of surface run-off entering sewers will reduce demand for pumping and therefore reduce operational carbon.
Need to improve ecology	Both run-off flow reductions and quality improvement contribute to this. SuDS provide habitat.
Need for development	Has multiple benefits within new developments, including amenity value. However, multiple stakeholders are typically involved which affects speed of delivery.
Mitigation of flooding	Will help manage surface water flood risk, including the risk of sewer system exceedance during extreme rainfall.[70]

3 Storage tanks

Public Health Impact

Stormwater storage tanks would capture peak flows to reduce overflow frequency.

Storage tanks are large structures that temporarily store excess volumes of wastewater from combined sewers rather than discharging directly into a body of water. They may be positioned at storm overflows, at pumping stations or at treatment works to store wastewater until peak flow has subsided and there is enough capacity to return it into the sewer system for treatment.

This requires that there is headroom in the sewer system for the wastewater to be returned. If multiple tanks are specified, more sewer and treatment capacity may be needed to cope with the stored wastewater. Typically placed underground, they require a large footprint and deep excavation making them expensive to build.

Pumping may be required to return the wastewater to the sewer, and tanks require cleansing after they are emptied, making them expensive to maintain. Storage tanks only provide limited treatment of the wastewater and without timely emptying the contents may turn septic.

Alternatively, storage may be provided 'online' through enlarged sewer pipes. It is difficult to achieve sufficient storage with online solutions, as in oversized pipes the reduced depth of the dry weather flow results in settlement of solids, causing blockages. This can be overcome by designing pipes with a smaller channel within the pipe to take the dry weather flow with the larger section only being used during storms. However, installing any large diameter pipe is expensive, particularly if it requires other than a circular profile.

Storage tanks are a well-established solution for reducing overflows, however, it is challenging to size them effectively to be able to cope with increasingly frequent and more intense storm events without their capacity being exceeded. Storage tanks do, however, capture the most polluted 'first flush' of surface run-off, but do not provide any treatment beyond solids settlement.

Storage tanks are not effective where overflows are caused by groundwater infiltration.

Assumption	**Cost**		**Risk reduction**		
	CapEx	**OpEx**		**Hazard reduction**	**Exposure reduction**
To provide sufficient storage to achieve zero overflows.[71] Storage tanks will prevent overflows until they reach capacity.	●●●●● *(high confidence)*[68]	●●●●○ *(high confidence)*[68]	Overflows	n/a	●●●○○ *(low confidence)*
			Treated effluent	n/a	n/a

Policy priorities	**Interaction with intervention**
Resilience of water supply	
Reaching net zero	These will typically be reinforced concrete structures with high embodied carbon. Storage tanks may need to be pumped to return wastewater to the network, increasing operational carbon.
Need to improve ecology	Positive, but limited given the relatively low impact of storm overflow discharges on rivers' good ecological status.
Need for development	No impact if new development has full surface drainage systems provision and separated sewers.
Mitigation of flooding	Will help reduce surface water flooding risk.[78]

4 **Water efficiency**

Public Health Impact

Widespread take up of water efficiency measures would reduce dry weather flows in combined sewers giving some reductions of overflows

Water saving technologies and engagement campaigns can help reduce the demand for water from households and businesses. This would then chiefly reduce the demand on our water resources but also reduce the volume of foul water that is discharged into our sewers. This would increase the headroom (to a limited extent) for surface run-off, and hence reduce storm overflow frequency and volume.

There are many different individual technologies including: metering and smart metering; retrofitting water saving products such as WCs and showers; water efficiency product labelling; the use of well-designed tariffs; education campaigns; standards for new homes; and net zero water developments. Grey-water reuse technologies and rainwater harvesting could also be more widely specified. Waterwise has developed a *UK Water Efficiency Strategy to 2030*[72] consisting of 10 key objectives which if achieved would deliver savings of at least 1,500 ML/d. but this requires large-scale roll out and the retrofitting of existing properties.

Influencing water use habits is challenging. Water use per capita is currently at 146 L per person per day without much change over recent years. The Environment Act 2021 set a legally binding target of reaching 122 L per person per day by 2038. Waterwise predict that if their strategy is implemented it would reduce consumption to about 124 L per person per day. Policy changes will be required to meet this, which may include water efficiency labelling, education campaigns, tariffs, and new standards.

Water efficiency measures will have limited impacts on overflows that occur during storms but will have a significant impact on overflows that occur during dry periods, whether due to groundwater infiltration or other reasons. Relieving some of the capacity in the network will improve resilience and concentrate waste for treatment.

Assumption	**Cost**		**Risk reduction**		
	CapEx	**OpEx**		**Hazard reduction**	**Exposure reduction**
For the national roll-out of smart water meters.	●●●○○ *(high confidence)*[73]	●●●○○ *(low confidence)*	Overflows	n/a	●○○○○ *(low confidence)*
			Treated effluent	n/a	n/a

Policy priorities	**Interaction with intervention**
Resilience of water supply	Primary function of water efficiency measures.
Reaching net zero	Lower water use is typically associated with lower energy use.
Need to improve ecology	May reduce demand on water reserves which support ecology.
Need for development	Limited water reserves are an acute pressure on development in the southeast. De facto installation of water efficiency technologies in new developments will help relieve this pressure.
Mitigation of flooding	May leave more capacity within sewer system for surface water drainage.

5 **Capacity for treatment**

Public Health Impact

More capacity for treatment will allow for more wastewater to be treated during high flows, reducing faecal organism concentration and reducing the volume of storm water overflowed.

Increasing capacity of the treatment works would allow them to accommodate more flow during storms, and extra capacity is required in many areas to support growing populations. Some treatment works already have the capacity to accommodate more flow within their design headroom, while other sites require upgrades to meet current or new permit conditions. This will only be effective where there is capacity in the sewer network to pass forward peak flows to the treatment works.

While extra capacity may not mean that all storm water can be treated, it will reduce the volume of overflows and it may allow for more of the most polluted 'first flush' of stormwater to be captured and treated.[74,75] Conventional treatment processes are not designed to remove faecal organisms so more capacity would not itself further reduce pathogen levels,[45] however, alongside maintenance, more capacity may be needed to ensure that some treatment works remain compliant.[76]

There are several strategies that can be used to increase the capacity of treatment works depending on local constraints, the most significant of these being the available space. Conventional treatment technology is cost effective but requires significant space, while some newer technologies occupy a smaller footprint, but are typically more expensive and have higher running costs.

While maintenance is critical in preserving the capacity of treatment works, parallel treatment trains, or extra treatment works may be needed to accommodate growing wastewater loads. Peak flow equivalent treatment provides a parallel treatment stream optimised for the treatment of stormwater.

Storm flows present a significant challenge given their sudden onset and significant variable volume as conventional treatment technologies depend on steady flows of wastewater. If storm flows were passed through conventional treatment sites, the large flows would interrupt the primary settlement of solids and reduce the time available for biological processes to treat them. Furthermore, high flows would interrupt the recovery of the biomass needed to support treatment causing 'wash-out' events, spiking pathogen contents, and significantly degrading treatment. Lower residence times of wastewater during higher flows also reduces the extent of microorganism die off.[45]

Equally, for redundant parallel treatment capacity it would be challenging to maintain enough healthy biomass for the effective treatment of high flows during periods of low flow.

Assumption	**Cost**		**Risk reduction**		
	CapEx	**OpEx**		**Hazard reduction**	**Exposure reduction**
	●●●○○ *(med. confidence)*[77]	●●●○○ *(med. confidence)*	Overflows	n/a	●●○○○ *(low confidence)*
			Treated effluent	n/a	n/a

Policy priorities	**Interaction with intervention**
Resilience of water supply	
Reaching net zero	High embodied carbon in concrete, extra pumping, and energy consumption of treatment steps.
Need to improve ecology	A reduction in overflows would alleviate nutrient pollution.
Need for development	More capacity will allow treatment works to remain compliant with population growth.
Mitigation of flooding	

6 **Effluent disinfection**

Public Health Impact

Disinfection of final treated effluent will significantly reduce the concentration of faecal organisms entering waterbodies.

Disinfection technologies are used to reduce pathogen loads in effluent following biological treatment in wastewater treatment works. As an extra process, all disinfection treatments will require more space and resources that may also require extra pumping of the wastewater through this process. There is a range of technologies using methods such as ionising radiation, chemical treatment, ultraviolet (UV) radiation, and ultrafiltration.

Ionising radiation:

- UV radiation is already widely used in the UK to treat effluents being discharged into bathing waters. Prefiltration of effluent to remove suspended solids and removal of biofilm from lamps is required for effective dosing. The dosing of UV systems must be carefully controlled to ensure standards are met.
- Electron irradiation is an established technology in medical sterilisation and scaling of this technology is being explored. There is potential for greater efficiencies and lower costs than UV.[78]

Chemical treatment:

- Chlorination is an effective and well-established technology for the treatment of drinking water, but it is likely to produce harmful byproducts when reacting with the organics present in treated sewage and river water which could cause ecological or further public health harms.
- Ozone is effective but requires significant assets and energy to both generate the ozone and destroy residual ozone before release to the atmosphere.
- Performic acid treatment is an emerging technique with low residual production but is yet to be proven at scale.[79]

Ultrafiltration:

- Membranes can completely exclude faecal organisms by providing an impermeable barrier. Membranes are complex to operate and require regular cleaning and regeneration, with high associated costs that scale with the required flow. Filtered faecal organisms will need to be separately destroyed.
- Slow sand filtration is a biological method that requires no chemical inputs. However, it requires a very large land area to treat significant flows.

Out of all these options, UV radiation is considered to be the most cost- and carbon-effective method despite high energy requirements to generate the UV.[80] However, the emergence of LED UV lamps may substantially reduce these requirements. There is some contradictory evidence on the effectiveness of UV, particularly against viruses, but it is widely considered to be highly effective at destroying bacteria.

Assumption	**Cost**		**Risk reduction**		
	CapEx	**OpEx**		**Hazard reduction**	**Exposure reduction**
All treatment works have UV disinfection applied all year round.	●●●○○ *(high confidence)*[80]	●●●●● *(high confidence)*[80]	Overflows	n/a	n/a
			Treated effluent	●●●●● *(high confidence)*	n/a

Policy priorities	**Interaction with intervention**
Resilience of water supply	
Reaching net zero	Significant power consumption and high embodied carbon.
Need to improve ecology	Extra filtration steps will help remove nutrients.
Need for development	Requires land for development.
Mitigation of flooding	Floodplains may need to be developed to locate expanded treatment.

7 Constructed wetlands

Public Health Impact

Wetlands as a final treatment step can significantly reduce numbers of faecal organisms in the final effluent.

Constructed wetlands use natural processes in soil, vegetation, and microbial communities to provide filtering and removal of residual nutrients and contaminants. They have been demonstrated to be effective at reducing pathogen loads and improving water quality.[81,82,83] Wetlands can be used alongside traditional treatment methods to improve the overall treatment efficiency.[84] There may be a risk for mosquito nuisance if wetlands are placed near settlements.

They are considered a sustainable and cost-effective treatment stage; however, they require significant land to treat a set volume of effluent[85] and are currently only employed at smaller, rural treatment sites. Their effectiveness is variable and influenced by many design factors, as well as by climate and levels of sunlight.[86] There is currently limited evidence on operational lifetimes and maintenance requirements.

Assumption	Cost		Risk reduction		
	CapEx	OpEx		Hazard reduction	Exposure reduction
Excluding the value of the land required.	●●○○ *(med. confidence)*[84]	●○○○ *(med. confidence)*[87]	Overflows	n/a	n/a
			Treated effluent	●●●○ *(high confidence)*[83]	n/a

Policy priorities	Interaction with intervention
Resilience of water supply	
Reaching net zero	Wetlands are a low carbon solution and healthy wetlands are net carbon sinks; however, unhealthy or disturbed wetlands are net carbon sources.[88] Further research is needed to understand the carbon implications of constructed wetlands.
Need to improve ecology	Provides habitat and nutrient removal, though studies are limited.[89] Under poor oxygen conditions, nutrients may be released into the environment.[90]
Need for development	Requires significant land for development but provides amenity.
Mitigation of flooding	If the wetland is designed to treat effluent only it will not attenuate surface run-off.

8 Overflow disinfection

Public Health Impact

Applying disinfection treatments to storm overflows will reduce the concentration of faecal organisms released during spills.

There are estimated to be around 20,000 overflows in the UK, including storm overflows, storm tank overflows and emergency overflows.[60] Disinfection of overflows would use similar technology to that at wastewater treatment works, namely technologies such as UV irradiation.[92] Disinfecting raw wastewater is challenging given its sudden volume changes and large flows during storm events and the high concentration of suspended solids within the wastewater. Pretreatment to remove these suspended solids to levels below <50 mg/L is essential for effective disinfection, which would include screening, grit removal, and filtration. Constructed wetlands may be suitable for the treatment of small overflows following screening.

To cope with significant flows during storm events, significant filter capacity and UV radiation dosing would be required. The filtered material would require further disinfection and disposal.

The number of sites and their locations will be demanding in terms of cost, land availability, providing power, and ensuring vehicular access for maintenance and removal of rags, grit, and solids.

Assumption	**Cost**		**Risk reduction**		
	CapEx	**OpEx**		**Hazard reduction**	**Exposure reduction**
Providing UV and pretreatment at all intermittent overflow sites.[93]	●●●●● *(high confidence)*[80]	●●●●● *(high confidence)*[80]	Overflows	●●●●● *(high confidence)*	n/a
			Treated effluent	n/a	n/a

Policy priorities	**Interaction with intervention**
Resilience of water supply	
Reaching net zero	Increased power consumption and high embedded carbon in concrete support structures.
Need to improve ecology	UV disinfection and prefiltration will reduce suspended solids and debris but will not remove dissolved nutrients.
Need for development	Requires a significant land footprint.
Mitigation of flooding	May require development of floodplains.

9 Water quality monitoring

Public Health Impact

Live information on river quality can support source tracking, enforcement, and provide localised warnings about exposure risk.

Monitoring river water quality helps to detect water pollution incidents and can then inform targeted risk communications to reduce exposure to pollution. Effluent quality monitoring can also support identification of new disease outbreaks as a further benefit. Monitoring can be targeted upstream and downstream of overflows and wastewater treatment works to understand the impact of discharges and to understand how pathogen concentrations vary once in the receiving water body.

Monitoring also supports the evaluation and improvement of water management strategies, including pollution prevention, regulation, and enforcement as well as maintenance diagnosis and optimisation opportunities. Flow measurements will also be important to ensure that water quality can be accurately represented.

Different methods and technologies are used to collect and analyse water quality data, such as sampling, sensors, and models. Sensors are readily available for many physiochemical properties such as temperature, pH, conductivity, and dissolved oxygen, and the data for these parameters can be collected in real time.[94]

Real-time data can enable automatic and continuous monitoring of water quality, without the need for human operations and analysis, which can reduce the workload and errors associated with sampling and laboratory-based analyses and provide quicker alerts of pollution incidents. However, selecting the correct parameters and instruments is critically important for robust and reliable real-time monitoring.

There are fewer options for monitoring microbiological pollution, with the techniques currently used requiring sample collection and laboratory analysis to monitor a selection of indicator organisms. Real-time measurement of microbiological pollution is still in its infancy. A less explored option for monitoring microbiological quality is the use of remote sensing and machine learning methods to integrate multisource information (for example, microbial sampling and continuous physiochemical water quality monitoring) to indirectly predict microbiological quality.

Development of fast, accurate, and automated microbial sensing techniques is needed, as well as a better understanding of pathogen behaviour and how pathogen count relates to risk.

Data sharing, standards, and platforms to integrate multiple sources of information will be needed to support monitoring programmes and may help with customer engagement. The impact of monitoring programmes will also depend on an effective system for communicating pollution alerts to the public.

Assumption	**Cost**		**Risk reduction**		
	CapEx	**OpEx**		**Hazard reduction**	**Exposure reduction**
Methods used will impact costs, average cost for individual sensors to be deployed at all storm overflows has been considered.	●○○○○ *(low confidence)*	●●●○○ *(low confidence)*	Overflows	n/a	●●○○○ *(low confidence)*
			Treated effluent	n/a	●●○○○ *(low confidence)*

Policy priorities	**Interaction with intervention**
Resilience of water supply	
Reaching net zero	May have an impact on operational costs and associated emissions, for example, increasing assets to be inspected and maintained and increased computer power needed for incoming measurements.
Need to improve ecology	Can inform on wider water quality and potentially support targeted intervention but does not prevent pollution.
Need for development	
Mitigation of flooding	

10 **Pollution forecasting**

Public Health Impact

Providing advanced warning of possible pollution incidents so that public users are informed, potentially reducing frequency of exposure.

By combining integrated river catchment models, including models of wastewater assets, with weather forecasts, the impact of rainfall on local wastewater systems can be predicted and pollution loads estimated. With weather forecasts as an input, pollution forecasts would depend on several factors and data sources:

1. storm severity – volume of water entering the sewer over a given time period
2. timing of the storm – differences between storms occurring during prolonged wet or dry periods
3. flow of receiving rivers – higher flows can offer increased dilution and reduce pathogen concentrations
4. proximity of bathing waters to discharges
5. population of conurbation – larger catchments pose more run-off as well as sewage
6. overflows – presence of overflows and their historical frequency of discharges.

With these forecasts, pollution risk could be quantified, an assessment of risk can be made, and advanced warning can be provided.

A successful forecast model will require good input data (i.e., measured data or modelled values) and monitoring in the downstream position to calibrate the model. Risk forecasts will be underpinned by our understanding of the fate of faecal organisms in the environment and acceptable exposure levels.

Forecasts are most desirable where there is a likelihood of bathing or of exposure, however, during hot summer months, it can be argued that much of the country's rivers could be informal bathing waters and, as such, a national map would be ideal. If costs are still prohibitive, there can be lower confidence about the forecast in areas not designated for bathing, while the remainder of the rivers are forecast primarily through modelled data.

There are several questions that would need to be answered in designing pollution forecasts, and it may be helpful to consult users on what information and features they would find most useful:

- What threshold of risk is used?
- What is the appetite for the information and at what level?
- How can it be most effective at reducing exposure risk?
- What is the acceptability of pollution levels year-round?
- Where should forecasts be produced for?
- What is seen publicly as an acceptable level of risk?
- How will the tool be used?
- What expectations are there for forecast accuracy?
- How far in advance should forecasts be produced?
- How are forecasts communicated?

Models would be enabled by water quality monitoring and the digitisation of assets. Data quality can affect the reliability and adaptability of models. Machine learning methods may be of use.

Assumption	**Cost**		**Risk reduction**		
	CapEx	**OpEx**		**Hazard reduction**	**Exposure reduction**
	●○○○○ *(low confidence)*	●●○○○ *(low confidence)*	Overflows	n/a	●●○○○ *(low confidence)*
			Treated effluent	n/a	●●○○○ *(low confidence)*

Policy priorities	**Interaction with intervention**
Resilience of water supply	
Reaching net zero	
Need to improve ecology	Could help identify priority areas for other mitigations.
Need for development	
Mitigation of flooding	

11 Engagement and risk communication

Public Health Impact

Targeted communication can reduce frequency of exposure by encouraging risk-aware behaviours around bathing.

Providing trusted information and advice to the public about where it is safe to bathe, what actions they can take to minimise their exposure, and warnings about pollution incidents can all reduce exposure risk. Populations entering water bodies during periods when overflows are operating and in areas where treated effluent is discharged are at most risk from direct exposure to faecal organisms.

Further to reducing physical health risks, encouraging the safe use of blue spaces can support the mental health and wellbeing benefits that growing numbers of people in the UK are discovering and highly valuing.[95]

Research shows that public health communications are best presented through message mapping, with specific and clear messages against different subgoals.[96] Table 6 summarises a proposed approach based on the message mapping strategy:

Intervention topic	Specific message example
Reducing short-term illness from **direct exposure** to faecal organisms.	During periods of high rainfall, consider not swimming downstream of wastewater treatment works and storm overflow locations.
Long-term illness and reduced productivity and wellbeing because of **prolonged exposure** to a range of pollutants.	Interacting safely with the local environment (e.g. taking precautions and reporting water pollution events) can support the wellbeing of yourself and others.
Environmental improvements through reducing strain on the wastewater system via behavioural change at the household level.	Reducing water use and unsuitable system inputs from the home (e.g. wet wipes) will support environmental health.

Table 6 | Proposed approach to reduce public exposure to health risks

Communications should be targeted and tailored to local contexts and groups to increase engagement and ultimately the success of these outputs.[97]

There is a risk of low adherence if the messaging itself is inconsistent or unclear. However, even with clear messaging, the perception of the credibility of the source, issuer, and channels used remains an obstacle. Currently, there exists low public trust in the water sector which should be considered a major factor in how communications are packaged and delivered.

This intervention is ultimately limited by the extent to which people are willing to change their behaviour pay attention to messaging, so the resulting health risk reduction cannot be guaranteed.

Assumption	Cost		Risk reduction		
	CapEx	OpEx		Hazard reduction	Exposure reduction
Precise cost estimates depend on scale of the campaign and delivery methods.	●○○○○ *(low confidence)*	●●○○○ *(low confidence)*	Overflows	n/a	●●●○○ *(low confidence)*
			Treated effluent	n/a	●●●○○ *(low confidence)*

Policy priorities	Interaction with intervention
Resilience of water supply	Engagement on water consumption will be needed to meet targets.
Reaching net zero	
Need to improve ecology	Engagement on reducing illicit inputs to sewers would reduce pollution burden of overflows.
Need for development	
Mitigation of flooding	

12 Addressing misconnections

Public Health Impact

In areas with separate sewers, ensuring building connections join the right flow into the right pipe will prevent both foul water bypassing treatment works and extra flow of surface water increasing pressure at pumping stations and treatment works, ultimately reducing overflows.

The flows in separate foul wastewater and storm water sewers have over time become compromised because of (illegal) misconnections by third parties – that is, direct discharges of foul wastewater to surface water sewers and surface water discharges into foul sewers.

An estimated 0.5% of domestic properties across the UK have sewer misconnections, which equates to approx. 128,000 properties. Finding misconnections can be difficult and has been estimated to cost £190 million, with extra costs for rectifying them.[98] Additionally, resolving the misconnection requires several parties where misconnections in pipes are not owned by water service providers with costs for ratification assumed to be taken on by the home or landowners who may be discontent.

Assumption	Cost		Risk reduction		
	CapEx	OpEx		Hazard reduction	Exposure reduction
	●●○○○ *(med. confidence)*[112]	●○○○○ *(low confidence)*	Overflows	n/a	●●○○○ *(low confidence)*
			Treated effluent	n/a	n/a

Policy priorities	Interaction with intervention
Resilience of water supply	
Reaching net zero	Removing surface water misconnections from foul sewers could reduce demand on pumping and treatment facilities and the associated operational emissions.
Need to improve ecology	Removing surface water misconnections from foul sewers will reduce direct contamination sources.
Need for development	No direct impact, but regulations for connections to sewers need to be monitored and enforced. .
Mitigation of flooding	Removing surface water misconnections from foul sewers will reduce pumping and treatment costs.

13 **Resolution of blockages**

Public Health Impact

Preventing and removing blockages in sewers reduces loss of capacity in combined sewers which minimises the frequency of overflows.

There are approximately 300,000 sewer blockages every year which cost water service providers £100 million to remove.[99] Regular cleaning of the sewer network and the enhancement of monitoring and control systems at a network-wide scale is needed. Some water service providers are trialling sewer level sensors to monitor flow levels. If levels rise unexpectedly, it could indicate a potential blockage forming, raising an alert for the site to be promptly investigated and cleared. Real-time monitoring and control is discussed further below.

Identifying and reporting blockages to be cleared and ensuring that all debris is properly cleared will support greater capacity in sewers and reduce premature overflows duration and frequency. More support from regulation and trade consents are needed for the effective prevention of blockages. The main sources of blockages include fats, oils, and grease (FOG) and wet wipes, though these are not the only 'un-flushable' products often found in sewers. However, FOG is predominantly introduced into the network by third party traders and source tracking is therefore difficult and the manufacture of wet wipes is not currently regulated.[100,101]

Blockage reduction can be supported through public engagement and education activities to limit unsuitable materials entering the sewers. This will require collaboration across stakeholders.

Assumption	**Cost**		**Risk reduction**		
	CapEx	**OpEx**		**Hazard reduction**	**Exposure reduction**
	●●○○○ *(low confidence)*	●●●●○ *(med. confidence)*[99]	Overflows	n/a	●●○○○ *(low confidence)*
			Treated effluent	n/a	n/a

Policy priorities	**Interaction with intervention**
Resilience of water supply	
Reaching net zero	Improved efficiency in the sewer system could reduce demands on treatment works and associated operational emissions. Additionally, fewer vehicles travelling to blockage sites would be needed.
Need to improve ecology	Prevention of build-up of FOGs and nonbiodegradable solids will reduce direct discharges into the environment that can be harmful to local wildlife and habitats.
Need for development	
Mitigation of flooding	Improved efficiency in the sewer system could reduce need for overflows and prevent wastewater backing up into properties.

14 Addressing sewer infiltration

Public Health Impact

Preventing extra ground and surface water entering the sewerage system reduces combined sewer flows.

Most catchments have some infiltration, however a lot of the reported ‘dry weather overflows’ at storm overflows are due to groundwater infiltration and some catchments are particularly sensitive. Defects that give rise to infiltration include cracks/fractures, pipe joint displacement due to ground movement, root intrusion, deformation of flexible pipes, poorly constructed connections, and poorly sealed manholes on both the privately and publicly owned drains and sewers. These require prompt identification and repair.

The main source of the infiltration can be difficult to identify as CCTV inspection is needed and has to be undertaken when the water table is high and so it can be difficult to survey the sewers when they are full of water. Also, the infiltration often consists of multiple small sources throughout the network.

Options include refurbishment with sewer linings or, where necessary, replacing sewers with infiltration problems and removing basement connections. Re-lining or replacing sewers and manholes is expensive and disruptive but is often the only realistic course of action. It has been suggested that the water service providers only own and have access to approximately 30% of the pipes where infiltration is occurring. In private drains, they have no right to access to monitor or repair. The efforts and costs to reduce infiltration can therefore have limited impact if there are sources of infiltration beyond the assets owned by water service providers.

Catchments with high levels of groundwater infiltration can be very difficult to resolve with no guarantees of success despite high expenditure.[68] Techniques are being developed that can identify the sources of infiltration and it is likely that progress can be made in this respect.

Assumption	**Cost**		**Risk reduction**		
	CapEx	**OpEx**		**Hazard reduction**	**Exposure reduction**
Rehabilitation of national sewer infrastructure.	●●●●● *(med. confidence)*[102]	●●●○○ *(low confidence)*	Overflows	n/a	●●○○○ *(low confidence)*
			Treated effluent	n/a	n/a

Policy priorities	**Interaction with intervention**
Resilience of water supply	
Reaching net zero	Reducing infiltration could reduce operation costs and carbon costs as there will be less flow to pump and treat. However, the solutions often have high embodied carbon costs..
Need to improve ecology	Reduces need for discharges at storm overflows, however in catchments with very high infiltration the discharges tend to be very dilute.
Need for development	No direct impact but if new developments are proposed in areas where the groundwater levels could be high, then construction and product standards should be improved to ensure that the new sewerage networks do not add to the problems.
Mitigation of flooding	If the groundwater does not drain into the sewer, then there is a danger that it will find its way into properties or cause highway flooding.

15 **Maintenance in treatment works**

Public Health Impact

Ensuring that treatment works are operating reliably and at higher efficiency by conducting regular maintenance and supporting predictive maintenance where possible would reduce discharges of untreated sewage.

Regular maintenance is necessary to ensure wastewater treatment works are operating at best performance levels. Preventative maintenance involves routinely inspecting, cleaning, and servicing equipment, such as pumps and motors. The introduction of real-time monitoring and modelling tools could also support predictive maintenance.

Improved maintenance of wastewater treatment works would help prevent overflows of untreated sewage by ensuring all assets are working so that the treatment works can operate at full capacity. It would also help maintain treatment levels within the wastewater treatment works.

Assumption	**Cost**		**Risk reduction**		
	CapEx	**OpEx**		**Hazard reduction**	**Exposure reduction**
	●●○○○ *(low confidence)*	●●●●○ *(low confidence)*	Overflows	n/a	●●○○○ *(low confidence)*
			Treated effluent	n/a	n/a

Policy priorities	**Interaction with intervention**
Resilience of water supply	
Reaching net zero	Efficient maintenance can extend the life of assets and minimise extra demand on systems reducing overall energy use.
Need to improve ecology	Operating treatment works at high efficiency and reliability would reduce reliance on overflows.
Need for development	
Mitigation of flooding	Operating treatment works at high efficiency and reliability would reduce reliance on overflows.

16 Automation and digitisation

Public Health Impact

Widespread adoption of automation and digitisation would help more accurate and timely interventions and alerts to be made to reduce both hazard and exposure.

Digital technologies have proven effective in improving utilities' operations by providing information when and where it is needed, leading to a more sustainable urban water cycle. Often this means real-time information that allows utility to behave proactively rather than reactively. In practice, automation and digital transformation require extensive deployment of sensors; advanced information and communication technology infrastructure; and automated system control with smart actuators.

One application of the resulting real-time control is for the coordination of storage assets at pumping stations to manage and buffer high flows during storms.[103]

Other technologies for the wastewater system include:

- Smart pumps and valves
- Device failure detection
- Automated controls
- Sensors for water quality monitoring
- Infiltration detection
- Blockage detection

Throughout the water utility sector, uptake of digital technologies is still quite slow, currently resulting in relatively low sensor coverage and data availability in most water infrastructure when compared to electricity, traffic, or telecommunication systems. The available technologies are also diverse and often require partnerships among sensor, communication, and data analytics providers.[104]

The implementation of new technologies seldom involves all operational aspects of a utility and is limited to piloting of single technologies. Cost–benefit analysis for the deployment of the technologies is in its infancy and requires better articulation of impacts. There is, however, a lot of scepticism within the industry about the level of digitalisation and automation that can be achieved.

Assumption	**Cost**		**Risk reduction**		
	CapEx	**OpEx**		**Hazard reduction**	**Exposure reduction**
Different tools have different costs.	●●●●○ *(med. confidence)*[105,106]	●●○○○ *(low confidence)*	Overflows	n/a	●●●○○ *(low confidence)*
			Treated effluent	n/a	n/a

Policy priorities	**Interaction with intervention**
Resilience of water supply	
Reaching net zero	Optimisation may reduce overall energy requirements, despite sensor and computational power demand.
Need to improve ecology	Fewer overflows would reduce pollution.
Need for development	
Mitigation of flooding	Optimising sewer capacity may help relieve flooding.

Selection of interventions

These interventions were collectively assessed in a workshop where participants were asked to collaborate to build portfolios of interventions against two scenarios: the greatest reduction in public health risks in the shortest time frame and the greatest reduction in public health risks in the long term with resilience in mind. These scenarios allowed a focus on both reducing public health risks and the other policy priorities and challenges faced by the water sector.

Some interventions, such as overflow disinfection, were deprioritised because of their potential to cause ecological damage and significant carbon cost. Other measures, such as water efficiency, were recognised to be highly beneficial for security of water supply but limited in their benefits for reducing public health risks.

Some interventions, such as sustainable drainage systems and capacity for treatment were recognised as long-term goals but challenging in the short term, while other measures such as storage tanks and effluent disinfection were recognised as having the ability to have short-term impact on reducing public health risks but are not necessarily sustainable as long-term solutions.

Participants were also asked to discuss enablers for change, and how these interventions might be incorporated within ongoing initiatives.

In reviewing the portfolios built across different groups, clear consensus was found for the priority interventions. In the following chapter, we outline those groups of interventions and propose actions for reducing public health risks in the short term, long term, and the enabling actions that underpin them.

Capital expenditure \ Relative risk reduction	Low	Low - medium	Medium	Medium - high	High
High		14	3	1, 2	8
Medium - high			16		
Medium	4	5		7	6
Low - Medium		12, 13, 15			
Low		9, 10	11		

Water management
1. Sewer separation
2. Sustainable drainage
3. Storage tanks
4. Water efficiency

Wastewater treatment
5. Capacity for treatment
6. Effluent disinfection
7. Constructed wetlands
8. Overflow disinfection

Monitoring and engagement
9. Water quality monitoring
10. Pollution forecasting
11. Risk communication

Maintenance and operations
12. Addressing misconnections
13. Resolution of blockages
14. Addressing sewer infiltration
15. Treatment works maintenance
16. Automation and digitisation

Figure 5 | shows a summary of the relative risk reduction effectiveness and indicative capital expenditure scores of all the interventions considered

Operational expenditure estimate for UK deployment	Low	Low - medium	Medium	Medium - high	High
High				2	8, 6
Medium - high		13, 15	3		
Medium	4	5, 9, 14		1	
Low - Medium		10	11, 16	7	
Low		12			
	Relative risk reduction				

Water management
1. Sewer separation
2. Sustainable drainage
3. Storage tanks
4. Water efficiency

Wastewater treatment
5. Capacity for treatment
6. Effluent disinfection
7. Constructed wetlands
8. Overflow disinfection

Monitoring and engagement
9. Water quality monitoring
10. Pollution forecasting
11. Risk communication

Maintenance and operations
12. Addressing misconnections
13. Resolution of blockages
14. Addressing sewer infiltration
15. Treatment works maintenance
16. Automation and digitisation

Figure 6 | shows a summary of the relative risk reduction and indicative operational expenditure scores of all the interventions considered

Chapter 4
Priorities for public health

To effectively address the public health risks for recreational users requires interventions to be introduced across the wastewater system, reducing the hazard, exposure, and vulnerability. For these interventions to have longevity they must also meet the needs of other policy priorities, including flood mitigation, water supply resilience, net zero, ecological recovery, the need for development, and affordability. The applicability of these interventions in different environments will depend on local needs and conditions. For example, local population size and urban developments, proximity to overflows or treatment works, land availability, or local geology, will impact how effective interventions can be. As such solutions for the wastewater system will likely need a portfolio of interventions, as outlined in Chapter 3, rather than one specific intervention at each site and catchment to try to maximise co-benefits where possible.

Through workshops with engineers, wastewater experts, water service providers, campaign organisations, and policymakers as well as reviewing published evidence, we have made risk-based assessments of the suitability of interventions for reducing public health risks. Our collaborative approach identified the need to take a risk-based approach to the deployment of interventions and to target those actions at those sites where public health risks are greatest.

This chapter outlines priority interventions that were identified in the workshop that would be needed at a national scale to reduce the public health risks for recreational water users in the UK. This chapter then sets out recommendations for policymakers and decisions makers to consider in planning for system improvements. These priority actions are categorised as:

- **Short-term actions**: those actions that can be done to mitigate public health risks in the shortest time while contributing to other policy priorities.
- **Opportunities for long-term transformation**: the interventions that can allow us to build a resilient wastewater system that protects public health.
- **Enablers**: actions that provide the foundation for the design and delivery of interventions.

4.1 Immediate actions to reduce the public health risks

Maintenance and rehabilitation

Blockages within sewers, pump failures, and equipment failures at treatment works are known to be major causes of overflows at storm overflows, emergency overflows, and storm tank overflows. Maintenance and rehabilitation of our existing infrastructure, namely sewers, pumping stations, or treatment works, can significantly resolve some of the causes of overflows.[107]

Wet wipes are recognised as the single biggest factor in sewer blockages which restrict existing sewerage capacity.[108] Reducing the input of nonbiodegradable material into the sewers, including fats, oils, and grease, nonbiodegradable items and wet wipes, is the most cost-effective way to reduce blockages.[109] This will be supported by new plans to ban wet wipes across the UK and may benefit from continuing a public campaign to reduce the flushing of other nonbiodegradable materials.[110] This should be accompanied by maintenance to remove imperfections that nonbiodegradable materials can snag on, causing blockages.

Other concerns for infrastructure failures that can restrict capacity include local infiltration of groundwater (for example, where a root intrusion breaks pipes) or misconnections of separate systems incorrectly depositing water into sewers. Addressing these multiple challenges together is important. This can be achieved through greater resource allocation to maintenance or better targeting informed by data.

Recommendation 1: Water service providers should further prioritise maintenance and rehabilitation of assets, informed by regulatory frameworks that require the demonstration of asset resilience including the reduction in sewer infiltration, and supported by enforcement measures.

Monitoring and forecasting

Water quality monitoring and modelling is essential for understanding public health risks and providing warnings to reduce public exposure to pollution. Monitoring can also allow for sources of pollution to be identified and will support the prioritisation of targeted interventions to address the greatest sources of risk.

While the roll-out of event duration monitoring has improved visibility of pollution events, and the Environment Act (2021) has introduced a duty for water service providers to monitor water quality upstream and downstream of wastewater discharges, this only covers environmental quality indicators. Event duration monitors only record the frequency and duration of overflows, not their volume, and emergency overflows and storm tank overflows are not currently monitored.[111]

The current monitoring regime at designated bathing waters is not sufficient to capture substantial same-day variation in faecal organisms, nor does it provide a reliable indication of the presence of viruses. More intensive sampling is needed in designated bathing waters and monitoring should be considered for other popular bathing sites. Improved sensors need to be developed for near-real-time monitoring of water quality.

It will be important to ensure that regulators have the resources to carry out surveillance at scale over time. New data streams on water quality should be made publicly available and shared transparently so that they can be used to support improved forecasting models.

Pollution forecasts built on water quality data, weather monitoring and understanding of asset behaviour can be used to predict pollution events and provide advanced warning and real-time information to the public to reduce public exposure, such as with the Safeswim service in New Zealand.[112] More research is needed to improve understanding of the impact of overflows and discharges on water quality and to develop modelling capabilities.

Recommendation 2: Department for Environment, Food & Rural Affairs (Defra) should revise targets to accelerate the roll-out of Continuous Water Quality Monitoring in England and extend the scope so environmental regulators monitor the microbiological quality of treated effluent. This includes accelerating the public availability of near-live data to inform improved pollution forecasting and provide clear public communications to reduce the public's exposure to poor water quality. Comparable data should be made available across the UK.

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Bathing standards

There are over 600 designated bathing sites in the UK; with 26 in Northern Ireland, 80 in Scotland, 109 in Wales, and 424 in England, the vast majority of which are coastal. There is limited evidence for the applicability of current bathing water standards to freshwater environments and outside of the bathing season, or for the suitability of current proxy indicators indicating the presence of viruses. An improved evidence base is needed to better understand the impact of faecal pollution on water quality and the public health risks posed to ascertain whether current indicators and classification methodologies are sufficient or need updating. With changes in bathing habits and demand, standards need to be proportionate to the risk and reduce it to an acceptable level.

Rivers and coastal environments will experience different rates of microbial die off. High quality research and methods are needed to develop an evidence base for the use of alternative indicator organisms.

Recommendation 3: Defra should initiate a review of the designation and protection of bathing waters, working with academic experts, regulators and devolved administrations to develop agreed methods to better quantify microbiological water quality, and ensure the standards that are applied are proportionate to the public health risks.

Asset monitoring and modelling

The information provided by event duration monitoring on storm overflows and Flow to Full Treatment monitors at wastewater treatment works will allow for problems to be better identified and addressed to ensure that treatment works are running at their designed capacity.

Together with data on weather, water quality, and the performance of other infrastructure assets, integrated models of assets can be built to better understand the performance of assets and test their response to events such as intense rainfall. These models should form part of plans to improve management of our existing infrastructure and should be bolstered by increased investment in staff and skills to support people on the ground to better maintain assets. Some studies have shown that digital twins of assets, where integrated models of assets are built and fed by real-time data, can further enhance the identification of operational improvements, the optimisation of assets, and adaptation efforts as the effects of changes can be tested and understood.[113]

Digitisation of assets also presents opportunities for system optimisation through asset coordination, real-time control, and predictive and preventative maintenance.[114,115] Pilot projects, starting in priority catchments, should be established to demonstrate the potential of digital twins and real-time control of wastewater infrastructure to reduce overflow discharges and improve water quality.

Creating agreed data standards for monitoring telemetry and water quality data will allow for large data streams to be integrated and data sharing frameworks will enable partnerships and transparency. This information would allow for the impacts of interventions and changes to be modelled, which can help reveal second-order effects. Furthermore, these models can support water quality forecasting to reduce public exposure when water quality is poor.

Recommendation 4: Water service providers should work in partnership with experts and researchers to develop models of catchments, supported by agreed standards for data sharing, to enable a better understanding of infrastructure asset health, to aid proactive management of its performance and to protect water quality.

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Storage tanks

As overflows are mostly caused by storm water entering the sewers, the most effective way to reduce their frequency is to prevent storm water from entering the combined sewer.[116] This is particularly important given the need for new housing provision and the scale of development that will result.

Storage tanks can provide a short-term fix for overflows and are well understood in terms of costs and behaviour which make them a safe option for high priority sites. They do not, however, address the source of the problem and are not a long-term sustainable solution. There are also limits to the amount of storage that you can have in a catchment before causing problems for the receiving wastewater treatment works. Increasing storm severity due to the changing climate means that storm tanks built for current flows will become inadequate in the future. Reducing the volume of storm flows should be achieved through sustainable drainage, active system management, and maintenance as a first resort where possible.[2]

Recommendation 5: UK government's calls for short-term relief of overflows based on storage tank construction should be weighed against sustainability considerations and opportunities for longer-term plans for capacity management across the whole system, only sanctioning storage tanks where environmental and public health risks are greatest and there are no acceptable alternative actions.

Managing surface water

Local authorities need to consider the impact of 'urban creep' – the expansion of the coverage of impermeable surfaces – which is a large driver of storm water generation. While the comprehensive roll-out and retrofit of sustainable drainage systems (SuDS) remains a long-term goal as part of flood management there are opportunities to have a significant impact in the short-term. These include increasing the use of permeable surfaces in urban spaces and diverting run-off from roofs, carparks, and some highways. For example, surface run-off from roofs may be stored either for direct reuse or slowed and gradually released into the sewer. Initiatives such as the provision of leaky water butts and water efficiency devices to customers have shown promise in reducing flows into the sewer and local overflow.[117]

Surface run-off from roads is a significant contributor to overflows, and diverting this run-off from combined sewers would relieve storm overflows. However, discharging directly into waterways introduces environmental risks as this run-off can contain large amounts of contaminants including oils, metals, faecal indicator organisms, and particulates such as microplastics and tyre wear.[118,119] .Opportunities for highway run-off to be treated using SuDS techniques or constructed wetlands should be explored by highway agencies.

There are several legislative barriers that have historically impeded increased provision of sustainable drainage, with new developments having a right to connect to existing public sewers, and water service providers are not included as statutory consultees on planning applications.[120] The recent implementation of Schedule 3 of the Flood Management Act (to be implemented in 2024 in England and already in force in Wales) requires drainage approval from a SuDs approval body before starting any construction work that has drainage implications.

Recommendation 6: To reduce the number of overflows, local authorities, regulators, and property owners should identify and implement mechanisms to reduce surface run-off. These may include incentivising the removal of impermeable surfaces as well as the diversion or slowing of surface run-off from private properties with sustainable drainage systems (SuDS) and other urban greening initiatives.

Risk communication

Active engagement with stakeholders and the public creates awareness of public health risks of bathing waters and provides information through educational campaigns. This includes raising awareness about the importance of clean water and promoting public awareness to allow recreational water users to make informed decisions about where and when they will use the water.

Maintaining public tools for sharing information on water quality within bathing and recreational sites is important for mitigating risk of exposure to faecal organisms. Existing tools from government provide public information on bathing sites such as recent water quality ratings and proximity to overflows but the various sources of information should be signposted more clearly and reviewed to ensure that information is being presented in an accessible way. Improvements to water quality monitoring will enable data sets to be brought together to improve quality of pollution forecasts and other publicly available tools and where feasible provide near-real-time warnings to inform local populations. User-centred design needs to be a focus as these tools are evolved so that they are easy to use and understand, if they are to be impactful.

Recommendation 7: Health protection authorities, environmental regulators, and local authorities should engage stakeholders and the public through educational campaigns and community involvement to increase public understanding of the health risk, promote responsible behaviour, and improve the effectiveness of signage and information at designated bathing sites.

Disinfection

Effluent disinfection may be needed where risk of exposure to faecal organisms from treated effluent is unacceptably high or at priority recreational sites where there are few alternatives to reducing levels of faecal organisms.

Ultraviolet irradiation, combined with tertiary filtration, is the most widely used solution for improving bacteriological standards.[80] There is a relatively mature supply chain for UV technology, however this would be challenged under a wider scale roll-out. One significant challenge is the difficulty in determining, reporting, and auditing the applied UV dose and so simplified dosage guidelines may be beneficial. Chemical dosing is another technology available at scale, though this comes with significant ecological and other public health harms due the production of toxic by-products. Other treatment technologies do exist but are not as mature as UV so would require further research and development.

Disinfection can be deployed quickly where it is needed or in the event of an emergency, however there are trade-offs that should inform decisions on roll-out at new sites. Especially for cost and sustainability, adding further treatment steps will increase the energy and operational cost of the treatment works along with regular maintenance which can involve replacing expensive parts. The use of disinfection must be driven by an evidence-led understanding of the risks posed, required standards, and the associated costs.

However, in the long-term this risk may be better addressed by using improved treatment technologies and system design. For example, UK Water Industry Research recently opened an expression of interest for research projects in efficacy of novel disinfection processes (March 2024) and similar programmes to develop and test new technologies will be important going forward.

Recommendation 8: Water service providers and environmental regulators should assess the need for the wider deployment of disinfection processes at priority sites as part of a public health risk-based approach to improving the UK's wastewater infrastructure.

4.2 Opportunities for long-term transformational change

The recommendations outlined in Section 4.1 would address the immediate public health risks in the short term. However, these need to be accompanied by seizing this opportunity for longer-term transformational change. This section sets out the opportunity and actions that should be initiated now to build greater resilience in the wastewater system going forward.

Joined-up vision

As the built environment expands and weather patterns are changing as a result of climate change, there is need for a broader plan to improve water and wastewater services. An aspirational vision for national scale transformation of our ageing wastewater infrastructure can set out the opportunity for a resilient sewerage system that puts public health on an equal footing to protection of nature and service resilience. Understanding of where the interdependencies exist, particularly for flooding planning, means that the long-term vision of the wastewater system would have benefits beyond just one sector. The vision for the wastewater system should align with our aspirations for water supply and guide the actions of governments, water service providers, and other key stakeholders. To ensure everyone is moving in the right direction it should be supported by a diverse set of ambitious evidence-based targets.

Recommendation 9: A vision for the UK's wastewater system should be developed by Defra and the devolved administrations, involving the public and diverse perspectives across the water sector. The vision should balance human health and wellbeing, protection of nature, security of supply, flood resilience, economic sustainability, and customer satisfaction and be supported by measurable targets to monitor delivery.

Sustainable drainage

Ensuring that as much raw sewage as possible can go through treatment works and be effectively processed is important for the quality of discharges to downstream environments. Building on the short-term opportunities to better manage surface run-off and optimise operation of existing infrastructure, the information from sensors and models can also identify parts of the system where extra capacity in sewers or treatment works is needed. Sustainable drainage solutions, including urban greening measures, can create a network for rainwater collection and free up capacity within sewers. These measures also support wider resilience in built environments by contributing to flood mitigation and reducing the need for pumping out or treating stormwater. They also have multiple wider benefits. Sustainable drainage solutions are one part of an overall surface water management strategy and could be incorporated into a wider programme of regenerative land-use change.

Vertical-flow constructed wetlands could be incorporated into planning for rural and coastal areas where there is more space and where separated flows can be feasibly directed. Constructed wetlands can remove nutrients and faecal organisms from wastewater and are comparatively cheaper to run than traditional treatment works, so by combining approaches there is an opportunity to reduce overall pressure on the system.[121] However, there are significant space requirements for constructed wetlands to be able to handle suitable levels of wastewater.

There are key knowledge gaps in the effectiveness of many types of sustainable drainage and constructed wetlands, including the degree of pathogen removal, effectiveness in flood mitigation, and the maintenance required to ensure optimal performance over time. As new interventions are deployed, they should be coupled with a proactive monitoring and evaluation programme.[122] As a quantitative database is developed, the evidence for impact on health risks can help to address challenges in perceptions and encourage buy-in across key stakeholders for deploying SuDS on a large scale.

As many SuDS are placed outside of the sewer system, they may not be owned by the water service providers, this could open new opportunities for third party investment allowing individual measures to be developed relatively quickly. It will be important to establish responsibilities for ongoing maintenance as part of developing these interventions. However, any action affecting drainage should be developed in collaboration with the local water service provider and flood management authorities.

Recommendation 10: Defra, devolved administrations, and local authorities should coordinate a national scale deployment strategy for sustainable drainage systems to future proof our wastewater infrastructure in a changing climate. These interventions must be supported with clear guidance and responsibilities for maintenance and evaluation to ensure long-term performance.

Public, trade, and industry engagement

Alongside improving operation and maintenance of the infrastructure, people's behaviour will have a role in improving overall resilience. There is a clear opportunity for a campaign and engagement to promote actions on an individual level that can reduce some of the pressures on the wastewater system. Campaigns and behavioural interventions will need to be developed in partnership with behavioural scientists to effectively enable change. For example, widespread implementation of smart water metering can offer benefits for both service providers and customers by flagging potential leaks or blockages. This can ensure maintenance is carried out and empowers users to monitor personal use and consider how to use water cost-effectively, if using meter-based billing. Widespread adoption of water efficiency measures will have the added advantage of reducing dry weather flows in sewers which will provide modest extra capacity for dealing with high flows.

Recommendation 11: Defra and devolved administrations should revisit their strategies for water efficiency and blockage prevention measures, which would be supported by other policy initiatives such as a ban on the flushing of nonbiodegradable items. This should be part of wider engagement to support a culture shift around our use of and shared responsibility for the water system.

Demonstrator programmes

Potential contamination from effluent discharges also needs to be considered, disinfection treatments are effective but can be restrictive particularly regarding cost and sustainability (as discussed above).

New advancements in treatment technologies are already being developed and there is a growing focus on holistic approaches that can incorporate wider benefits such as resource recovery or low carbon operation.[123] Continued research is needed to explore new treatment paradigms that can more effectively address pathogen removal and carriage of antimicrobial genes as well as nutrient and pollution removal, to further build on these areas and opportunities for co-benefits that can reduce costs or emissions.[124] A collaborative approach would be valuable to run large-scale testing with real loads of wastewater as well as learning from examples of international best practice.

Recommendation 12: Water service providers, regulators, and UK Research and Innovation should dedicate funding to pilot large-scale demonstrator programmes for the development and deployment of new treatment approaches for improved performance and pollutant removal, to support operational optimisation, and the development of real-time monitoring of faecal organisms.

4.3 Enablers

Understanding

Current measurements of faecal indicator organisms only provide a proxy of the presence of faecal pathogens and associated risks. Research and innovation are needed to develop more direct measurements of human pathogens and the exposure thresholds for wider public health hazards. This should include reducing the cost of monitoring, data integration, pollution forecasting and information communication, Researchers and policymakers could then develop more targeted risk monitoring and mitigation strategies to minimise health risks for recreational users. This research should inform the standards and guidelines for water quality testing and compliance and designating other areas for protection under regulatory frameworks.

Research that creates stronger links between technological and institutional innovation is essential. By fostering collaboration and investment in research, the research community can play a pivotal role in developing sustainable solutions as well as supporting initial pilot schemes to enhance the efficiency and effectiveness of wastewater treatment processes.

Recommendation 13: UK Research and Innovation and other funders should support multidisciplinary research to better understand faecal microbial behaviour and antimicrobial resistance in inland and coastal waters and develop better monitoring technology for near-real-time monitoring of faecal organisms and other microorganisms of human concern in waterbodies used for recreation. This should support policymakers and water service providers to take a risk-based approach, identifying priority sites for improvement and informing where certain interventions should be targeted.

Skills and capacity

A renewed focus on public health will require more skilled staff to install and maintain existing assets and new technologies, to monitor and process data for modelling and automation, and to design and implement sustainable drainage solutions.

Though technologies may be available, water service providers may not have the resource or capacity to implement them. Poor public perceptions of water service providers can make recruiting new staff and graduates challenging, compounding pre-existing skills shortages.[125]

Thorough enforcement of regulations is resource intensive. Strategic investment is needed to enhance the capacity of regulators to monitor compliance and support service providers to address complex water quality challenges.

Recommendation 14: An increase in the capacity of regulatory and engineering skills will be required to enable the delivery of the interventions and resource the monitoring and enforcement of water quality targets. Collaborative efforts between government bodies, regulators, and water service providers should allocate resources towards recruiting and developing skilled staff.

Strategic oversight

There will also be interactions with other areas including decarbonisation efforts, construction and development demands, or highways maintenance. There is a need for coordination across national policymakers, water service providers, and wider stakeholders to drive system-wide change. Systems thinking offers helpful tools to make sense of complexity, change our understanding of issues, find ways of achieving better outcomes, and see new opportunities to solve multiple problems at the same time.

While the portfolio of interventions deployed at the catchment level will vary depending on the specific conditions, there will be opportunities to share insights and lessons. The recommendations discussed in this report would require collaboration across a variety of stakeholders to deliver better social, economic, environmental, and public health outcomes.

Recommendation 15: Defra, with the support of the devolved administrations, should appoint a wastewater champion to enable effective collaboration across different stakeholder groups to deliver these recommendations and coordinate action to reduce these public health risks across the UK.

Chapter 5
Recommendations

A portfolio of interventions is needed to create multiple barriers of protection to minimise public health risks from treated effluent and storm overflows. Our collaborative approach identified the need to take a risk-based methodology to the deployment of interventions and to target those actions at those sites where public health risks are greatest, while balancing the need for action against other policy priorities. These recommendations identify those actions that need to be addressed collectively by water service providers, UK government, devolved administrations, and public bodies to reduce public health risks while also supporting a more effective and resilient wastewater system across the UK.

Immediate actions to reduce the public health risk

1. **Maintenance and rehabilitation**: Water service providers should further prioritise maintenance and rehabilitation of assets, informed by regulatory frameworks that require the demonstration of asset resilience including the reduction in sewer infiltration, and supported by enforcement measures.
2. **Monitoring and forecasting**: Department for Environment, Food & Rural Affairs (Defra) should revise targets to accelerate the roll-out of Continuous Water Quality Monitoring in England and extend the scope so environmental regulators monitor the microbiological quality of treated effluent. This includes accelerating the public availability of near-live data to inform improved pollution forecasting and provide clear public communications to reduce the public's exposure to poor water quality. Comparable data should be made available across the UK.
3. **Bathing standards**: Defra should initiate a review of the designation and protection of bathing waters, working with academic experts, regulators and devolved administrations to develop agreed methods to better quantify microbiological water quality, and ensure the standards that are applied are proportionate to the public health risks.
4. **Asset monitoring and modelling**: Water service providers should work in partnership with experts and researchers to develop models of catchments, supported by agreed standards for data sharing, to enable a better understanding of infrastructure asset health, to aid proactive management of its performance and to protect water quality.
5. **Storage tanks**: UK government's calls for short-term relief of overflows based on storage tank construction should be weighed against sustainability considerations and opportunities for longer-term plans for capacity management across the whole system, only sanctioning storage tanks where environmental and public health risks are greatest and there are no acceptable alternative actions.

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6. **Managing surface water**: To reduce the number of overflows, local authorities, regulators, and property owners should identify and implement mechanisms to reduce surface run-off. These may include incentivising the removal of impermeable surfaces as well as the diversion or slowing of surface run-off from private properties with sustainable drainage systems (SuDS) and other urban greening initiatives.

7. **Risk communication**: Health protection authorities, environmental regulators, and local authorities should engage stakeholders and the public through educational campaigns and community involvement to increase public understanding of the health risk, promote responsible behaviour, and improve the effectiveness of signage and information at designated bathing sites.

8. **Disinfection**: Water service providers and environmental regulators should assess the need for the wider deployment of disinfection processes at priority sites as part of a public health risk-based approach to improving the UK's wastewater infrastructure.

Opportunities to seize now for long-term transformational change:

9. **Joined-up vision**: A vision for the UK's wastewater system should be developed by Defra and the devolved administrations, involving the public and diverse perspectives across the water sector. The vision should balance human health and wellbeing, protection of nature, security of supply, flood resilience, economic sustainability, and customer satisfaction and be supported by measurable targets to monitor deliver.

10. **Sustainable drainage**: Defra, devolved administrations, and local authorities should coordinate a national scale deployment strategy for sustainable drainage systems to future proof our wastewater infrastructure in a changing climate. These interventions must be supported with clear guidance and responsibilities for maintenance and evaluation to ensure long-term performance.

11. **Public, trade, and industry engagement**: Defra and devolved administrations should revisit their strategies for water efficiency and blockage prevention measures, which would be supported by other policy initiatives such as a ban on the flushing of nonbiodegradable items. This should be part of wider engagement to support a culture shift around our use of and shared responsibility for the water system.

12. **Demonstrator programmes**: Water service providers, regulators, and UK Research and Innovation should dedicate funding to pilot large-scale demonstrator programmes for the development and deployment of new treatment approaches for improved performance and pollutant removal, to support operational optimisation, and the development of real-time monitoring of faecal organisms.

Enabling actions:

13. **Understanding**: UK Research and Innovation and other funders should support multidisciplinary research to better understand faecal microbial behaviour and antimicrobial resistance in inland and coastal waters and develop better monitoring technology for near-real-time monitoring of faecal organisms and other microorganisms of human concern in waterbodies used for recreation. This should support policymakers and water service providers to take a risk-based approach, identifying priority sites for improvement and informing where certain interventions should be targeted.

14. **Skills and capacity**: An increase in the capacity of regulatory and engineering skills will be required to enable the delivery of the interventions and resource the monitoring and enforcement of water quality targets. Collaborative efforts between government bodies, regulators, and water service providers should allocate resources towards recruiting and developing skilled staff.

15. **Strategic oversight**: Defra, with the support of the devolved administrations, should appoint a wastewater champion to enable effective collaboration across different stakeholder groups to deliver these recommendations and coordinate action to reduce these public health risks across the UK.

Chapter 6
Conclusions

The recreational use of inland and coastal waters and access to clean green spaces has many health benefits. However, if those same waters are polluted with human faecal organisms from our wastewater system, this exposes users to a health risk. Pollution can be introduced from overflows and final effluent from treatment works as some existing treatment processes are not designed to remove faecal organisms and many treatment facilities do not have disinfection stages. Coordinated action is needed to address these various sources and reduce the public health risk.

With the recreational use of public waterways increasing in popularity, there have been numerous reports of people becoming unwell following water-based activities. While we lack sufficient evidence to identify specific causality, there remains a need to protect our recreational waters from all sources of pollution, including from wastewater, taking a precautionary principle.

Sewers were initially introduced in England as a health policy measure. Centuries later it is time to bring public health benefit back to the core of our wastewater system. It is important to note, however, that public health is not considered in isolation. Instead we must seek alignment with:

- **Sustainability and resilience**: Ensuring that long-term climate resilience is factored into planning so our wastewater system can manage an increasing frequency and intensity of storms and floods, or periods of drought that disrupt the sewage flow. Additionally, the operational and embodied carbon of any interventions need to be well understood and prioritised for high-risk sites.
- **Operational costs and capacity**: The interventions set out in this report require resource to cover the costs and the skills required for implementing and maintaining rapid infrastructure upgrade. However, many of the priorities outlined in this report have the potential to increase the efficiency of the infrastructure, which is likely to result in lower operational cost.
- **Impacts on consumers**: It is vital that our public services remain affordable. By taking a risk-based approach, interventions can be prioritised where they will have the greatest reduction in the public health risks. The responsibility for implementing these recommendations should be spread across a range of actors including the water service providers, developers, and public bodies.

Taking the wider system into account this report calls for an evidence-led, risk-based approach to reducing public health risks of both overflows and continuous effluent discharges.

We know that overflow spill reduction is best achieved through reducing surface water inputs, managing capacity, and resolving blockages.

Optimisation of our existing infrastructure combined with wide-scale provision and retrofit of sustainable drainage will be essential.

In mitigating the public health risks from continuous effluent discharges, disinfection must be targeted to priority sites to reduce the risk of exposure. Given the associated costs of disinfection, there is also need for development and deployment of new treatment methods to offer improved performance, removal of faecal organisms, and other emerging contaminants of concern.

There are actions underway to improve the wastewater system and generally reduce overflows, including funding for sustainable drainage, increasing storage, and rolling out UV disinfection.

However, this activity needs to be guided by an ambitious vision of our future wastewater system – a shared endeavour that helps all stakeholders to balance human health and wellbeing, protection of nature, security of supply, flood resilience, economic sustainability, and customer satisfaction, to deliver a measurably better wastewater system.

It is vital this vision is built on a robust evidence base so that we understand what the public health risks really are and can accurately measure them, both now and into the future. This vision should underpin regulatory instruments, technical standards, and policy targets across the UK, so that together governments, regulators, and water service providers can effectively mitigate the public health risks and provide safe open waters for everyone to use.

Annexes

Annex A **Project methodology**

At the outset, the project sought to define the area of public health to be considered and the leverage points within the wastewater system where interventions could impact public health. A comprehensive framework for evaluating interventions was developed, considering factors such as intensity (for example, concentration of faecal organisms) and exposure to hazards. Exposure levels to hazards were defined and reviewed, considering its implications for public health. A multidisciplinary working group of experts in public health, engineering, and related fields was established (Annex C). This working group were pivotal in shaping the project's approach. Moving into the evidence gathering and testing phase, key stakeholders and experts were identified to provide input with focus on identifying how interventions could contribute to reducing the public health risk. System dependencies and trade-offs for key leverage points were identified and analysed.

Data cards were produced for selected interventions, encompassing essential elements such as intervention principles, effectiveness relative to the defined framework, costs (CapEX, OpEx), risks, policy priorities, and confidence levels. The proposal for these data cards was tested and refined through collaboration with the working group. Subsequently, the working group members produced data cards for all interventions, which then underwent review to ensure accuracy and completeness.

The intervention data cards were introduced to key stakeholders in a multidisciplinary workshop held to assess systems improvement. Participants attended from organisations including: Arup, AtkinsRéalis, British Canoeing, British Water, Chief Medical Officer, Consumer Council for Water, Cranfield University, Department for Environment, Food & Rural Affairs, Department for Health and Social Care, Dŵr Cymru Welsh Water, Environment Agency, Flood Forecasting Centre, Imperial College London, Institute of Water, Mott MacDonald, National Infrastructure Commission, Natural Resources Wales, Northumbrian Water Group, River Action, Rivers Trust, Scottish Water, Severn Trent Water, South Tyneside Council, Southern Water, Surfers Against Sewage, The Chartered Institution of Water and Environmental Management, UK Centre for Ecology and Hydrology, UK Health Security Agency, UK Water Industry Research, United Utilities, University College London, University of Exeter, University of Leeds, University of Newcastle, Wessex Water, Windrush Against Sewage Pollution, WRc, and Yorkshire Water.

Participants were asked to identify the most important interventions for two scenarios – interventions which can be implemented as quickly as possible and interventions with the most co-benefits. Participants were then asked to discuss enablers for change, as well as effective deployment of interventions and incorporation of the enablers to reduce public health risk. The final set of interventions were further tested through collaborative discussions with industry representatives and policymakers.

Primary input for this report was gathered via the stakeholder workshops. The report underwent a comprehensive review, including by industry experts, partner organisations in the National Engineering Policy Centre and the Royal Academy of Engineering's Engineering Policy Centre Committee. Details of reviewers are listed in Annex C.

Annex B **Legislative & regulatory framework**

Introducing new interventions into the wastewater system to better protect against sewage and microbial discharges must be informed by the current legislative context and state of the sector to consider the changes it is already undergoing. Across the UK water service providers differ in ownership model with government owned companies in Scotland and Northern Ireland, and private companies in England and Wales (as set out in the Water Industry Act 1989), with Welsh Water operating a not-for-profit business model. These water service providers across the UK have regional monopolies and most homeowners or businesses do not have a choice of service providers. With regards to wastewater, water service providers operate a network of collection pipes, sewers, and wastewater treatment works which process wastewater and provide storm water drainage for properties. However, they do not have full responsibility for all drainage infrastructure as this is also spread across local authorities and private owners. In England and Wales alone water service providers are responsible for a network of around 335,000km of sewers and over 20 million connections to homes and industrial properties.[126]

Responsibility for water and sewerage policy and related targets is devolved to the national governments, national legislation sets out the responsibilities for water and sewerage providers, including legal requirements for reporting performance. Some primary legislation covers requirements for water and sewerage services specifically, but service providers can be affected by various policy areas including environmental protection and flood management In England, key legislation that water service providers need to comply with include:

- The Water Industry Act
- The Water Resources Act
- The Environment Act
- The Competition and Services (Utilities) Act
- The Water Act
- The Flood and Water Management Act.

There are dedicated regulators that have a role to monitor and enforce performance of water service providers to ensure that set standards are met and that water service providers properly carry out and finance their functions. Regulators include the following – see table 7.

Key elements of legislation and regulation for managing public health risks from wastewater

Public health concerns in sewerage chiefly consider the contents of wastewater discharges and permits for storm overflows. The most relevant selection of the legislative framework and industry guidance (in England) for the purpose of this report have been outlined below. Devolved administrations have set their own policies which largely follow similar principles.

The Water Industry Act (1991) sets out the powers and duties of water service providers, including provision, maintenance, and records of sewers. With regards to in-flow management to sewers, this Act also provides for all domestic properties to have a right to connect foul and surface waters to a public sewer as well as a mechanism for private sewers to be adopted by water service providers. However, the automatic right to connect will be changed as part of the Flood and Water Management Act Schedule 3 (to be implemented in 2024 in England and already in force in Wales) which ensures that new developments make use of sustainable drainage systems. Owners (domestic properties) must apply for new connections to inform water service providers of new demands on

	England	Wales	Northern Ireland	Scotland
Setting policy framework – including to set standards and draft legislation	Defra	Welsh government (working with Defra)	The Department for Infrastructure	Scottish government
Economic regulator	The Water Services Regulation Authority (Ofwat)	The Water Services Regulation Authority (Ofwat)	Northern Ireland Authority for Utility Regulation	Water Industry Commission for Scotland (WICS)
Environmental regulator	Environment Agency and Natural England	Environment Agency and Natural Resource Wales	Northern Ireland Environment Agency	Scottish Environment Protection Agency
Drinking water quality	Drinking Water Inspectorate	Drinking Water Inspectorate	Drinking Water Inspectorate (unit within the Environment Agency)	Drinking Water Quality Regulator
Customer representation	Consumer Council for Water	Consumer Council for Water	Consumer Council	Consumer Scotland, Scottish Public Services Ombudsman

Table 7 | Overview of UK water sector regulators

treatment, the overall capacity of the sewer and treatment system is vital as new properties are added to existing infrastructure.

From 2022 water service providers were required to develop Drainage and Wastewater Management Plans based on guiding principles developed by Defra, the Welsh government, Environment Agency, Natural Resources Wales, and Ofwat. These plans should cover at least 25 years and outline current and estimated future capacity, which is growing under pressures such as climate change and population growth, and the potential pressures in the infrastructure to manage risks with other risk management authorities. Part of the guiding principles incorporate the role of collaboration; though water service providers own their individual plans there is a need to engage with stakeholders that have a shared responsibility over different system elements. This could provide a potential framework for engaging cross networks in long-term planning for mitigating public health risks and ensuring that considerations for health are included in discussions.

For England environmental standards are set by Defra, as the overseeing government department, and the Environment Agency regulates environmental performance including issuing environmental permits for effluent and sewage discharges and assessing water quality against compliance limits. The Environment Agency have a role in investigating cases of noncompliant discharges and enforcement options in the case of offending discharges, such as civil sanctions. The availability of resources has a direct impact on the ability of regulators to investigate cases on noncompliance and provide support to water service providers.

Environmental permit conditions specify the nature of the discharge, the outlet, monitoring procedures, and provision of information. Requirements are set for the level of treatment at wastewater treatment works and frequency and parameters for monitoring of effluent discharges, based on location of discharges and the population equivalent that the treatment works serves. Advanced tertiary treatment is only required in sensitive areas for treatment works with a population equivalent over 10,000. Water service providers must submit annual sampling plans, including location of sampling points which are agreed in the environmental permits, and monthly results to the Environment Agency. In these cases, there are no requirements for monitoring faecal organisms to inform associated public health risks.[127]

Service providers are also legally obliged to undertake event duration monitoring of storm overflows, and report data annually to the Environment Agency. Overflow spills are covered within environment permits; however, event duration monitoring data can show alignments with storm events and help to improve understanding of environmental impacts. In 2022, the UK government also tightened targets for service providers regarding raw sewage discharges in the storm overflow reduction plan, with all storm overflows to be improved starting with most damaging sites by 2035. These actions aim to prevent raw sewage discharges and therefore faecal organisms being released.

There are dedicated monitoring requirements for designated bathing waters set out in the Bathing Water Regulations. The Environment Agency will sample water quality at these sites up to 20 times during the bathing season including to assess levels of bacterial indicators E. coli and intestinal enterococci. Classification of sites is calculated annually based on four-year samples to determine the status of the site. Assessment against the bathing water standards could trigger action, however up to 15% of failed samples may be disregarded to allow flexibility for short term pollution events. Indicator organisms are a valuable proxy measurement of sewage pollution but there can be various sources of these organisms and the relationship between the common indicators and waterborne pathogens can be tenuous, especially for viruses. The Bathing Water Regulations require more management measures to be taken by the Environment Agency, water service providers, and local authorities at designated bathing waters which are subject to pollution and designated sites that have "poor" water quality status.

Economic regulation and price reviews – financing improvements to our wastewater system
Water services and assets are financed and maintained through private investment, public funding and consumer bills for services provided to households and commercial buildings.

The industry serves millions of domestic and non-domestic customers, which is overseen by the economic regulator Ofwat (in England and Wales). Ofwat have a role to set controls that limit what water service providers can charge their customers. Every five years water service providers must submit a business plan to the regulator detailing planned spend for the upcoming cycle including for maintenance, building assets, and the amount of revenue they feel they should be permitted. Ofwat reviews and challenges these plans, determining how much it will cost to keep services running efficiently.

Ofwat contribute to environmental aims in the price review process by ensuring investment is ringfenced for environmental initiatives to ensure water service providers deliver environmental improvements efficiently. For the next review – PR2024 covering 2025–30 – Ofwat have set out ambitions for water service providers including for delivery of greater environmental value through improving river quality (with a focus on reducing raw sewage overflows), taking steps towards net zero, and supporting resilient, affordable services. Any planning for new measures or major improvement works, such as implementing disinfection would need to be set out in the business plans and suitably financed.

Annex C **Acknowledgements**

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