CENTRE OF EXPERTISE FOR WATERS

Emerging Contaminants: Informing Scotland's strategic monitoring and policy approaches on substances of increasing concern

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Acronyms

AMR	Antimicrobial resistance
ARG	Antimicrobial-resistant gene
ARB	Antimicrobial-resistant bacteria
CEC	Chemical of Emerging Concern
CIC	Contaminant of Increasing Concern
CIP	Chemicals Investigations Programme
CSO	Combined Sewer Overflow
DWI	Drinking Water Inspectorate
DWQR	Drinking Water Quality Regulator
EQS	Environmental Quality Standard
EE2	17alpha-Ethynylestradiol
EDC	Endocrine Disrupting Chemical
E1	Estrone
E2	17beta-Estradiol
EMEA	European Medicines Evaluatory Agency
ENM	Engineered Nano Material
EMA	European Medicines Agency
EPR	Extended Producer Responsibility
EU	European Union
FSA	Food Standards Agency
JNCC	Joint Nature Conservation Committee
MPA	Marine Protected Area
NM	Nano material
NNSS	Non-Native Species Secretariat
NP	Nano particle
PE	Polyethylene
PET	Polyethylene Terephthalate
PFAS	Per- and polyfluoroalkyl substances
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctanesulfonate
PP	Polypropylene
PPCP	Pharmaceuticals and Personal Care Products
PS	Priority Substance
PVC	Polyvinyl Chloride
QSAR	Quantitative structure–activity relationship
REACH	The Registration, Evaluation and Authorisation of Chemicals
ROS	Reactive Oxygen Species
SASA	Science and Advice for Scottish Agriculture
SEPA	Scottish Environment Protection Agency
SFM	Substance Flow Map
SPRI	Scottish Pollutant Release Inventory
WFD	Water Framework Directive
WHO	World Health Organisation
WWTP	Wastewater Treatment Plant
TEA	Total Estrogenic Activity
POP	Persistent Organic Pollutants
RFR	Replacement Flame Retardants
PFOA	Perfluorooctanoic acid
PFHxS	Perfluorohexane sulphonic acid
MNP	Micro(nano) particle
EDTA	Ethylenediaminetetraacetic acid
ECHA	European Chemicals Agency
UWWTD	Urban Waste Water Treatment Directive

Executive Summary

Purpose of research

The aim of this project was to inform, prioritise, and coordinate actionable monitoring and policy-based approaches to identify, assess, and mitigate risks from substances of increasing concern to Scotland's water environment.

To this end, the team adopted a Substance Flow Mapping approach, which enabled knowledge sharing and the identification of research gaps. The project took into consideration a broad range of micropollutants, including those defined by chemical, biological and physical characteristics. Through literature review and expert elicitation, it sought to identify specific substances of interest within the various contaminant groups; to collate information on the sources, pathways, fate and occurrence of the contaminant groups; to provide a policy summary; to identify hazards associated with these specific substances; and to develop a logic model to inform the research agenda on contaminants of increasing concern in Scotland.

The project objectives were:

1. To identify the key substances or groups of substances of increasing concern in Scotland's waters
2. To identify the risks of these substances to Scotland's water environment including human health.

Background

Contaminants of increasing concern (CICs) comprise a diverse range of substances and organisms, including chemical groups such as pharmaceuticals and pesticides; biological contaminants such as pathogens and antimicrobial-resistant (AMR) genes; nanomaterials; and microplastics. CICs include compounds and organisms that are 'new' or increasing in presence in the environment or compounds or organisms already known to be present for which new information becomes available, e.g. on pathways or toxicities. Substances and groups considered CICs therefore evolve over time, due to new insights or new patterns of use.

For most CICs, significant data gaps still exist on their environmental baseline, environmental pathways and fate, exposure of human and ecological receptors, as well as potentially adverse impacts on human and ecological health. Risk management is further hindered by knowledge gaps of how CICs are transferred through environmental media and may bioaccumulate or be biomagnified in receptors along the food chain. Understanding the risks of biological contaminants is hindered by uncertainty around dose-response. Finally, risk assessment is rendered even more complex by limitations in our understanding of 'the cocktail effect': water environments typically receive a mixture of contaminants, for example in the sewage effluent matrix, that may act synergistically in terms of their effects on aquatic organisms and ecosystems. Vector interactions and characteristics of the receiving environment may also affect CIC's bioavailability, behaviour and impact.

Generally, CICs are not yet fully addressed in policy, regulation and monitoring programmes.

Key findings

A wide range of contaminant groups with potential relevance for Scotland was identified, including several that have never been investigated for Scotland but are known to be a concern elsewhere.

Substance Flow Maps for five selected contaminant groups – microplastics, nanomaterials, pharmaceuticals, per- and polyfluoroalkyl substances, and antimicrobial resistance – were produced (Appendix I) and Substance Flow Mapping was demonstrated to be an effective framework for knowledge exchange and research gap analysis. The project identified specific research needs to understand sources, pathways, receptors, and risks, which are provided in this report. Treated and untreated sewage effluent from domestic and industrial sources; agriculture and aquaculture; landfill leachate; road run-off and litter were common pathways across most contaminant groups, whilst substance-specific insights also emerged.

Scotland is not alone in focusing on policy, regulation and monitoring options to address the complex issues around CICs and several useful approaches and data sources were identified, which could be explored for applicability to Scotland.

To address the science-policy interface, the following areas should be considered:

- Data sharing, data sufficiency, and cross-organisational working
- The role of climate change, including adaptation and mitigation measures, on future trends

- Understanding and managing sources, pathways and interactions
- Research infrastructure and capacity.

Recommendations

Based on the findings of the project, the research team would like to make the following recommendations:

1. That no emerging contaminant groups can be discounted for Scotland on the basis of the evidence we found;
2. That many national and international databases are available to aid understanding of emerging contaminants; these should be reviewed and consolidated for Scotland;
3. That the current organisational infrastructure of teams (academic, government, committees, partnerships, non-governmental organisations) working on emerging contaminants in Scotland is reviewed and assessed for comprehensiveness with respect to the water environment;
4. That new partnerships are considered for contaminant groups as required;
5. That such new or existing partnerships refine the knowledge gaps in collaboration based on the knowledge needs of water policy teams;
6. That funding is made available to address the knowledge gaps;
7. That an international review of policy options is conducted, in particular for integrated approaches and approaches to mixtures, including effect-based monitoring;
8. That capacity is expanded both in research teams and policy teams.

1 Introduction

1.1 Background and scope

Contaminants of increasing concern (CICs) comprise a diverse range of substances and organisms. The way they are grouped and categorised is not uniform: by use (e.g. pharmaceuticals, pesticides); by physical, physico-chemical, or biological properties (e.g. microplastics, nanomaterials, polyfluoroalkyl substances, cyanotoxins); or by impact (e.g. endocrine disrupting chemicals, very persistent and very bio-accumulative chemicals, pathogens).

It is increasingly clear that physical, chemical and biological contaminants interact in complex ways. Chemicals that act on the same receptors may have synergistic toxicities; microplastics may act as vectors for microorganisms and chemicals; and a variety of chemicals including but not limited to antibiotics can drive selection for antimicrobial resistance (AMR). CICs include compounds and organisms that are ‘new’ or increasing in presence in the environment or compounds or organisms already known to be present for which new information becomes available, e.g. on pathways or toxicities. Many are collated into “watch lists” or data bases, such as the Water Framework Directive Watch List (Cortes et al. 2020), the World Health Organisation (WHO)’s AWaRe list for antibiotics (WHO, 2021), the NORMAN Network databases (Norman-network, 2023), or the UK REACH Substances of Very High Concern data base and supply chain information. Substances and groups considered CICs therefore evolve over time. Climate-driven societal change, for example, may lead to greater presence of sunscreen additives (oxybenzone, methoxycinnamate, titanium dioxide) or waste from new consumer products such as solar panels or batteries (silver, copper, indium, tellurium, lithium, cadmium); for ibuprofen and other chemicals, toxicity thresholds are lower than previously thought; whilst for very persistent chemicals concentrations may not yet be problematic but may become so in the future. For most CICs, significant data gaps still exist on their environmental baseline, environmental pathways and fate, exposure of human and ecological receptors, as well as potentially adverse impacts on human and ecological health. Often, no effective monitoring strategies are in place, due to analytical limitations; funding limitations; or the sheer number of substances under consideration. In many cases, there are no defined standards and we do not know what concentrations or synergies cause harm, or what markers should be monitored. Risk assessment is further hindered by knowledge gaps of how CICs are transferred through environmental media and may bioaccumulate or be biomagnified in receptors along the food chain. Understanding the risks of biological contaminants is hindered by uncertainty around dose-response and, in the case of AMR, the importance of non-pathogenic vectors and delayed clinical impacts (e.g. carriage of resistance genes in the gut may subsequently lead to a resistant urinary tract infection in the future). Finally, risk assessment is rendered even more complex by limitations in our understanding of 'the cocktail effect': water environments typically receive a mixture of contaminants, for example in the sewage effluent matrix, that may act synergistically in terms of their effects on aquatic organisms and ecosystems. Characteristics of the receiving environment, such as pH, may also affect CICs' bioavailability, behaviour and impact.

The project took into consideration a broad range of micropollutants, including those defined by chemical, biological and physical characteristics. Through literature review and expert elicitation, it sought to identify specific substances of interest within the various contaminant groups; to collate information on the sources, pathways, fate and occurrence of the contaminant groups; to provide a policy summary; to identify hazards associated with these specific substances; and to develop a logic model to inform the research agenda on contaminants of increasing concern in Scotland.

1.2 Project objectives

The project objectives were:

1. To identify the key substances or groups of substances of increasing concern in Scotland's waters
2. To identify the risks of these substances to Scotland's water environment including human health.

1.3 Structure of the report

The report first outlines the project overview and method, including the approaches taken to complete the literature review, the survey, and the workshop. In section 3.1 and 3.2, we report the findings of the literature and the policy summary, both organised by contaminant group, and in section 3.3 the survey results. The Substance Flow Maps (SFM; see section 2.4) produced during the workshop can be found in Appendix I. The knowledge gap analysis carried out during the workshop, augmented by subsequent targeted literature review, is presented in section 3.4.2, again organised by contaminant group. A synthesis of the findings to address the science-policy interface is presented in 3.4.3, followed by an overall reflection and discussion in section 4. Section 5 presents our recommendations and the report finishes with a conclusion in section 6.

2 Research undertaken

2.1 Project overview

The project took a substance flow mapping approach, enabling the team to make cross-comparisons, identify synergies and conflicts, understand complexities involving multiple CICs, and evaluate the tools available to understand occurrence and assess risk.

Phase 1 entailed drawing together the state of knowledge via a high-level review of literature and suitable data bases, and an electronic survey targeted to respondents with relevant expertise.

Phase 2 consisted of an in-person workshop during which substance flow mapping (SFM), research gap analysis, and knowledge sharing activities took place, followed by a post-workshop survey.

Phase 3 comprised of further targeted literature review, including sources recommended by survey and workshop participants; the production of a policy summary for the main contaminant groups; peer-reviewed analysis of the workshop data; and the development of a logic model to draw together the current state of knowledge and provide recommendations to inform further research in this area.

2.2 Approach to literature review and policy summary

The research team initially identified 18 diverse contaminant groups through brainstorming (Appendix II); these were subsequently ratified by the Project Steering Group.

The purpose of the literature review was:

- to identify specific substances within these contaminant groups
- to record in which environmental compartments the substance is usually detected

- to describe (qualitatively) the risk or hazard the substance poses to humans, animals, or plants, and describe any other type of environmental risk such as eutrophication.
- to note any information relating to the substance in mixtures.

We searched the Web of Science database, where a simple search string was constructed:

> TOPIC = [contaminant group] AND TOPIC = (Scotland OR United Kingdom OR Britain) AND TOPIC = (Water OR Environment).

Contaminant groups are not homogenous, and due to their diversity, a flexible approach to the search was essential. We aimed to examine 10-20 journal articles per contaminant group and used a progressive multi-stage methodology to ensure we reached the targeted number for each group (see Appendix II). In the first stage, only review articles were included (either by addition of the word 'Review' to the search string or by using the filters in the data base). If this did not yield sufficient results, the search was widened to include all papers, not only reviews. The third stage widened the time line, conducting searches initially at 5 years, then if the target number was still not obtained, at 7, 10, or all years, until the required number of papers had been identified. In the fourth stage, if the number of publications was still insufficient, a Google Scholar search was conducted, using the following string:

> [contaminant group] + Scotland OR United Kingdom OR Britain + Water + Review

for years 2013 – 2023. As Google Scholar returns thousands of entries, only the first two pages of articles were reviewed, thereby limiting the number of journal articles to 20.

A policy summary was also produced for the main contaminant groups of interest. Following the workshop, the literature review was consolidated and strengthened by drawing on the sources identified by the survey and workshop participants.

2.3 Approach to Survey

An online survey was constructed to seek wider input into the range of substances and contaminant groups, levels of knowledge and understanding, and levels of concern. It was targeted at "people with knowledge or expertise of emerging contaminants". The link to the survey was disseminated via email and X (formerly Twitter) in the professional networks of Project Team members, Project Steering Group members, and CREW. The survey was deployed in RedCap from 29 November 2023 until 8 January 2024.

The survey comprised three parts.

In **Part 1**, an initial set of questions served as a basic verification of the participant's expertise, to gain consent, and to identify any respondents that would be willing and appropriate to attend the workshop.

In **Part 2**, participants were asked to list the main contaminants or contaminant groups they thought are of emerging or increasing concern in the Scottish water environment. They were then asked to select a single contaminant or contaminant group, for which they were asked to gauge understanding of sources, pathways, processes of transport and degradation in the environment, and occurrence; what organisms or ecosystems they perceived to be most at risk from the contaminant; to gauge understanding of risk to human health and to aquatic organisms; to explain how they thought exposure occurred; to identify specific risks posed by the contaminant; and to describe any trends they expected in prevalence and hazard. Participants could enter this information for multiple contaminants by 'looping' through this part of the survey multiple times.

In **Part 3**, the survey asked participants for their view on which groups of contaminants they thought need to be addressed as a priority by policy makers and regulators, by rating the 18 main contaminant groups in terms of the level of concern they pose, firstly to human health and secondly to aquatic organisms. The purpose of this part was to provide comparability between the contaminant groups and to determine overall knowledge gaps and research priorities.

The survey questions are available in Appendix III.

2.4 Workshop

An in-person workshop was held on 10 January 2024 on GCU premises in Glasgow, opening with a welcome and presentations from the Project Team on the headline findings of the literature review.

Substance Flow Mapping

The purpose of the first activity was to develop detailed Substance Flow Maps (SFM), on which the sources, pathways, processes, relevant environmental compartments, and organismal receptors would be mapped in some detail. For most contaminant groups, the pathways are broadly known and these were drawn and produced as posters by the project team in advance of the workshop. The mapping exercise served to add the detail: participants were asked to refine the maps and to indicate what data sources and models we have to quantify the pathways and exposure risks by adding post-it notes to the posters. Participants moved freely between poster stations and could add comments to multiple maps if they wished.

Gap analysis

Subsequently, the five maps that had attracted the most interest were selected and taken into break-out rooms for further discussion; participants self-selected which discussion they joined. The map was taken as a starting point to identify gaps and uncertainties in our knowledge and understanding during these facilitator-led discussions. Discussions were audio-recorded and notes were scribed for analysis.

Knowledge sharing

In the ensuing plenary session, a representative from each break-out group shared its main findings. Other workshop attendees were invited to add further gaps and uncertainties in a brief discussion, which again was recorded and transcribed.

Presentation and discussion: mixture effects

A particular challenge for understanding risk from emerging and other contaminants is that they normally occur in the environment in a mixture, where they may interact with each other. A Project Team member presented the results of the literature review on mixtures, followed by a discussion.

Towards a shared research agenda

The final discussion of the workshop was a facilitated discussion designed to arrive at a shared research agenda.

2.5 Limitations

The project covered a large and diverse range of contaminant groups, which made it challenging to interrogate the current state of knowledge through a singular approach. Details of our approach are provided in the method section of this report. As with any project where participant recruitment is done through the professional networks of the researchers, a certain amount of bias is unavoidable: people in these networks often have similar interests to the researchers. This limitation was mitigated by sending targeted invitations to take part in the survey, which was later used to select workshop participants, to authors of the papers identified in the project's literature review.

3 Findings

3.1 Findings of the literature review

A total of 275 entries were made (Appendix IV), some of which are subgroups of the main contaminant group and some individual substances. This depended on how the literature search evolved, the type of articles returned and reviewed, and the information those articles provided. Whilst a sheet with pharmaceuticals relevant to AMR is included in the database, the broader category of pharmaceuticals is not, since a full collation of data on pharmaceuticals in Scottish waters was very recently produced (Helwig *et. al.,* 2022). It should be noted that the number of entries is therefore not an indication of the importance of the contaminant group.

Below, a brief summary is provided for each of the contaminant groups considered in the initial stages of the project. Broadly, these are ordered as follows: organic chemicals, plastics, nanomaterials, other chemicals, biological contaminants, although as noted before, common categorisations are complex and intertwined. In this report, these summaries serve to provide the reader with a broad understanding before considering the survey and workshop results.

3.1.1 Industrial pollutants

Substances with an industrial use are termed industrial chemicals. As such, there is a vast array of substances that could be termed industrial chemicals. The main industrial chemicals that act as pollutants include petroleum hydrocarbons (i.e. fuels, lubricants, and fuel combustion by-products, from oil spills or storm water run-off), volatile organic compounds (e.g. industrial solvents), paints and dyes, and persistent organic pollutants, pharmaceuticals (see section 3.1.2), and pesticides (see section 3.1.5).

Industrial chemicals associated with the fishing or aquaculture industries are directly discharged into waters. Petrochemical contamination in the sea derives from tanker operations and accidents, however, approximately 28% of the estimated world input of petroleum hydrocarbons to the sea is from river runoff, suggesting chronic pollution of freshwater (Robotham and Gill, 1989). Other industrial chemicals enter waste streams to be treated at wastewater treatment plants (WWTPs), though some may remain unchanged and are discharged in the wastewater effluents.

Both the Environment Agency and Scottish Environment Protection Agency (SEPA) monitor a wide range of industrial chemicals as part of their legal requirements. In Scotland, the Scottish Pollutant Release Inventory (SPRI) reported annual releases of specified pollutants to air and water from SEPA-regulated industrial facilities (SEPA, 2023). Data published by SEPA (2023) in the 2022 SPRI report, detail the release of approximately 82,000 tonnes of chemicals released from regulated industrial facilities into water bodies primarily chlorides and fluorides, but with halogenated organic compounds; nonyphenol and nonylphenol ethoxylates and phenols also released in the greater than 3 tonne quantities. This is compared to the release of heavy metals (just over 525 tonnes), also detailed in the 2022 SPRI report, with iron, zinc and copper released in the largest amounts[1].

Other than regulatory bodies, the most comprehensive study of release of industrial chemicals was undertaken as part of the 10-year Chemical Investigations Programme quantifying over seventy substances at more than 600 WWTPs (Gardner *et. al.*, 2022). While the mean concentrations of metals are listed in µg/l, most industrial chemicals were found at ng/l levels. Additionally, industrial chemicals are monitored when AMR is studied as co-selection of genes that confer resistance to chemical hazards (solvents, biocides or metals) are often linked with antibiotic resistance.

The ecological effects of chemicals are often measured by the application of a weighting factor such as the potentially affected fraction of species derived from species sensitivity distributions (Wang *et. al.*, 2021).

Scotland is the third largest producer of Atlantic salmon. Substances used in the aquaculture industry promote fish health and growth, including antibiotics, parasiticides, antifoulants, feed supplements, disinfectants and anaesthetics, many of which are toxic to aquatic organisms (Burridge *et al.,* 2010). Moreover, antifoulant paint particles can act as micronanoparticles, and present the same risk as other nanoparticles (see section 3.1.8), but also causes toxicity to animals from the metals contained within them, particularly Cu and Zn (Turner, 2010).

Since 1942, the Forth river has received effluent from Scotland's major petrochemical industry and refinery, as well as hydrocarbons from other sources. This has created a large residue of hydrocarbons, particularly in sediments. This has produced localised lethal effects such that productive estuarine intertidal habitat has been lost or its function altered. It has therefore become difficult to assess effects of new petrochemical discharges due to this historical contamination (Elliott and Griffiths, 1987).

Textile dyes produce toxic effects to humans through the metals contained within them, and are toxic, mutagenic and carcinogenic to animals. They also obstruct sunlight, affecting aquatic animals and the photosynthesis cycle of aquatic plants and algae (Islam *et. al*., 2023).

Industrialisation is a crucial driver of economic growth, particularly in lower income countries. Therefore, as industry expands, there will likely be an increase in industrial chemicals as pollutants. However, as evidence emerges on their effects, restrictions are likely to be made. For example, azo dyes are currently restricted in the EU due to their carcinogenic effects.

3.1.2 Pharmaceuticals and personal care products

Pharmaceuticals are an indispensable component of a healthy society establishing and maintaining a healthy population of both humans and livestock. Pharmaceuticals for human use as well as personal care products typically enter the environment via the sewer, although few data are available on other potential sources such as landfill or manufacturing effluent. Many of the products may persist through WWTP and eventually enter the aquatic environment as parent compounds, metabolites, or transformation products. Additionally, untreated effluent from combined sewage overflows may contain even those compounds that could be

[1] This data was taken from "Scottish Pollutant Release Inventory 2022 Full data" with waste discharge into water was identified based on the provided MEDIUM descriptor and the pollutant was classified as chemical, metal, nutrient or radioactive source material. As the SPRI is a register of reported annual releases of pollutants from SEPA-regulated industrial facilities, all chemicals listed in this SPRI were considered as being from an industrial source. The figures quoted are an underestimation of the total amount discharged, due to each pollutant having a threshold for reporting.

removed. Pathways for veterinary pharmaceuticals, including those used in livestock and aquaculture, are different and typically do not include a treatment step. Additionally, due to the huge numbers of companion animals (ca 21 million cats and dogs in the UK), emissions from these sources could also be an important source of diffuse water pollution (Little and Boxall, 2020).

Since the late 1990s, over 30 monitoring studies have been reported on the occurrence of pharmaceuticals in British surface waters. These studies have identified, in total, 154 active ingredients (Aus der Beek *et. al*., 2016) with the most commonly monitored classes include analgesics, antibiotics, antidepressants, anti-inflammatories, β-blockers and lipid regulators.

Designed to be biologically active, pharmaceuticals may have effects on organisms in receiving water bodies even at low concentrations (Rand-Weaver *et. al.,* 2013). Using predicted concentrations, Helwig *et al.* (2016) identified nine pharmaceuticals commonly prescribed in the Scotland that could pose a significant environmental risk, i.e. the amount present in the environment is greater than the predicted no-effect concentration values. Although the majority of these nine are antibiotics (amoxicillin; ciprofloxacin; erythromycin; flucloxacillin; ketoconazole; oxytetracycline; phenoxymethyl penicillin (Penicillin V); piperacillin and tazobactam), the evaluation was based on the overall toxicity of the compound. More recently, Helwig *et. al.* (2022) collated environmental monitoring data on 60 pharmaceutical substances found in Scottish waters, taken from a range of academic and regulatory monitoring programmes. This study identified higher ecotoxicological risks for ibuprofen, clarithromycin, erythromycin, diclofenac, 17alpha-ethynylestradiol (EE2), metformin, ranitidine, and propranolol, whilst noting that significant data gaps remain both in terms of the range of compounds and in terms of spatial coverage.

Several studies furthermore point to specific AMR risks associated with various pharmaceuticals in the UK and Scotland (Alejandre et al. 2022, Mavragani *et al.,* 2016, Helwig *et al.,* 2022). Whilst in most locations, antibiotic residues in Scottish surface waters do not exceed the threshold for driving AMR, they do so in WWTP (Helwig *et al.,* 2022), from where resistant microorganisms or genetic material could find its way into the water environment.

In UK pig production, colistin, enrofloxacin, marbofloxacin, ceftiofur, and cefquinome pose zoonotic AMR transmission risks through water and food chains (Coyne, 2016). AMR in aquaculture bacteria highlights erythromycin, with risks in Scottish shellfish hatcheries (Lane, 1997).

Triclosan, a prevalent antimicrobial agent in personal care products like soaps, is associated with endocrine disruption, AMR and environmental risks. Prolonged exposure to triclosan raises concerns about cross-resistance to clinically significant antibiotics, posing potential risks to public health. Triclosan enters the aquatic environment primarily through human activities and waste disposal during routine activities like bathing and handwashing.

3.1.3 Hormones and endocrine disrupters

Hormones and endocrine disruptors include a wide range of substances. Synthetic hormones tend to be included in studies on pharmaceuticals in the environment, but naturally occurring hormones and those from veterinary sources less so. Many non-pharmaceutical chemicals can also have endocrine disrupting effects. The distinction between natural and synthetic endocrine disruptors is blurred. Heavy metals, for example, are naturally occurring, but it is their often man-made concentration in the environment that causes effects. Risks to humans may include impacts on male reproductive health, metabolic disease and neurodevelopment (Bajard *et. al.,* 2021).

For synthetic hormones, the environmental concentrations of EE2 as found in contraceptives and hormone replacement products are often reported. However, in terms of effect, mestranol was found to have the highest contribution to the total estrogenic activity (TEA) in hospital wastewater effluent (Lopez-Herguedas, González-Gaya *et. al.,* 2023). It is noteworthy that the contribution of this synthetic hormone was almost identical to that of estrone, and that both substances together contributed 50% of the total estrogenic activity. Similarly, much of TEA in effluents and surface waters is ascribed to natural rather than synthetic hormones and, whilst their release can obviously not be controlled, it can also be the density of livestock that can lead to elevated levels of hormones in surface waters and effluents. Other synthetic hormones of environmental relevance are reported to include glucocorticoids (steroid), thyroid, androgenic (growth) and progestogenic (contraceptive) compounds.

Removal efficiency in wastewater treatment works for this group varies and even though several are reported to be well removed they still show in receiving waters (Finckh, Buchinger *et. al.,* 2022) in European rivers and an urgent need is stipulated to develop effect-based rather than compound-based trigger values in environmental monitoring, especially for the effect of mixtures of compounds. This is especially so once the effect of non-hormonal endocrine disrupting substances is also taken into account.

Among non-hormonal endocrine disrupting substances, bisphenol-A is reported as the most abundant compound in waste- and surface waters and is frequently detected, even in drinking water (Čelić, Škrbić *et. al.,* 2020; Arnold *et. al.,* 2013). Other notable groups of endocrine disrupting substances are (butyl) parabens (preservatives in cosmetics), alkyl-phenols (e.g. in detergents; including nonyl-phenols which even though banned still show in environmental samples), phthalates (plastic softeners), some pesticides and polychlorinated biphenyls, and citalopram and alprazolam (anxiety treatment). The latter demonstrate the often multi-effect characterisation of some substances, which could be seen as endocrine disrupting alongside having other (desired or undesired) biological effects. As a use-related category, flame retardants also deserve a mention. As previous formulations were increasingly recognised as persistent organic pollutants (POPs), so-called replacement flame retardants (RFR) have emerged, with large numbers of chemically diverse substances commercially available (Bajard *et. al.,* 2021). Various adverse effects relating to reproductive and other outcomes have been reported (ibid.), although for human exposure, the water environment may not be the most relevant environmental medium as, for example, house dust is also a pathway.

Particularly for the endocrine disrupting effect of mixtures of pollutants, the classical approach of single-substance (ecotoxicological) risk assessment has been questioned (e.g. Gosset, Polomé *et. al.,* 2020) and elevated mixture risk quotients (RQ) highlighted of particular concern for medium sized waste water treatment plants releasing into small streams, with climate change increasing this potential.

Vitellogenin is an established biomarker for estrogen exposure that has also been proposed as a biomarker for exposure to mixtures of endocrine disruptors (e.g. Müller, Markert *et. al.,* 2020; Zezza, Bisegna *et al.,* 2020)

3.1.4 Per- and polyfluoroalkyl Substances (PFAS)

Per- and polyfluoroalkyl substances (PFAS) are a class of thousands of synthetic chemicals that are used throughout society. Many PFAS are known to be mobile and persistent and have been associated with human health conditions and negative environmental impacts (Brunn *et. al.,* 2023; Sebe *et. al.,* 2023; Sunderland *et. al.,* 2019). They are frequently found in food (Roberts, McNaughtan, and de las Heras Prieto 2023), readily absorbed into the body and the foetus, implicated in several cancers, hepatic damage, endocrine-system dysfunction (e.g., thyroid and fertility problems), and are known to suppress antibody response (Fuller *et. al.,* 2022).

These substances have numerous domestic and industrial uses, for example, fast food wrapping, cosmetics, coatings, paints, medical devices and metal manufacturing (Glüge *et. al.,* 2020). Most PFAS were designed to be chemically robust and heat resistant with perfluorooctanoic acid (PFOA) and perfluoroctane sulphonic acid (PFOS) having environmental half-lives of decades (EU Commission 2017).

PFAS are from approximately 40 different chemical families (Buck *et. al.,* 2011) and US EPA have listed over 14,000 different compounds containing fluorine to date (US EPA 2022). Due to the number and diversity of these compounds, even using several different sophisticated analytical techniques many PFAS cannot be identified or quantified, therefore there is a gap in knowledge regarding the extent of this pollution.

PFOA, PFOS and perfluorohexane sulphonic acid (PFHxS) have not been commercially produced in Europe for over a decade as they were added to the Stockholm Convention list for restricted use (UNEP 2023). Despite this, they still have the potential to reach the environment from, for example, landfill leachate which contains legacy chemicals from discarded paper, furniture and textiles.

Confining these pollutants is now impossible and they have been found in formerly pristine parts of the world far from where they were manufactured or used. This has created an immense environmental challenge which does not respect national boundaries.

3.1.5 Pesticides

Environmental effects of pesticides have been in the public eye ever since Rachel Carsons published 'Silent Spring', in 1962. Whilst many pesticides are already covered by existing regulation, new developments, new insights into effects, and changing usage including due to regulatory changes mean that this contaminant group continues to include emerging contaminants. Pesticides have also been implicated in driving AMR (Qiu *et.. al.*, 2022). The term pesticides is broad and can be taken to include herbicides, fungicides, insecticides, acaricides, molluscicides, plant growth regulators and repellents (European Food Safety Authority, 2023). These comprise many chemical classes, including organochlorides, organophosphates and pyrethroids.

Pesticides are generally toxic to both target and non-target organisms. Different classes differ in their persistence in the environment and toxicity, but several studies have indicated toxic levels in UK rivers (Poyntz-Wright *et. al.*, 2024; Perkins *et. al,* 2021). In water environments, herbicides have been shown to affect phytobenthic communities (Biggs and Stevenson, 2023), whilst insecticides affect invertebrate communities (Poyntz-Wright *et. al.,* 2024). Birds also suffer toxic effects (Tassin de Montaigu and Goulson, 2020), although not necessarily via the water environment, and are further impacted due to a reduction in food supply.

Whilst the total weight of pesticides has decreased significantly over the past 25 years, a much larger area is now treated (Tassin de Montaigu and Goulson, 2020). A recent passive sampling study in the South of England found 128 pesticides, of which 61 were prioritised by the authors for inclusion in future risk assessment (Taylor *et. al.,* 2021). Pesticide metabolites are commonly found in groundwater in the UK (Stuart *et. al.,* 2012). In the Netherlands, pesticides were detected in the majority of drinking water sources (Sjerps *et. al.,* 2019), including a number of recently authorised pesticides, amongst these acetamiprid and thiamethoxam, both neonicotinoids. In Scottish studies in the River Ugie, chlortoluron, metaldehyde, isoproturon, and atrazine were the dominant pesticides found, although only a small number were analysed (Cui *et. al.,* 2020). Seasonal variation was also observed.

Aside from agricultural use, aquaculture may be particularly relevant to Scottish water environments. Strachan and Kennedy (2021) identified localised risks to non-target organisms when recommended concentrations were used. A number of recent UK papers have further identified widespread contamination in rivers associated with veterinary flea products, used on cats and dogs, including fipronil and imidacloprid (Perkins *et. al.,* 2021).

Pathways into the environment depend on the source and type of pesticide, and may include direct entry (e.g. from aquaculture), as run-off or spray drift (from products used on crops), via soil (livestock), and via the sewer (veterinary flea products).

Mixture effects for pesticides are particularly relevant for the aquatic environments, where chemicals from a range of sources combine.

3.1.6 Food additives

Food additives are substances that are not normally consumed as a food by themselves but are added to food to enhance flavour, freshness, appearance, taste, texture or to preserve quality attributes. They therefore include substances such as flavourings, preservatives, antimicrobials, food colourants, emulsifiers and chelating agents.

Food additives enter the environment from wastewater effluent. Although many food additives can be degraded during wastewater treatment, some are consumed in such vast quantities that the concentrations overwhelm treatment processes and are discharged in wastewater effluent, resulting in ‘pseudo-persistence’ in the environment. From here, they can be transported through surface water to coastal or seawater.

The risks associated with food additives depends on the substance. In humans and animal models, effects have been measured through ingestion rather than dermal exposure. Titanium dioxide is a white pigment used to make food look brighter. Since it is a nanoparticle, it presents the same risk as other nanomaterials (see section 3.1.8), including inflammation, genotoxic effects and accumulation in organs in both humans and animals. It also has detrimental effects on soil fertility, plant growth and crop yield (Baranowska-Wojcik *et. al.,* 2020, Dedman *et. al.,* 2021). Some sweeteners alter the gut microbiome and cause migraines and vomiting in humans, while also being toxic to invertebrates, fish and rat models. In plants, there is evidence that it can be absorbed and increase chlorophyll production, which has both positive and negative effects (Praveena *et. al.,* 2019). Emulsifiers, antimicrobials, and synthetic food colourants have been shown to modify the gut microbiome and cause intestinal disorders in both humans and animal models (Cox *et. al.,* 2021, Mwale, 2022). Caffeine is toxic to clams, sea urchins, hydra and zebrafish (Korekar *et al.,* 2020). Ethylenediaminetetraacetic acid (EDTA), used as a chelating agent, is toxic to fish, and re-mobilises heavy metals, which are further environmental pollutants (Knepper, 2003).

For some food additives, particularly sweeteners, there is no evidence that current concentrations found in the environment can harm biodiversity or ecosystems, but it cannot be assumed that this will continue to be the case. A study showed that ultra-high processed foods (typically high in food additives) are increasing globally (Baker *et. al.,* 2020), which is likely to see an increase in food additives as environmental pollutants. The effects this will have on the environment remains to be seen.

3.1.7 Microplastics

Microplastics, minute plastic particles less than 5mm in size, have emerged as a prevailing environmental concern due to their ubiquitous nature (they have been found in almost all environments), but whether they impact the environment is still debated by researchers (Burns and Boxall, 2018). Microplastics are as broad as chemicals; there are over a thousand different chemicals and over a thousand different microplastics. Primary microplastics are intentionally produced (e.g. for cosmetics), while secondary microplastics result from degradation of larger pieces of plastic. There are three types of degradation: physical, chemical and biological. The type of polymers that constitute the microplastic and their morphologies will determine how fast it can biodegrade or photo-degrade. For microplastics to naturally degrade, polymers should be water-loving (hydrophilic) rather than hydro-phobic.

A particular focus on smaller sized 'micro(nano) plastics' (MNPs; ~<100 µm) is important as they have been found to affect the water and nutrient absorption capacities of plants, altering rhizosphere communities (Chen *et. al.*, 2022), and have the ability to cross through cell membranes and enter the food chain.

MNPs can enter surface waters from various sources and pathways (e.g. storm water runoff, wastewater effluent release, agricultural runoff, industrial spills), depending on plastic usage. Within aquatic systems, denser polymer types (e.g. Polyethylene Terephthalate (PET); Polyvinyl Chloride (PVC)) are expected to sink more readily than lighter plastics (e.g. Polyethylene (PE); Polypropylene (PP)) (Rochman *et. al.,* 2019). Although it is widely accepted that freshwater systems serve as mere pathways for transport of MNPs to oceans, recent research suggests that MNPs can persist in rivers with extended residence times, implying that rivers may act as long-term sinks for MNPs. During dry seasons, MNPs continue to degrade, whereas wet seasons lead to resuspension of sediment-bed-trapped MNPs (Allen *et. al.,* 2022).

MNPs have the potential to modify the physical and chemical attributes of soil, including soil density, porosity, nutrient adsorption, and toxin release. These alterations can impact the soil's microorganisms. Microbes utilise MNPs as substrates for propagation, facilitating the transmission of pathogens, prompting recent studies to concentrate on AMR transmission. Additionally, microorganisms possess the ability to biodegrade MNPs through their enzymatic activities (Grande-Tovar, 2022).

Gallo *et. al*., (2018) called for urgent preventative measures, arguing that whilst knowledge gaps remain, there is no doubt that micro and nano-plastics play a role in exposing marine organisms to a wide range of contaminants, including EDCs, throughout the food chain.

Since 2012, there has been a consistent growth in research focusing on the impacts of MNPs on various biota. However, a substantial portion of these studies has been conducted in controlled laboratory conditions. The insufficient number of studies conducted in real environmental conditions hampers a comprehensive understanding of MNP effects, exacerbated by the absence of standardized techniques for their identification. Notably, MNP research is now extending its scope to consider trophic transfer and their implications in the food chain. Recognizing that MNPs comprise diverse polymers with various morphologies and additives, it is crucial to regard them as a diverse collection of substances rather than a singular entity. This recognition is important for making informed policy decisions and for developing effective mitigation strategies.

3.1.8 Nanomaterials

A nanomaterial (NM) is defined as having at least one dimension of 1 – 100 nm, whilst a nanoparticle (NP) has all dimensions in this range. NMs and NPs behave very differently to the bulk materials due to surface and quantum effects, which can enhance the mechanical, thermal, magnetic, electronic, optical and catalytic properties. NMs are used in a wide range of applications, including bioremediation, building materials, analytical technologies, medicinal applications, targeted drug delivery, intelligent food packaging, food additives, sunscreen, cosmetics, and inks. There are naturally occurring NMs and also engineered nanomaterials (ENM) which are sometimes distinguished as a subgroup (Colvin, 2003).

There are three general groups of NMs (Joudeh and Linke 2022)

1. Organic, such as proteins, carbohydrates and lipids. An example is ferritin, which is a natural protein found in blood.
2. Carbon NMs, which are made entirely from C atoms. Examples are fullerenes, quantum dots and carbon nano-onions.
3. Inorganic NMs, which are metallic or ceramic. They consist of single metals, alloys and can be bimetallic or polymetallic. The ceramic NMs are metal carbonates, phosphates, carbides and oxides.

A 2014 CREW report (Hartl *et al.,* 2014) found that substantial knowledge gaps at every stage of the lifecycles of NP made risk assessment extremely challenging. This is in part due to the diverse range of chemistries and small size of NMs making them difficult to isolate, detect and quantify in environmental matrices. Whilst concerns about substances in this diverse group were first raised several decades ago, these ongoing uncertainties justify their inclusion here as contaminants of increasing concern.

Organic NMs are considered biodegradable and carbon NMs break down after several months (USEPA 2010). However, inorganic NMs are considered persistent and can have negative impacts on ecosystems (Whiteley *et al.,* 2013; Horie and Tabei, 2020). The environmental impact is also influenced by the chemical composition and chemical and physical properties of the NMs (Horie and Tabei, 2020, Baker *et al*., (2014), Marcelo-Silva *et al.,* 2019). The use of NMs generally is predicted to increase (Jones *et. al*., 2014). A frequently mentioned effect is that NPs are known to cause oxidative stress by inducing Reactive Oxygen Species (ROS) formation (e.g. Whiteley *et al.,* 2013; Horie and Tabei, 2020). However, not all NPs cause ROS and both chemical composition and chemical and physical properties play a role (Horie and Tabei, 2020). A review by Baker *et. al*., (2014) identified a much wider range of effects, including cell membrane damage; reduced growth; mortality; impaired embryo development, to name but a few, in various phyla and classes including bacteria, algae, arthropods, annelids, echinoderms, bivalves, and teleosts. The studies reviewed also reported accumulation, particularly in the latter two groups, and transfer from protozoans to rotifers. Trophic effects in coastal environments are still under-researched (Marcelo-Silva *et. al.,* 2019).

3.1.9 Chemical mixtures

Toxicity assessments for chemicals have traditionally focused on individual substances when establishing regulatory limits. However, human and aquatic organism exposure in real-life scenarios involves continuous contact with complex chemical mixtures from both the environment and food sources. Therefore, regulatory authorities are increasingly realising the need for cumulative risk assessments for chemical mixtures. Often, exposures involve multiple chemicals at doses near or below the regulatory limits set for individual substances.

One of the main challenges currently is lack of suitable toxicological data for chemical mixtures. This deficiency is linked to limitations in standardised testing protocols, which are hindered by various challenges. These challenges include complexity of grouping chemicals for exposure studies, determining whether their effects are dose-additive or synergistic-antagonistic and addressing the extensive number of potential combinations and variations in exposure scenarios.

The development of practical frameworks for the human risk assessment of chemical mixtures is an evolving field. While various protocols have been published for how to assess risks of chemical mixtures, no consensus has been reached (Tsatsakis *et. al*., 2016). Studies are ongoing to understand the interactions between different chemicals, their combined effects, ways to group chemicals and exploring methodologies to assess risks associated with exposure to chemical mixtures. Boberg *et. al.* (2019) have proposed a methodology that combines in-vivo and in-vitro data or assessing the effects of chemical mixtures where available. In instances where data is lacking, they suggest the use of computational methods such as Quantitative Structure-Activity Relationship (QSAR) models, to predict toxicities and to group chemicals in the absence of experimental data.

3.1.10 Cyanotoxins

Cyanotoxins are produced by cyanobacteria (blue-green algae) and are found in marine and freshwater environments with high phosphorus concentrations (Turner *et al.,* 2018). Cyanobacteria can rapidly reproduce to form algal blooms (Filatova *et. al.,* 2021). Blooms can produce cyanotoxins at a level that is harmful to plants, animals and humans (Svircev *et. al.,* 2017). They are also able to accumulate in organisms such as shellfish. Potential routes of exposure to cyanotoxins can include injection, skin contact, inhalation and ingestion (via drinking water or accidentally via recreational activity) (Turner *et al.,* 2018).

Five main cyanotoxins were identified in the literature search: microcystins (cyanoginosins), anatoxins, cylindrospermopsin, saxitoxins and nodularins. Microcystins are the most commonly found and researched cyanotoxins with over 250 currently identified (Svircev *et. al.,* 2017). Microcystins are produced by multiple cyanobacteria genera, including *Microcystis, Dolichospermum Planktothrix, Nostoc, Oscillatoria*, and *Anabaenopsis* (Filatova *et. al.,* 2021). These can be found in both fresh and salt water. In mammals (including humans) these toxins can be hepatotoxic, neurotoxic, genotoxic and tumerogenic (Turner *et. al.,* 2018). Cases of microcystin intoxication are not common within the UK and normally occur in animals such as dogs and sheep (Evans *et. al.,* 2016). Acute contact with microcystins produced by the cyanobacteria, *Microcystis aeruginosa*, has been recorded in the UK as inducing symptoms such as malaise, mouth blisters, coughing, pleuritic and abdominal pain, vomiting, diarrhoea, confusion, hallucinations and in some cases pneumonia (Svircev *et. al.,* 2017). Widespread intoxication of humans has not yet occurred within the UK, however this remains a possibility in the future (Turner *et. al.,* 2018).

The most common and widely researched of the anatoxins is anatoxin-a. Anatoxin-a is predominantly produced by the cyanobacterial genus *Anabaena*, but also, *Planktothrix*, *Oscillatoria*, *Microcystis, Aphanizomenon, Cylindrospermum,* and *Phormidium*. Anatoxin-a is a potent neurotoxin which can cause lethal cardiac or respiratory arrest in humans and animals (Wood, 2016, Filatova *et. al.,* 2021, Svircev *et. al.,* 2019).

Cylindrospermopsin is produced by the genera *Cylindrospermopsis*, *Aphanizomenon, Anabaena,* and *Lyngbya*. This cyanotoxin is a cyclic guanidine alkaloid which can negatively affect the liver, kidneys, thymus and heart of both humans and animals (Filatova *et al.,* 2021) and cause genotoxic effects (Wood, 2016). Intoxication with cylindrospermopsin can present with nausea, vomiting, bloody diarrhoea, headaches and dehydration (Svircev *et. al.,* 2019).

The cyanotoxins, saxitoxins and nodularins are less studied and recorded than microcystins, anatoxins and cylindrospermopsin (Svircev *et. al.,* 2017). Saxitocin acts as a neurotoxin in both humans and animals causing symptoms such as numbness in the mouth, arms and hands, respiratory difficulty breathing and muscle paralysis, which can lead to death (Svircev *et al.,* 2019). These cyanotoxins can be produced by the cyanobacterial genera *Aphanizomenon, Lyngbya, Planktothrix, Phormidium, Scytonema, Geitlerinema, Raphidiopsis, Cuspidothrix* and *Cylindrospermopsis* (Svircev *et. al.,* 2019). Nodularins are carcinogenic hepatotoxins produced by the genera *Nodularia* and *Nostoc* (Svircev *et al.,* 2019).

3.1.11 Invasive species

Invasive species are species that are not native or indigenous to an area but have managed to colonise to a level that is detrimental to the environment. They can emerge in a new environment due to activities such as global trade, accidental release or purposeful release (e.g. rhododendron). Invasive species can cause the extinction of native species affecting biodiversity and can also lead to a change of the indigenous habitat. It should be noted that some non-native species cause no harm to their new environment or in some cases are beneficial, filling lost ecological niches. Only harmful non-natives will be focused on in this report.

In terms of plants, one of the more well-known invasives is Japanese knotweed (*Reynoutria japonica*) which was introduced as an ornamental garden plant in the UK in the late 1800s (Moore, 2021). It is widespread and difficult to control costing the economy an estimating £166 million per year (Williams *et. al.,* 2010). Water primrose (Ludwigia peploides) is an emerging invasive species in the UK; currently it only occupies a small number of sites in England in Wales, however it is capable of rapidly spreading (Eschen *et al.,* 2023) and causes huge problems for native wildlife and creates flooding issues in France (Thouvenot *et al.,* 2013). Like water primrose, floating pennywort (*Hydrocotyle ranunculoides*) is an escaped garden pond plant. Floating pennywort grows rapidly forming dense mats which are a danger to humans and animals, both by looking like a solid surface and by blocking out light and reducing oxygen for aquatic organisms. Furthermore, floating pennywort inhibits leisure activities on lakes and ponds (Moore, 2021). Similarly, parrot feather (*Myriophyllum aquaticum*), stonecrop (*Crassula helmsii*) and water fern (*Azolla filiculoides*) also create dense mats which block out light and oxygen for aquatic organisms (Moore, 2021).

As for animals, the Asian native, topmouth gudgeon (*Pseudorasbora parva*; a freshwater fish), is an emerging invasive species in UK waterways, although it is currently restricted to England

and Wales. The topmouth gudgeon breeds very quickly and feeds on young fish and eggs, and spreads disease to native fish (Robinson *et al.,* 2019). The carpet sea squirt (*Didemnum vexillum*) is an emerging marine invasive in the UK, and has currently only been identified in two locations in Scotland, Largs marina and Loch Creran. It grows quickly, smothering reefs as well as scallop, oyster and muscle beds. It also covers boat hulls and fishing equipment causing issues for fishermen (Matejusova *et. al.,* 2021). *Boccardia proboscidea*, a polychaete worm is found in temperate sea waters where it threatens biodiversity and outcompetes native species (Radashevsky *et al.,* 2019). The quagga mussel (*Dreissena rostriformis bugensis*) clogs equipment and water treatment pipes, and impacts benthic communities (Mills *et. al.,* 2017). Currently restricted to southern England, the Asian date mussel (*Arcuatula senhousia*) outcompetes other bivalves, inhibits the growth of seagrass and causes sediment and substrate shifts altering the physical ecosystem (Watson *et. al.,* 2021). Finally, the American lobster (*Homarus americanus*) is not yet established in the UK but could arrive and become invasive with global trade and climate change. The American lobster hybridises with native European lobsters (*Homarus gammarus*) and has a competitive advantage as it is larger and more aggressive (Barrett *et. al.,* 2020).

Invasive species can be managed through active control measures such as destruction of the non-native plant or animal, and by cutting off or disrupting pathways into a new area if possible.

3.1.12 Pathogens

Pathogens which negatively impact humans, animals and plants are ubiquitous and found in all environmental compartments, including marine and freshwater. Exposure to pathogens in the marine and freshwater environment can occur though skin contact (with or without a break in the skin barrier), injection, inhalation or ingestion (via drinking water or accidentally via recreational activity).

Seventeen human pathogens were identified as being of significant or serious concern in waters, including *Escherichia coli* (bacteria), *Cryptosporidium parvum* (protozoa) and norovirus (virus) (Avery *et. al.,* 2023). Of these eight were also considered animal pathogens, including *Campylobacter spp.* (bacteria), *Aliarcobacter butzleri* (bacteria) and *Rhizomucor pusillus* (fungi). Only three plant pathogens were identified in the high-level literature review, *Xanthomonas spp.* (bacteria) (Alegbeleye *et. al.,* 2018), Pseudomonas syringae (bacteria) (Alegbeleye *et al.,* 2018) and pepper mild mottle virus (PPMoV) (virus) (Kitajima *et al.,* 2018). PPMoV is not yet in Scotland/UK but is present in Europe and can also be used as a water quality indicator for identifying the presence of human faeces.

In the UK and Europe bathing water is tested for *E.coli* and intestinal *Enterococci* during the bathing season and enteroviruses, faecal *Streptococci* and *Salmonella spp*. if suspected to be an issue (Avery *et. al.,* 2023) (European Commission, 2006; European Commission, 1975). Surface waters are tested for total coliforms, faecal coliforms, faecal *Streptococci* and *Salmonella* throughout the year (European Commission, 1979; Avery *et. al.,* 2023).

Water for a private supply may be tested[1] for total coliforms, faecal coliforms, faecal *Streptococci* (Enterococci) and sulphite-reducing Clostridia prior to source exploitation (European Commission, 1980; Avery *et. al.,* 2023). In Scotland, *Enterococci* and *E. coli* (a sub-group of faecal coliforms) are used (The Water Intended for Human Consumption (Private Supplies) (Scotland) Regulations 2017). Mains water, which is routinely disinfected, is tested for *Enterococci* and *E.coli* at the time of distribution, as well as for *Cryptosporidium* and *Clostridium perfringens* (and any other issues of concern) if a risk assessment deems it necessary due to the origin of the water. If the water is to be sold in bottles, testing for *Pseudomonas aeruginosa* also takes place (Avery *et. al.,* 2023; European Commission, 2020).

During the literature review no evidence was found that waters are monitored specifically for plant or animal pathogens, although it should be noted that some crossover exists between animals and human pathogens. Furthermore, no UK government policies were found which detailed the monitoring or control of plant or animal pathogens in marine or freshwater.

[1]In Scotland, Private Water Supplies that provide less than 10 m^3 of water a day (as an average); serve fewer than 50 persons, and do not provide water as part of, or on premises used for, a commercial or public activity, are exempt from The Water Intended for Human Consumption (Private Supplies) (Scotland) Regulations 2017 and do not require to be tested at all.

3.1.13 Antimicrobial resistance

AMR means that bacteria, viruses, fungi and parasites no longer respond to antimicrobial medicines. A natural phenomenon, exacerbated by human activities such as overuse of antibiotics (Sweileh, 2021), AMR is a critical global environmental pollution issue (Stanton *et al.,* 2022) costing £1.5bn per year in healthcare and productivity losses (Sweileh, 2021).

Genes coding for resistance to antimicrobials (ARGs) are acquired or develop when selected for by the presence (even at low concentrations) of antimicrobial pharmaceuticals (e.g. antibiotics, antifungals, anti-helminthics) but it can also develop due to the presence of "co-selectors" such as heavy metals, personal care productions, and even pesticides. Little is known about how mixtures of these chemicals interactively influence AMR.

AMR enters waters from the following sources (derived from Pagaling *et. al.,* 2023, Wojcik *et al.,* 2024): faeces (human, livestock or wildlife); naturally present resistant bacteria in soils, sediments and biofilms; and indigenous microorganisms impacted by chemical drivers.

Wastewater treatment is not designed to remove ARGs (Stanley *et. al.,* 2022), thus sewage via treated wastewater (mains sewage), combined sewer overflows or septic tank outflows are pathways via which AMR reaches water courses. Other potential exposure pathways include agricultural activities, such as run-off from slurry, manure or digestate or livestock access to watercourses. Human exposure can arise from contaminated fruit and vegetables (mixed findings) air, animals, sediment, soil, and water, via ingestion, direct contact and inhalation (Stanton *et. al.,* 2022).

The presence of clinically relevant antimicrobial-resistant bacteria (ARB) and ARGs in the environment is widely reported and prevalence varies depending on levels of pollution (Stanton *et. al.,* 2022). Despite water being the most investigated environmental matrix for AMR, Meier (2022- cited by Wojcik *et. al.,* 2024) concluded that there is a "fragmented and incomplete understanding of AMR acquisition, diversity, and the interspecies spread between humans, animals and the environment". Transfer of ARBs and ARGs between humans, animals and environment is understood to be common but health outcomes are difficult to quantify (Larsson and Flach, 2022 cited by Wojcik *et al.,* 2024) and clear evidence of direct transmission to humans is limited, not least because infection can occur long after exposure and subsequent colonisation. Wojcik *et. al.,* (2024) didn't identify any Scotland-specific evidence on this. Some but not the majority of resistant *E. coli* strains found in clinical and food samples cross over with strains found in environmental samples (Day *et. al.,* 2019 & PATHSAFE; cited by Wojcik *et. al.,* 2024).

Avery et al (2022) noted that there is currently no baseline for AMR in Scotland's waters, and yet we know that ARGs can enter the gut microbiome through recreational water use (Leonard *et al.,* 2022). Further, SEPA detected cefotaxime resistant-*E. coli* in 50-78% of bathing waters, although less than 1 % of *E. coli* tested were found resistant to this antibiotic. ARBs have been isolated from tap water (Bridle *et al.,* 2022) and private water supplies (which likely pose a greater risk of exposure to AMR than public supplies) (Wojcik *et al.,* 2024). Combined Sewer Overflows (CSO), treated wastewater, and agriculture are considered key sources of ARGs and ARBs, but their relative contributions and the contributions of wildlife, including birds and pet animals, are poorly understood (Wojcik *et. al.,* 2024). Some of the risk factors that are more specific to Scotland include the prevalence of Private Water Supplies and septic tanks, aquaculture activity, and run-off from the agricultural land use dominating many areas.

3.2 Policy summary

The focus of this research project was CICs present in the water environment. For many substances, regulatory controls apply directly to natural water environment, for example by setting maximum allowable concentrations, or by controlling their release, via effluent limit values. A much broader set of regulations, however, controls the use of the substances, which therefore also has potential to reduce their presence and impact in the environment. The main applicable provisions have been included below.

3.2.1 Chemicals policy and regulation

In Scotland, the overall regulatory context for chemicals is provided in SEPA's Chemical Framework (SEPA, 2022). It acknowledges the benefits of chemicals and proposes to work in partnership with business and industry to discourage the use of harmful products. Specifically mentioned are plastics pollution, AMR and EDC. Specific regulations, however, are largely still derived from EU provisions that were transposed into Scottish policy.

The initial Priority Substances Directive in 2008, established as part of the requirements of the Water Framework Directive, produced a list of 33 Priority Substances for surface water and their associated Environmental Quality Standards. These concentrated on metals, pesticides and organic industrial chemicals. This list was extended to 45 Priority Substances under the amendment made in 2013. For many other substances it was not clear whether they posed a risk, as insufficient monitoring data was available. This led to the further introduction in 2015 of the first Watch List, designed to address chemical of emerging concern (CEC). This Watch List is revised every three to four years and outlines substances for European Union-wide monitoring. The List refers to different CECs: antibiotics; synthetic and natural hormones; pharmaceuticals and "newer" pesticides such as the neonicotinoids. None of the chemicals on the various Watch Lists have yet been transferred to the Priority Substances list, but the European Commission (2022a) has proposed to significantly expand the list of Priority Substances with 23 new substances and substance groups. Five substances and substance groups are also proposed for groundwater management. Furthermore, several generic sum-EQS values have been proposed and various effect-based provisions are being considered, although these are still explorative (Backhaus, 2023).

In line with WFD provisions, 'Specific Pollutants' are identified for Scotland in WAT-SG-53 (SEPA, 2020).

The proposed revision of the Urban Wastewater Treatment directive indicates that there will be additional monitoring activities and advanced treatments required for micro-pollutants (pharmaceuticals and personal care products mentioned), microplastics and antimicrobial resistant genes and organisms. The redraft considers that by 2040, when all measures are expected to be in place, the toxic load of micro-pollutants would be reduced by 77,4 million population equivalents (p.e.). Overall, the limits for CECs in wastewater discharge or water bodies are still not regulated.

Generally, chemicals are covered by The Registration, Evaluation and Authorisation of Chemicals (REACH) Regulation, concerned with the registration of chemicals and their authorisation for placement on the European Market. Detailed regulations apply to specific groups of chemical and are covered below.

3.2.2 Pharmaceuticals and personal care products

As pollutants that enter the environment primarily via sewage, provisions such as the Water Environment (Controlled Activities) (Scotland) regulations 2012 and the Pollution Prevention and Control (Scotland) Regulations 2021 provide a general framework for controlling and monitoring the release of pharmaceuticals and personal care products (PPCP) into the environment. Pharmaceutical substances have been included on various iterations of the Watch List, including diclofenac (removed again in 2018); the hormones EE2, 17beta-Estradiol (E2), and estrone (E1); as well as the antibiotics amoxicillin, ciprofloxacin, and macrolides (erythromycin, clarithromycin, and azithromycin). No pharmaceuticals are currently regulated in the UK water environment. A common ingredient in personal care products, the antimicrobial agent triclosan is a WFD UK Specific Pollutant; it is banned in the EU but not in the UK.

The 2019 EU Strategic Approach to Pharmaceuticals indicates interest in preventative approach such as guidance for 'green' prescribing and green(er) chemistry. In the EU, veterinary pharmaceuticals have had to complete an environmental risk assessment prior to being authorised by the European Medicines Evaluatory Authority (EMEA, now European Medicines Agency (EMA)) since 1992. Since 2006, new human medicines have to complete a similar process as part of their marketing authorisation, although environmental risks do not weigh in the authorisation decision. Furthermore, it has long been acknowledged that a gap remains for human pharmaceuticals authorised prior to 2006, which has only partially been filled by academic research. The 2019 Strategic Approach notes the relevance of pharmaceutical pollutants to AMR and references the One Health approach, which emphasises the links between human, animal and environmental health.

Significantly, as part of the European Green Deal, the European Commission identified that 92% of toxic micropollution derives from pharmaceuticals and cosmetics (European Commission, 2022a) and proposed a new Extended Producer Responsibility (EPR) scheme as part of the recast Urban Waste Water Treatment Directive (UWWTD), which means producers will be liable for the costs of removing these. A provisional political agreement to adopt this proposal, with producers responsible for 80% of treatment costs, was reached in January 2024 (Council of the EU, 2024). This application of EPR in the field of water policy is new, with potential far reaching consequences for other pollutants.

In the UK, medicines are authorised by the Medicines and Healthcare Products Regulatory Agency (HRA). In Scotland, also relevant in this context are the National Clinical Strategy for Scotland, the Realistic Medicine strategy, and Achieving Excellence in Pharmaceutical Care – A strategy for Scotland (Alejandre *et. al.,* 2022). The Cosmetic Products Regulation is responsible for ensuring that chemicals used in cosmetics are safe for consumers. To our knowledge extension of the EPR concept to the field of water policy has not yet been proposed in UK regulation.

3.2.3 Endocrine Disrupting Substances

In 1999, an EU Community Strategy for Endocrine Disrupters was adopted (Commission of the European Communities, 1999), which led to significant research funding over the next 25 years. Specific criteria for identifying EDCs were included in the pesticides and biocides legislation, medical devises, and through biological quality indicators in the Water Framework Directive. Under REACH, some EDC substances require special authorisation and others have been placed on a candidate list (European Commission, 2018). Other substances have been constrained due to safety concerns, for example through concentration limits in products containing certain phthalates and a ban on the use of bisphenol A in certain products with (European Commission, 2018a). Several are also included as Priority Substances and, as mentioned, the Watch List contains a number of hormones.

The recast Drinking Water Directive limits Bisphenol A and also establishes a drinking-water specific Watch List, on which nonylphenol and E2 have been placed (European Commission, 2020). In Scotland, a standard of 2.5 µg/l (measured at the consumer's tap) applies Bisphenol A under The Public Water Supplies (Scotland) Amendment Regulations 2022.

3.2.4 Per- and polyfluoroalkyl substances (PFAS)

PFAS fall within the scope of UK REACH, and restrictions are currently in place for three PFAS substances: PFOA, PFOS, PFHXs, and their salts. More recently under the auspices of UK REACH, the Health and Safety Executive (HSE) published a regulatory management options analysis in April 2023 with recommendations to limit the use of PFAS-containing foams used by firefighters to put out fires, as well as the use of PFAS in textiles, furniture, and cleaning products. At the same time, the European Chemicals Agency (ECHA), on 7 February 2023, proposed a "universal" restriction on around 10,000 per- and polyfluoroalkyl substances with each PFAS in the scope of the proposal considered very persistent in the environment.

Certain PFAS are banned as a result of restrictions on the manufacture, sale and use of products containing POPs. POPs are regulated internationally under the Stockholm Convention and the Aarhus Protocol and via the UK's The Persistent Organic Pollutants Regulations (2007). Perfluorooctane sulfonic acid and its derivatives (PFOS) have been restricted in the EU since 2000 under the EU's Persistent Organic Pollutants (POPs) Regulation. PFOA, PFOS, their salts and related compounds were added in 2020; PFHxS, its salts, and related compounds in 2023.

There are currently no statutory standards for PFAS in drinking water England and Wales, nor is there a World Health Organisation guideline value. However, the Drinking Water Inspectorate (DWI) issued advise to water companies in England and Wales "that a guidance limit of 0.1 micrograms per litre for PFAS is a robust level with an appropriate margin of safety to ensure the wholesomeness of drinking water."

The only PFAS currently listed as a Priority Substance is perfluorooctane sulfonic acid and its derivatives, but a sum-EQS approach for PFAS is now proposed (European Commission, 2022a). The recast of the EU Drinking Water Directive, which took effect on 12 January 2021, includes a limit of 0.5 µg/l for total PFAS. A subset of the 'PFAS Total' substances considered a concern as regards to water intended for human consumption and described as "Sum of PFAS" was set at a lower level of 0.1 µg/l. The Scottish Government transposed the rDWD. In guidance to Scottish Water, the Drinking Water Quality Regulator (DWQR) notes that the Public Water Supplies (Scotland) Amendment Regulations 2023 stipulates a standard for the 'Sum of PFAS', which should not exceed 0.1µg/l at consumers' taps. Additionally, action is required if any of the listed individual 20 PFAS exceed 0.01 µg/l, as per a tiered system depending on the PFAS concentration encountered (DWQR, 2022).

3.2.5 Pesticides

In surface waters, various pesticides are already controlled as Priority Substances. The 2022 proposal (European Commission, 2022a) to expand this list suggests the addition of triclosan[2], nicosulfuron, glyphosate, neonicotinoids, and pyrethroids, with a quality standard also set for the total of active substances in pesticides (Halleux, 2023). The Groundwater Directive also controls some pesticides, their metabolites and degradation products. The WFD Watch List currently contains the pesticides imazalil, ipconazole, metconazole, penconazole, prochloraz, tebuconazole and tetraconazole) and the fungicides famoxadone and dimoxystrobin (European Commission, 2022b). Directive EU 2009/128 EC provides a framework for the sustainable use of pesticides.

Pesticides are regulated through various provisions, depending on their use category. In the UK, The Official Controls (Plant Protection Products) Regulations 2020 govern pesticide use on crops. These apply to any business involved in the production, storage or distribution of Plant Protection Products, as well as business users. Regulation (EU) No 528/2012 of the European Parliament and of the Council concerning the making available on the market and use of biocidal products, as amended by The Biocidal Products (Health and Safety) (Amendment) Regulations 2022 and the Biocidal Products (Health and Safety) (Amendment and Transitional Provision etc.) Regulations 2024, covers a broader range of products, such as wood preservatives and insect repellents. Veterinary medicines, which include certain pesticides, are controlled via The Veterinary Medicines and Residues (Amendment) (EU Exit) Regulations 2020. The Water Environment (Controlled Activities) (Scotland) Regulations of pesticides further place constraints on the use of pesticides (including herbicides) near Scottish surface waters. Pesticide use in Scotland is monitored by the Pesticide Survey Unit at Science and Advice for Scottish Agriculture (SASA, n.d.).

Pesticides are also covered in relevant food standards provisions (e.g. Regulation (EC) No 396/2005 on maximum residue levels of pesticides on food and feed), in drinking water (The Public Water Supplies (Scotland) Amendment Regulations 2022, which also cover metabolites) as well as Health and Safety provisions, whilst the Health and Safety Executive also maintain a register (Health and Safety Executive, n.d.) of approved and withdrawn Plant Protection Products. In Scotland, Pesticide Storage and Application (GBR 23) (Scotland) stipulates use requirements such as constraints on application near water courses.

Since Brexit, there has been a divergence between EU and UK pesticides policy. The Pesticides Action Network (PAN) reports that there are now 36 pesticides that can be used in the UK but not in the EU (PAN, 2023). Thirteen of these are classed as Highly Hazardous, according the PAN (PAN, 2021).

3.2.6 Food Additives

Food and feed additives in Scotland are regulated by Food Standards Scotland, who work with the Food Standards Agency (FSA), as part of a wider remit. The main regulatory provision is The Food (Scotland) Act 2015. A register (FSA, n.d.) is in place for all authorised food and feed additives.

All additives must be evaluated in terms of safety evaluation before they can be authorised. Regulations on additives come in the form of bans, restrictions, or labelling requirements. Other than food additives, food contact materials, such as those used in packaging, are also regulated.

Due to the known risks of titanium dioxide, there is already a ban on it as a food additive in the EU and Northern Ireland, but there is currently no such ban in the UK. The FSA are aware of this discrepancy and are considering risk management (FSA, 2023). Extension of such bans may limit the extent of titanium dioxide, pollution, at least from the food industry.

3.2.7 Microplastics

The European Commission has aimed to reduce microplastic release by 30% by 2030. According to the Brochure on EU action against microplastic pollution (European Commission, 2023), existing and proposed EU legislation for monitoring microplastics are covered under the following areas:

- The Marine Strategy Framework Directive introduced monitoring along coastlines, surface of the sea and in seabed sediment.
- The recast of the Drinking Water Directive and proposed revisions to the lists of pollutants for both the Groundwater Directive and the Environmental Quality Standards Directive added microplastics as substances to be monitored.
- Proposed revisions of the Urban Wastewater Treatment Directive include monitoring at inlets and outlets of urban WWTP and in sludge.
- The proposed EU rules on soil monitoring and resilience include the introduction of voluntary monitoring in soil.

[2]Triclosan is best known for its antimicrobial properties as an ingredient in PPCP, but likely included as a pesticide in the European Parliament briefing (Halleux, 2023) due to its fungicidal properties.

The Commission and the EEA are developing standardised measurement and monitoring methodologies to facilitate generation of data on microplastics occurrence across the EU. In 2023, they adopted the REACH restriction, which restricts microplastics intentionally added to products, and developed a proposal for regulation on preventing plastic pellet loss. The proposed monitoring will therefore help to assess whether such initiatives are effective in reaching the 30% target.

In the UK, existing and proposed policy are focussed on reducing sources of microplastic and plastic. The All-Party Westminster Parliamentary Group on Microplastics (APPG) published its first report on policy recommendations to limit microfibre contamination from textiles. It also highlighted that the Environment Bill and the Resources and Waste Strategy for England does not address the issue of microplastics and that the APPG's proposals aim to close this legislative gap (CMS Law-Now, 2021). Meanwhile, in 2022, Scotland became the first UK nation to ban single use plastics, including cutlery, plates, straws, stirrers and polystyrene food and drink containers (Scottish Government, 2022).

3.2.8 Nanomaterials

Nanomaterials fall under the existing REACH and CLP definition of a substance, and provisions set by both regulations apply. Annex VI of REACH defines the terms "nanoform" to cover nanomaterials.

In 2022, the European Commission released a recommendation for a definition of a nanomaterial (now updated in Recommendation 2011/696/EU). Under this new definition, "nanomaterial" means a natural, incidental, or manufactured material consisting of solid particles present on their own or as constituent particles in aggregates or agglomerates and where 50% or more of these particles in the number-based size distribution fulfil at least one of the following conditions:

- One or more external dimensions of the particle are between 1 and 100 nm.
- The particle has an elongated shape where two external dimensions are smaller than 1 nm and the other dimension is larger than 100 nm.
- The particle has a plate-like shape where one external dimension is smaller than 1 nm and the other dimensions are larger than 100 nm.

As of 1 January 2020, explicit legal requirements under REACH apply for companies that manufacture or import nanoforms associated with compilation of safety data sheets. Commission Regulation (EU) 2018/1881 of 3 December 2018 require ecotoxicity analysis of nanoforms using Daphnia, algae and fish, as well as activated sludge respiration inhibition testing and in-vitro gene mutation study in bacteria are called for where appropriate.

Regulations for nanoforms is a work-in-progress and subject to significant evolution with time. It is likely that all EU regulations (i.e. Water Framework Directive) will adapt to formally include nanoform requirements.

3.2.9 Cyanotoxins

In The Bathing Water Regulations, 2013, cyanobacterial proliferation is noted as contamination affecting bathing water quality and presenting a risk to bathers. As such each appropriate agency within the UK must undertake appropriate monitoring and management if a proliferation occurs. In Scotland the Scottish Government are responsible and have produced a document outlining cyanobacteria assessment and minimising public health risks (Scottish Government, 2012). SEPA analyse between 300 and 500 *ad-hoc* samples annually from suspected cyanobacterial blooms to ascertain the presence of potentially toxic cyanobacteria (Krokowski, 2021). In terms of drinking water, cyanobacteria are included in the European Union's Drinking Water Directive under the minimum requirements to assess the quality of water intended for human consumption. In the case of a potential bloom in source water the cyanotoxin Microcystin-LR must not exceed 1 µg/l (European Commission, 2020).

There is also guidance for England issued by the Environment Agency for both the public and landowners (Environment Agency, 2017) in addition to advice for fisheries (Environment Agency, 2022). Furthermore, a citizen science app was developed by the Centre for Ecology and Hydrology (CEH), "Bloomin' Algae", in which the public can record the presence of algal blooms. Throughout the summer of 2023 the Environment Agency urged the public to report sightings of algal blooms and fish in distress due to a prolonged spell of hot and dry conditions (Environment Agency, 2023) and the app is also listed on the Scotland Environment Web (SEWEB; 2022).

3.2.10 Invasive species

EU Regulation 1143/2014 was retained in Scots law under the European Union (Withdrawal) Act 2018. In Scotland, this regulation was amended through the Invasive Non-native Species Regulations 2020 to ensure it was operational following the UK's exit from the EU. This only applies to Scotland (Scottish Government, 2023). The Invasive Non-native Species Regulations 2020 also amend the Wildlife and Countryside Act 1981, which makes it an offense to sell or exchange, import, keep, breed or propagate, release or allow the escape of certain non-native species into the wild and provides information on controlling, licensing (e.g. for the interests of scientific research) and eradicating invasive species (The Wildlife and Countryside Act 1981). In terms of monitoring, Marine Scotland alongside NatureScot and the Joint Nature Conservation Committee (JNCC) have developed a monitoring strategy for Scottish Marine Protected Areas (MPAs) (Marine Scotland, 2017). This includes the assessment of invasive activity. Furthermore, the Scottish government recommend databases such as the GB Non-Native Species Secretariat (NNSS) (Non-Native Species Secretariat, 2024) and NatureScot (NatureScot, 2023) for detailed information on invasive species and urge the public to record non-native invasive species sightings through iRecord (iRecord, 2024).

3.2.11 Pathogens

In the UK there are pathogen monitoring regulations for various water compartments. The Drinking Water Quality (Scotland) Regulations 20014 (as amended), cover Scotland and set the acceptable limits for drinking water at the consumers' tap as 0/100 mL *Enterococci* and 0/100 mL *Escherichia coli*. Similarly, at service reservoirs and water treatment works the acceptable limits are 0/100mL coliform bacteria and 0/100 mL *E. coli*. For each reservoir 95% of coliform bacteria samples must be in compliance (The Water Supply (Water Quality) (Scotland) Regulations 2001).

In recreational waters, areas are classified as being of excellent, good or sufficient quality dependent partly on pathogen monitoring which occurs every bathing season. For inland recreational waters intestinal Enterococci must be measured at 200 cfu/100mL or less (based on a 95-percentile evaluation) to be classed as excellent, 200– 400 cfu/100mL (based on a 95-percentile evaluation) to be classed as good and 330 cfu /100mL (based on a 90-percentile evaluation) to be classed as sufficient. Similarly *E.coli* must be measured at 500 cfu/100mL or less (based on a 95-percentile evaluation) to be classed as excellent, 500-1000 cfu/100mL (based on a 95-percentile evaluation) to be classed as good and 900 cfu /100 mL (based on a 90-percentile evaluation) to be classed as sufficient. For coastal and transitional recreational waters intestinal Enterococci must be measured at 100 cfu/100 mL or less (based on a 95-percentile evaluation) to be classed as excellent, 100-200 cfu/100mL (based on a 95-percentile evaluation) to be classed as good and 185 cfu/100mL (based on a 90-percentile evaluation) to be classed as sufficient. Similarly *E.coli* must be measured at 250 cfu/100 mL or less (based on a 95-percentile evaluation) to be classed as excellent, 250-500 cfu/100mL (based on a 95-percentile evaluation) to be classed as good and 500 cfu/100mL (based on a 90-percentile evaluation) to be classed as sufficient (The Bathing Waters (Scotland) Regulations 2008).

Shellfish waters are also monitored and have an excellent, good or insufficient rating. To achieve an excellent rating shellfish flesh must have ≤ 230 MPN/100g of *E.coli* and to achieve a good rating there must be ≤ 4600 MPN/100g of *E.coli*. Anything outside of this is considered insufficient (The Scotland River Basin District (Quality of Shellfish Water Protected Areas) (Scotland) Directions 2021). In Scotland, Food Standards Scotland (FSS) is responsible for ensuring that designated shellfish harvesting areas meet health standards (Food Standards Scotland, 2024).

3.2.12 Antimicrobial resistance

There is no specific set of regulations that focuses on the monitoring of AMR in the environment in the UK. However, the UK Antimicrobial Resistance Strategy (HM Government, 2019) and UK Biological Safety Strategy (HM government, 2023) addresses the importance of improved surveillance and monitoring of AMR in different environmental compartments, including water, across various sectors such as healthcare and agriculture. Furthermore, although the Water Framework Directive (WFD) does not focus on AMR it does aim to safeguard water quality from contaminants such as biocides and pharmaceuticals which can contribute to the development of AMR (Cortes *et al.,* 2020). These reflect the UK's adoption of the One Health approach which recognises the connection between human, animal and environmental health in addressing health issues such as AMR (Wolmouth-Gordon, 2023).

The 4th Watch List under the WFD identified the antibiotics clindamycin and ofloxacin (a 2nd generation fluoroquinolone) for inclusion, thus resistance genes that confer resistance to these antibiotics should be considered as priority resistances to monitor and mitigate against (Gomez-Cortez *et. al.* 2022). The ARGs erm, msrA/B and Inu can induce clindamycin resistance (Jeong, Lee *et al.;* Leclerc 2002). Genes involved in transmissable resistances to fluoroquinolones include qnr, aac (6')-lb-cr, oqxAB and quepA (Redgrave *et al.,*2014). Bridle *et al*., (2022) highlighted the following ARGs as potential monitoring targets: intI1, sul1, sul2, blaCTX-M, blaTEM, blaNDM-1, blaOXA1, blaVIM, blaKPC, qnrS, ac-(6')-lb-cr, aph, vanA, mecA, ermB, ermF, tetM, tetW.

The proposed redraft Urban Waste Water Treatment Directive (COM/2022/541 final) calls for AMR monitoring to be introduced. Also, it is recommended that selected antimicrobial resistance genes be included in the next Watch List (COM/2022/540 final). In both, the specific genes to be monitored nor the methods used are currently available.

3.3 Survey results

3.3.1 Survey engagement and verification

The survey was started by 42 respondents. Some completed Part 2 for multiple contaminants and not everyone completed all parts. The questions in Part 2 were completed for 46 selected contaminants, whilst the comparative ratings of concern in Part 3 were completed 33 times.

As anticipated, responses were predominantly from people working in academia, with others from government, regulatory agencies, consultancy, industry, and NGOs. All responses were accepted.

3.3.2 Survey participants' contaminant groups

When asked 'Please list the main contaminants that you think are of emerging or increasing concern in the Scottish water environment', a wide range of contaminants were suggested. Using various categorisations and terminology, 201 entries of contaminants or contaminant groups were given (Figure 1), including a number of groups not initially considered separately by the project team, such as phthalates, heavy metals, and bracken toxins,

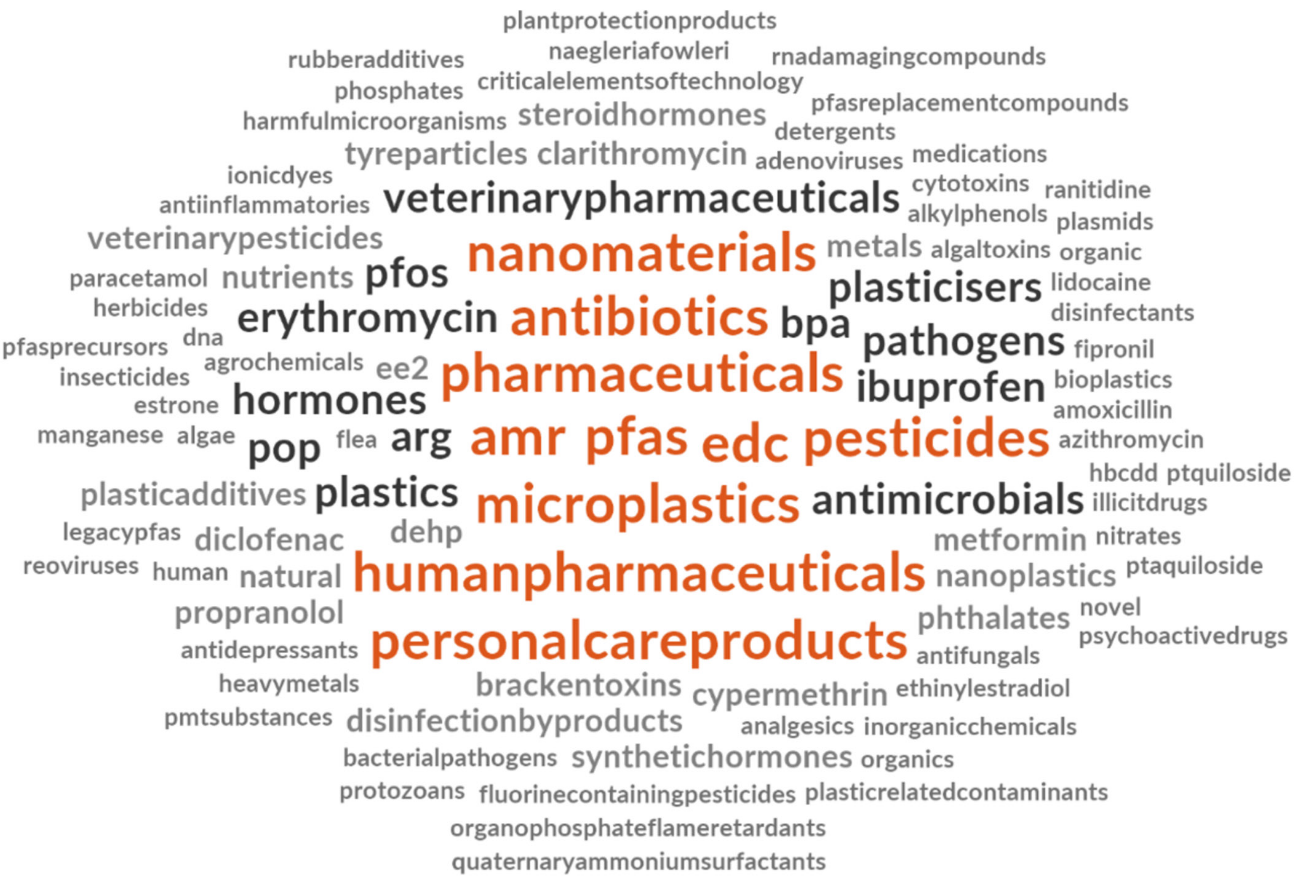

Figure 1 Response to 'Please list the main contaminants that you think are of emerging or increasing concern in the Scottish water environment' Text size indicates the number of entries.

as well as a considerable number of refinements of contaminant groups initially included. The contaminants mentioned were edited slightly to enable the count required to generate the word cloud (for detail see Appendix V, A.).

One respondent signposted to the series of Chemicals Investigation Programmes (CIP) by the water industries and was able to include contaminants of concern identified in CIP2 Scotland. These were: DEHP, HBCDD, cypermethrin, PFOS, EE2, E2, E1, azithromycin, clarithromycin, erythromycin, propranolol, ibuprofen, and diclofenac.

Next, respondents were asked to select a specific contaminant and answer questions for this substance. Two responses were removed as no specific contaminant was given. The selected contaminants were categorised (see Appendix V, B) by the research team.

This enabled the collation of views on understanding of sources, pathways, fate and occurrence (Figure 2). Broadly, responses indicate that understanding of sources was thought to be better than our understanding of pathways and environmental fate, which in turn tended to be rated higher than our understanding occurrence (Figure 2). Understanding of environmental fate was relatively poorly rated for PFAS and plasticisers, whilst understanding of occurrence was rated particularly poorly for EDCs, manganese and plasticisers. Understanding of risk to human health and risk to aquatic organisms was good to excellent for manganese, pathogens, and veterinary pesticides, and basic to poor for other contaminant groups (Figure 2).

3.3.3 Survey participants' prioritisations

Part three of the survey gave us comparable ratings of the different contaminant groups (as selected by the research team) in terms of the level of concern for human health (Figure 3) and aquatic organisms (Figure 4). In terms of human health, AMR was thought to be of highest concern, but in fact most compound groups were thought to be concerning or very concerning by a majority of respondents. Personal care products, cyanotoxins and invasive species were rated as less concerning than other groups, whilst a higher number of respondents said they did not know about risks from nanomaterials and food additives to human health.

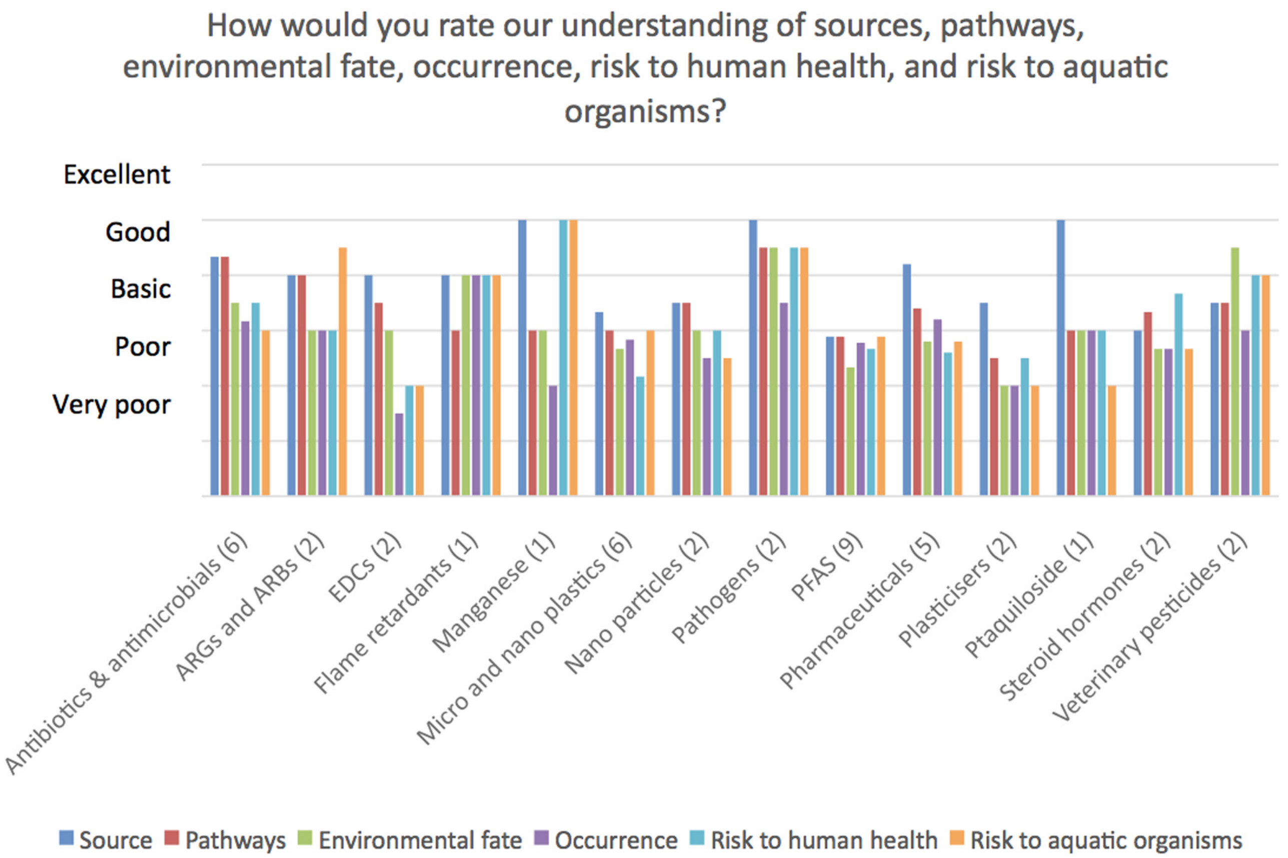

Figure 2 Understanding of sources, pathways, environmental fate and occurrence of the contaminant groups (number of respondents to select this contaminant in brackets)

In terms of risk to aquatic organisms, all contaminant groups apart from food additives were seen as concerning or very concerning by a large majority of respondents. Quite a few respondents also indicated 'I don't know', particularly for nanomaterials, synthetic hormones, food additives, cyanotoxins and flame retardants.

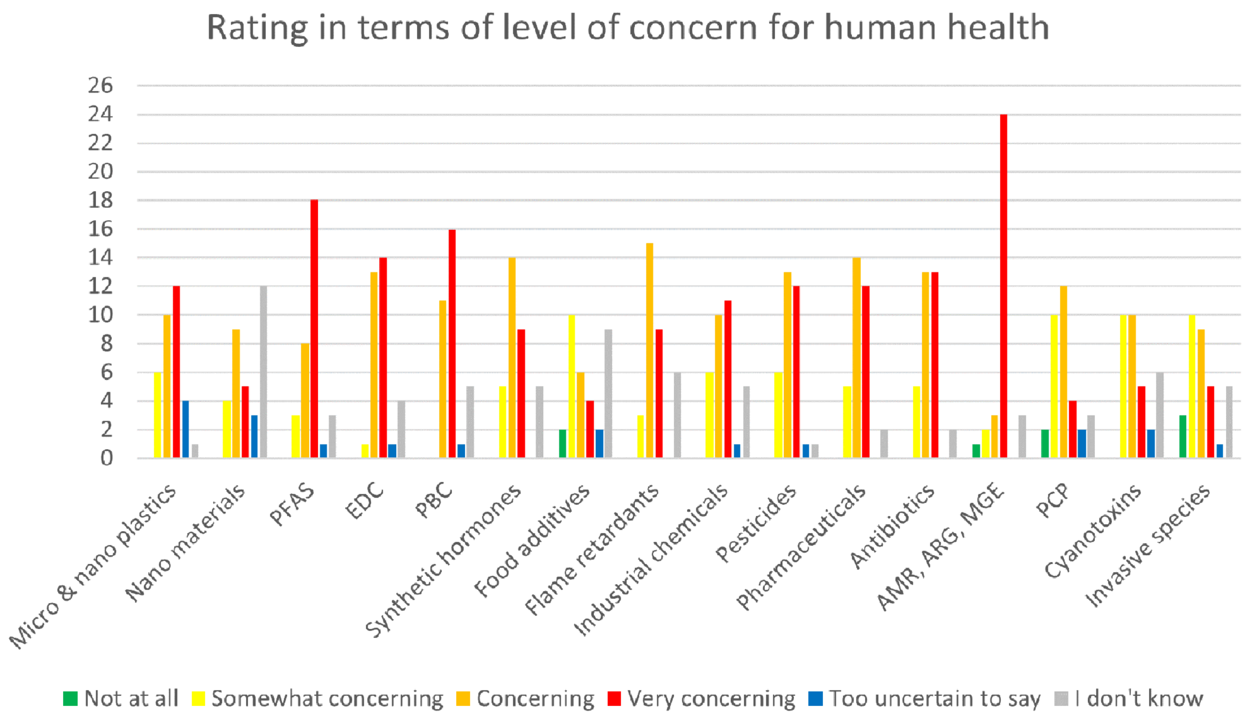

Figure 3 Levels of concern about risk to human health for the contaminant groups

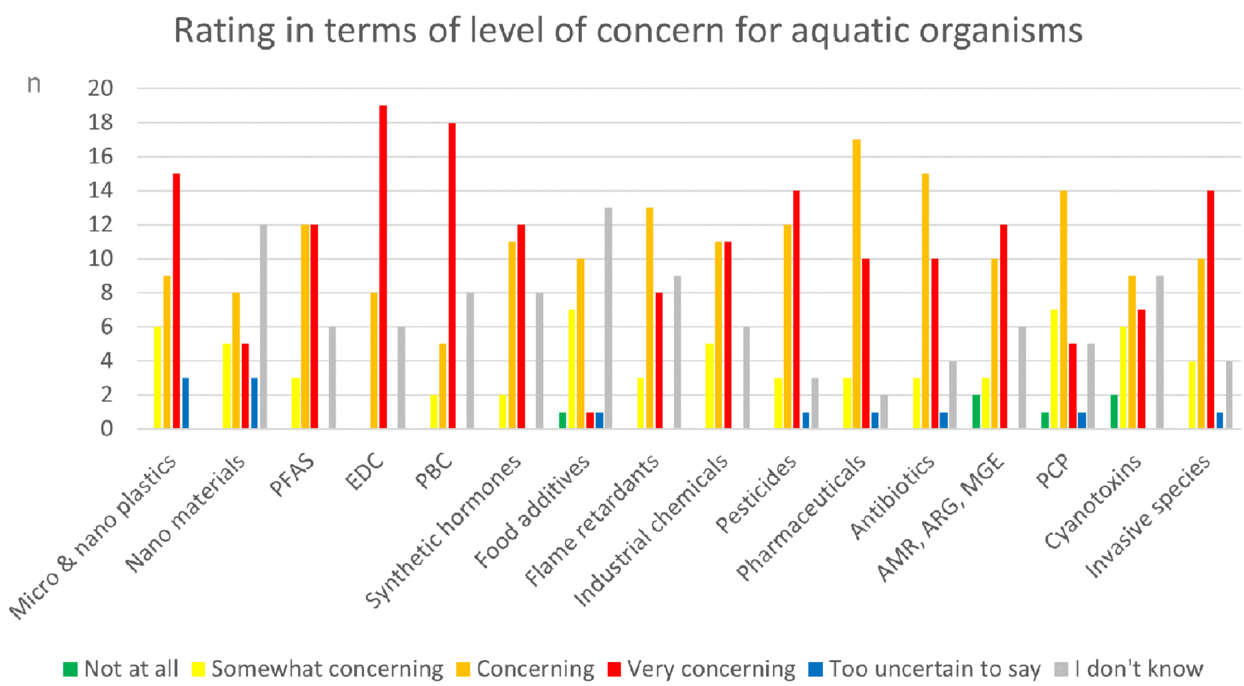

Figure 4 Levels of concern about risk to aquatic organisms for the contaminant groups

3.4 Workshop findings

3.4.1 Substance Flow Maps

Eight draft Substance Flow Maps, on human pharmaceuticals, micro(nano)plastics, PFAS, nano materials, AMR, cyanotoxins, pathogens, and invasive species, were produced in advance by the research team. Workshop participants added considerable additional information, including on additional sources or use categories; available literature e.g. on available models; complexities in the substance pathways; additional receptors and exposure routes; analytical methods; and available databases. Various suggestions for control of pathways were also recorded. The resulting refined Substance Flow Maps are available in Appendix I.

3.4.2 Knowledge gap analysis

Following an assessment of the level of interest the 8 maps attracted, five were taken forward into break-out group discussions: PFAS, human pharmaceuticals, AMR, nano materials, and micro(nano)plastics.

This section reports primarily on the knowledge gaps identified in the break-out group discussions, subsequently verified by the research team. It should not be considered exhaustive. Occasionally, references are provided either when the participants referred to publications or where those were used during the verification process.

PFAS

The *PFAS* breakout workshop discussion led to a number of interesting knowledge gaps emerging. Participants noted that this field is evolving, complex and constantly changing. There was also a mixture of knowledge and experience of PFAS in the group participants. The knowledge gaps identified were as follows:

- Greater understandings of the main sources is needed to support action; PFAS are used across multiple sectors making it challenging to track their presence and determine exactly how they end up in the environment these high risk areas have not been identified in Scotland Our attention was drawn (post-workshop) to Glüge et al. (2020), who describe over 200 uses of over 1400 individual PFAS; these could be reviewed for Scotland.
- Participants reported a lack of understanding of exposure pathways and PFAS breakdown routes (some are much more persistent than others) which could be by groundwater (including private water supplies), seawater, septic tanks and biosolids applied to land. There were concerns about the lack of testing on sediments. Materials which are incinerated may contain unknown amounts of PFAS which can produce by-products such as fluorocarbons (a potent greenhouse gas) and hydrofluoric acid vapour (highly corrosive and toxic). Exposure pathways via inhalation in this manner and from landfill emissions for humans and animals is unknown.
- One analytical technique would not be capable of detecting all PFAS and investment is required to develop a standard method using several techniques to get a true quantity of PFAS in the environment. This is especially important given the small quantities of PFAS present in some products not expected to contain PFAS but have been contaminated with them during production and other difficult to detect PFAS.
- Although certain PFAS are no longer used in the UK due to their persistence they are still occurring as legacy effects from unexpected sources of emission. Participants highlighted the potential for PFAS to be constantly recycled throughout the environment by bio-accumulation via biosolids applied to land followed by ingestion and excretion and re-application of biosolids. PFAS are also used in food wrapping and little is known about how and if they can transfer to food (although some data is available; see e.g. Ramirez Carnero *et al*., 2021; Curtzwiler *et. al.,* 2020) and what happens to the PFAS on the wrapping after disposal – is it washed into the sewage system or does it go to landfill?
- It was thought that there are very few regulatory requirements for routinely testing food and environmental samples, such as sediment, for PFAS. It was considered this should be implemented. There were particular concerns about testing food as PFAS are known to bio-accumulate however, the room was divided on how much data was available on this.
- Toxicology data is available for some PFAS, but mainly PFOS and PFOA others, such as perfluorocarboxylic and sulphonic acids are much less studied and even less for other PFAS groups.

Human pharmaceuticals

The workshop discussions led to a number of interesting knowledge gaps emerging. The *Pharmaceuticals* breakout group identified the following thematic knowledge gaps:

- There are still gaps in our understanding of sources of drugs, particularly from private prescriptions, illegal and drugs of abuse, online pharmacies, and over-the-counter (OTC) medicines.
- The volume of pharmaceuticals being sent to landfill, which will now or in the future leach into the environmental matrices, is unknown and needs to be quantified.
- The role of temperature on release from WWTP is not fully understood.
- Environmental release may occur as high-volume excretion via urination and defecation of large populations simultaneously in unexpected geographies such as at festivals; the extent and consequences of this are unknown.
- Knowledge gaps were identified regarding human exposure, including the presence of pharmaceuticals in animal feed and whether this constitutes an exposure pathway for humans; exposure and risk for recreational and professional water users; exposure via contamination in private water supplies; and potential exposure via inhalation from the incineration of some volatile pharmaceuticals. Some research is available on human exposure to veterinary medicine residues via uptake in plants for human consumption (Boxall *et al.,* 2006).
- The environmental fate is not always known from septic tanks and even small WWTW – more research is required to understand where and how these treatment systems are vulnerable to failure. From the septic tank, excreted pharmaceutical substances go either to surface water or to the soil; solids disposal from septic tanks is unrecorded and data is lacking on septic tanks removal efficiencies.
- Greater understanding is needed of the transformation and degradation processes of (stereoselective amd non-stereoselective) pharmaceuticals in the environment, particularly with regards to microbial metabolism and reformation of parent compound (deconjugation). Not all metabolites of pharmaceuticals are known.
- Knowledge gaps exist in environmental media other than water. More data on pharmaceuticals in sludge is needed, especially if sludge is applied to farmland; interactions between suspended solids and sediment are largely unknown; data are lacking on pharmaceuticals in suspended solids.
- More understanding is required of the different ways in which mixtures of chemicals may impact upon multiple species, and therefore the impact at ecosystem level.
- Whilst upstream solutions have been suggested, questions remain over their effectiveness or optimisation. Specific examples mentioned were the efficacy of including environmental information on medicine labels; the influence of patient stigma around returning prescribed medicine via take-back schemes; returning of unused OTC medicines; public awareness of take-back schemes and how this could be increased.
- Multiple agencies are working on these issues, however there is a gap in understanding around the coordinative mechanism that will bring together all these different agencies to share data, resources, knowledge, and to avoid replication of initiatives.

Nanomaterials

The *Nanomaterials* breakout workshop discussion deliberated on the environmental impacts and uncertainties tied to nanomaterials. The primary discussion points revolved around identifying research questions necessary for understanding the environmental consequences of nanomaterials, detecting contaminants, researching the possible toxicity of certain substances, and tracking nanomaterial in the environment. Participants identified the following current knowledge gaps:

- Further research and agreement are needed to improve differentiation between incidental, engineered and naturally occurring nano-materials in the natural environment. Participants pointed to the GRACIOUS framework proposed by Stone *et. al.* (2020).
- There are significant gaps in understanding of the sources of nanomaterials, including on the presence of nanomaterials in leachate, which is likely but unknown. Participants also discussed possible increasing use in cosmetics.

- There is no routine monitoring of nanomaterials, and monitoring cannot distinguish between engineered and natural particles of the same substance. This is important because engineered particles have a functional coating that may affect toxicity.
- The detection of nanomaterials, particularly in complex matrices, still poses challenges. There is a lack of standardised methods for detection and characterisation of nanoparticles in different environments, particularly in water. Predicted environmental concentrations are estimated but are unverified and hence factually unknown.
- Further research on the behaviour of nanomaterials in the environment, particularly their interactions with other contaminants in a mixture situation and their behaviour in various environmental media.
- The transport from organism to organism, bioaccumulation, and retention between the life stages, are poorly understood and under-investigated but may be significant. Participants shared findings of an interesting study by Al Shaer *et. al*. (2022), which showed that when mussels are fed algae, they expel algae containing carbon nanotubes.
- Greater understanding is needed about the environmental impact and effect of nanomaterials. The potential toxicity of certain substances is poorly understood, such as common nanomaterials in sunscreen or cosmetics. Participants did highlight an environmental risk assessment presented by Wang and Nowack (2018) and Hong, Adam and Nowack (2021), who were able to calculate Predicted Environmental Concentrations for several engineered nanomaterials. Both studies used a Predicted No Effect Concentration based on a Species Sensitivity Distribution, with the latter study indicating that form-specific risk analysis of nanomaterials can change the results of the risk assessment.
- In marine or river environments, nanotubes tend to agglomerate but then tend to attract and accumulate metals. Because they tend to bind, it is sometimes assumed that they are not a problem but, in reality, this is unknown.
- In Scotland, while the research on toxicity, safety and material science is strong, significant gaps remain in researching nanomaterials and their behaviour in natural environments in the real world.

Microplastics

The *Microplastics* breakout workshop discussion delved into the complexities surrounding secondary microplastics, emphasizing the need for further investigation across a range of areas, particularly the following current knowledge gaps:

- Extraction methods and analytical analysis techniques are still quite rudimentary for microplastics and require further research. New technologies for extraction and analysis are required that have lower concentration and size limits to obtain higher quality occurrence data. These then require standardisation to allow comparisons across studies.
- Difficulty in controlling and monitoring microplastics in a broad range of matrices, whose uncontrolled nature, coupled with monitoring challenges, impedes effective management, and research is needed to better understand this.
- Both systemic change and public education require more investigation. Strategies for changing systems and educating the public to alter consumption patterns and waste management practices require further exploration. These strategies are essential to combat microplastic pollution, but there remains a research gap in how to develop and implement these strategies effectively.
- There is a lack of research in the development of plastic alternatives and how these may be implemented to alter plastic consumption.
- The potential human health effects of microplastic exposure remain largely unknown, yet each person consumes vast amounts of microplastics per day and it has been found in foetuses in the womb, emphasising the need for in-depth research in this area. There is currently no guidance on microplastic particles permitted in or on food.
- The potential environmental effects need to be investigated further. Studies need to consider effects of environmentally relevant microplastic morphologies (particularly fibres and films), mixtures of microplastic morphologies, environmentally relevant concentrations and weathered secondary microplastics on fresh-water and terrestrial plants and animals as well as marine. Moreover, the effects of plastic degradation products need more research.

- Better consideration of risk assessment needs to be incorporated into discussions around microplastics. Better effect studies and occurrence studies (see above points) will make it easier to establish the degree of risk in different areas and indicate activities contributing to the most risk.
- While more than 95% of microplastics are removed at wastewater treatment plants (Burns and Boxall, 2018), the fate of the resulting sewage sludge remains a critical concern. Sewage sludge used as organic amendments to soil requires further research as an important exposure pathway. In some drinking water treatment works, microplastics also end up in the sludge (Johnson *et. al*., 2020), which may be disposed of in landfill (Scottish Water, 2020). Since microplastics could potentially leach back into the environment from landfill, there may be a research gap on what to do with the waste product.
- Research is needed on microplastics from tyres, especially in electric vehicles, as the environmental impact of tyres and their sustainable safe reuse poses a critical knowledge gap that demands investigation. Tyre microplastics, which are older than most microplastics, have been neglected, perhaps because there is a lack of methods to analyse these microplastics.
- The link between agriculture, synthetic fertilisers, and microplastics needs further exploration, as understanding how synthetic fertilisers contribute to microplastic pollution in the environment is an under-developed research area.
- Currently, nanoplastics in water are under-researched, yet nanoplastics in water abrogate and nanoparticles tend to clump together because they are so reactive. Once plastic becomes nanoscale, it can enter into plants and subsequently into animals.
- Much greater understanding of microplastics as vectors is needed, as they can carry or absorb chemical and biological pollutants. The risks associated with microplastics as vectors are still unclear.
- Identifying the polymers constituting these particles is essential to addressing microplastic pollution. The lack of knowledge about the types of polymers hampers the development of effective degradation and removal strategies. The intricate mixture of microplastics, coupled with variations in size and shape, further complicates monitoring efforts. Research in this area is crucial for advancing our understanding of microplastic behaviour.

AMR

The *AMR* breakout workshop discussion concluded that the field, including in Scotland, is still far from fully grasped. There are no legislative limits and increased awareness of AMR across both stakeholders and the general population is needed. However, participants also acknowledged the challenge in setting legislative limits due to the complex nature of the issue. Participants identified the following current knowledge gaps:

- There is a research gap in understanding of interactions between other drivers such as heavy metals, pharmaceuticals, disinfectants, and how mixed drivers interact with microorganisms.
- Modelling of the impact on development or maintenance of AMR of mixtures of pharmaceutical and heavy metals and anti-biotics and pesticides is required as this is currently a research gap.
- How sources and pathways vary with geographic area isn't well understood and may be related to socioeconomic demographics and local industries e.g. farming, hospitals.
- There is a lack of understanding of the relative importance of each source, making targeting effort more difficult until this research gap can be investigated e.g. sewage versus livestock.
- Various methods and approaches are used to determine AMR and there is no consensus on which is best for monitoring. This also makes data difficult to compare. Defining a consensus approach to detection and analysis would help (this is being approached).
- There is a research gap on temporal differences in emission patterns, and what little is known is impacted by variety across the year and climatic/weather events, such as seasonal prescribing, sewage releases, river flow and temperatures etc.

- There is also a research gap on the persistence of AMR genes particularly how long they last in the environment, as this is currently unknown.
- More data is needed to understand the correlation between prescribing patterns, emissions in waste water treatment plants for instance, and AMR genes.
- Rainfall and flooding in Scotland are increasing due to climate change. This increases run-off and the use of Combined Sewer Overflows, but also increases dilution, so we do not yet understand what impact that is having on concentrations of AMR genes or bacteria. We also don't know whether prescribing during the seasons most at risk impacts the concentration e.g. increase in summer rainfall perhaps coincides in a low-point of antibiotic prescription.
- There is currently little knowledge about concentration and ingestion, and the probability of developing resistance when ingested.
- There is a major research gap regarding the relationship between AMR genes and clinical cases of infection with resistant microorganisms. This is critical for risk assessment. For example, if you ingest a dose of resistant bacteria, what is the probability that you are developing a resistance inside you or becoming ill with an untreatable disease?
- We do not know what the presence of AMR genes does to the health of plants, animals, microbial communities in the environment and their functioning.
- There is a lack of monitoring data, and models are still undeveloped, perhaps because there is currently no requirement to monitor in the environment, and while there are plenty of different techniques that could be adapted for this, there is an absence of standardized methods.

3.4.3 The Science-Policy Interface

Following the knowledge exchange and ensuing discussion, participants were asked to identify their research priorities to develop a shared research agenda. Four broad thematic areas emerged: a) climate adaptation and preparedness; b) data sharing, data sufficiency, and cross-organisational working; c) understanding and managing environmental fate, pathways and interactions; and d) research infrastructure.

Climate change adaptation and preparedness

1. Impacts of climate change on chemical emissions and effects in Scotland.
2. Evaluate understanding on the role of climate change in enhancing the risk posed by emergent contaminants (lower flow rates, higher temperature, change in sediment – suspended sediment interactions).
3. Effects of climate change on mobilization, transformation and toxicity of contaminants.

Data sharing, data sufficiency, and cross-organizational working

1. Participants identified a need for inventorising available data; the need for open databases; and for standardisation of datasets and measurements.
2. Sources attribution was an important topic for several contaminant groups: effective mitigation is only possible if we understand the most important sources in Scotland. To address this, some targeted sampling could be done, but also arrange for the compilation of data across agencies/data sharing and harmonization
3. Many CICs are not yet regulated. However, it was commonly felt that greater data was needed to inform policy and regulation, in particular to enable tightening of regulation for greater environmental protection. It was not always clear exactly what data was required to enable this.
4. The One Health Breakthrough Partnership was hailed as an effective, cross-sector approach for pharmaceuticals, which could possibly be applied to other CIC groups. The visualisation of pharmaceutical pollution via an open-access map was also highlighted, although it was noted that this could include more locations and a greater number of compounds.
5. There was interest in the development and application of non-targeted analysis to identify potential future contaminants for targeted analysis. It was suggested this could be developed through cross-agency, cross-sector collaboration.

Understanding and managing pathways, environmental fate, and interactions

1. Better conceptual understanding of the different contaminants' sources, both human and natural, using a holistic framework.
2. For several contaminant groups, there are no standardised methodologies yet to monitor and quantify large groups of emerging contaminants. To agree techniques, which would enable data sharing via large-scale open datasets for Scotland, would require working with regulators, researchers, public and private agency representatives.
3. Sector-based approaches could be useful to consider whether specific CIC issues are more likely to impact Scotland than elsewhere in the UK, e.g. those associated with septic tanks, salmon farming, oil and gas, or the drinking water reservoir network.
4. It was widely acknowledged that assessment of the effects of single substances may not be sufficiently protective and a move towards the assessment of mixture effects on environment and human receptors was seen as desirable.
5. Significant questions remain on how to model and assess the impact of mixtures, on a suite of biological end points.
6. Whilst data on occurrence and effect is at best incomplete for most contaminant groups, more research is specifically required into their presence of toxins in (drinking) water sources
7. Understanding how effective upstream solutions, including behaviour change can be instigated is also required.

Research infrastructure

1. Understanding and further developing laboratory capability and capacity around the UK and Scotland for microbiological and chemical contaminants will help develop scientific understanding and the generation of evidence to support policy
2. There may be potential to work with industry professionals and innovative scientists, which could lead to new research areas and attract funding, but significant investment from the government and existing funding bodies is required to address the many uncertainties in this area.
3. Work with universities across Scotland, as many of the gaps in literature could be addressed by Scottish teams already working in these areas.

4 Discussion

This project sought to start broadly, with literature search on 18 contaminant groups, and had anticipated a subsequent narrowing of focus depending on interest amongst survey and workshop participants. However, whilst certain contaminant groups indeed received more interest than others, participants actually sought to broaden the frame further or reemphasised the specific importance of contaminant subgroups we had proposed to merge into broader groups. Additional suggested compound groups included tyre particles; bioplastics; plasticisers; bracken-derived toxins including ptaquilosides; phthalates; replacement flame retardants; veterinary pesticides; illicit drugs; several viruses; protozoans; quaternary ammonium surfactants; alkyl phenols; DNA/RNA damaging compounds; and ionic dyes. Survey respondents highlighted the latest article in a series of biannual reviews of trends in analytical chemistry (Richardson and Ternes, 2022), which drew attention to Covid-19, amidst general growing interest in wastewater epidemiology; disinfection by-products (DPBs), particularly from drinking water and swimming pool treatments; sunscreen and UV filters; brominated and emerging flame retardants; and algal toxins (including the newly-discovered *Aetokthonos hydrillicolaone* which is responsible for killing bald eagles in the US). Several compound groups covered in the current project, including microplastics, nanomaterials, hormones and pharmaceuticals and PFAS are also covered in significant detail, with attention for analytical methods (ibid.). Mueller *et. al.* (2024) further list rare earth elements and liquid chrystal monomers as emerging contaminants. Both in the participant responses in the current project and in the literature, there were differences between contaminants in terms of the context in which they are seen as problematic, e.g. for human health or for aquatic organism, and in the extent to which the water environment is a significant exposure route.

For some contaminants, including PFAS and AMR, complexities and uncertainties are widely reported. For others, risks or contaminants have been quantified in England (e.g. veterinary medicines, tyre particles) but no data is available yet in Scotland, or it is unclear whether data is available (e.g. various contaminants in drinking water). For other groups, including microplastics and nanomaterials, widespread occurrence is the main reason for concern although it is still rather unclear to what extent and to what receptors this poses a risk. For some, including pharmaceuticals, reasonable source data is available, although gaps still exist, but questions remain about environmental fate and risks. Mixture effects and vector interactions render comprehensive risk assessment even more difficult.

The project nevertheless also uncovered a substantial toolbox for source attribution, environmental monitoring, and risk assessment. We were alerted to a Canadian approach – Science Approach Document: Ecological risk classification of organic substances version 2.0 (ERC2) – which includes a database with detailed information in no less than 110 columns on the hazard, exposure and risk for over 12,000 organic contaminants. Whilst exposure information is locally specific, much of the database is directly useful for the estimation of risk in Scotland. The earlier-mentioned review by Richardson and Ternes (2022) presents an excellent overview of review papers, analytical methods, occurrence, and fate of emerging contaminants. New legislative proposals as part of the European Green Deal contain innovative approaches to monitoring and management, including Effect Bases Monitoring; utilising the Extended Producer Responsibility model to address aquatic pollutants; and the use of 'sum of' approaches to environmental regulation.

It was beyond the scope of the current project to quantify risks for Scotland; we have not been able to de-prioritise with any confidence any of the initial 18 groups and indeed more may need to be considered. However, clear thematic similarities emerged in terms of the research priorities across the groups.

The Logic Model (Figure 5) summarises the key research gaps identified in this research. The model was constructed using a combined analysis of the collected data from the project which identified where further research was required. This data was then thematically grouped into 1) **inputs** needed (funding; researchers and partnerships, time and equipment); 2) **activities** (outputs) urgently needed around the key emerging research gaps, and 3) the **impact/outcomes** of conducting activities to address those relevant knowledge gaps. These impacts are presented in the short-, intermediate and long-term.

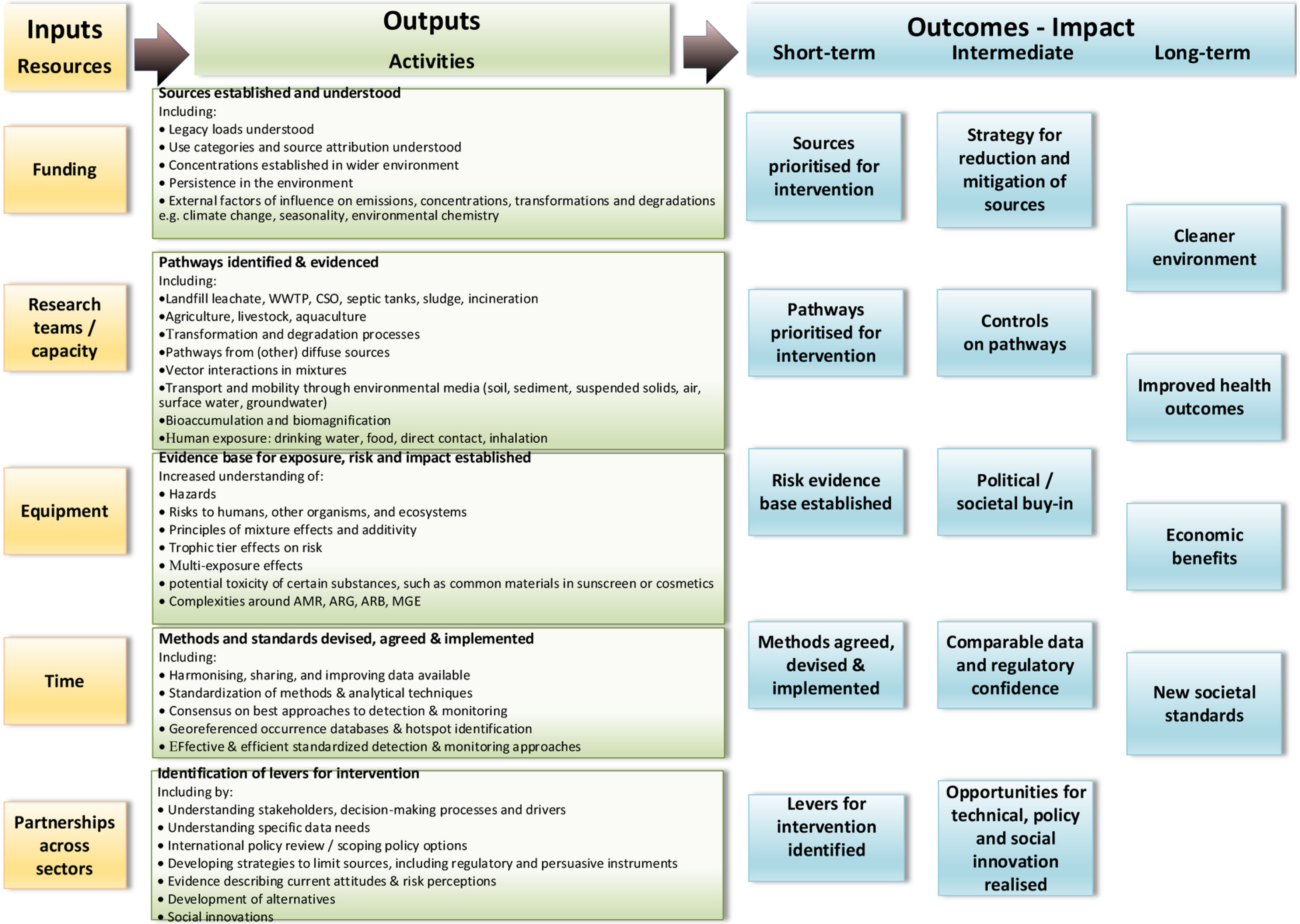

Figure 5 The Logic Model

5 Recommendations

Based on the findings of the project, the research team would like to make the following recommendations:

- That no emerging contaminant groups can be discounted for Scotland on the basis on the evidence we found;
- That many national and international databases are available to aid understanding of emerging contaminants; these should be reviewed and consolidated for Scotland;
- That the current organisational infrastructure of teams (academic, government, committees, partnerships, NGOs) working on emerging contaminants in Scotland is reviewed and assessed for comprehensiveness with respect to the water environment;
- That new partnerships are considered for contaminant groups as required;
- That such new or existing partnerships refine the knowledge gaps in collaboration based on the knowledge needs of water policy teams;
- That funding is made available to address the knowledge gaps;
- That an international review of policy options is conducted, in particular for integrated approaches and approaches to mixtures, including effect-based monitoring;
- That capacity is expanded both in research teams and policy teams.

6 Conclusions

The research team was able to uncover information and expert views on a broad range of CICs. The Substance Flow Mapping approach proved an effective framework for knowledge sharing and gap analysis. Specific knowledge gaps were identified for all contaminant groups, in most cases on all stages in the contaminants' life stages – sources, distribution and pathways, environmental fate and occurrence, hazard, receptor exposure, and risk – although most knowledge gaps would require refinement in further research projects through more focused review of the recent literature.

Crucial issues identified at the science-policy interface included first of all climate change adaptation and preparedness. Sources, pathways, and environmental fate of CICs are all likely to change due to climate change or due to adaptation and mitigation responses to climate change. The second theme was data sharing, data sufficiency, and cross-organisational working; standardisation of methods was considered important to this end. There was recognition that further work on understanding and managing pathways, environmental fate, and interactions is required to enable optimisation of upstream interventions; this could also inform sector-based approaches. Finally, the science-policy interface would benefit from strengthening the research infrastructure by highlighting analytical capability and capacity in Scotland; further developing national and international academic connections; and enhancing innovative industry collaborations.

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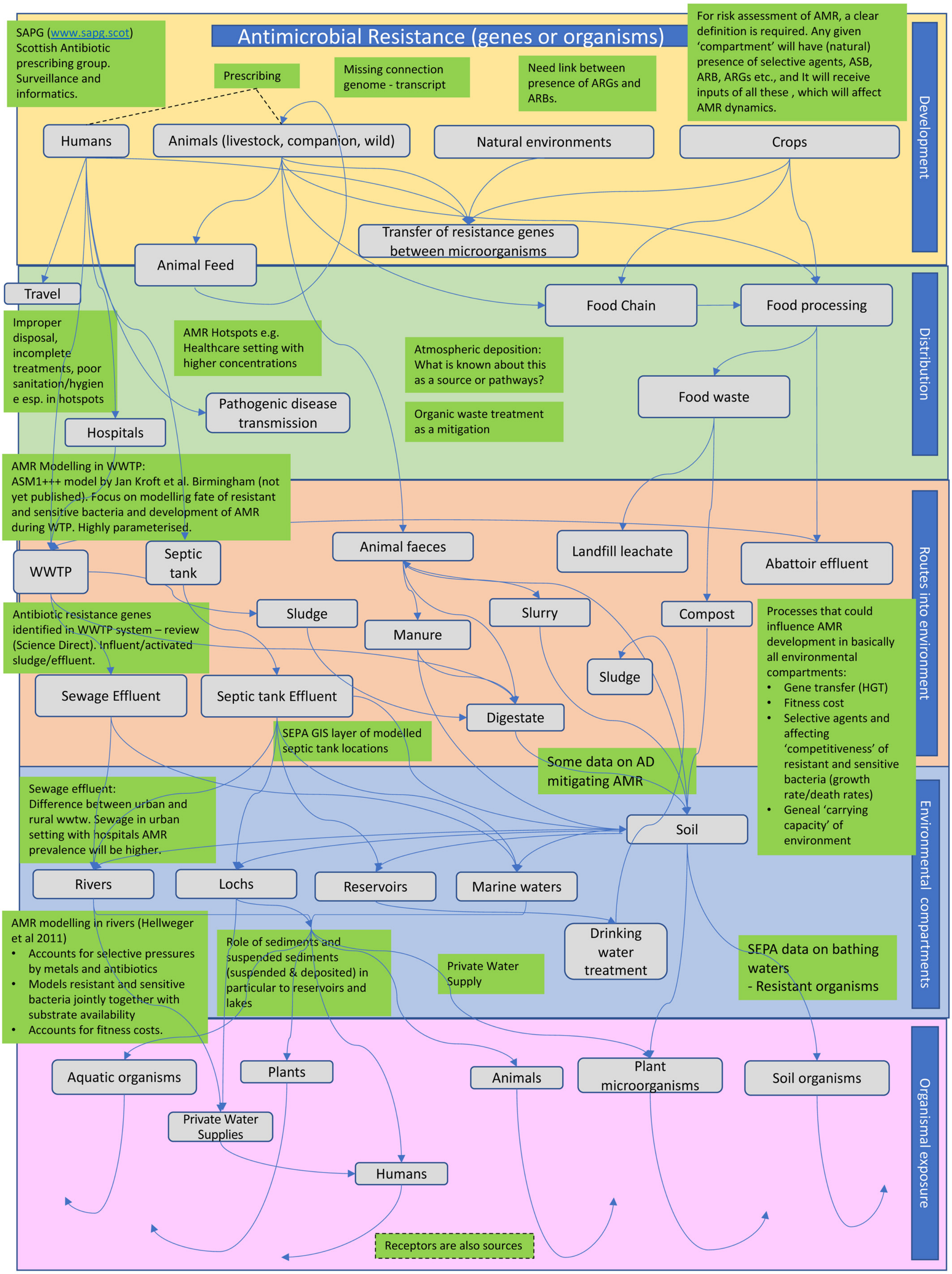
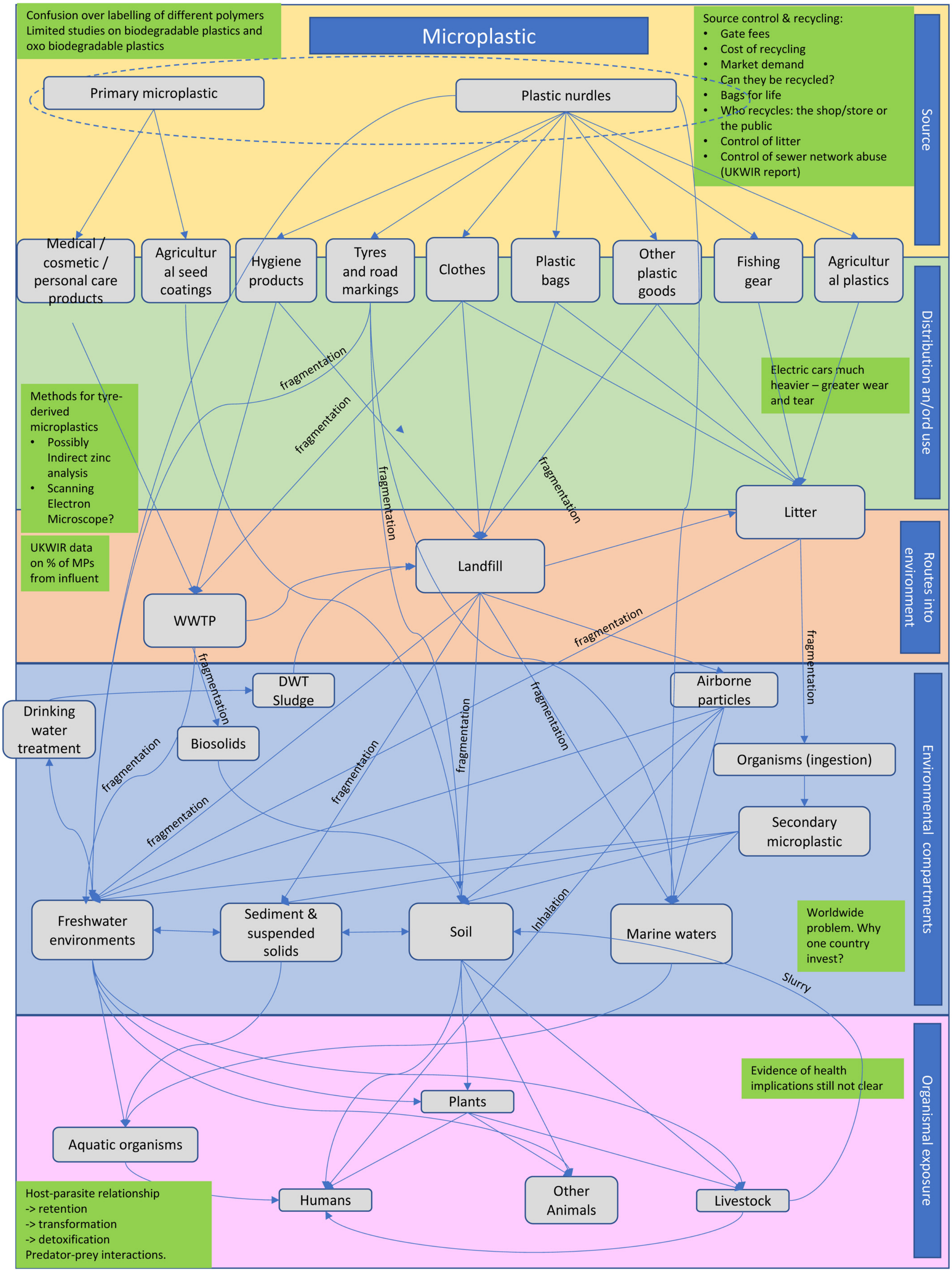
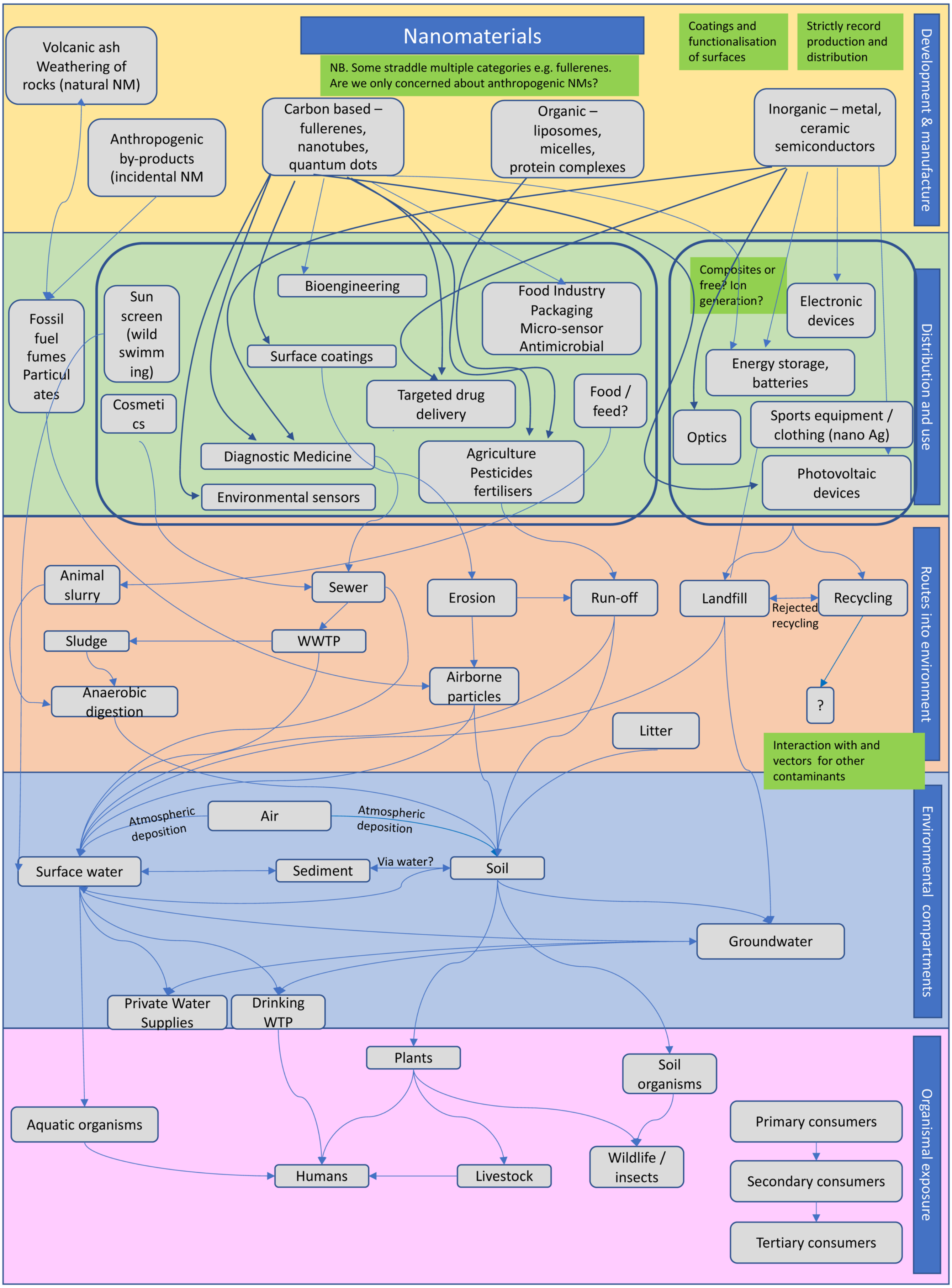
Zezza, D., Bisegna, A., Angelozzi, G., *et al.,* (2020). Impact of Endocrine Disruptors on Vitellogenin Concentrations in Wild Brown Trout (Salmo trutta trutta). *Bulletin of Environmental Contamination and Toxicology*, 105, 218–223. [Online] Available at: https://doi.org/10.1007/s00128-020-02916-8.

Appendix I – Substance Flow Maps

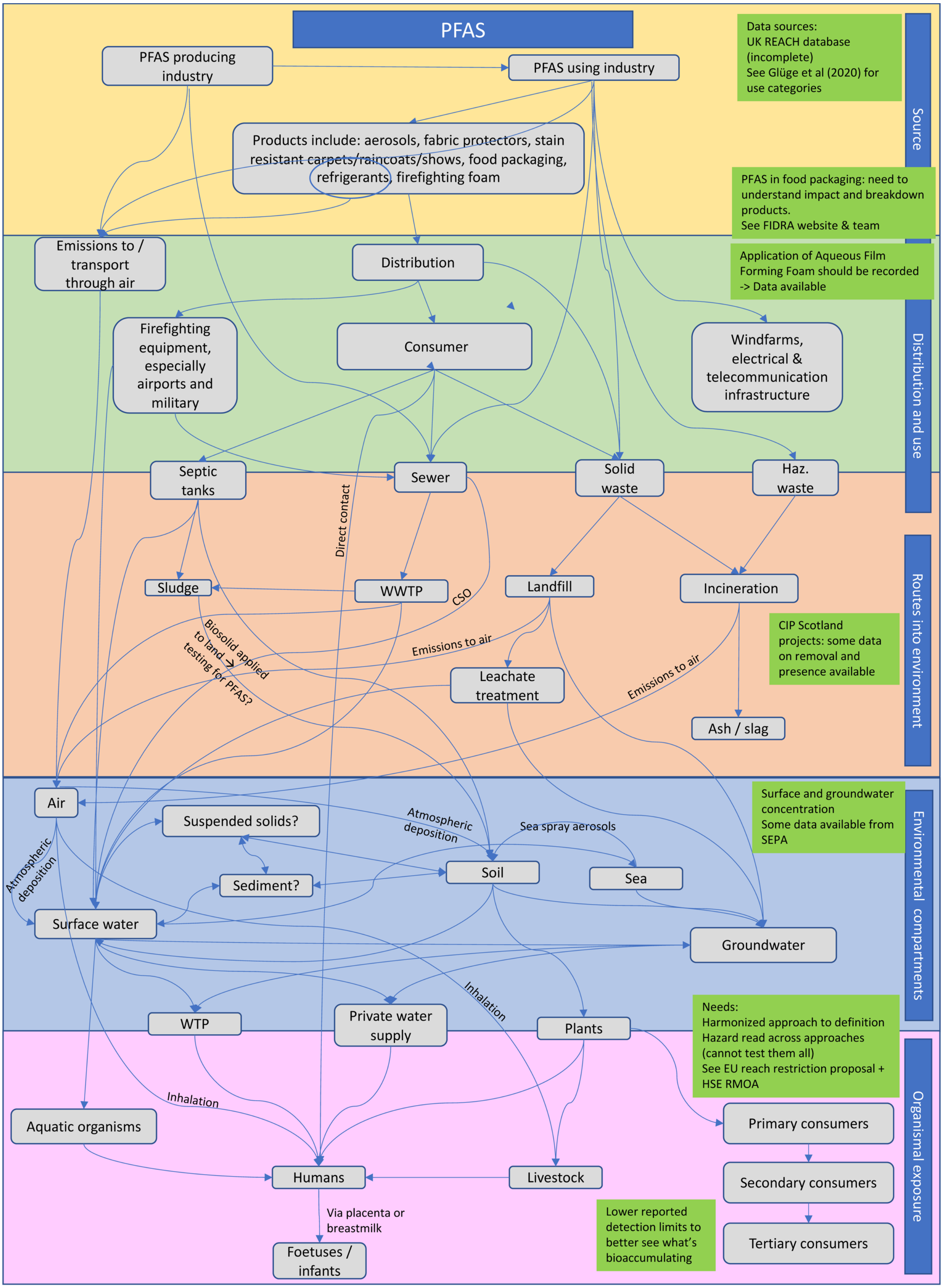


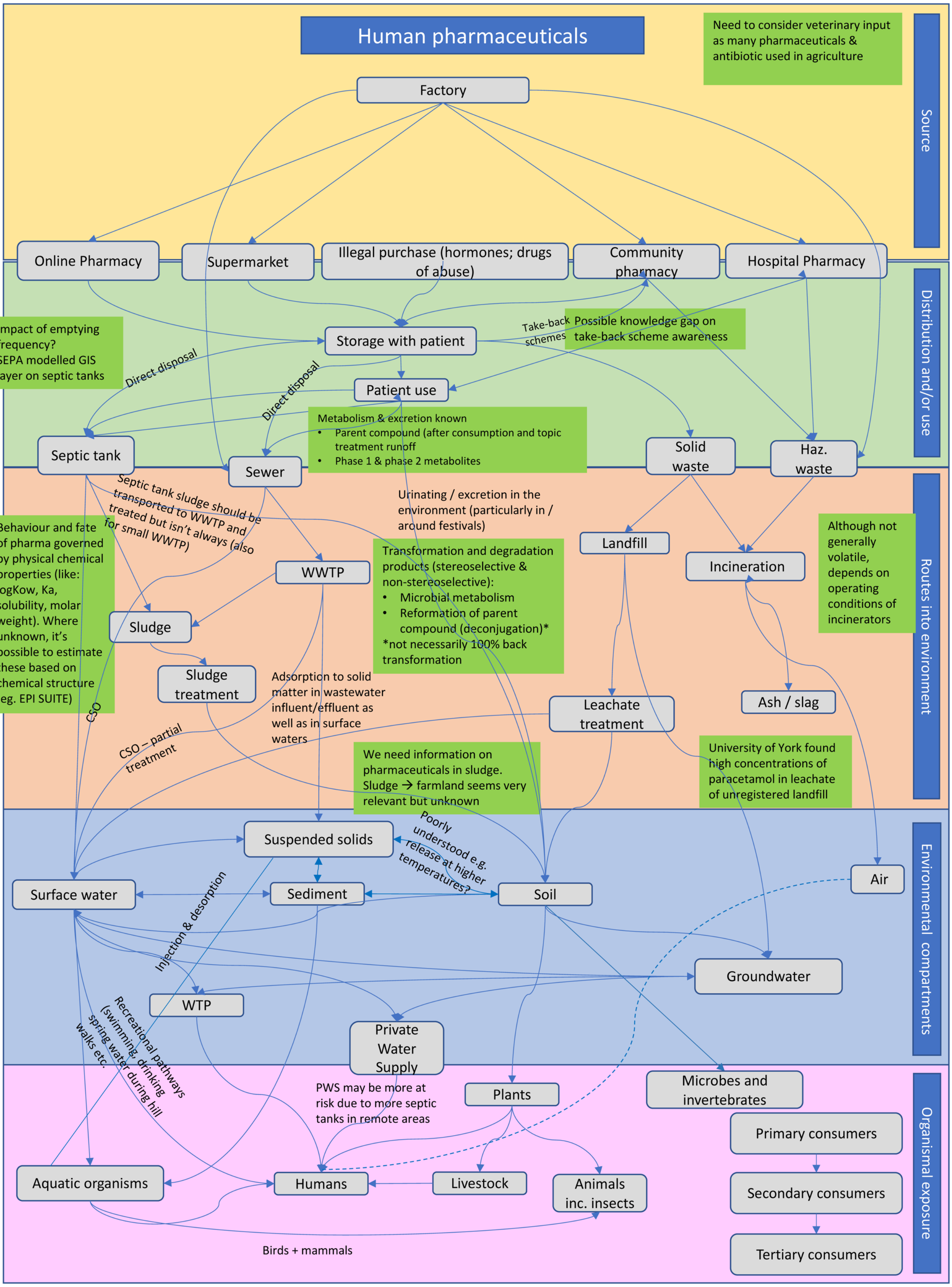


Confusion over labelling of different polymers
Limited studies on biodegradable plastics and oxo biodegradable plastics
Microplastic
Source control & recycling:
Gate fees
Cost of recycling
Market demand
Can they be recycled?
Bags for life
Who recycles: the shop/store or the public
Control of litter
Control of sewer network abuse (UKWIR report)
Source
Primary microplastic
Plastic nurdles
Medical / cosmetic / personal care products
Agricultural seed coatings
Hygiene products
Tyres and road markings
Clothes
Plastic bags
Other plastic goods
Fishing gear
Agricultural plastics
Distribution an/ord use
Electric cars much heavier – greater wear and tear
Methods for tyre-derived microplastics
Possibly Indirect zinc analysis
Scanning Electron Microscope?
UKWIR data on % of MPs from influent
fragmentation
Litter
Landfill
WWTP
Routes into environment
DWT Sludge
Biosolids
Drinking water treatment
Airborne particles
Organisms (ingestion)
Secondary microplastic
Freshwater environments
Sediment & suspended solids
Soil
Marine waters
Inhalation
Slurry
Worldwide problem. Why one country invest?
Environmental compartments
Evidence of health implications still not clear
Plants
Aquatic organisms
Humans
Other Animals
Livestock
Host-parasite relationship
-> retention
-> transformation
-> detoxification
Predator-prey interactions.
Organismal exposure



Nanomaterials
NB. Some straddle multiple categories e.g. fullerenes.
Are we only concerned about anthropogenic NMs?
Coatings and functionalisation of surfaces
Strictly record production and distribution
Development & manufacture
Volcanic ash Weathering of rocks (natural NM)
Anthropogenic by-products (incidental NM
Carbon based – fullerenes, nanotubes, quantum dots
Organic – liposomes, micelles, protein complexes
Inorganic – metal, ceramic semiconductors
Distribution and use
Fossil fuel fumes Particulates
Sun screen (wild swimming)
Cosmetics
Bioengineering
Surface coatings
Diagnostic Medicine
Environmental sensors
Targeted drug delivery
Food Industry Packaging Micro-sensor Antimicrobial
Food / feed?
Agriculture Pesticides fertilisers
Composites or free? Ion generation?
Electronic devices
Energy storage, batteries
Optics
Sports equipment / clothing (nano Ag)
Photovoltaic devices
Routes into environment
Animal slurry
Sewer
Sludge
WWTP
Anaerobic digestion
Erosion
Run-off
Airborne particles
Landfill
Recycling
Rejected recycling
?
Litter
Interaction with and vectors for other contaminants
Environmental compartments
Air
Atmospheric deposition
Atmospheric deposition
Surface water
Sediment
Via water?
Soil
Groundwater
Private Water Supplies
Drinking WTP
Organismal exposure
Plants
Soil organisms
Aquatic organisms
Humans
Livestock
Wildlife / insects
Primary consumers
Secondary consumers
Tertiary consumers


PFAS
PFAS producing industry
PFAS using industry
Data sources:
UK REACH database (incomplete)
See Glüge et al (2020) for use categories
Source
Products include: aerosols, fabric protectors, stain resistant carpets/raincoats/shows, food packaging, refrigerants, firefighting foam
PFAS in food packaging: need to understand impact and breakdown products.
See FIDRA website & team
Emissions to / transport through air
Distribution
Application of Aqueous Film Forming Foam should be recorded -> Data available
Firefighting equipment, especially airports and military
Consumer
Windfarms, electrical & telecommunication infrastructure
Distribution and use
Septic tanks
Sewer
Solid waste
Haz. waste
Direct contact
Sludge
WWTP
CSO
Landfill
Incineration
Biosolid applied to land → testing for PFAS?
Emissions to air
Leachate treatment
CIP Scotland projects: some data on removal and presence available
Emissions to air
Ash / slag
Routes into environment
Air
Suspended solids?
Atmospheric deposition
Sea spray aerosols
Surface and groundwater concentration
Some data available from SEPA
Atmospheric deposition
Sediment?
Soil
Sea
Surface water
Groundwater
Environmental compartments
Inhalation
WTP
Private water supply
Plants
Needs:
Harmonized approach to definition
Hazard read across approaches (cannot test them all)
See EU reach restriction proposal + HSE RMOA
Inhalation
Aquatic organisms
Primary consumers
Humans
Livestock
Secondary consumers
Via placenta or breastmilk
Lower reported detection limits to better see what's bioaccumulating
Foetuses / infants
Tertiary consumers
Organismal exposure


Human pharmaceuticals
Need to consider veterinary input as many pharmaceuticals & antibiotic used in agriculture
Source
Factory
Online Pharmacy
Supermarket
Illegal purchase (hormones; drugs of abuse)
Community pharmacy
Hospital Pharmacy
Distribution and/or use
Impact of emptying frequency? SEPA modelled GIS layer on septic tanks
Storage with patient
Take-back schemes
Possible knowledge gap on take-back scheme awareness
Direct disposal
Direct disposal
Patient use
Metabolism & excretion known
• Parent compound (after consumption and topic treatment runoff
• Phase 1 & phase 2 metabolites
Septic tank
Sewer
Solid waste
Haz. waste
Routes into environment
Septic tank sludge should be transported to WWTP and treated but isn't always (also for small WWTP)
Urinating / excretion in the environment (particularly in / around festivals)
Behaviour and fate of pharma governed by physical chemical properties (like: logKow, Ka, solubility, molar weight). Where unknown, it's possible to estimate these based on chemical structure (eg. EPI SUITE)
WWTP
Transformation and degradation products (stereoselective & non-stereoselective):
• Microbial metabolism
• Reformation of parent compound (deconjugation)*
*not necessarily 100% back transformation
Landfill
Incineration
Although not generally volatile, depends on operating conditions of incinerators
Sludge
Sludge treatment
Adsorption to solid matter in wastewater influent/effluent as well as in surface waters
CSO
CSO – partial treatment
Leachate treatment
Ash / slag
We need information on pharmaceuticals in sludge. Sludge → farmland seems very relevant but unknown
University of York found high concentrations of paracetamol in leachate of unregistered landfill
Environmental compartments
Suspended solids
Poorly understood e.g. release at higher temperatures?
Surface water
Sediment
Soil
Air
Injection & desorption
Groundwater
WTP
Private Water Supply
Recreational pathways (swimming, drinking spring water during hill walks etc.
Organismal exposure
PWS may be more at risk due to more septic tanks in remote areas
Plants
Microbes and invertebrates
Primary consumers
Secondary consumers
Tertiary consumers
Aquatic organisms
Humans
Livestock
Animals inc. insects
Birds + mammals

Appendix II – Detailed overview of the literature review

Due to the large number of substance groups included in our remit, the variability of available data, inconsistent categorisations, and the fact that necessarily some of the research activities had to happen in parallel rather than sequentially, our approach to selecting substance groups to take forward for final analysis was also iterative. During the literature review process, some groups were dropped either because of substantial overlap with other contaminant groups or because insufficient results (Table II-1). Some of these groups were however listed by the survey respondents and indeed further groups were suggested (see Report Section 3.2.2).

Table II-1 Overview of the contaminant groups considered at various stages in the project

	Initially proposed to PSG	Literature review completed	If not, reason why not	Highlighted by survey respondents	Substance Flow Map produced	Taken forward
Nano and micro plastics	Y	Y		Y	Y	Y
Nano materials	Y	Y		Y	Y	Y
Per-and polyfluoroalkyl substances (PFAS)	Y	Y		Y	Y	Y
Endocrine Disrupting Chemicals (EDC)	Y	Y		Y		
Persistent and Bio-accumulative chemicals	Y	N	Search conducted but all contaminants fell within another group, i.e. PFAS			
Synthetic hormones	Y	Y		Y		
Food additives	Y	Y				
Flame retardants	Y			Y		
Industrial chemicals	Y	Y				
Pesticides	Y	Y		Y		
Pharmaceuticals	Y	Y		Y	Y	Y
Personal Care Products	Y	Y		Y		
Pathogens (human, animal, plant)	Y	Y		Y	Y	
AMR, ARGs and MGEs	Y	Searches for ARG and ARB were completed		Y	Y	Y (AMR)
Cyanotoxins	Y	Y		Y	Y	
Invasive species	Y	Y			Y	
Solar panel contaminants	Y	N	Search carried out but no relevant literature returned. Decided that this group was potentially covered by other contaminant groups.			
Tyre contaminants	Y	N	Search carried out but no relevant literature returned. Decided that this group was potentially covered by other contaminant groups.	Y		
Mixtures	Y	Y				
Macronutrients	N	Y	Contaminant group revealed during another search.	Y		
Heavy metals	N	Y	Contaminant group revealed during another search.	Y		

Detailed approach to the literature review

Further amendments to the search approach due to the heterogeneity of the contaminant groups were made as necessary (Figure II-1). For example, for pesticides, the Scottish Pesticides Usage Database offers more useful data on which to base a Scottish risk assessment than the peer-reviewed literature. Reviewers also often found that it was more useful to extend the geographical range to other developed areas, such as Europe, with similar contaminant regulations and climates.

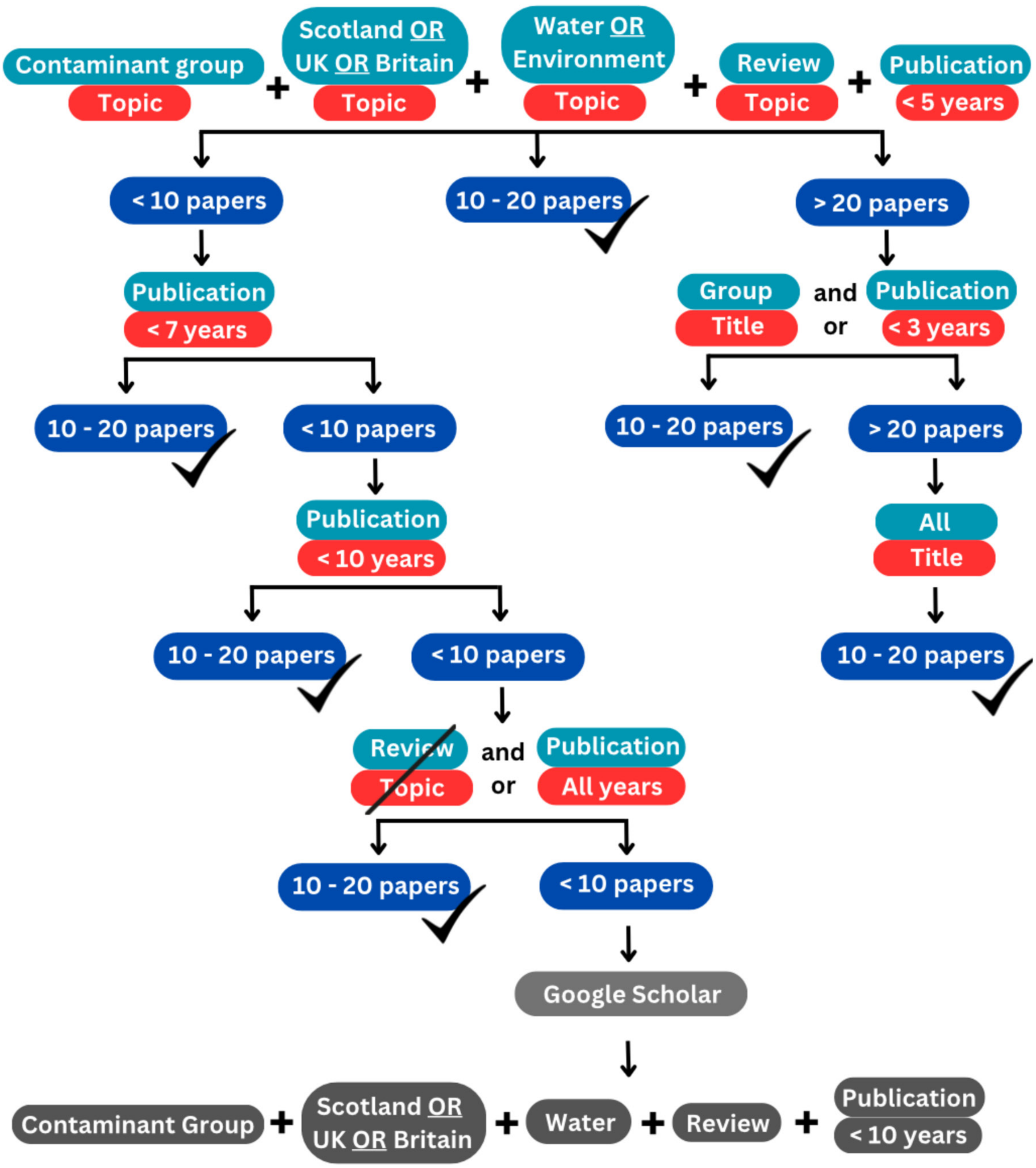


Figure II-1 Decision tree for Web of Science and Google Scholar searches

Appendix III – Survey questions

The Emerging Contaminants Survey

This survey is for anyone with knowledge of emerging contaminants in the environment. It has three parts. In the first part, we will provide information about our research project, collect some information about you, and ask you to indicate your consent to take part. In the second part, you will be asked to select a specific contaminant (or contaminant group) and answer some questions about it. You can repeat this second part as many times as you like to tell us about different contaminants. In the third and final part, you will be invited to indicate your level of concern about different contaminant groups.

The survey will take about 15-20 minutes to complete. If you need to, you can save your responses and return to them later. The survey will remain open until 8 January 2024.

EMERGING CONTAMINANTS: INFORMING SCOTLAND'S STRATEGIC MONITORING AND POLICY APPROACHES ON SUBSTANCES OF INCREASING CONCERN

Participant Information

This introduction contains important information about the research project. Please read it before taking part in the survey.

Background, funding and aims of the project

This project aims to identify the key contaminants of emerging or increasing concern ('emerging contaminants') for Scotland and to draw together the state of knowledge on these. The outputs from the project will inform monitoring and policy on emerging contaminants, including the prioritisation of further research projects. This project is funded by the Scottish Government's Centre for Research Expertise in Waters (CREW) and was developed by researchers from the James Hutton institute, led by Dr. Lisa Avery, and the Glasgow Caledonian University, led by Dr Karin Helwig, who is also the overall Project Lead.

Taking part

We invite anyone with knowledge or expertise on emerging contaminants to take part in this survey. The survey responses will inform a knowledge sharing workshop in January 2024.

Participation is voluntary and you can withdraw from the study, up to the point of submitting your answers, without giving reasons and without any negative consequences.

What are the benefits of taking part?

Taking part in the survey may be of no direct benefit to you. However:

Participating in the survey provides an opportunity for you to inform future developments in monitoring and policy development around emerging contaminants. It may also result in you being invited to take part in the in-person workshop at the next stage of the project. The results of this project may also inform the formulation of future research priorities.

The project should help our understanding of emerging contaminants and our ability to mitigate their adverse effects as appropriate. This, in turn, is expected to lead to healthier water environment and a reduction of risk, thereby improving planetary health.

Will my taking part be kept confidential?
We collect your name and organisation in case we need to determine expertise and perform quality control. We will not reveal your name or organisation at the workshop, nor in any of the publications that may result from the project.

What will happen to the information I provide?
The James Hutton Institute and Glasgow Caledonian University will both be data controllers. The James Hutton Institute and Glasgow Caledonian University will use your personal data for the purposes of the research undertaken in this project in accordance with the UK General Data Protection Regulation. The James Hutton Institutes full Privacy Notice can be found at https://www.hutton.ac.uk/terms and GCU's Privacy Policy at https://www.gcu.ac.uk/aboutgcu/universitygovernance/data-protection. If you have any queries about how Hutton or Glasgow Caledonian University as a data controllers process your personal data, you can contact our Data Protection Officers on dpo@hutton.ac.uk and dataprotection@gcu.ac.uk respectively. You also have the right to lodge a complaint with the Information Commissioner's Office that can be contacted on casework@ico.org.uk.

We will collect data about your role and organisation to enable quality control. Beyond quality control, this information will not be included in the survey data collation. All the information collected during the survey will be stored on secure drives that only the team of researchers from The James Hutton and Glasgow Caledonian university can access. The data will be held for no more than 5 years from the end date of the project.

The data you will provide, other than your name, role, and organisation, may be used to support other ethically approved research in the future, and may be shared in anonymised form with other researchers.

How can I withdraw from the project if I wish to?
The survey is in three parts. Whilst you are completing each survey, you can stop at any time and your answers will not be retained. Once you have submitted responses, it will not be possible to remove these from the study.

Personal Risks
All studies involve some level of risk and inconvenience. The possible risks involved with this study are that secure data storage systems are breached or that the topics discussed during the workshops are distressing to you. The research team judge these risks to be very low and will make every effort to mitigate them.

Ethical Review
All studies involving human participants carried out at Glasgow Caledonian University are reviewed by an ethics committee. The role of the ethics committee is the protect the safety, rights, wellbeing, and dignity of study participants. This study was reviewed by the School of Computing, Engineering and the Built Environment's Civil Engineering and Environmental Management departmental committee of the Glasgow Caledonian University (scebe_ethics@gcu.ac.uk).

Further Information

For further project details, please contact the project principal investigator:

Dr. Karin Helwig
Email: Karin.Helwig@gcu.ac.uk
Glasgow Caledonian University
Cowcaddens Road, Glasgow
G4 0BA

If you have any concerns about the way in which the project has been conducted, or you wish to make a complaint, you can contact the SCEBE Research Ethics Committee via scebe_ethics@gcu.ac.uk.

I have read and understood the above terms of participation	◯ Yes ◯ No
I agree to take part in the survey	◯ Yes ◯ No

PART 1: YOUR INFORMATION

We collect your name and organisation in case we need to determine expertise and perform quality control. We will not reveal your name or institution at the workshop, nor in any of the publications that may result from the project.

We may want to contact you again about the project. If you agree to be contacted, we will also ask for your contact details.

What is your name?	______________________
I agree to being contacted at a later date if the researchers want to request further information or share project findings.	◯ Yes ◯ No
Please enter your contact details:	______________________
I would like to be contacted at a later date to be invited to the project workshop, to be held in Glasgow in December 2023. More detail will be provided in due course and you are not committing to attending, nor are the researchers committing to inviting you.	◯ Yes ◯ No
Please enter your contact details:	______________________

In which type of organisation or sector are you employed?	◯ Academic ◯ Environmental Regulator ◯ Food Regulator ◯ Government or Policy related ◯ Public Health ◯ Animal Health ◯ Water Industry Sector ◯ Food Industry Sector ◯ Farming ◯ Other
Please specify:	__________________________________
Please briefly describe your expertise:	____
In what country do you operate?	◯ UK - England ◯ UK - Scotland ◯ UK - Wales ◯ UK Northern-Ireland ◯ Other
Please specify:	__________________________________

PART 2: IDENTIFYING CONTAMINANTS OF EMERGING OR INCREASING CONCERN

We are interested in identifying key substances of emerging or increasing concern (henceforth "emerging contaminants") in Scottish waters. We aim to draw together the state of knowledge on these contaminants and the risks associated with them.

By "substance" or "contaminant" we mean any chemical, biological or physical agent. We are interested in hazard or risk associated with these key contaminants to humans, animals, plants, or ecosystems.

For the questions below, please answer with the Scottish context in mind, in as much as you are able to.

Please list the main contaminants that you think are of emerging or increasing concern in the Scottish water environment.

You may list individual contaminants or groups of contaminants; list as many as you like. Feel free to group them as you see fit, or to highlight specific contaminants to us. Please answer in line with your knowledge. Please also include contaminants that are not a concern at present but are likely to pose a concern in the future.

(This survey contains a loop; you may skip this question if you have already answered it).

____

Now, please select ONE contaminant (or contaminant group) about which you would like to give us more information.

You will be able to repeat this process for further contaminants; to do so, click on 'Complete the survey again for another contaminant' at the end of Part 2.

____

UNDERSTANDING OCCURRENCE OF EMERGING CONTAMINANTS

In the next set of questions, we will ask you to think more about the sources and pathways of the emerging contaminant (or contaminant group) that you have chosen above. Please feel free to group them or to pick those that you feel are important to bring to our attention. You are welcome to write as much or as little as you wish, and you can repeat the survey for as many contaminants (or contaminant groups) as you like.

Please describe the main SOURCES and PATHWAYS by which this contaminant enters the water environment.

____

	Very poor	Poor	Basic	Good	Excellent	I don't know

How would you describe our understanding of the SOURCES of this contaminant?	◯ Very poor	◯ Poor	◯ Basic	◯ Good	◯ Excellent	◯ Don't know
How would you describe our understanding of which PATHWAYS into the water environment are the most important for this contaminant?	◯ Very poor	◯ Poor	◯ Basic	◯ Good	◯ Excellent	◯ Don't know
How would you describe our understanding of the PROCESSES that determine the transport or degradation of the contaminant in the environment? For example, how well can we quantify these?	◯ Very poor	◯ Poor	◯ Basic	◯ Good	◯ Excellent	◯ Don't know
How would you describe our knowledge of the OCCURRENCE of this contaminant? In other words, how much do we know about where and in what concentrations the contaminant is present in the water environment??	◯ Very poor	◯ Poor	◯ Basic	◯ Good	◯ Excellent	◯ Don't know

ASSESSING RISK FROM EMERGING CONTAMINANTS

In the next questions, we will ask you to think more about the RISK AND HAZARD associated with the emerging contaminant (or contaminant group) you have chosen. You are welcome to write as much or as little as you wish.

What organisms - including humans - or ecosystems are most at risk from this contaminant? ____________________________________

How would you describe our understanding of the risk of this contaminant to HUMAN HEALTH?	◯ Very poor	◯ Poor	◯ Basic	◯ Good	◯ Excellent	◯ Don't know

How would you describe our understanding of the risk this contaminant poses to AQUATIC ORGANISMS? ○ ○ ○ ○ ○ ○

How do humans, animals and/or plants come into contact with the contaminant?

____

What specific risks does the contaminant pose? Tick all boxes that apply.

☐ Toxicity
☐ Endocrine disruption
☐ Bioaccumulation
☐ Pathogenic
☐ Teratogenic
☐ Carcinogenic
☐ Involved in antimicrobial resistance
☐ Other
☐ Don't know

Please specify:

____

How do you think prevalence and hazards associated with this contaminant may change under future scenarios (e.g. climate and land use changes)?

○ Likely to increase
○ Likely to stay the same
○ Likely to decrease
○ Don't know

Please explain your answer:

____

MANAGEMENT OPTIONS AND SOLUTIONS

In this section, we will ask you about management options or other solutions that can prevent or reduce the presence of the contaminant in the water environment.

What activities or management practices do you think cause or increase the likelihood of this contaminant being present in the Scottish water environment?

____

Do you have any suggestions for mitigating risk from the contaminant you selected?

____

MIXTURES AND INTERACTIONS

Many substances reach the water environment, resulting in a 'cocktail' of contaminants. We are interested in understanding the risk from contaminant mixtures and in any potential interactions between different contaminants.

Please describe any interactions or mixture effects relevant to the contaminant that you have listed.

____

FURTHER INFORMATION

Please use this section to tell us about anything else relating to this contaminant you think the research team should consider.

Please list any key publications you think we should be aware of relevant to this contaminant.

____

Is there anything else you would like to tell us in relation to this contaminant?

____

Prioritising Emerging Contaminants

PART 3: PRIORITISING EMERGING CONTAMINANTS

RISK TO HUMAN HEALTH

We are interested in your view on which groups of contaminants you think need to be addressed as a priority by policy makers and regulators. Please rate the following contaminant groups in terms of the level of concern they pose to HUMAN HEALTH.

NB. We are aware that there is some overlap between some of the groups.

		Not at all	Somewhat concerning	Concerning	Very concerning	There are too many uncertainties to say	I don't know
1)	Microplastics or nanoplastics	○	○	○	○	○	○
2)	Other nanomaterials	○	○	○	○	○	○
3)	Per- and polyfluoroalkyl substances (PFAS)	○	○	○	○	○	○
4)	Endocrine disrupting chemicals	○	○	○	○	○	○
5)	Persistent and bioaccumulative chemicals	○	○	○	○	○	○
6)	Synthetic hormones	○	○	○	○	○	○
7)	Food additives	○	○	○	○	○	○
8)	Flame retardants	○	○	○	○	○	○
9)	Industrial chemicals	○	○	○	○	○	○
10)	Pesticides (inc. herbicides, insecticides, and fungicides)	○	○	○	○	○	○
11)	Pharmaceuticals	○	○	○	○	○	○
12)	Antibiotics	○	○	○	○	○	○
13)	Antimicrobial resistant (AMR) pathogens and antimicrobial resistant genes (including Mobile Genetic Elements)	○	○	○	○	○	○
14)	Personal care products	○	○	○	○	○	○
15)	Cyanotoxins	○	○	○	○	○	○
16)	Invasive species	○	○	○	○	○	○

RISK TO AQUATIC ORGANISMS

Now, please rate the following contaminant groups in terms of the level of concern they pose to AQUATIC ORGANISMS.

NB. We are aware that there is some overlap between some of the groups.

	Not at all concerning	Somewhat concerning	Concerning	Very concerning	There are too many uncertainties to say	I don't know
17) Microplastics or nanoplastics	○	○	○	○	○	○
18) Other nanomaterials	○	○	○	○	○	○
19) Per- and polyfluoroalkyl substances (PFAS)	○	○	○	○	○	○
20) Endocrine disrupting chemicals	○	○	○	○	○	○
21) Persistent and bioaccumulative chemicals	○	○	○	○	○	○
22) Synthetic hormones	○	○	○	○	○	○
23) Food additives	○	○	○	○	○	○
24) Flame retardants	○	○	○	○	○	○
25) Industrial chemicals	○	○	○	○	○	○
26) Pesticides (inc. herbicides, insecticides, and fungicides)	○	○	○	○	○	○
27) Pharmaceuticals	○	○	○	○	○	○
28) Antibiotics	○	○	○	○	○	○
29) Antimicrobial resistant (AMR) pathogens and antimicrobial resistant genes (ARG), including Mobile Genetic Elements (MGE)	○	○	○	○	○	○
30) Personal Care Products	○	○	○	○	○	○
31) Cyanotoxins	○	○	○	○	○	○
32) Invasive species	○	○	○	○	○	○

Appendix IV – Emerging Contaminants MASTER Database

This appendix is provided separately.

Appendix V – Categorisation of survey responses

Categorisation of contaminants selected by survey participants adopted to enable collation of rankings of concern and understanding.

Categorisation	Respondent-generated entry
Antibiotics and antimicrobials	Includes entries for ‘antibiotics’, ‘antimicrobials’, and combinations of the two.
ARG, ARB and MGE	Contains entries such as ‘AMR genes’ and ‘resistant microorganisms’
Micro and nanoplastics	Contains entries for ‘microplastics’ as well as ‘nanoplastics’
Nanomaterials	Includes one general entry for nanomaterials and one specific one for titanium dioxide
PFAS	Contains one entry for ‘PFOS’; all others were for PFAS generally
Pharmaceuticals	Contains one entry specified to be ‘human pharmaceuticals’ but also ‘human and veterinary pharmaceuticals’
Veterinary pesticides	Contains one entry of ‘veterinary pesticides’ and one of ‘cypermethrin’ specifically
Steroid hormones	Contains one entry for ‘steroids’ and one for ‘EE2’

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