Worst-case ranking of organic substances detected in groundwater and surface waters in England

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Glossary

ADI – Acceptable Daily Intake

CA – Concentration Addition

CMR – Carcinogenic, Mutagenic, Reprotoxic

DW – Drinking Water

ECHA – European Chemicals Agency

ECx – Effect concentration for x% change in a measured endpoint

EQS – Environmental Quality Standard

EFSA – European Food Safety Authority

GC-MS – Gas Chromatography Mass Spectrometry

HCx – Hazardous Concentration for effects (acute or chronic) for x% of species

HQ – Hazard Quotient = exposure (i.e. concentration) / hazard value (i.e. PNEC)

IA – Independent Action

LC-MS – Liquid Chromatography Mass Spectrometry

LCx – Lethal concentration for x% of individuals

NOEC - No Observed Effect Concentration

PAHs – Polycyclic Aromatic Hydrocarbons

PCBs – Polychlorinated Biphenyls

PFAS - Per and Polyfluoroalkyl Substances

POPs – Persistent Organic Pollutants

PNEC – Probable No Effect Concentration

QSAR – Quantitative Structure-Activity Relationship

REACH - Registration, Evaluation, Authorisation and Restriction of Chemicals

SSD – Species Sensitivity Distribution

TDI – Tolerable Daily Intake

TTC – Threshold of Toxicological Concern

WFD – Water Framework Directive

WHO – World Health Organization

Executive summary

Background: The Environment Agency has been using GC-MS and LC-MS scans to semi-quantitatively measure organic substances in groundwater and surface waters. Lapworth *et al*. (2018) analysed this groundwater data to consider concentration ranges and spatial distribution. In this study, we extend this analysis to generate a worst-case hazard ranking of the detected substances in these groundwater samples and also in surface waters. It is intended that this ranking may be used to help identify substances for further consideration, e.g. for hazardous substance determinations under the Joint Agencies Groundwater Directive Advisory Group (JAGDAG), and/or through the Environment Agency's Chemical Prioritisation and Early Warning System (PEWS). The results of ranking should not be used directly for control or management measures, due to the uncertainties inherent in the ranking process, for example, as a result of the semi-quantitative nature of the measurement data and preliminary nature of some of the hazard values used and also as it is a worst case ranking using the maximum concentration detected. The rankings are instead a means of identifying substance for further consideration.

Overall approach: Accessible and downloadable hazard resources were used to collate hazard values for human health and ecological endpoints. UK Drinking Water Standards, and EFSA ADIs/TDIs were used in relation to human health and Water Framework Directive EQSs, NORMAN Network PNECs and chronic species sensitivity distribution (SSD) HC50 from Posthuma *et al*, 2019 for ecological hazard. The hazard values within each metric were compared to the highest measured concentration for each chemical to determine a hazard quotient. These hazard quotients were ranked for each of the human health metrics. For the three ecological hazard values, an average rank hazard rank was determined from the three metrics. These ranks were then multiplied by the substance detection frequency ranking to calculate an overall score for each chemical which was used as the final ranking of the substances in each media, i.e. surface water and groundwater, and for each analytical method, i.e. GC-MS and LC-MS. Use of a worst case approach, i.e. comparison with the highest detected concentration, was pragmatic as mean, median or 90th percentile values could not be estimated for most chemicals due to insufficient detections. To assess if the highest concentrations was an outlier, an assessment of this value in relation to other measured concentrations was conducted for 40 chemicals. Mixture effects were also considered using a concentration addition approach that assumes additivity of substance toxicity.

Results: Substances detected using GC-MS and LC-MS screens were ranked for two human health metrics and for a combination of 3 ecological hazard values. Pesticides present in the top 30 ranked chemicals included legacy pesticides (particularly in groundwater) and current use actives (particularly in surface water). Intentional monitoring of specific uses were responsible for certain substances appearing in the top 30 ranked, for example rotenone which is used for invasive species control. A number of industrial and plastics associated chemicals were ranked highly in groundwater, while more consumer goods, personal care products and pharmaceuticals were ranked highly in surface waters. In all of the 40 individual substances cases assessed, the highest measured concentration was not found to be a substantial outlier. Both analysis methods identified the presence of complex mixtures in groundwater and surface water, although of lower complexity for GC-MS due to the higher detection limit.

The GC-MS and LC-MS data and hazard metrics were used to generate a number of ranked lists of substances for future investigation. In developing the ranking approach, a number of decisions were made that could affect outcome, including hazard metric choice, metric weighting; hazard ranking correction by detection frequency, choice of detected concentration, assigning use categories and choice of mixture model. This final ranked list is not intended as a formal ranking of risk, but rather a prompt towards consideration for more detailed substance assessment within schemes such as JAGDAG and PEWS, as well as for other regulatory assessments and for designing research programs.

The mixture assessment identified that cocktail effects can exceed those for any single chemical. Often, however, the magnitude of difference between predicted mixture risk effect and that for the most important single chemical was small. Indeed in >99% of all cases, the most toxic chemical contributed ≥ 20% of the mixture effect. This result demonstrates the feasibility of mixture assessment and the results are consistent with previous work (Backhaus and Faust, 2012).

1 Background and project rationale

The scale and range of current chemical use results in releases of pollutants to the environment. Point source emissions from industry and domestic water treatment and diffuse releases from distributed chemical use and agriculture have resulted in the contamination of air, soil and surface and groundwater leading to potential impacts on human health and ecosystems. Recognition of these effects underpin a desire to improve the chemical condition of our environment. Landmark policies on the abatement of acid rain; controls on the use of certain persistent organic pollutant (POPs), biocides and pesticides; improvements in wastewater treatment; and, economic and cultural shifts in energy production, transportation and metal processing, have changed the types and amounts of chemicals entering the environment. Despite these changes, continued domestic, industrial and agricultural chemical use means contaminants still enter groundwater and surface water. The pace at which new chemicals are being developed challenges our regulatory and monitoring response. As a consequence, surveillance and horizon scanning are needed to identify current and emerging chemicals risks in groundwater and surface waters.

Direct and indirect chemical releases to groundwater and surface water bodies can come from multiple sources. In the UK there has been a ~50% rise in the average number of different pesticide active ingredients applied to arable crops in the last two decades (from 11 in 2000 to 17 in 2015 in Pesticide Usage Survey data from FERA). Substantive sources for diffuse entry into the environment remain for established pollutants such as polycyclic aromatic hydrocarbons (PAHs) and POPs such as polychlorinated biphenyls (PCBs), dioxins and short-chain chlorinated paraffins, as well as for newer groups of POPs (polybrominated diphenyl ethers (PBDEs), perfluorinated compounds); human and veterinary pharmaceuticals; personal care products and household chemicals (including those associated with plastics use). Despite restriction on the use of some of the more hazardous chemicals (e.g. PCB, PBDEs), there is a legacy effect because of their persistence and presence in consumer products with a long life-time of use. There is also more than 10 million tonnes of biosolids, composts, and digestate applied to UK land each year acting as a further potential vector of pollutant transfer to soil and from there through percolation and run-off into groundwater and surface waters.

The widespread use of chemicals and the presence of pathways to reach soil, groundwater and surface waters has meant there is interest in measuring micro-organic pollutants in water bodies. This interest has been reflected in several studies that have measured suites of organic pollutants, in different countries, mainly in surface waters (Altenburger *et al.*, 2019; Hermes *et al.*, 2018; Houtman *et al.*, 2019; Park *et al.*, 2018; Peng *et al.*, 2018). Since 2007, the Environment Agency has been using the scanning capability of gas chromatography mass spectrometry (GC-MS) and liquid chromatography mass spectrometry (LC-MS) to screen against a database of target substances in groundwater and surface water samples. This has provided the capacity to identify a much larger range of substances than previously possible. The GC-MS method has been widely used for chemical monitoring since 2009. The method provides detection of a wide range of industrial compounds, halogenated solvents, plasticisers and pesticides, and a relatively small number of pharmaceuticals. The addition of the ultra-high-definition accurate mass time-of-flight LC-MS method for regular use in chemical detection in groundwater and surface water monitoring programs from 2014 onwards has provided data on polar, more hydrophilic compounds including many pesticides and pharmaceuticals, as well as perfluorinated chemicals (PFCs).

Lapworth *et al*. (2018) analysed the available groundwater data to provide summary statistics, detection ranges and maps of the spatial distribution of the top 50 most frequently GC-MS and LC-MS detected compounds. In that work, however, no consideration was made to the potential hazard of the different chemicals. This work aims to build on this analysis by comparing the concentrations detected with readily available hazard values to identify substances for further consideration, for example under the Joint Agencies Groundwater Directive Advisory Group (JAGDAG) and the Environment Agency's Chemical Prioritisation and Early Warning System (PEWS). **The comparisons of environmental concentrations to available hazard values conducted was not intended to provide a quantitative assessment of the risk of chemicals in drinking water or ecological risk potential for groundwater and surface water environments.** Such an analysis would require a more in depth assessment of the monitoring data-set, as well as consideration of additional aspects such as routes of exposure, treatment efficiency for drinking waters; potential exposure to the same chemical from other sources (e.g. air, food) and substance bioavailability, bioaccumulation and potential for food chain transfer. Similarly, for location specific risk assessments using site specific concentrations, additional effort will be needed to develop a better contextual understanding of the drivers of local concentrations. *Instead, the scope of the study was limited to a screening exercise to rank the relative worst-case risks of the GC-MS and LC-MS detected chemicals in groundwater and surface water samples. The aim was to rank substances based on both their concentration and potential hazard and to use this information to identify potential substances for further assessments, e.g. through JAGDAG or PEWS, as well as acting as a wider driver for additional regulatory relevant and risk assessment research.*

2 Workflow for worst-case ranking of groundwater and surface water organic pollutants

The approach used in this report to rank substances was based on a comparison of the highest concentration of a chemical detected in groundwater and surface water to a range of readily available values that characterise the potential hazard of each detected chemical for human health and the environment (Fig. 1). The approach used to prepare the groundwater and surface water data-set concentrations for statistical analysis followed that originally described by Lapworth *et al*. (2018) and is summarised below.

1. Chemical data selection. The results of the GC-MS and LC-MS scans from the groundwater and surface water data-sets were initially compiled. For the groundwater monitoring network, the GC-MS analysed samples were taken between 2009 and April 2020 and the LC-MS samples between 2014 and February 2020. In total, there were approximately 850 groundwater samples analysed by LC-MS and 16,000 by GC-MS. For the surface waters data-set, GC-MS samples were taken routinely between 2007 and Feb 2020 providing approximately 23,000 and LC-MS routinely from 2014 to Feb 2020 giving 2,800 (see Section 2 for further details).

2. CAS number and excluded substances. Substance CAS numbers were formatted to make them consistent and searchable against databases of hazard values. Records lacking CAS number or chemical name fields or for which units were not provided were excluded as their

reliability was uncertain (the number of removed values was always <5% of all values). The sulphur compounds S8 (CAS number 10544-50-0; cyclooctasulphur) and S6 (CAS number 13798-23-7; hexathiane) were excluded as they are not organic chemicals. The total number of substances potentially measured is 1,144 for the combined GC-LS and LC-MS suite (excluding duplicated substances detected by both methods) with 684 and 769 showing positive detects in one or more groundwater or surface water samples respectively. A summary of the number of analytes, samples analysed and concentrations ranges is provided in Table 1.

Method	Hazard criteria	Ground water	Surface water
GC-MS	Substances in analytical suite	707	709
	Substance detected >LOD	491	515
	Substance detection frequency	1 - 2,212	1 - 13,989
	Analysed samples by compound	267 - 16,631	473 - 23030
	Maximum concentration range (µg/L)	0.001 - 4,000	0.004 - 8,700
LC-MS	Substances in analytical suite	619	621
	Substance detected >LOD	290	398
	Substance detection frequency	1 - 377	1 - 2,612
	Analysed samples by compound	75 - 858	374 - 2,855
	Maximum concentration range (µg/L)	0.0001 - 32	0.0001 - 257
Combined GC-MS & LC-MS	Substances in analytical suite	1,144	1,144
	Substance detected >LOD	684	769

Table 1. The number of measured substances detected in any sample above LOD, number of samples with detections above LOD and maximum concentrations ranges for all chemicals measured by GC-MS and LC-MS in the groundwater and surface water monitoring data-sets.

3. <u>Assignment of use categories.</u> The detected compounds were classed into broad usage groups. (Table 2). These categories were based on those of Lapworth *et al* (2018), except that the "Pharmaceutical, Personal Care Product, Lifestyle" class was split into three separate categories: Pharmaceuticals (including veterinary medicine); Personal care products; and Consumer products. For many compounds, allocation to a use category was not a simple task. For example, pesticides were identified from listings in the Pesticide Properties Data (https://sitem.herts.ac.uk/aeru/ppdb), however, active ingredient listed here can also be used as veterinary medicines, human pharmaceutical and in consumer products (e.g. household biocides) and there are similar cross overs for other classes. However, while the use categorisation approach has clear limitations (as recognised by Lapworth *et al* (2018), it still provides a pragmatic approach deliverable i/n the time available to catalogue chemicals in a manner which assists in some aspects of source identification.

Use category	Description of relevant compounds
Pesticide	Herbicides, insecticides, fungicides and transformation products
Halogenated solvent	Chlorinated solvents, trihalomethanes
Polyaromatic hydrocarbon	PAH compounds and associated metabolites
Personal care product	Perfumes, musks, hygiene products
Pharmaceutical	Pharmaceutical, including veterinary medicines
Plastic associated	Phthalate, Bisphenols, other plasticisers and plastics associated chemicals
Industrial	Industrial chemicals and process intermediates
Consumer products	Detergents, cleaning products

Table 2. Compound major use categories (adapted from Lapworth *et al*. (2018) attributed to each detected chemical.

4. <u>Collate hazard values from the identified sources for each chemical in the analytical data-sets (total of 1,144 substances).</u> As groundwater and surface waters can act as a source of drinking water, and groundwater supplies base flow to rivers, lakes, wetlands, estuaries and coastal waters, consideration of risk to both humans and ecosystem status was considered relevant. Due to the limited time available, data sources of already compiled potential hazard values were used to assemble a set of relevant substance hazard values. The underlying methodologies for the derivation of the various thresholds and relevant screenshots from websites from which values were retrieved are summarised in Section 3 and given in detail in Appendix 2. The listed sources of hazard information to be searched were outlined in the initial tender specification. From these resources five hazard values were selected for use in the assessment. Two human health relevant and three ecological hazard values.

<u>Human health</u>

- EU Drinking Water Standards

- Tolerable Daily Intake data and Acceptable Daily Intakes for food additives and contaminants

<u>Aquatic toxicity</u>
- Water Framework Directive Environmental Quality Standard (WFD EQSs)

- NORMAN network PNEC database (see https://www.norman-network.com/nds/)

- Estimated HC50 values from published species sensitivity distribution (SSD) model fits of Posthuma *et al.* 2019. *Environ. Toxicol. Chem.* 38, 905–917.

With additional time available, it would be possible to use other sources of information to compile further bespoke lists of hazard values from data-sets such as the REACH registration information listed on the ECHA website (https://echa.europa.eu) or experimental ecotoxicology data listed in the US-EPA ECOTOX database. (https://cfpub.epa.gov/ecotox/).

Collated values were compiled into a single hazard value resource (as an Excel spreadsheet available by contacting the report author) that also included any relevant information or notes on the uncertainty associated with the specific values provided in the data source.

5. <u>Concentration used for ranking.</u> To calculate the hazard quotient, the highest detected concentration was used as the exposure term for all chemicals. The use of the highest value clearly provides the basis for a worst-case assessment. ***The highest value was chosen rather than a value more embedded in the distribution such as the mean, median, or upper 90th percentile, because for the large majority of chemicals, a high proportion of samples reported values below the detection limit. This limitation precluded the use of distribution based values and also the calculation of a reliable mean, median or 90th percentile*** *(for a detailed discussion on the problems of calculating summary statistics for these data see Lapworth et al., 2018).* For the prioritisation, this highest concentration was compared against each of the five considered hazard metrics (where available) for each chemical to generate a hazard quotient (calculated as concentration / hazard value).

6. <u>Ranking substances for human health and ecological hazard.</u> The substances detected in groundwater and surface by GC-MS and LC-MS were ranked against the selected set of five metrics based on the derived hazard quotients. ***For human health assessment, substances in each data-set were ranked separately for their UK Drinking Water Standard and EFSA reported ADI/TDI value hazard quotient.*** The hazard quotients for each metric were placed in rank order from 1 – X, with 1 being the substance with the highest HQ for that metric (i.e. the highest potential risk based on the highest concentration) to X being the substance with the lowest HQ (i.e. substances with the lowest risk indicated from the data considered), with X being the number of substances in the ranked list. Four separate substance rankings were, therefore, developed based on the calculated hazard quotients for each combination of analytical detection method (i.e. GC-MS and LC-MS) and sampled environment (i.e. surface water and groundwater). To avoid focussing on rarely detected substances, only substances detected ≥ 10 times in each data-set were included in each ranking.

For the ecological hazard assessment, ranking was made based on the corrected average rank of substance hazard quotient for each of the three separate hazard metric available (WFD EQS, NORMAN PNEC, chronic SSD HC50). To calculate the average environmental hazard rank, highest measured concentrations for the substance were compared to each of the three ecological hazard values (where available). These HQs were then ranked in order from highest to lowest for each metric in turn (1 – X). The substance hazard rank was then divided by the number of detected substances with a hazard quotient for that metric. These values were then averaged across the three metrics (where available) to give the average ecological hazard value for the substance. This average ecological value was then ordered from lowest to highest to give the final ecological hazard ranking for all substances. As for the human health rankings, only substances detected ≥ 10 time were included in the assessment.

7. <u>Detection frequency correction.</u> It was considered that substances to which human and ecological species are more likely to be exposed at measureable levels would be of greater interest for further consideration than substances that occur less frequently. Therefore, a

detection frequency correction term was included in the calculation of the final prioritisation ranking. For detection frequency correction, all substances ranked for hazard for the two human health and average ecological values were ranked by their detection frequency for the relevant analytical method in the relevant sampled environment. Substances were then given a detection frequency rank from 1 – X, with 1 being the substance with the highest detection frequency (i.e. the substance most commonly detected in the specific environment) to X being the substance detected fewest times (n.b. substances detected <10 time were not included in the assessment to avoid focussing on substances only very rarely detected).

8. Calculation of the final ranking. To calculate the final score for ranking, the substance rank for each human health and average ecological hazard metric were separately multiplied by the numeric rank of the substances for detection frequency (i.e. Hazard rank score * Detection frequency rank score). This final value was used to order substances from 1 - X for the final ranking. All substances with ≥10 positive detected in the sample data-set were ranked. As in some case the ranking list contain >100 substances, for brevity only the top 30 ranked substances are presented for each hazard metric in this report. The full ranking list for all metrics are, however, available as an Excel file spreadsheet (by contacting the report author).

9. **Mixture assessment.** *A mixture assessment was conducted to determine the extent to which potential exposure to multiple substances at a site may result in relative risk greater than for the single chemicals. This analysis can, thus, support an understanding of the extent of increased prioritisation needed for mixtures, including the potential magnitude of any mixture assessment factor.* The assessment of mixture effects was conducted using the measured data for all substances within each sample, rather than for the maximum concentration for the complete sample set, as the latter approach would overestimate worst-case risk because these high values would occur in different samples and not in direct combination.

The full approach used for the mixture assessment with underlying concepts is presented in Section 7, with further details presented in Appendix 3. Briefly, the assessment was conducted using an additive mixture model. Additive models have been widely tested in experimental and field studies, where they have been found to correctly predict the effects of a given combination of chemicals from single substance hazards at relatively high frequency (Cedergreen, 2014; Van Gestel *et al.*, 2010). The method used here was based on the default assumption of additivity through a similar mode of action according to concentration addition (CA). This model is widely used as the default assumption for mixture effects and is supported for relevance in the majority of mixture studies. The CA model generally predicts greater effects for mixtures than the alternative independent action (IA) model, hence, it is a conservative approach. The CA model was selected rather than IA, because CA requires only a single hazard metric to be available to calculate each substance contribution to the mixture effect, rather than a full concentration response relationship as is needed for IA. A further consideration for the mixture assessment is that if there is no hazard value available for a chemical, then that substance cannot be included in the mixture risk calculation according to either the CA or IA models. This means that calculation of HQmix for a given site may frequently underestimate actual risk due to the presence of chemicals with no hazard values that are, therefore, not included in the mixture assessment. Similarly chemical that are not detected in GC-MS and LC-MS scan are also not included.

10. <u>Hazard metric for mixture assessment.</u> To assess the mixture effect, the analysis was conducted using the chronic SSD HC50 values as the hazard metric. This value was selected as it has a very high substance coverage, thus allowing a robust assessment across the large majority of detected chemicals in the mixture with relatively few missing substances. Thus in the GC-MS data-sets, 384 (77%) groundwater and 397 (77%) surface water substances of a total number of 493 and 515 detected chemicals have a chronic SSD HC50 value. For the LC-MS data-set, 185 (63%) for groundwater and 236 (59%) surface water of the 290 and 398 detected substances have a corresponding chronic SSD HC50 value.
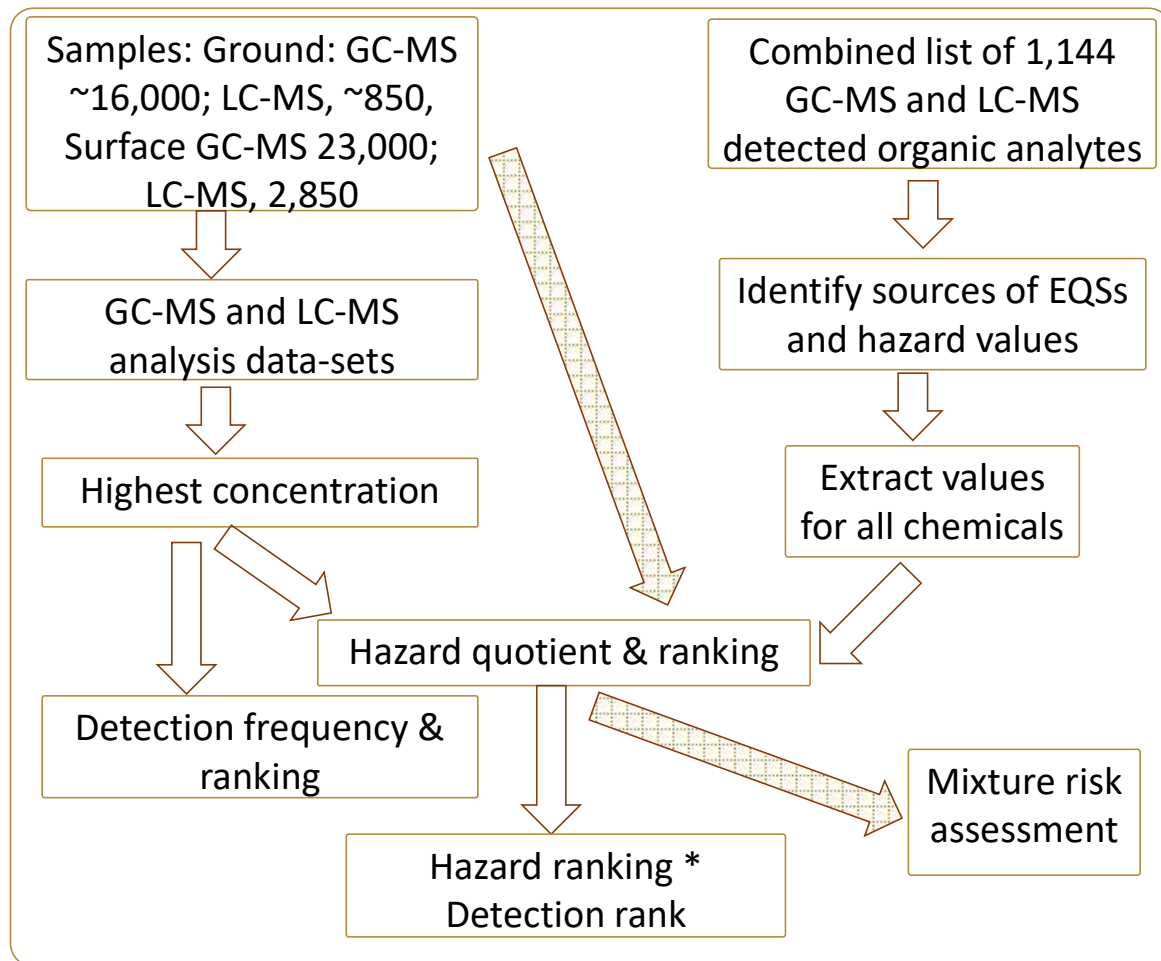
Fig. 1. Schematic of the approach used for worst-case risk ranking. The exposure term for hazard quotient calculation (left branch of the diagram) is identified as the highest measured concentration and detection frequency from the measured GC-MS and LC-MS data. The hazard value (right branch of the diagram) is collected for multiple metrics from easily available toxicological and ecotoxicological resources. Calculated HQ direct from the individual sample data are used for mixture assessment (hatched arrows) using an established and widely used additive mixture toxicity modelling approach.

2   Description of the monitoring data-sets, laboratory analysis and data processing

2.1   Environment Agency Groundwater Monitoring Data-set

The Environment Agency manages a Groundwater Quality Monitoring Network across England that currently comprises of about 2000 groundwater monitoring points. These points are boreholes, wells or springs and they have been selected by local Environment Agency hydrogeologists to represent the regional groundwater resources. Obvious point sources of pollution have been excluded as far as practical. This monitoring network, therefore, provides a robust picture of groundwater quality across England. Samples for GC-MS and LC-MS scan analyses are typically taken across the monitoring network once every three years. For the groundwater monitoring network the GC-MS samples analysed were taken between 2009 and April 2020 and the LC-MS samples between 2014 and Feb 2020. In total, there are approximately 10,800 GC-MS and 800 LC-MS analysed samples in the groundwater data-set. The limited number of LC-MS samples means that there is not complete coverage of the aquifers in England as of this time.

2.2   Environment Agency Surface Water Monitoring Data-set

The Environment Agency has collated a large surface water data-set of GC-MS and LC-MS measurements across England. Samples within the monitoring data-set have been collected from a range of different surface water bodies (rivers, lakes and ponds). Surface water samples have been analysed by GC-MS from 2009 to April 2020 and by LC-MS from 2014 to Feb 2020. The total number of samples analysed was approximately 23,000 by GC-MS and 2,800 by LC-MS. Thus, the coverage for LC-MS is sparser and is still developing in both the surface and groundwater schemes. This sparsity reflects not just a shorter time of use of the LC-MS method, but also a reduced sample coverage within years.

Over 600 surface water sites have been sampled across England with the GC-MS method. Of these, over 300 have been sampled at least 10 times and over 100 sampled at least 50 times. This is, therefore, a comprehensive monitoring data-set. Almost all of the samples were taken as a result of either statutory monitoring linked with domestic or EU legislation or as result of non-statutory monitoring linked to policy. Samples taken for pollution incidents have mostly been excluded from this data-set, however, in some cases, measurements have been associated with specific management and regulatory actions. This includes measurements of piscicides, i.e. rotenone, used for invasive species control applied at biocidal levels, which is explained in the Text box in Section 6.1.2. In contrast to the groundwater data-set, the surface water monitoring data-set therefore does not entirely reflect typical environmental concentrations as the data will in some cases be influenced by the reasons for taking the sample

Over 100 surface water sites have been sampled in England with the LC-MS method. Ten sites have been singled out for frequent monitoring, each being sampled over 100 times as part of the Government's Catchment Sensitive Farming programme. All other sites have been

sampled at much lower frequently. The spatial coverage of the LC-MS method is, therefore, not as comprehensive as for GC-MS.

2.3 Analytical methods

The data provided for the groundwater and surface water analysis comes from analyses undertaken by the National Laboratory Service. For the GC-MS method, a double liquid-liquid extraction was employed, using acid-neutral dichloromethane, to extract non-polar substances (for further details see Lapworth *et al.*, 2018). The GC-MS target based (multi-residue) screening method allowed for almost all GC-amenable pesticides as well as hundreds of other organic contaminants to be identified in a sample. Chemicals can be identified at concentrations as low as 0.01 µg/L. Progression of the method over time has allowed a number of changes and improvements to be operationalised for the analysis. These modifications include the addition of further substances to the analytical suite and the lowering of many substance detection limits. From the suite of potential analytes, there are 491 chemicals that are detected in one or more samples above the LOD in the groundwater data-set and 515 in the surface water data-set (see Table 1).

LC-MS (Q-TOF) was used to screen for polar organic compounds in each sample. Oasis® HLB cartridges were used for solid-phase extraction for the LC-MS method, elution was done using 0.1% formic acid in methanol/acetonitrile (1:1) as detailed by Lapworth *et al.* (2018). Target compounds for quantification have been analysed in a blank and at a concentration of 0.1 µg/L, the response factor obtained is used to create a single point calibration curve. Estimates of concentration is based on quant ion response and the response of the internal standard. The LC-MS multi-residue target based screening method allowed for almost all LC-amenable pesticides as well as other organic contaminants to be identified from a single sample. In total, the measurement comprises over 740 substances. Target compound identification is made by retention time, accurate mass and isotope distribution patterns (mass, ratio, spacing). Quantification limits are compound specific and are typically between 0.001-0.1 µg/L for the vast majority of compounds. Similar to the GC-MS approach, changes to the method over time have allowed the measurement of additional substances and the reduction of detection limits. From the LC-MS analysis, there are 290 chemicals detected above the LOD in the groundwater samples and 398 in the surface water samples (see Table 1).

The data that is generated by both methods is semi-quantitative and so provide an estimate of how much of the measured substance is present in the sample, however, it does not provide a definitive validated concentration. In this study, we have undertaken a worst-case ranking of substances detected in the GC-MS and LC-MS analytical suites based on these semi-quantitative values. Because the data is semi-quantitative, any assessment of risk (i.e. comparison of hazard/exposure) should be treated with caution. Further work would be needed to confirm that concentrations exceed any hazard values and the extent to which this is the case. Further the assessment is worst-case using only the highest measured concentrations, rather than a median for risk assessment (n.b. highest concentrations were selected because most analytes report few values above the LOD making the estimation of distribution based parameters impossible, especially for GC-MS analytes).

As it is based on assessment for the highest recorded concentration, the overall approach for ranking and prioritisation is potentially subject to artefacts resulting from the presence of a single anomalous measurement in a sample. Further for hazard criteria such as for WFD EQS, our analysis compares these highest measurements to values that are intended as annual averages, providing a further precautionary level to the overall assessment. To assess the extent to which the highest concentration may be a potential outlier, an analysis of the range of concentrations in the full set of measured samples was made to assess concentrations relative to the hazard metric across a wider series of samples for 40 specific priority pollutants. This analysis of the full range of measured concentrations allowed an assessment of the extent to which the highest measured value exceeds the other concentrations detected.

3 Collation of human health and ecological hazard values

The hazard values used in this report cover both human health and environmental hazard and include regulatory values from the Water Framework Directive and Drinking Water Directive as well as values proposed in peer reviewed sources. The latter covers a much greater number of chemicals which enables more of the substances detected to be considered in the prioritisation. A range of sources of hazard values is available. Of these, the current UK Drinking Water Standards and EFSA published ADI/TDI values were selected for the human health focussed assessment, as these are more relevant to chronic exposures than alternatives such as the acute reference dose. CMR values were collected and are included in the summary Excel file of hazard values available in a NERC Open Research Archive record. However, these hazard values were not used because of their binary nature (yes/no), which means that they were not considered suitable for comparative ranking across substances. The approach used for data collection and retrieval for the five hazard metrics is summarised below with further details in Appendix 2.

1. _Water Framework Directive Environmental Quality Standards (EQS)._ WFD EQSs expressed as Annual Averages were collated. The latter were selected above the Maximum Allowable Concentrations because the presence of substances in groundwater or surface water indicates the potential for a continuous rather than single pulse exposure. Using the Annual Average to compare with one off concentrations provides a further precautionary aspect to the assessment. The Water Framework Directive EQSs are statutory standards and, therefore, have a high degree of regulatory acceptance. However, values are only available for a small number of organic substances (61) meaning that they have limited coverage among the measured analytes.

2. _UK Drinking Water Standards._ The UK Drinking Water (England and Wales) Regulations 2000 SI No.1297 sets minimum quality standards for water intended for human consumption (drinking, cooking, other domestic purposes). The current regulation includes standards for 48 microbiological and chemical indicators. Chemical standards for drinking water are set at concentrations not expected to result in any significant risk to health over a lifetime of consumption. For most kinds of toxicity (the exception being

genotoxic carcinogens), a threshold dose is used. For most chemicals, this threshold is derived from the acceptable daily intake (ADI) or tolerable daily intake (TDI), itself derived from toxicity data with an associated uncertainty factor. The assessment for drinking water assumes that a 60 kg adult consumes 2 L/day. Substance specific drinking water standards are available for only a small proportion of the organic chemicals (22) in the Groundwater and Surface Water Monitoring database. However, a standard of 0.1 μg/L is set for all pesticides. This generic value captures a large number of active ingredients and metabolites which are present in the GC-MS and LC-MS suites. A further chemical class specific standards is that for PAHs, which within the regulation refers to 4 specific PAHs (benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[g,h,i]perylene, indeno[1,2,3,c,d]pyrene). In the groundwater and surface water database, concentrations for individual PAH compounds outside of these four are reported that can be related to the value reported for these four PAHs based on substance similarities. For both pesticides and PAHs, the risk assessment for substances in these classes was conducted by comparing individual substance measured concentrations to the threshold for the relevant chemical class (for pesticides) or limited set of substance (for PAHs). Hence in this case, risk may be underestimated as the sum exposure to all chemicals in that class is not considered or the threshold is not specific to the chemical.

3. _EFSA Tolerable Intake (TDI) and Acceptable Daily Intake (ADIs) values._ The European Food Safety Authority (EFSA) produces risk assessments for pesticides, as well as additives and contaminants applicable to food, feed and food contact materials. A summary of human health assessments is provided in EFSA's chemical hazards database. This OpenFoodTox resource acts as a freely available source of information on substance characteristics and Reference Point and Reference values relevant for assessing chemical hazard and risk. For the evaluation of groundwater and surface water pollutants, the ADI and TDI were selected as the most comprehensive set of readily available human health hazard values. The ADI and TDI are defined as the estimated maximum amount of an agent, expressed on a body mass basis (standard body mass 60 kg), to which an individual may be exposed daily without appreciable health risk over a full lifetime. ADI relates to intentionally added substances, while the TDI is used for contaminating chemicals (Van Leeuwen and Hermens, 1995).

In addition to ADI/TDIs, TTC Cramer Class - Threshold of toxicological concern (TTC) are also available and can be used to increase substance coverage of indicative values for human health protection. Three groups of generic TTC Cramer Classes have been proposed for substances.

- Low toxicity (Group I: 30 μg /kg bw/day);
- Intermediate toxicity (Group II: 9 μg /kg bw/day); and
- High toxicity (Group III: 1.5 μg /kg bw/day).

In addition to these generic values, a series of chemical class specific TTC groups are also provided,

- Genotoxic carcinogens (excluding aflatoxin-like substances, azoxy-and nitroso-compounds) have a TTC of 0.0025 μg/kg bw/day suggested by Kroes _et al_. (2004)

based on linear extrapolation of bioassay data for structurally-related substances (Renwick, 2005).

- Organophosphates and carbamates with anti-cholinesterase activity have an allocated TTC of 0.3 μg/kg bw/day;

For the worst-case ranking, TTC from all three classes calculated under the new EFSA evaluation and substance specific categories, have been used to provide hazard metrics for assessment under the ADI/TDI category. To calculate the HQs, the ADI/TDI values were compared to the amount consumed assuming that an individual intakes 2 L of water per day following standard recommendations for a drinking water risk assessment according EFSA guidance. The calculation allows the assessment of substance measured concentration in water against the daily dose based ADI and TDI values.

4. *NORMAN network database PNECs* (see https://www.norman-network.com/nds/). The Norman Network maintains, and makes public, a range of different databases relating to the measurement and risk assessment of emerging chemicals. For hazard assessment, the database on ecotoxicology is the most relevant to risk ranking applications. The NORMAN ecotoxicology database collates PNEC values for ≥ 40,000 substances, the large majority of which are derived from QSAR predicted values for four different taxonomic groups: protist (*Tetrahymena*), vertebrate (fish), aquatic plant (algae), and invertebrate (*Daphnia*), as well as the lowest PNEC taken from across the four species. To generate the PNEC value for each substance, the available or QSAR modelled NOEC is generally divided by an assessment factor of 1,000. Each PNEC derived from QSAR modelling is ascribed a level of certainty depending on whether the substance is within the chemical space of the model (greater certainty) or outside of the model domain (lower certainty). The particular benefit of NORMAN PNEC database risk ranking is the high degree of substance coverage, with >80% of all GC-MS and LC-MS measured analytes having an available lowest NORMAN PNEC value.

5. *Chronic Species Sensitivity Distribution HC$_{50}$ values as derived by Posthuma et al. (2019).* Posthuma *et al* (2019) used a comprehensive set of ecotoxicity data (for details see Appendix 1) to derive species sensitivity distribution (SSD) models for 12,386 compounds, each with a quality score. The hazardous concentration for 50% of species (HC50) values derived from these SSDs (and associated quality score) was available for this study. HC50 values were selected for use for ranking for two reasons. Firstly, these values are readily available from Posthuma *et al*. (2019) in the supplementary information of the paper, rather than needing to be recalculated from the primary toxicity data that underlies the SSD model, as would be needed for alternative metrics such as the HC5. Secondly, the HC50 is placed in the middle of the distribution and, so, has higher certainty, making the assessment more robust for hazard ranking applications. For a full risk assessment, selection of a value with different protection goals, such as the HC5 (often with the inclusion of additional assessment factors) will often be more appropriate and precautionary for any individual substance.

The chronic SSDs generated and published by Posthuma *et al*. (2001) were derived from a database of toxicity test results assembled from multiple sources, including the aquatic ecotoxicity database of Posthuma *et al*. (2001); USEPA ECOTOX database; fish embryo toxicity data from Procter & Gamble Company (Oris *et al.*, 2012); acute EC50 for

pharmaceutical (Das *et al.*, 2013; Sanderson and Thomsen, 2009); acute and chronic aquatic toxicity data for pesticides and pharmaceuticals; EFSA and the Pesticide Properties Database toxicity information; and pharmaceutical and pesticide ecotoxicity data provided by The Swiss Centre for Applied Ecotoxicology (see Appendix 2 for full details and web links to resources). Where possible, log-normal SSDs were initially derived using only measured chronic EC_{50} or NOEC data. The use of only experimentally derived chronic data would result in a restricted number of chronic SSDs being available. Therefore to increase substance coverage, additional toxicity values derived by extrapolation from acute EC_{50}s to chronic NOECs were also included. The conversion followed a previously established approach (Duboudin *et al.*, 2004; Posthuma *et al.*, 2019). The use of this algorithm for acute to chronic conversion introduced an additional level of uncertainty, especially for chemicals with a specific mode of action, for which this approach may fail to correctly translate acute to chronic effects. Recognising this, Posthuma *et al.* (2019), categorise each substance HC50 according to the nature of data included in the SSD as:

- High - The SSD was based on chronic NOEC data for 10 or more species.

- Medium - The SSD was based on chronic NOEC data for 5 or more species or on chronic NOEC data extrapolated from acute LC_{50} values for 10 or more species or on some combination of these data types.

- Low - The SSDs were based on chronic NOEC data for 2 or more species or on chronic NOEC data extrapolated from Acute EC_{50} values for 5 or more species or on some combination of these data types.

4 Assembling the hazard data-set for use in substance ranking

4.1 Organisation of hazard criteria for ranking

The data sources identified above were accessed and hazard values for the GC-MS and LC-MS detected chemicals were downloaded into a single database. The number of chemicals in the combined GC-MS and LC-MS analysis suites with hazard values for each metric is shown in Table 3. The greatest number of hazard values was found for the chronic SSD HC50 and NORMAN PNEC and the least for the WFD EQS, with the human ADI/TDI and Drinking Water Standard values intermediate (although the latter mainly relating to substance class values allocated to pesticides and the specific PAH compounds). The resulting database lists each chemical and its associated hazard value for each metric and is available as an Excel file associated with a NERC Open Research Archive record.

Hazard criteria	Yes	No
Water Framework Directive EQS	61	1083
UK Drinking Water Standard	519	625
EFSA ADI/TDI value	262	882
Norman Network Lowest PNEC	979	165
Chronic Species Sensitivity Distribution HC50	719	425
Substance with one or more hazard value	1077	67

Table 3. Number of chemicals in the full set of 1144 determinants that have hazard values for each metric. (N.B for UK Drinking Water Standards chemical class values (e.g. pesticides, specific PAH substances) are applied to all individual analytes from that substance class.)

For the initial stage of the assessment, the maximum environmental concentrations for each chemical was compared to each hazard value to allow a worst-case HQ to be calculated for that substance and metric. Where a hazard value is not available for a chemical, a hazard quotient could not be derived and that substance is not ranked for that metric. In the groundwater data-set there were 475 and 274 substances for which either a WFD EQS, UK drinking water standard, ADI/TDI, NORMAN network PNEC or chronic SSD HC50 was available in the GC-MS and LC-MS analyses, respectively. For the surface water data-set there was 497 and 356 for the GC-MS and LC-MS analytes respectively with one or more hazard metric.

As well as differing in their assumptions leading to different values, there is also a number of differences in the degree of substance coverage between the metrics (see Section 4.2). There were 14 chemicals in the GC-MS data-set and seven in the LC-MS groundwater data-set that had values for all five hazard metrics. Pesticides and some biocides are often among the substances for which the richest sets of toxicity data, and as a result metrics are available. In contrast, there are other chemicals (e.g. some metabolite and intermediary chemicals), for which little or no toxicity data or QSAR prediction exist. For these chemicals, no reliable hazard values can be derived. In the surface water data-set there were 12 such chemicals in the GC-MS data-set and nine in the LC-MS groundwater data-set that had values for any metric.

4.1.1 Method for ranking hazard quotients

The hazard values for each of the two human health hazard metrics (UK Drinking Water Standard and EFSA ADI/TDI) were each used to generate a separate rank list of substances by HQ for that metric from highest to lowest for GC-MS and LC-MS detected chemicals in groundwater and surface water. The two human health values were considered distinct from the ecological value because of their relevance to different receptors. Further, the two human values were considered separately, as each has different protection goals. As detailed above (see the workflow in Section 1), the hazard ranking of substances (were available) for each of the three ecological hazard values (WFD EQS, NORMAN PNEC, chronic SSD HC50) was used to calculate an average ecological hazard rank. To generate the average hazard value, the ranking for each substance was divided by the number of chemicals with a hazard value

for that metrics and the resulting three values averaged. This average ecological hazard rank score was then multiplied by the detection frequency ranking for the substance.

For the final ranking, the HQ ranks were then each multiplied by the substance detection frequency rank to provide the final endpoint ranking for each substance in the measurement data-set. The detection frequency ranking was generated for each data-set by ordering the substances from the high proportion of positive detections across all samples measured for that substance. The product of the hazard raking and the detection frequency ranking was ordered for lowest to highest for each data-set to provide the final ranking for substances for each measurement method and sample set (four lists for each hazard metric).

4.2 Comparison of hazard metric across chemicals

The use of multiple hazard values for ranking presents a challenge when comparing outcomes as the hazard values used are derived for different endpoints, using different approaches, data-sets and assumptions. The use of an average hazard value for ranking across the three ecological endpoints to a degree limited the extent to which this ranking is influenced by the assumptions underlying each hazard metric. However, it is still important to understand the relationships and different bases for each metric. The extent of coverage of the chemical detected and the regulatory status of the hazard values also differ between sets of values. For example, environmental quality standards used in regulatory regimes such as the Water Framework Directive are derived from a relatively rich set of data for the specific substance and are included within a legal framework. Yet such values exist for only a few substances. This relatively high level of regulatory acceptance also applies to the drinking water standard guideline values and the ADI and TDI values on which some, but not all, of the drinking water limits are based.

For other hazard values such as the NORMAN network PNECs and chronic SSD HC50s of Posthuma *et al* (2019), the metrics have not yet undergone regulatory review, although some such as the chronic SSD HC50s have been scientifically peer reviewed for the validity of the underpinning approach. In many cases, the information collated for the generation of these values is derived from read across tools, such as QSAR models (for the NORMAN network PNEC) or acute to chronic conversion factors (for the chronic SSD HC50s). Such values are, however, available for a much greater proportion (≥ 75%) of the measured chemicals. Their inclusion, thus, increases the substance coverage of the assessment.
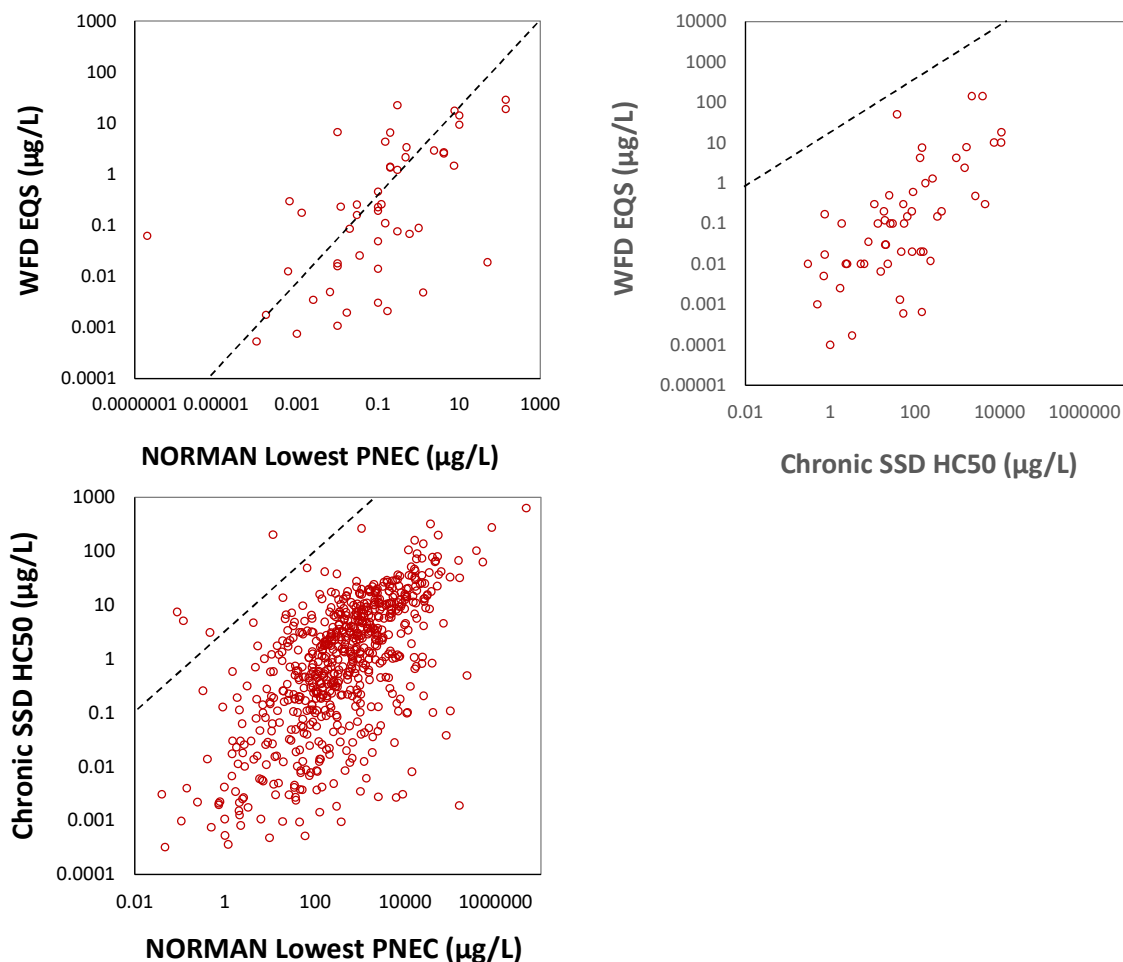
Fig. 2 Comparisons of a) WFD EQS and NORMAN lowest PNEC values, b) WFD EQS and chronic SSD HC50 value, and c) NORMAN Network PNEC and chronic SSD HC50 values. In all cases, the dashed line indicates the 1:1 relationship between values. Note the WFD EQS and NORMAN Network PNEC values sit around the 1:1 line indicating that while any one substance may have a higher or lower value for one or the other metric, there are no systematic differences across all values which is reasonable as each is based on the common use of the lowest species NOEC including an assessment factor (i.e. division of the NOEC by 1000) for their calculation. The chronic SSD HC50 values show some degree of agreement with the WFD HC50 and NORMAN Network PNEC when compared for the same chemical (i.e. there is a clear correlation between values), consistent with the fact that all values are derived from a distribution of ecotoxicity data that may include the lowest value, however, the chronic HC50 values lie below unity indicating that the NORMAN PNEC values and WFD EQSs are lower than the chronic HC50 values, as to be expected as the former two values include an assessment factor not placed on the chronic SSD HC50.

The five hazard metrics are derived using different data and approaches, e.g. experimental data, QSAR model prediction, historical analytical limits, and with different assumptions, e.g. use of lowest toxicity value or distribution of values, use of an assessment factor and magnitude of the assessment factor. The implication of these differences can be visualised using scatter plots of paired hazard metric values for substances. Where any point sits on the 1:1 line between the two axes, then that chemical has the same hazard value for each metric.

Positions below the line indicate a higher hazard value, and hence lower toxicity, for the X-axis metric, points above the line have a higher hazard value, and hence lower toxicity, for the Y-axis metric. The degree of scatter of values also indicates the variation in hazard value pairs for the same chemical, with high scatter indicating large differences between value predictions. Comparative analysis between metrics is only relevant for values that address the same receptor, e.g. human health or the ecosystem. Among human health values, comparison of the ADI/TDI value to Drinking Water Standard values was not informative, as the generic pesticide threshold for drinking water meant that many substances have the same hazard value. Comparison between the three ecosystem metrics (WFD EQS, NORMAN PNEC, chronic SSD HC50) was, however, possible and is informative (Fig. 2).

For any substance, the precise magnitude of difference in its reported WFD EQS, NORMAN PNEC and chronic SSD HC50 will reflect a number of aspects relating to assumption made during the calculation of the metric for that value. Such factors may include the suitability of the QSAR model used for NORMAN PNEC derivation; the nature of the ecotoxicity data available for WFD EQS and chronic SSD HC50 calculation; the suitability of the acute to chronic conversion algorithm used for each substance prior to SSD generation; and, the magnitude of assessment factor applied for WFD EQS calculation. Further, for individual chemicals agreement may be better between modelled and measured value for some types of substance than for others. For example, chemicals with a narcotic mode of action may be better predicted (and hence be more similar between metrics) by current QSARs than may be specifically acting chemicals, for which QSAR model prediction and acute to chronic assessments may be less reliable.

Although based on QSAR model predictions, there is no clear evidence that the NORMAN network PNEC values are more uncertain (i.e. show greater scatter from a best linear correlation line) when compared to the other metrics, such as the WFD EQSs and chronic SSD HC50s, even though the latter two are based on measured rather than modelled values. The NORMAN Network PNEC and WFD EQSs are, however, both lower than the SSD derived chronic HC50s by 1-2 orders of magnitude, as indicated by the displacement of the best regression line from the theoretical 1:1 line (Fig. 2a). This reflects the use of the lowest value and inclusion of an assessment factor of up to 1000 placed on any predicted acute (e.g. LC_{50}) value in the NORMAN PNEC calculations and WFD EQS derivation compared to the use of the concentration predicted to have a chronic effect for 50% of exposed species without an assessment factor as in the HC50 calculation.

4.3 Comparing hazard metric for individual chemicals

Patterns in the ordering and magnitude of difference between hazard metrics for substances were visualised along with the highest measured GC-MS and LC-MS concentrations for that substance in groundwater (Fig. 3) and surface water (Fig. 4). Plots confirmed that the chronic SSDs HC50 values are always highest for each substance and that WFD EQSs are largely consistent with NORMAN PNECs. However, individual WFD EQS are both lower and higher than the NORMAN PNEC, with maximum variation up to 5 orders of magnitude (e.g. WFD EQS ~5 orders of magnitude lower than NORMAN PNEC for heptachlor and ~4 orders of magnitude higher for 1,1,2,2-Tetrachloroethane).
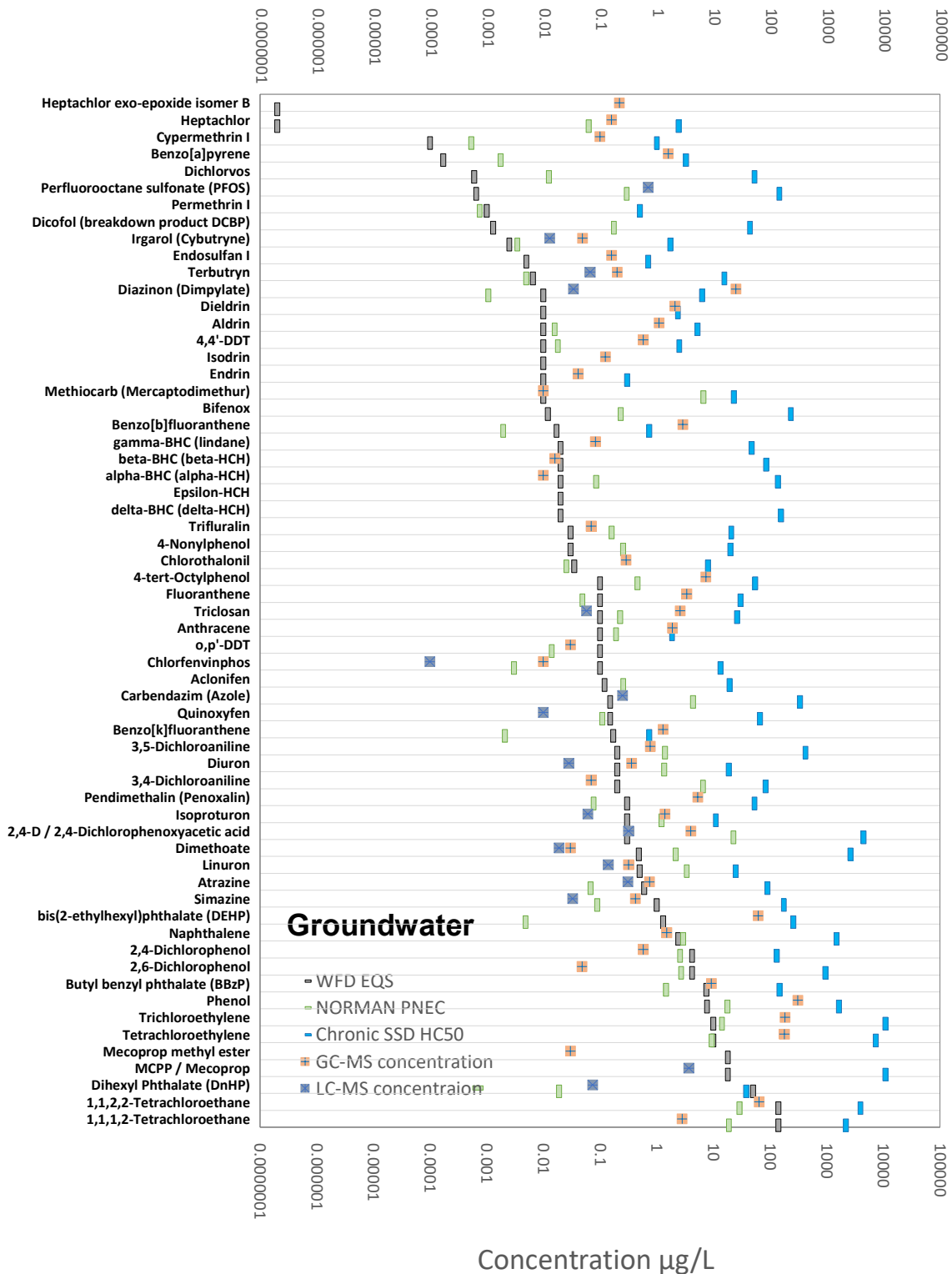
Fig. 3. Comparison of environmental hazard values (WFD EQS, NORMAN PNEC, chronic SSD HC50) and maximum GC-MS and LC-MS concentration measured in groundwater. Maximum reported concentration values reported in these tables must be considered in the context that they are based upon semi-quantitative data. For display purposes the data has been compared against various thresholds including WFD EQS values within these figures. However it should be noted that fully validated data would be required for undertaking a formal comparison against EQS.
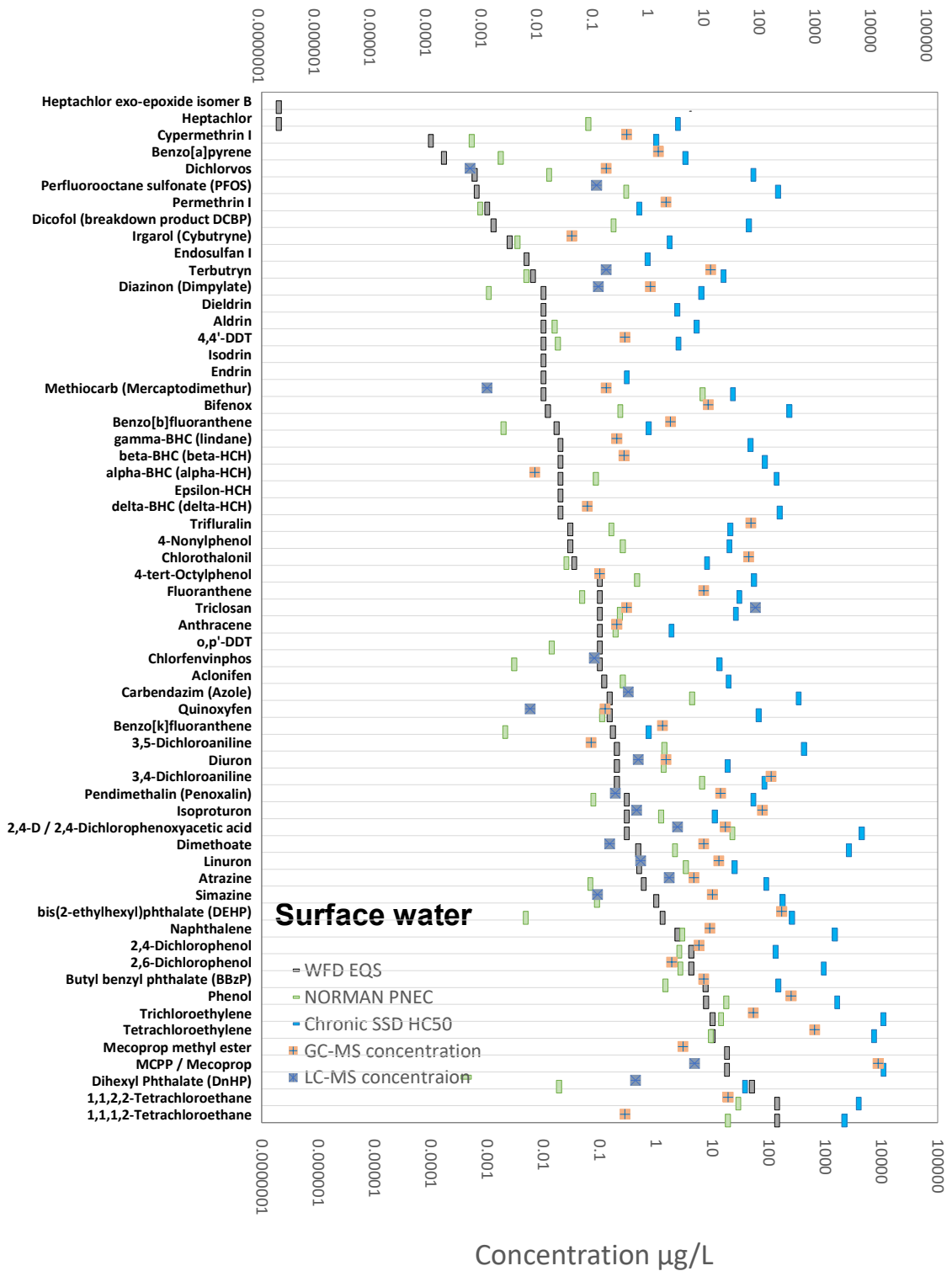
Fig. 4. Comparison of environmental hazard values (WFD EQS, NORMAN PNEC, chronic SSD HC50) and maximum GC-MS and LC-MS concentraion measured in surface water. Maximum reported concentration values reported in these tables must be considered in the context that they are based upon semi-quantitative data. For display purposes the data has been compared against various thresholds including WFD EQS values within these figures. However it should be noted that fully validated data would be required for undertaking a formal comparison against EQS.

5 Ranking of substances for human heath related hazard metrics

5.1 Drinking water standards

The UK Drinking Water Standards for individual substances are derived from available ADI/TDI values assuming that a 60kg adult drinks 2L of water per day. Some values are provided on this basis for individual chemicals. However, additionally, some groups of substances are given generic threshold values, such as those for pesticides set based on analytical capabilities rather than through any hazard based approach or only for certain substances in a class that can be used for related chemicals, as for the value for PAHs. These values have different protection goals, although they remain relevant for assessment due to their regulatory relevance. These chemical class specific values and wider PAHs class extended substance specific values provide the majority of the available drinking water standard values, particularly the generic 0.1 µg/L value for pesticides.

5.1.1 Ranking of substances detected by GC-MS in groundwater and surface water by Drinking Water Standard

5.1.1.1 Groundwater

There are 227 substances in the GC-MS groundwater data-set that have a corresponding UK Drinking Water Standard values, including a large number for pesticides and the value of 0.1 µg/L that is given to four specific PAHs (benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[g,h,i]perylene, indeno[1,2,3,c,d]pyrene), but here extended to other PAHs. Of these chemicals, 92 substances are detected in ≥10 or more samples allowing them to be included in the final UK Drinking Water Standard ranking list. Of these 92 ranked substances, only one has a substance specific Drinking Water Standard value, this being benzo[a]pyrene. All the remainder relate to chemicals assessed against the Drinking Water Standard of 0.1 µg/L for pesticides or for the four PAHs benzo[b]fluoranthene, benzo[k]fluoranthene, benzo[g,h,i]perylene and indeno[1,2,3,c,d]pyrene)applied to call chemicals in this class. There are 80 substances detected ≥10 times in groundwater in the GC-MS data-set that exceed their relevant UK Drinking Water standard value. The only substance specific exceedance is for benzo-a-pyrene. All other remaining exceedances are for pesticides (64 substances) or PAHs (15 substances). The top 30 substance by HQ against the UK Drinking Water Standard correspondingly comprise a mix of PAHs and pesticides (Table 4). Since in each case they are compared against a generic class value, substance HQs rank directly in relation to the maximum measured concentrations, with the single exception of benzo-a-pyrene which is higher ranked due to its lower UK Drinking Water Standard limit. Multiplication of the UK Drinking Water Standard rank by the detection frequency rank further modified the overall ranking. However, the top two ranked substances 2,6-dichlorobenzamide and propiconazole retain top ranking, although in reverse order.

Rank	CAS Registry Number	Compound Name	Number of positive detects	Detection frequency Rank	Max reported conc. (µg/L)	UK Drinking Water Standard HQ	UK Drinking Water Standard HQ rank	UK DW rank *detection frequency rank
1	2008-58-4	2,6-Dichlorobenzamide	422	6	70	700	2	12
2	60207-90-1	Propiconazole	69	35	85	850	1	35
3	206-44-0	Fluoranthene	1099	2	3.4	34	22	44
4	1912-24-9	Atrazine	1396	1	0.75	7.5	56	56
5	129-00-0	Pyrene	1080	3	2	20	32	96
6	1702-17-6	Clopyralid	42	51	69	690	3	153
7	101-42-8	Fenuron (N,N-Dimethyl-N-phenylurea)	136	20	20	200	8	160
8	77732-09-3	Oxadixyl	315	8	3.6	36	20	160
9	50-32-8	Benzo[a]pyrene	124	22	1.6	160	9	198
10	6190-65-4	Atrazine-desethyl (Desethylatrazine)	873	4	1	10	51	204
11	188425-85-6	Boscalid (Nicobifen)	44	47	29	290	5	235
12	56-55-3	Benz[a]anthracene	313	9	2.4	24	27	243
13	15545-48-9	Chlortoluron (Chlorotoluron)	24	61	33	330	4	244
14	83-32-9	Acenaphthene	191	16	5	50	16	256
15	2164-08-1	Lenacil	49	43	27	270	6	258
16	87674-68-8	Dimethenamid (SAN 582H)	137	19	5.3	53	14	266
17	25057-89-0	Bentazone	92	30	13	130	10	300
18	87-41-2	Phthalide	380	7	1.2	12	45	315
19	314-40-9	Bromacil	161	17	3.7	37	19	323
20	86-73-7	Fluorene	230	11	2	20	30	330
21	122-34-9	Simazine	659	5	0.42	4.2	66	330
22	496-11-7	Indane	203	12	2.2	22	29	348
23	19666-30-9	Oxadiazon	68	36	12	120	11	396
24	333-41-5	Diazinon (Dimpylate)	28	59	25	250	7	413
25	218-01-9	Chrysene	281	10	1.4	14	42	420
26	205-99-2	Benzo[b]fluoranthene	150	18	2.9	29	25	450
27	142459-58-3	Flufenacet (Fluthiamide) (BAY FOE 5043)	105	26	4.2	42	18	468
28	60-57-1	Dieldrin	58	40	2.1	70	12	480
29	91-20-3	Naphthalene	202	13	1.5	15.0	41	533
30	85-01-8	Phenanthrene	200	14	1.2	12	46	644

Table 4. Top 30 substance ranked by detection frequency corrected UK Drinking Water Standard rank (e.g. detection frequency rank * UK Drinking Water Standard HQ rank) for chemicals in the GC-MS groundwater data-set (excludes substance detected in < 10 samples)

5.1.1.2 Surface water

There are 224 substances in the GC-MS surface water data-set that have a drinking water standard value, the large majority are pesticides with the generic 0.1 µg/L value. Additionally, there are 17 values for PAHs, 16 for the generic value of 0.1 µg/L attributed to four individual PAHs applied across other PAHs and the remaining value for benzo-a-pyrene. Of the 224 substances with a drinking water standard value, 113 are detected in ≥10 samples. There are 104 substances for which the maximum measured concentrations exceed the relevant UK Drinking Water standard. Only one exceedance is for an individual substance, this being benzo-a-pyrene. The remainder is for pesticides against the class specific value (87 substances) or PAHs against the four compound PAH standard. The top 30 substances by HQ are all pesticides, with the rank order of HQ reflecting the measured concentrations assessed against the common hazard value (Table 5). The correction for detection frequency influences less commonly detected chemicals (e.g. mecoprop, phenmedipham) by reducing their overall ranking compared to more commonly detected substances (e.g. fluoranthene and propyzamide) that are elevated in the final prioritisation list.

Rank	CAS Registry Number	Compound Name	Number of positive detects	Detection frequency Rank	Max reported conc. (µg/L)	UK Drinking Water Standard HQ	UK Drinking Water Standard HQ rank	UK DW rank *detection frequency rank
1	83-79-4	Rotenone	678	15	2030	20300	3	45
2	206-44-0	Fluoranthene	9006	1	7	70	45	45
3	87674-68-8	Dimethenamid (SAN 582H)	1091	10	230	2300	6	60
4	23950-58-5	Propyzamide (Pronamide)	2833	4	72	720	22	88
5	7085-19-0	MCPP / Mecoprop	19	97	8700	87000	1	97
6	129-00-0	Pyrene	8970	2	1.2	12	68	136
7	127-63-9	Diphenyl sulfone	3383	3	5.3	53	52	156
8	142459-58-3	Flufenacet (Fluthiamide) (BAY FOE 5043)	1182	9	98	980	20	180
9	25057-89-0	Bentazone	357	27	229	2290	7	189
10	135319-73-2	Epoxiconazole (BAS 480F)	113	49	770	7700	4	196
11	13684-63-4	Phenmedipham	18	100	3060	30600	2	200
12	101-21-3	Chlorpropham (Chloropropham)	410	24	200	2000	10	240
13	83164-33-4	Diflufenican	572	19	152	1520	14	266
14	107534-96-3	Tebuconazole (Terbuconazole)	300	33	210	2100	9	297
15	26225-79-6	Ethofumesate	959	13	60	600	23	299
16	2303-17-5	Triallate	1935	6	3.2	32	57	342
17	56-55-3	Benz[a]anthracene	2049	5	1	10	71	355
18	41394-05-2	Metamitron	43	72	350	3500	5	360
19	218-01-9	Chrysene	1780	7	5	50	53	371
20	907204-31-3	Fluxapyroxad	196	40	190	1900	11	440
21	2164-08-1	Lenacil	70	61	218	2180	8	488
22	886-50-0	Terbutryn	1014	12	9.3	93	41	492
23	188425-85-6	Boscalid (Nicobifen)	294	34	100	1000	19	646
24	120068-37-3	Fipronil	1263	8	0.5	5	83	664
25	50-32-8	Benzo[a]pyrene	548	20	1.1	110	34	680
26	118-79-6	2,4,6-Tribromophenol	1038	11	1.4	14	66	726
27	81777-89-1	Clomazone	363	26	22	220	29	754
28	52888-80-9	Prosulfocarb	814	14	4.6	46	55	770
29	16118-49-3	Carbetamide	583	18	8.8	88	43	774
30	1698-60-8	Pyrazon	62	63	150	1500	15	945

Table 5. Top 30 substance ranked by detection frequency corrected UK Drinking Water Standard rank (e.g. detection frequency rank * UK Drinking Water Standard HQ rank) for chemicals in the GC-MS surface water data-set (excludes substance detected in < 10 samples).

5.1.2 Ranking of substances detected by LC-MS in groundwater and surface water by Drinking Water Standard

5.1.2.1 Groundwater

There are 165 substances in the LC-MS groundwater data-set with a UK Drinking Water Standard. All are pesticides, meaning that in all cases the maximum measured concentrations are compared to the same value of 0.1 µg/L. Of these pesticides, 67 are detected in ≥10 or more samples. Of these, 30 have a maximum concentration that exceeds the hazard value. The rank order by HQ reflects the order of maximum concentration measured by LC-MS as the generic hazard value of 0.1 µg/L is applied to all the substances in the top 30. Chloridazon-desphenyl, atrazine-desethyl, 2,6-dichlorobenzamide and bentazone are the four highest ranked substances (Table 6). The most frequently detected substances with an HQ ≥ 1 are atrazine, atrazine-desethyl, atrazine-desisopropyl and simazine, which are each detected in around 40% of samples. Nine of the top 10 ranked substances are detected in >100 analysed samples. This worst case assessment, thus, suggests there is a relatively widespread occurrence of a number of these high priority ranked pesticides in groundwater.

Rank	CAS Registry Number	Compound Name	Number of positive detects	Detection frequency Rank	Max reported conc. (µg/L)	UK Drinking Water Standard HQ	UK Drinking Water Standard HQ rank	UK DW rank *detection frequency rank
1	6339-19-1	Chloridazon-desphenyl	111	11	6.3	63	1	11
2	6190-65-4	Atrazine-desethyl (Desethylatrazine)	377	1	0.3	2.8	14	14
3	2008-58-4	2,6-Dichlorobenzamide	141	10	2.9	29	3	30
4	25057-89-0	Bentazone	195	7	1.9	19	6	42
5	17254-80-7	Chloridazon-desphenyl-methyl	249	6	1.5	15	8	48
6	188425-85-6	Boscalid (Nicobifen)	105	12	2.4	24	4	48
7	7085-19-0	MCPP / Mecoprop	52	25	3.7	37	2	50
8	1912-24-9	Atrazine	339	4	0.3	3.1	13	52
9	1007-28-9	Atrazine-desisopropyl (Deisopropylatrazine)	370	2	0.0	0.5	40	80
10	122-34-9	Simazine	362	3	0.0	0.33	43	129
11	2163-69-1	Cycluron	155	8	0.1	1.2	28	224
12	330-54-1	Diuron	254	5	0.0	0.28	45	225
13	940-31-8	2-Phenoxypropionic acid	14	54	2.2	22	5	270
14	77732-09-3	Oxadixyl	33	34	0.8	8.3	9	306
15	34123-59-6	Isoproturon	148	9	0.1	0.61	36	324
16	101-42-8	Fenuron (N,N-Dimethyl-N-phenylurea)	76	20	0.2	2.2	17	340
17	2303-17-5	Triallate	17	50	1.7	17.0	7	350
18	10605-21-7	Carbendazim (Azole)	69	22	0.3	3	16	352
19	1698-60-8	Chloridazon (PAC)	88	16	0.2	1.5	23	368
20	122-59-8	Phenoxyacetic acid	24	40	0.5	4.5	10	400
21	1698-60-8	Pyrazon	88	17	0.2	2	24	408
22	142459-58-3	Flufenacet (Fluthiamide) (BAY FOE 5043)	69	23	0.2	2	18	414
23	152-16-9	OMPA / Schradan	48	28	0.3	2.8	15	420
24	60207-90-1	Propiconazole	87	18	0.1	1.20	29	522
25	131860-33-8	Azoxystrobin	90	14	0.1	0.5	38	532
26	15545-48-9	Chlortoluron (Chlorotoluron)	75	21	0.1	1.3	27	567
27	23950-58-5	Propyzamide (Pronamide)	79	19	0.1	1.1	30	570
28	2164-08-1	Lenacil	15	53	0.4	3.8	11	583
29	150-68-5	Monuron	90	15	0.1	0.5	39	585
30	87674-68-8	Dimethenamid (SAN 582H)	39	32	0.2	1.7	21	672

Table 6. Top 30 substance ranked by detection frequency corrected UK Drinking Water Standard rank (e.g. detection frequency rank * UK Drinking Water Standard HQ rank) for chemicals in the LC-MS groundwater data-set (excludes substance detected in < 10 samples)

5.1.2.2 Surface water

There are 206 substances in the LC-MS surface water data-set that have a UK drinking water standard value, of which 131 are detected in ≥10 or more samples. All are pesticides. Thus in all cases, the measured concentrations are compared to the same class reference value, i.e. the generic 0.1 µg/L value for pesticides. In the full data-set, 67 pesticides have a maximum measured concentration that exceeds this common hazard value (Table 7). As they are assessed against a common value, the rank order by HQ reflects the maximum concentration of each pesticide. The final ranking is, however, modified after detection frequency rank correction. Of the top 30 overall ranked pesticides, 19 are found in >1000 samples. These include both high hazard ranked substance (bentazone, chloridazon-desphenyl-methyl mecoprop, chloridazon-desethy) and also lower hazard ranked chemicals with a high detection frequency rank (fipronil, boscalid, diuron, azoxystrobin) (Table 7).

Rank	CAS Registry Number	Compound Name	Number of positive detects	Detection frequency Rank	Max reported conc. (µg/L)	UK Drinking Water Standard HQ	UK Drinking Water Standard HQ rank	UK DW rank *detection frequency rank
1	25057-89-0	Bentazone	2377	8	51	510	1	8
2	120068-37-3	Fipronil	2603	1	0.98	9.8	28	28
3	17254-80-7	Chloridazon-desphenyl-methyl	2322	10	5.2	52	4	40
4	7085-19-0	MCPP / Mecoprop	2328	9	4.8	48	5	45
5	188425-85-6	Boscalid (Nicobifen)	2522	2	0.63	6.3	32	64
6	6339-19-1	Chloridazon-desphenyl	611	37	18	180	2	74
7	23950-58-5	Propyzamide (Pronamide)	2400	6	2.2	22	14	84
8	330-54-1	Diuron	2522	3	0.48	4.8	37	111
9	131860-33-8	Azoxystrobin	2405	4	0.76	7.6	31	124
10	142459-58-3	Flufenacet (Fluthiamide) (BAY FOE 5043	2111	11	1.5	15	20	220
11	94-75-7	2,4-D / 2,4-Dichlorophenoxyacetic acid	1489	17	2.4	24	13	221
12	122-59-8	Phenoxyacetic acid	74	85	9.3	93	3	255
13	26225-79-6	Ethofumesate	315	50	3.7	37	6	300
14	94-74-6	MCPA (MCP)	372	47	3.5	35	7	329
15	135319-73-2	Epoxiconazole (BAS 480F)	2380	7	0.2	2	50	350
16	60207-90-1	Propiconazole	2404	5	0.082	0.82	74	370
17	110488-70-5	Dimethomorph	411	44	2.9	29	9	396
18	1912-24-9	Atrazine	813	30	1.7	17	19	570
19	131341-86-1	Fludioxonil	788	34	2.5	25	12	408
20	1698-60-8	Pyrazon	474	42	2.8	28	11	462
21	107534-96-3	Tebuconazole (Terbuconazole)	1781	14	0.5	5	36	504
22	113096-99-4	Cyproconazole	831	29	1.7	17	18	522
23	2303-17-5	Triallate	1158	20	0.98	9.8	27	540
24	153719-23-4	Thiamethoxam	794	33	1.8	18	17	561
25	87674-68-8	Dimethenamid (SAN 582H)	1473	18	0.6	6	33	594
26	120983-64-4	Desthio-Prothioconazole	2111	12	0.18	1.8	53	636
27	330-55-2	Linuron	1328	19	0.53	5.3	35	665
28	69335-91-7	Fluazifop	44	97	3	30	8	776
29	361377-29-9	Fluoxastrobin	1765	15	0.19	1.9	52	780
30	239110-15-7	Fluopicolid	1965	13	0.14	1.4	60	780

Table 7. Top 30 substance ranked by detection frequency corrected UK Drinking Water Standard rank (e.g. detection frequency rank * UK Drinking Water Standard HQ rank) for chemicals in the LC-MS surface water data-set (excludes substance in < 10 samples)

5.2 Human ADI/TDI values

5.2.1 Ranking of substances detected by GC-MS in surface water and groundwater by ADI/TDI

The EFSA OpenFoodTox database reports 262 ADIs, TDIs or TTC Cramer Class calculated ADIs. Reported values include 204 ADIs primarily for pesticides, biocides and a small number of pharmaceuticals and food additives, 17 TDIs mainly for industrial chemicals and 41 TTC Cramer Class calculated ADI mainly for industrial chemicals and chlorinated solvents. The TDI, ADI and TTC Cramer Class ADIs all have the same protection goal of ensuring no risk to health following daily exposure to a given amount of chemical for a 60 kg adult over a full lifetime. The ADI/TDI is given in milligrams per kilogram of body weight per day. To compare these values to the measured sample measurements, concentrations are transferred to daily intakes by assuming consumption of 2 litres of water per day (and hence the amount of chemical in that volume based on measured levels). The protection goal used for ADIs and TDIs is the same, the difference being that TDIs are usually for contaminants not used intentionally, while ADI often refers to intentionally added chemicals, such as pesticides and food additives. ADI and TDI values are used as the foundation for other quality standards relating to specific endpoints under other regulatory regimes such as the WFD and Drinking Water Guidelines.

5.2.1.1 Groundwater

There are 142 substances in the GC-MS groundwater data-set with a substance specific ADI, TDI or TTC Cramer Class calculated ADI values. Of these, 76 are detected in ≥10 or more samples and so are included in the final ranking. Among these chemicals, 14 have a HQ ≥ 0.1 and 4 have an ADI/TDI HQ for the maximum measured concentration of ≥ 1. These four are cyclohexanone (HQ = 8.6), diazinon (HQ = 3.6), p-cresol (HQ = 3.4) and isopropyl palmitate (HQ = 1.4) (Table 8). Many of the substances that have the highest HQ values are relative to a TTC Cramer Class calculated ADI. The TTC values are derived as ADI based on chemical structural features using a database of NOAELs value. To derive a TTC Cramer Class calculated ADI, structural chemical features are used to place the chemical into one of three different classes. Available chemical NOAELs for chemicals in that class are then used to identify a class specific fifth percentile NOAEL (in mg/kg bw/day) to which a 100-fold safety factor is then applied. Although derived from chemical structure, TTC Cramer class ADIs are not chemical specific. As such, these values have a higher uncertainty than ADI/TDI derived directly from toxicological data available for the specific substance. Further, since they are derived from fifth percentile values for the structural class, TTC based ADIs are likely to be mainly conservative, meaning they may overestimate worst case risk. However, they remain valuable as an indicator of risk for ranking and prioritisation.

Rank	CAS Registry Number	Compound Name	Number of positive detects	Detection frequency Rank	Max reported conc. (µg/L)	ADI/TDI HQ	ADI/TDI HQ rank	ADI/TDI rank * detection frequency rank
1	108-94-1	Cyclohexanone	837	2	300	8.6	1	2
2	80-05-7	Bisphenol A	1191	1	100	0.7	5	5
3	106-44-5	p-cresol (4-methylphenol)	99	18	120	3.4	3	54
4	117-81-7	bis(2-ethylhexyl)phthalate (DEHP)	740	3	62	0.035	25	75
5	2008-58-4	2,6-Dichlorobenzamide	422	4	70	0.04	23	92
6	333-41-5	Diazinon (Dimpylate)	28	54	25	3.6	2	108
7	142-91-6	Isopropyl palmitate	61	28	49	1.4	4	112
8	98-86-2	Acetophenone	125	14	18	0.51	9	126
9	105-60-2	Caprolactam	166	12	32	0.09	16	192
10	67129-08-2	Metazachlor	349	7	44	0.016	31	217
11	87-41-2	1(3H)-Isobenzofuranone	380	5	1.2	0.003	44	220
12	60-57-1	Dieldrin	58	30	2.1	0.6	8	240
13	95-48-7	o-Cresol (2-methylphenol)	31	49	23	0.66	6	294
14	78-59-1	Isophorone	78	23	7.2	0.21	13	299
15	119-61-9	Benzophenone	330	8	6.3	0.006	40	320
16	93-04-9	2-methoxynaphthalene	217	11	6	0.017	30	330
17	4359-46-0	2-ethyl-4-methyl-1,3-dioxolane	48	34	9.2	0.26	11	374
18	19666-30-9	Oxadiazon	68	27	12	0.095	15	405
19	87674-68-8	Dimethenamid (SAN 582H)	137	13	5.3	0.008	35	455
20	120-47-8	Ethylparaben	46	38	8	0.23	12	456
21	122-39-4	Diphenylamine	255	9	3	0.00114	51	459
22	60207-90-1	Propiconazole	69	26	85	0.061	18	468
23	576-26-1	2,6-Dimethylphenol	13	71	21.5	0.61	7	497
24	128-37-0	Butylated hydroxytoluene	236	10	8.7	0.0	54	540
25	76674-21-0	Flutriafol	104	17	2.2	0.0063	38	646
26	80-62-6	Methyl Methacrylate	13	72	1	0.29	10	720
27	85509-19-9	Flusilazol	41	43	4.2	0.060	19	817
28	25057-89-0	Bentazone	92	20	13	0.0041	41	820
29	626-43-7	3,5-Dichloroaniline	44	40	0.77	0.044	22	880
30	118-58-1	Benzyl Salicylate	16	67	5.4	0.15	14	938

Table 8. Top 30 substance ranked by detection frequency corrected EFSA ADI/TDI rank (e.g. detection frequency rank * EFSA ADI/TDI) for chemicals in the GC-MS groundwater data-set (excludes substance detected in < 10 samples)

5.2.1.2 Surface water

There are 149 substances in the surface water GC-MS data-set that have a reported ADI, TDI or TTC Cramer Class calculated ADI value. The maximum HQ of 19.9 is for the preservative benzenepropanoic acid, however, this substance was only found in five samples and is, therefore not considered in the final ranking. Among the remaining chemicals, there are 47 with ADI/TDI values that are detected in ≥10 or more samples (Table 9). Of these, 32 have an HQ ≥ 0.1 and 7 an HQ ≥ 1. Four substances, isopropyl palmitate (HQ = 5.14), flusilazol (HQ = 3.14), isophorone (HQ = 3.14), p-cresol (HQ = 2) and tetraconazole (HQ = 1.19) that have a maximum concentration that exceeds the relevant substance ADI/TDI and are detected in >10 samples. Of these, only isophorone and isopropyl palmitate are found in > 100 samples. Those substances with an HQ ≥ 1 that are not commonly detected are not necessarily included in the top detection corrected ADI/TDI ranked substances, although isophorone and isopropyl palmitate are in the top 5. Instead chemicals with HQ values in the 0.1 – 1 range that also have a high frequency of detection (>1000 samples) form the majority of the top 10 ranked GC-MS detected substances in surface waters (Table 9). Indeed some substances, such as triallate (17th) and ethofumesate 29th) are included in the top 30 rank list even though they have a relatively low HQ (<0.01 in both cases) because of their high detection frequency.

Rank	CAS Registry Number	Compound Name	Number of positive detects	Detection frequency Rank	Max reported conc. (µg/L)	ADI/TDI HQ	ADI/TDI HQ rank	ADI/TDI rank * detection frequency rank
1	119-61-9	Benzophenone	3244	1	234.7	0.22	21	21
2	108-94-1	Cyclohexanone	1791	6	30	0.86	8	48
3	78-59-1	Isophorone	373	19	110	3.14	3	57
4	142-91-6	Isopropyl palmitate	199	32	180	5.14	2	64
5	23950-58-5	Propyzamide (Pronamide)	2833	2	72	0.041	45	90
6	80-05-7	Bisphenol A	1426	7	55	0.39	13	91
7	117-81-7	bis(2-ethylhexyl)phthalate (DEHP)	2355	3	170	0.1	33	99
8	67129-08-2	Metazachlor	2031	4	340	0.12	30	120
9	87674-68-8	Dimethenamid (SAN 582H)	1091	9	230	0.33	17	153
10	85509-19-9	Flusilazol	63	54	220	3.14	4	216
11	98-86-2	Acetophenone	656	12	10	0.29	18	216
12	120068-37-3	Fipronil	1263	8	0.5	0.071	38	304
13	106-44-5	p-cresol (4-methylphenol)	64	53	70	2	6	318
14	105-60-2	Caprolactam	236	27	140	0.4	12	324
15	5915-41-3	Terbuthylazine (TERBA)	96	45	118	0.84	9	405
16	333-41-5	Diazinon (Dimpylate)	625	13	0.79	0.11	32	416
17	2303-17-5	Triallate	1935	5	3.2	0.0037	84	420
18	127-51-5	alpha Isomethyl Lonone	284	25	8.5	0.24	20	500
19	101-21-3	Chlorpropham (Chloropropham)	410	17	200	0.11	31	527
20	107534-96-3	Tebuconazole (Terbuconazole)	300	24	210	0.2	22	528
21	52888-80-9	Prosulfocarb	814	11	4.6	0.026	49	539
22	112281-77-3	Tetraconazole	20	85	167	1.19	7	595
23	907204-31-3	Fluxapyroxad	196	33	190	0.27	19	627
24	5989-27-5	d-Limonene	67	50	12	0.34	15	750
25	25057-89-0	Bentazone	357	21	229	0.073	36	756
26	83164-33-4	Diflufenican	572	15	152	0.022	52	780
27	4359-46-0	2-ethyl-4-methyl-1,3-dioxolane	387	18	1.4	0.04	46	828
28	526-75-0	2,3-Dimethylphenol	15	93	20	0.57	10	930
29	26225-79-6	Ethofumesate	959	10	60	0.0017	94	940
30	34123-59-6	Isoproturon	148	39	77	0.15	26	1014

Table 9. Top 30 substance ranked by detection frequency corrected EFSA ADI/TDI rank (e.g. detection frequency rank * EFSA ADI/TDI) for chemicals in the GC-MS surface water data-set (excludes substance detected in < 10 samples)

5.2.2 Ranking of substances detected by LC-MS in groundwater and surface water by ADI/TDI

5.2.2.1 Groundwater

There are 95 substances in the LC-MS groundwater data-set with a corresponding ADI TDI or TTC Cramer Class calculated ADI value. Of these, 43 are detected ≥10 times. No substance in the LC-MS data-set has a maximum measured concentration that exceeds its ADI/TDI (Table 10). The two highest HQ values were for perfluorooctane sulfonate (PFOS) and perfluoroctanoic acid (PFOA). However, even in these two cases HQs are <1 and for the majority of chemical HQs are lower than this (<0.01 in all cases). Both PFOS and PFOA are commonly detected, being found in >200 (29.3% and 26.6%) of all analysed samples. Of these two known persistent fluorinated compounds, PFOS has a higher HQ (0.135) compared to PFOA (0.023). Given that their maximum concentration is closest to the ADI/TDI value and their frequency of occurrence, PFOS and PFOA have the highest overall ranking. Other top ten ranked substances include a number of pesticides (diuron, 2,6-dichlorobenzamide, bentazone, fipronil, diazinon, isoproturon, triallate) and one substance, sucralose, that is categorised as a pharmaceutical, but is also commonly associated with food and beverage products.

Rank	CAS Registry Number	Compound Name	Number of positive detects	Detection frequency Rank	Max reported conc. (µg/L)	ADI/TDI HQ	ADI/TDI HQ rank	ADI/TDI rank * detection frequency rank
1	1763-23-1	Perfluorooctane sulfonate (PFOS)	227	4	26.5	0.135	1	4
2	335-67-1	Perfluoro Octanoic Acid	246	3	29.3	0.023	2	6
3	56038-13-2	Sucralose	306	1	35.7	0.000036	28	28
4	330-54-1	Diuron	254	2	29.6	0.000114	17	34
5	2008-58-4	2,6-Dichlorobenzamide	141	8	25.8	0.0017	5	40
6	25057-89-0	Bentazone	195	5	22.9	0.0006	10	50
7	120068-37-3	Fipronil	105	9	12.4	0.0014	7	63
8	333-41-5	Diazinon (Dimpylate)	12	37	1.4	0.0049	3	111
9	34123-59-6	Isoproturon	148	7	17.4	0.000116	16	112
10	2303-17-5	Triallate	17	31	2.1	0.0019	4	124
11	85509-19-9	Flusilazol	17	30	2.0	0.0016	6	180
12	10605-21-7	Carbendazim (Azole)	69	15	8.0	0.00036	12	180
13	330-55-2	Linuron	22	24	2.6	0.0013	8	192
14	122-59-8	Phenoxyacetic acid	24	22	2.9	0.0013	9	198
15	81-07-2	Saccharin	178	6	27.9	0.000003	37	222
16	76674-21-0	Flutriafol	43	18	5.0	0.00029	13	234
17	67129-08-2	Metazachlor	55	16	6.5	0.00013	15	240
18	60207-90-1	Propiconazole	87	12	10.1	0.000086	21	252
19	87674-68-8	Dimethenamid (SAN 582H)	39	19	4.6	0.00024	14	266
20	1698-60-8	Chloridazon (PAC)	88	11	10.3	0.000043	26	286
21	23950-58-5	Propyzamide (Pronamide)	79	13	9.3	0.000063	23	299
22	131860-33-8	Azoxystrobin	90	10	10.5	0.000007	31	310
23	94-75-7	2,4-D / 2,4-Dichlorophenoxyacetic acid	13	34	1.5	0.00046	11	374
24	138261-41-3	Imidacloprid	74	14	8.7	0.000015	30	420
25	1689-84-5	Bromoxynil	19	27	2.2	0.000095	19	513
26	5234-68-4	Carboxin	18	29	2.1	0.0001	18	522
27	107534-96-3	Tebuconazole (Terbuconazole)	24	23	2.8	0.000057	24	552
28	5915-41-3	Terbuthylazine (TERBA)	32	21	4.6	0.000037	27	567
29	21087-64-9	Metribuzin	19	28	2.2	0.00007	22	616
30	361377-29-9	Fluoxastrobin	22	25	2.6	0.000053	25	625

Table 10. Top 30 substance ranked by detection frequency corrected EFSA ADI/TDI rank (e.g. detection frequency rank * EFSA ADI/TDI) for chemicals in the LC-MS groundwater data-set (excludes substance detected in < 10 samples)

5.2.2.2 Surface water

There are 95 substances in the LC-MS groundwater data-set with a corresponding ADI, TDI or TTC Cramer Class calculated ADI. Of these, 85 are found in >10 samples. Five chemicals found in surface waters have a maximum concentration that exceeds the ADI/TDI giving an HQ ≥ 1 (firponil, bentazone, PFOS, phenoxyacetic acid and PFOA). A further 10 have an HQ ≥ 0.1 (Table 11). Identification of perfluorinated chemical among the highest ranked chemicals is consistent with their high ranking in the groundwater analysis. The high ranking of the perflourinated chemicals is accompanied by a high level of detection in ≥ 75% of samples (90% in the case of PFOA). Bentazone and fipronil, which also have an ADI/TDI HQ ≥ 1 are also detected in ≥ 80% of samples, indicating the widespread presence of these two highest ranked chemicals in surface waters. A further 13 substances in the top 30 ranked list are detected in >1000 samples, indicating their widespread presence in surface waters.

Rank	CAS Registry Number	Compound Name	Number of positive detects	Detection frequency Rank	Max reported conc. (µg/L)	ADI/TDI HQ	ADI/TDI HQ rank	ADI/TDI rank * detection frequency rank
1	120068-37-3	Fipronil	2603	1	0.98	9.8	1	1
2	335-67-1	Perfluoro Octanoic Acid	2444	3	0.16	2.1	2	6
3	330-54-1	Diuron	2522	2	0.48	0.1	13	26
4	25057-89-0	Bentazone	2377	7	51	1.1	5	35
5	1763-23-1	Perfluorooctane sulfonate (PFOS)	2252	9	0.088	1.2	4	36
6	23950-58-5	Propyzamide (Pronamide)	2400	6	2.2	0.1	16	96
7	330-55-2	Linuron	1328	18	0.53	0.35	8	144
8	333-41-5	Diazinon (Dimpylate)	531	28	0.094	0.94	6	168
9	94-75-7	2,4-D / 2,4-Dichlorophenoxyacetic acid	1489	16	2.4	0.24	11	176
10	122-59-8	Phenoxyacetic acid	74	61	9.3	1.86	3	183
11	131860-33-8	Azoxystrobin	2405	4	0.76	0.01	48	192
12	56038-13-2	Sucralose	2352	8	257	0.03	28	224
13	60207-90-1	Propiconazole	2404	5	0.082	0.0041	56	280
14	107534-96-3	Tebuconazole (Terbuconazole)	1781	11	0.5	0.033	29	319
15	87674-68-8	Dimethenamid (SAN 582H)	1473	17	0.6	0.06	19	323
16	2303-17-5	Triallate	1158	19	0.98	0.078	17	323
17	1689-84-5	Bromoxynil	1667	15	0.052	0.035	27	405
19	361377-29-9	Fluoxastrobin	1765	12	0.19	0.025	34	408
20	67129-08-2	Metazachlor	1673	14	1.1	0.028	32	448
21	34123-59-6	Isoproturon	798	25	0.45	0.06	18	450
22	110488-70-5	Dimethomorph	411	33	2.9	0.12	14	462
23	138261-41-3	Imidacloprid	1706	13	0.36	0.012	38	494
24	60-51-5	Dimethoate	82	59	0.15	0.3	9	531
18	36734-19-7	Iprodione (Glycophen)	86	57	2.8	0.28	10	570
25	131807-57-3	Famoxadone	17	82	1.3	0.43	7	574
26	239110-15-7	Fluopicolid	1965	10	0.14	0.0035	59	590
27	1698-60-8	Chloridazon (PAC)	474	30	2.8	0.056	20	600
28	1698-60-8	Pyrazon	474	31	2.8	0.056	21	651
29	16118-49-3	Carbetamide	657	27	1.2	0.04	26	702
30	136426-54-5	Fluquinconazole	420	32	0.05	0.05	23	736

Table 11. Top 30 substance ranked by detection frequency corrected EFSA ADI/TDI rank (e.g. detection frequency rank * EFSA ADI/TDI) for chemicals in the LC-MS surface water data-set (excludes substance detected in < 10 samples)

6 Ranking of substances for ecological hazard metrics

Graphic representation of the GC-MS or LC-MS detected chemicals in groundwater and surface water samples ranked against by their hazard quotient calculated against each of the three individual ecological hazard metrics (WFD EQS, NORMAN PNEC, chronic SSD HC50) is included in Appendix 3. All detected substances with a relevant ecological hazard value were ranked, however, for ease of presentation, only the top 30 substances are presented for each metric.

The overall assessment for ecological risk was based on the average rank for the three ecological hazard metrics (WFD EQS, NORMAN PNEC, chronic SSD HC50) for each substance where available (n.b. only 40 substances had values for all three metrics, although >70% had both NORMAN PNEC and chronic SSD HC50 values). This average ecological hazard rank value was then multiplied by the substance detection frequency ranking. This detection corrected ecological hazard value derived from this calculation was, thus, used for the final ranking of the GC-MS and LC-MS detected chemicals for each of the groundwater and surface water sample data-sets. The top 30 ranked substances for each analysis and sample type data-set are shown in Table 12 a-b, and Table 13 a-b.

6.1 Ranking GC-MS substances in groundwater and surface water

6.1.1 Groundwater

The integrated ecological hazard ranking for the GC-MS detected chemicals in groundwater identified multiple PAHs, pesticides, solvents, personal care products and industrial and plastics associated chemicals among the top 30 substances. Within this group of high ranked analytes, eight are PAHs (benzo[ghi]perylene, benz[a]anthracene, indeno[1,2,3-cd]pyrene, pyrene, fluoranthene, benzo[a]pyrene, benzo[b]fluoranthene, dibenz[a,h]anthracene). PAHs have a long-history of interest for their toxicological effects and widespread environmental occurrence. Identification of them here as highly ranked for potential ecological risk provides support for the validity of the prioritisation approach.

Plastics associated chemicals are also represented among the top 30 integrated ecological ranked substances. Polymer synthesis and plasticiser compounds have previously been identified as being of ecological concern. Bisphenol A, a well known plasticiser, is ranked highest of any substance, reflecting both its relatively high hazard rank against especially the chronic SSD HC50, as well its comparatively high frequency of detection (>1000 samples). Phthalates (bis(2-ethylhexyl)phthalate) and phosphate plasticisers (triphenyl phosphate) are also included in the top 30 ranked list. N-butyl benzenesulfonamide, a plasticiser used in a range of consumer products (e.g. cosmetics), materials (e.g. polyacetals, polyamides, and polycarbonates) and industrial applications, is also highly ranked. The comparatively high ranking of phthalates, phosphate plasticisers, bisphenol A and N-butyl benzenesulfonamide is driven by their comparatively high ranking for the NORMAN PNEC and/or chronic SSD HC50 metrics. Further, these substances are all detected in a relatively high number of samples. For example, bisphenol A is detected >1,000 times and bis(2-ethylhexyl)phthalate (DEHP), triphenyl phosphate and N-butyl benzenesulfonamide all >500 times. N-butyl

benzenesulfonamide also has the highest maximum measured concentration of any substances of 4000 µg/L which further contributes to its high ranking.

The remaining top 30 integrated ecological hazard ranked GC-MS chemicals in groundwater include a number of well-known historic pollutants (Table 12 a). Examples include the legacy herbicide atrazine (6th ranked), its metabolite atrazine-desethyl (12th ranked), legacy insecticide diazinon (22nd ranked) and the chlorinated solvents trichloroethylene (7th ranked) and tetrachloroethylene (17th ranked). All of these substances are widely detected (>500 samples) except for diazinon, which despite being present in only 28 samples is ranked highly based on it's high ranking across all three ecological hazard metrics (4th WFD EQS, 2nd NORMAN PNEC, 3rd chronic SSD HC50).

Not all of the top 30 integrated ecological hazard ranking substances are of established ecological concern. Examples include the pesticide metazachlor, pharmaceutical caffeine, plastic associated chemical tributyl acetylcitrate, halogenated solvent bromoform and industrial chemicals butanedioic acid and 2(3H)-benzothiazolone. In all cases except (3H)-benzothiazolone, the average ecological hazard rank for these substances is derived from HQs calculated from the available NORMAN PNEC and/or chronic SSD HC50 values, but not WFD EQS, as this is not available for any of these substances. For such substances, any further consideration would need to look in more details at further available hazard data, including REACH registration documents, as well as relevant published scientific literature.

6.1.2 Surface water

The integrated ecological hazard ranking for the GC-MS analytes in surface water data identifies a range of substances that differ somewhat from those highly ranked in groundwater. Between the two lists, eleven substances are common, benzo[a]anthracene, N-butyl benzenesulfonamide, benzo[a]pyrene, bis(2-ethylhexyl)phthalate, bisphenol A, caffeine, dibenz[a,h]anthracene, fluoranthene, metazachlor, pyrene and triphenyl phosphate (TPPA). Known high hazard legacy pesticides (e.g. atrazine and its metabolites, dieldrin) are absent from the top 30 rank list for surface waters. PAHs, commonly listed in the groundwater assessment, are also represented in surface waters, although only for five substances benzo[a]anthracene, benzo[a]pyrene, dibenz[a,h]anthracene, fluoranthene, pyrene. This number is lower than that for PAHs in groundwater, although this is driven by the presence of additional highly ranked chemicals in surface water, rather than lower detection frequency or reduced maximum concentrations of PAHs. The common high ranking of multiple PAHs in groundwater and surface water indicated that consideration is needed of the risks associated with the presence of additional PAHs beyond those most commonly assessed (e.g. benzo[a]pyrene, fluoranthene) in substance prioritisation programs.

The highest ranked substances in the list is caffeine. This is driven in particular by a high frequency of detection, the highest for any analyte. The second highest overall ranked substance is rotenone. This piscicide is top ranked by both NORMAN Network PNEC HQ and chronic SSD HC50 HQ. It is, however, detected in only a moderate number (678) of samples. Within the data-set there are specific reasons relating to the use of this substance and subsequent monitoring that potentially lie behind the high ranking (see Textbox 1).

The top 30 integrated ecological hazard ranking substances included in the surface water GC-MS list that are missing from the groundwater listing include a number of current or recent use pesticides (Table 12 a-b). These pesticide active ingredients in the top 30 for surface waters include a number of herbicides (dimethenamid, flufenacet, metazachlor, phenmedipham, propyzamide, terbuthylazine, terbutryn) and fungicides (boscalid, fluxapyroxad, epoxiconazole, tetraconazole). The relatively high HQs of many pesticides is driven by high ranking against the NORMAN PNEC and chronic SSD HC50 metrics. For both of these metrics, the available data used to identify the lowest PNEC or to generate the underlying SSD for HC50 derivation are taken from the results of toxicity studies conducted in a range of different plant and animal species. Hence, the underlying data can identify potential risks relating to the impacts of each assessed chemical on primary producers (e.g. algae), as well as for primary and secondary consumer species (e.g. invertebrates and vertebrates). Hence, herbicides, fungicides and insecticides all have the potential to be highly ranked.

Textbox 1: Rotenone ranking in surface water

The high ranking of rotenone in the surface water GC-MS data-set stems from targeted monitoring of this substance associated with operational work in which this piscicide is used in programs to eradicate non-native fish species, such as top mouth gudgeon, from invaded surface water bodies.

In these programs, monitoring of this substance, conducted as part of a wider analytical suite, is undertaken to ensure that the chemical has reached a sufficiently high dose for the treatment to be successful. Biodegradation is then monitored over the following weeks to ensure that it has reached safe levels.

Measurements of this substance during these applications explain both the moderate levels of detection (reflective of targeted use and not wider environmental exposure) and also why value exceeds effect levels for aquatic species reflecting its piscicidal use. This substance and the associated samples could potentially have been removed from the analysis. However, for this exercise, it was useful to include all substances and samples.

The fact that rotenone was highest ranked indicates the effectiveness of the overall approach to identifying substances that could potentially cause effects. Further, it illustrates the need for further detailed substance assessments that build from this prioritisation exercise.

Other compounds ranked in the top 30 for surface water are associated with consumer uses. Crotamiton is categorised as a pharmaceutical that is used in over the counter medications. Caffeine is also categorised as a pharmaceutical, although it is more associated with food and of course, hot drinks consumed widely by the general population which can enter surface water bodies after passage through the body and wastewater treatment systems. Six plastics associated chemicals are included in the top 30 surface water ranked GC-MS substances, bisphenol A, bis(2-ethylhexyl)phthalate, tris (1,3-dichloroisopropyl) phosphate, triphenyl phosphate, tri-(2-chloroethyl) phosphate and benzophenone. All of these plastics associated chemicals are commonly detected (>2,000 samples) indicating that both older plasticiser (e.g. bisphenol A and phthalates) and also alternative plasticiser and chemical used in other aspects of plastic synthesis are widely present in surface waters. Consumer products, which are also likely to reach surface waters via sewage effluent, are also represented in the top 30 detection corrected average ecological ranked substances. These include N,N,N',N'-tetraacetylethylenediamine and 2,4,7,9-tetramethyl-5-decyne-4,7-diol two substances present in a range of consumer products including detergents and in surface coating.

Rank	CAS Registry Number	Compound Name	Number of positive detects	Detection frequency Rank	Max reported conc. (µg/L)	WFD EQS HQ	WFD EQS HQ Rank	NORMAN PNEC HQ	NORMAN PNEC HQ rank	Chronic SSD HC50 HQ	Chronic SSD HC50 Rank	Average HQ value	Average HQ rank	Average HQ rank * detection frequency rank
1	80-05-7	Bisphenol A	1191	3	100			49.9	45	0.589	15	0.07	14	42
2	191-24-2	Benzo[ghi]perylene	113	68	1.9			5938	5	40.1	1	0.0071	1	68
3	56-55-3	Benz[a]anthracene	313	28	2.4			175	24	5.83	2	0.031	4	112
4	3622-84-2	Benzenesulfonamide, N-butyl	566	17	4000			189	21	0.774	13	0.041	7	119
5	129-00-0	Pyrene	1080	7	2			70.0	39	0.222	28	0.082	18	126
6	1912-24-9	Atrazine	1396	1	0.75	1.25	32	11	87	0.0084	120	0.394	130	130
7	79-01-6	Trichloroethylene	1322	2	184	18.4	19	13.0	82	0.017	96	0.279	86	172
8	206-44-0	Fluoranthene	1099	5	3.4	34	13	69.9	40	0.113	41	0.157	39	195
9	117-81-7	bis(2-ethylhexyl)phthalate (DEHP)	740	12	62	47.7	11	12810	3	0.24	24	0.1	20	240
10	934-34-9	2(3H)-Benzothiazolone	244	34	1000			253	18			0.042	8	272
11	193-39-5	Indeno[1,2,3-cd]pyrene	33	154	4.4			12222	4	3.69	5	0.011	2	308
12	6190-65-4	Atrazine-desethyl (Desethylatrazine)	873	9	1			3.9	122	3.03	6	0.150	36	324
13	77-90-7	Tributyl acetylcitrate	247	33	154			105	32	0.204	30	0.076	16	528
14	124-48-1	Chlorodibromomethane	516	19	180			128	29	0.038	70	0.125	28	532
15	50-32-8	Benzo[a]pyrene	124	64	1.6	9412	3	914	12	0.485	16	0.044	9	576
16	106-65-0	Butanedioic acid, dimethyl ester	1107	4	74			0.540	213	0.0029	169	0.468	152	608
17	127-18-4	Tetrachloroethylene	913	8	180	18	20	19.3	65	0.024	84	0.262	79	632
18	205-99-2	Benzo[b]fluoranthene	150	53	2.9	171	7	1487	7	3.92	4	0.058	12	636
19	53-70-3	Dibenz[a,h]anthracene	12	224	0.278			284	16	2.55	7	0.028	3	672
20	75-25-2	Bromoform	507	20	96			20	64	0.059	57	0.149	35	700
21	95-14-7	1H-Benzotriazole	99	77	2000			258	17	0.286	22	0.048	11	847
22	333-41-5	Diazinon (Dimpylate)	28	170	25	2500	4	23364	2	3.96	3	0.032	5	850
23	115-86-6	Triphenyl phosphate (TPPA)	624	16	7.2			105	31	0.00825	123	0.196	54	864
24	58-08-2	Caffeine	802	11	7.2			0.523	216	0.37	18	0.275	85	935
25	134-62-3	N,N-Diethyl-m-toluamide	1098	6	17			0.848	191	0.0016	199	0.481	157	942
26	19666-30-9	Oxadiazon	68	98	12			182	23	0.74	14	0.045	10	980
27	108-94-1	Cyclohexanone	837	10	300			3.778	125	0.0058	134	0.32	100	1000
28	75-27-4	Bromodichloromethane	519	18	150			138	28	0.0063	131	0.203	56	1008
29	67129-08-2	Metazachlor	349	24	44			10.8	89	0.069	53	0.172	43	1032
30	128-37-0	Butylated hydroxytoluene	236	35	8.7			22.8	61	0.069	52	0.14	31	1085

Table 12a. Top 30 substances ranked by detection frequency corrected by integrated ecological hazard rank (e.g. detection frequency rank * integrated ecological hazard rank) for chemicals in the GC-MS groundwater data-set (excludes substance detected in < 10 samples). Maximum concentration values reported in these tables must be considered in the context that they are based upon semi-quantitative data. For the purposes of this analysis, concentrations have been taken at face value, and therefore are assumed to demonstrate a worst-case scenario. However, comparisons against specific threshold levels, should be further validated using certified, fully quantitative methods. This is particularly true for some PFAS substances.

Rank	CAS Registry Number	Compound Name	Number of positive detects	Detection frequency Rank	Max reported conc. (µg/L)	WFD EQS HQ	WFD EQS HQ Rank	NORMAN PNEC HQ	NORMAN PNEC HQ rank	Chronic SSD HC50 HQ	Chronic SSD HC50 Rank	Average HQ value	Average HQ rank	Average HQ rank * detection frequency rank
1	58-08-2	Caffeine	13989	1	46			3.34	140	2.37	15	0.170	44	44
2	83-79-4	Rotenone	678	48	2030			341176	1	344	1	0.006	1	48
3	206-44-0	Fluoranthene	9006	3	7	70	15	144	44	0.234	50	0.204	59	177
4	13674-87-8	Tris (1,3-dichloroisopropyl) phosphate	3887	13	50			5896	10	0.108	60	0.086	15	195
5	129-00-0	Pyrene	8970	4	1.2			42	64	0.133	55	0.231	68	272
6	87674-68-8	Dimethenamid (SAN 582H)	1091	33	230			55.7	60	6.94	5	0.07	9	297
7	134-62-3	N,N-Diethyl-m-toluamide	11595	2	19			0.948	209	0.0018	218	0.5	170	340
8	115-86-6	Triphenyl phosphate (TPPA)	2147	20	85			1237	23	0.097	63	0.104	18	360
9	135319-73-2	Epoxiconazole (BAS 480F)	113	132	770			631	28			0.018	3	396
10	119-61-9	Benzophenone	3244	15	234.7			77.3	53	0.274	46	0.123	28	420
11	142459-58-3	Flufenacet (Fluthiamide) (BAY FOE 5043)	1182	32	98			419	37	1.04	23	0.079	14	448
12	13684-63-4	Phenmedipham	18	255	3060			11378	6	3.63	7	0.013	2	510
13	298-46-4	Carbamazepine	6083	6	5.3			2.33	158	0.022	99	0.295	90	540
14	117-81-7	bis(2-ethylhexyl)phthalate (DEHP)	2355	19	170	131	12	35124	3	0.659	28	0.139	35	665
15	126-86-3	2,4,7,9-Tetramethyl-5-decyne-4,7-diol	5415	7	48			2.15	162	0.015	107	0.309	96	672
16	67129-08-2	Metazachlor	2031	22	340			83.4	49	0.534	32	0.128	31	682
17	80-05-7	Bisphenol A	1426	29	55			27.4	72	0.324	41	0.115	24	696
18	886-50-0	Terbutryn	1014	37	9.3	1431	5	1875	18	0.597	29	0.11	21	777
19	23950-58-5	Propyzamide (Pronamide)	2833	16	72			18.3	82	0.101	62	0.185	49	784
20	50-32-8	Benzo[a]pyrene	548	57	1.1	6471	1	629	29	0.334	40	0.095	17	969
21	5915-41-3	Terbuthylazine (TERBA)	96	145	118			5332	11	0.569	30	0.062	7	1015
22	107534-96-3	Tebuconazole (Terbuconazole)	300	85	210			613	31	1.12	21	0.076	12	1020
23	907204-31-3	Fluxapyroxad	196	107	190			13204	5	0.287	43	0.074	10	1070
24	483-63-6	Crotamiton	5195	8	8.8			1.34	191			0.412	134	1072
25	3622-84-2	Benzenesulfonamide, N-butyl	4554	12	60			2.84	147	0.012	115	0.303	93	1116
26	188425-85-6	Boscalid (Nicobifen)	294	87	100			3483	14	0.276	44	0.078	13	1131
27	10543-57-4	N,N,N',N'-Tetraacetylethylenediamine	6221	5	25			0.782	222	0.00016	320	0.642	228	1140
28	115-96-8	Tri-(2-chloroethyl) phosphate	4950	9	16			24.3	75	0.00098	243	0.387	127	1143
29	53-70-3	Dibenz[a,h]anthracene	10	288	21			21429	4	193	2	0.055	4	1152
30	56-55-3	Benz[a]anthracene	2049	21	1			72.8	55	2.43	14	0.196	56	1176

Table 12b. Top 30 substances ranked by detection frequency corrected by integrated ecological hazard rank (e.g. detection frequency rank * integrated ecological hazard rank) for chemicals in the GC-MS surface water data-set (excludes substance detected in < 10 samples). Maximum concentration values reported in these tables must be considered in the context that they are based upon semi-quantitative data. For the purposes of this analysis, concentrations have been taken at face value, and therefore are assumed to demonstrate a worst-case scenario. However, comparisons against specific threshold levels, should be further validated using certified, fully quantitative methods. This is particularly true for some PFAS substances.

6.2 Ranking LC-MS substances in groundwater and surface water

6.2.1 Groundwater

The top 30 detection corrected average ecological ranked LC-MS substances in groundwater are dominated by pesticides, human and veterinary pharmaceuticals and industrial chemicals (Table 13 a-b). The three highest ranked substances are the herbicide metabolite atrazine-desethyl, fungicide boscalid and the herbicide trietazine. For atrazine-desethyl, high placement is based on a relatively high ranking for multiple ecological hazard metrics (NORMAN PNEC 26th ranked, chronic SSD HC50 1st ranked) and also its high detection frequency ranking (highest overall). Boscalid, which is an in use fungicide, has a high hazard ranking, being 1st ranked against the NORMAN PNEC value and 7th ranked against the Chronic SDD HC50. Boscalid also has a relatively high detection frequency rank (27th ranked). The high positioning of trietazine is based on a high ranking against the only available hazard values NORMAN PNEC (4th ranked) and moderate detection frequency (69th ranked).

Several pesticides including multiple insecticides, herbicides and fungicides are top ranked in the LC-MS groundwater list. These include legacy compounds (e.g. atrazine, clothianidin, diuron, simazine), as well as products in current use (e.g. bentazone, azoxystrobin, fipronil, flufenacet, terbutryn, propiconazole, triallate). The high detection corrected average ecological rank for these pesticides draws on their inherent toxicity, which means they are frequently highly ranked for the NORMAN PNEC and/or the chronic SSD HC50 HQ. Further, especially in the case of atrazine (and its metabolites), bentazone, simazine, clothianidin, diuron, these high ranked substances are also frequently detected (all in >100 of ~850 samples).

The LC-MS groundwater assessment also identifies pharmaceuticals in the top 30 ranked list (Table 13a). In addition to the recreational drug cocaine, veterinary drugs such as clopidol and human medicines such as carbamazepine are identified. For the two approved use pharmaceuticals, the frequency of detection is relatively high indicating that these substances are widely present in samples. This is not the case for cocaine, which is detected in only 38 samples, with high ranking driven mainly by high hazard ranking. Further work is needed to confirm the high priority identified for these pharmaceuticals relating to potential ecological effects, especially in relation to their potential to have effects in a range of different species. This applies especially for cocaine and clopidol, which are both hazard ranked based on an HQ calculated against a NORMAN PNEC.

Six perfluorinated chemicals PFOS, perfluorobutane sulfonate, PFOA, perfluoro hexanoic acid, perfluoro pentanoic acid, perfluoro heptanoic acid are also top 30 rated (Table 13a). These substances are high to moderate ranked for the ecotoxicological hazard values represented by for the NORMAN PNEC and chronic SSD HC50. However, all have a relatively high frequency of detection, all being present in >150 samples. A number of further perfluorinated chemicals are also found in groundwater (and surface water) including some at high frequency (e.g. perfluorohexane sulfonate). Limited hazard information is available for these substances (e.g. NORMAN PNECs only or no values), indicating that these substances may require further investigation in future assessment exercises (see Section 8, Tables 9 & 10).

6.2.2 Surface water

The top 30 LC-MS substances by detection frequency weighted multiple hazard rank in surface water are dominated by pesticides, human and veterinary pharmaceutical and industrial chemicals. The two highest ranked substances are the insecticide fipronil and herbicide bentazone. For fipronil, the high positioning is due to both high ranking against the NORMAN PNEC (12th ranked) and chronic SSD HC50 (2nd ranked), as well as a relatively high detection frequency. For bentazone, high placement is also based on a high ranking against the chronic SSD HC50 and to a lesser extent the NORMAN PNEC. Both of these two pesticides were detected in >2,000 samples indicating that they are widespread in surface water.

A number of the top 30 LC-MS substances in surface water are current use pesticides, this includes fipronil and its degradation product fipronil sulfon, as well as herbicides such as propyzamide, flufenacet, triallate and multiple fungicides including boscalid, epoxiconazole, propiconazole and azoxystrobin. Many of these in use active ingredients have high detection rate, being found in >2,000 samples (>75%) in surface waters. Hence, while some of these pesticides may rank relatively low by one or more hazard metric (e.g. propiconazole 145th for NORMAN PNEC, 114th for chronic SSD HC50), these substances make the top 30 ranking because of their high detection frequency (e.g. propiconazole 2,404 of 2,702 samples). Such information on the relative importance of hazard ranking for different hazard metrics and detection frequency of the substances in different environments may form part of any more detailed substance assessment.

A range of pharmaceutical substances are among the top 30 LC-MS detected chemicals in surface waters. These include well know and widely used human drugs such as diclofenac and carbamazepine, as well as less familiar human and veterinary medicines. The high overall ranking of pharmaceutical substances have multiple underlying causes. Some, such as iohexol and atazanavir and clopidol have relatively high hazard ranking, in each of these cases based only on one metric, the NOMAN PNEC. Both of these substances are, however, relatively rarely detected (iohexol in 422 samples, atazanavir in 12 samples), which means that their overall ranking is lower than their rank for hazard alone (Table 13b). In other cases, the primary driver for high ranking is a relatively high detection frequency coupled to moderate to high ranking against the available hazard metrics. This is the case both for diclofenac which in 35th ranked for the NORMAN PNEC and 28th ranked for the chronic SSD HC50, but is found in 2360 of 2850 samples, atenolol, which is 59th ranked for the chronic SSD HC50, but found in 2383 of 2850 samples and clopidol which is 265th ranked by NORMAN PNEC, but 4th ranked for detection frequency.

Three perfluorinated chemicals PFOS, PFOA and perfluorobutane sulfonate are ranked in the top 30 LC-MS detected analytes for surface waters. All the perfluorinated substances score moderately for ecological risk. Further, all are commonly detected in the surface water samples (PFOS 2,252 of 2,824, PFOA 2,444 of 2,702, perfluorobutane sulfonate 1028 of 2708), indicating a frequent presence that contributes to their high overall ranking. Other perfluorinated substances are also widely detected in surface waters indicating that these substances may require further investigation due to their common presence and more limited hazard information than that for PFOS and PFOA, which are to date better studied (see Section 8).

Rank	CAS Registry Number	Compound Name	Number of positive detects	Detection frequency Rank	Max reported conc. (µg/L)	WFD EQS HQ	WFD EQS HQ Rank	NORMAN PNEC HQ	NORMAN PNEC HQ rank	Chronic SSD HC50 HQ	Chronic SSD HC50 Rank	Average HQ rank	Average HQ value	Average HQ rank * detection frequency rank
1	6190-65-4	Atrazine-desethyl (Desethylatrazine)	377	1	0.28			1.09	26	0.849	1	5	0.032	5
2	188425-85-6	Boscalid (Nicobifen)	105	27	2.4			83.6	1	0.0066	7	2	0.01	54
3	1912-26-1	Trietazine	26	69	0.18			15.3	4			1	0.009	69
4	1763-23-1	Perfluorooctane sulfonate (PFOS)	227	12	0.71	1092	1	2.41	18	0.0049	13	6	0.038	72
5	1007-28-9	Atrazine-desisopropyl (Deisopropylatrazine)	370	2	0.048			0.123	64			38	0.149	76
6	56038-13-2	Sucralose	306	5	19			0.64	32			16	0.074	80
7	1912-24-9	Atrazine	339	4	0.31	0.517	8	4.56	11	0.003	15	30	0.12	120
8	50-36-2	Cocaine	38	58	32			13	7			3	0.016	174
9	25057-89-0	Bentazone	195	15	1.9			0.312	45	0.0066	6	12	0.060	180
10	122-34-9	Simazine	362	3	0.033	0.033	15	0.372	43	0.00019	59	73	0.27	219
11	2971-90-6	Clopidol	245	10	3.5			0.4	41			22	0.095	220
12	2303-17-5	Triallate	17	85	1.7			3.65	15	0.028	2	4	0.02	340
13	375-73-5	Perfluorobutane sulfonate	196	14	1.1			0.27	47			25	0.109	350
14	120068-37-3	Fipronil	105	28	0.0095			0.416	40	0.00524	11	13	0.061	364
15	142459-58-3	Flufenacet (Fluthiamide) (BAY FOE 5043)	69	40	0.2			0.855	29	0.0021	19	10	0.058	400
16	330-54-1	Diuron	254	6	0.028	0.14	12	0.021	118	0.0015	23	70	0.26	420
17	335-67-1	Perfluoro Octanoic Acid	246	9	0.12			0.42	39	0.000026	104	50	0.181	450
18	298-46-4	Carbamazepine	229	11	0.1			0.044	93	0.00041	47	46	0.169	506
19	210880-92-5	Clothianidin	215	13	0.15			0.067	78	0.00031	51	42	0.157	546
20	131860-33-8	Azoxystrobin	90	30	0.052			0.455	37	0.00069	36	19	0.09	570
21	307-24-4	Perfluoro Hexanoic Acid	178	18	0.16			0.15	60			36	0.14	648
22	65277-42-1	Ketoconazole	14	95	0.12			14.7	5	0.0011	27	7	0.041	665
23	886-50-0	Terbutryn	17	86	0.067	10	2	13.5	6	0.0043	14	8	0.041	688
24	6339-19-1	Chloridazon-desphenyl	111	26	6.3			0.251	49			27	0.114	702
25	115-28-6	1,4,5,6,7,7-Hexachloro-5-norbornene-2,3-dica	64	44	2.1			0.508	35			17	0.081	748
26	84057-84-1	Lamotrigine	168	20	0.13			4.64	10	0.000023	107	39	0.151	780
27	2706-90-3	Perfluoro Pentanoic Acid	182	17	0.25			0.064	79			51	0.184	867
28	375-85-9	Perfluoro Heptanoic Acid	151	22	0.053			0.105	66			40	0.153	880
29	120067-83-6	Fipronil Sulfide	12	105	0.006					0.0019	21	9	0.055	945
30	60207-90-1	Propiconazole	87	34	0.12			0.222	52	0.00046	43	28	0.116	952

Table 13a. Top 30 substance ranked by detection frequency corrected by integrated ecological hazard rank (e.g. detection frequency rank * integrated ecological hazard rank) for chemicals in the LC-MS groundwater data-set (n. b. excludes substance detected in < 10 samples). Maximum concentration values reported in these tables must be considered in the context that they are based upon semi-quantitative data. For the purposes of this analysis, concentrations have been taken at face value, and therefore are assumed to demonstrate a worst-case scenario. However, comparisons against specific threshold levels, should be further validated using certified, fully quantitative methods. This is particularly true for some PFAS substances.

Rank	CAS Registry Number	Compound Name	Number of positive detects	Detection frequency Rank	Max reported conc. (µg/L)	WFD EQS HQ	WFD EQS HQ Rank	NORMAN PNEC HQ	NORMAN PNEC HQ rank	Chronic SSD HC50 HQ	Chronic SSD HC50 Rank	Average HQ value	Average HQ rank	Average HQ rank * detection frequency rank
1	120068-37-3	Fipronil	2603	2	0.98			42.9	12	0.541	2	0.05	6	12
2	25057-89-0	Bentazone	2377	13	51			8.36	28	0.178	5	0.038	4	52
3	83881-51-0	Cetirizine	1820	31	53			129	5			0.015	2	62
4	84057-84-1	Lamotrigine	2612	1	1.6			57.1	11	0.00028	116	0.263	65	65
5	144701-48-4	Telmisartan	826	67	0.082			149	4			0.012	1	67
6	298-46-4	Carbamazepine	2578	3	1.5			0.659	91	0.0062	34	0.212	43	129
7	188425-85-6	Boscalid (Nicobifen)	2522	5	0.63			21.9	20	0.0017	60	0.16	31	155
8	3380-34-5	Triclosan	874	61	58	580	1	256	3	2.22	1	0.02	3	183
9	15307-86-5	Diclofenac	2360	14	0.76			5.3	35	0.0089	28	0.11	14	196
10	330-54-1	Diuron	2522	6	0.48	2.4	7	0.355	110	0.026	14	0.216	46	276
11	142459-58-3	Flufenacet (Fluthiamide) (BAY FOE 5043	2111	25	1.5			6.41	33	0.016	19	0.10	13	325
12	23950-58-5	Propyzamide (Pronamide)	2400	10	2.2			0.561	94	0.0031	44	0.17	33	330
13	131860-33-8	Azoxystrobin	2405	8	0.76			6.64	31	0.01	25	0.21	45	360
14	56038-13-2	Sucralose	2352	15	257			8.65	27			0.17	34	510
15	335-67-1	Perfluoro Octanoic Acid	2444	7	0.16			0.560	95	0.000035	177	0.35	87	609
16	29122-68-7	Atenolol	2383	11	1					0.0018	59	0.25	57	627
17	81103-11-9	Clarithromycin	2025	29	1.1			3.60	44	0.0039	38	0.15	29	841
19	66108-95-0	Iohexol	422	98	1.4			10.1	25			0.08	9	882
20	2971-90-6	Clopidol	2551	4	0.077			0.0088	265			0.82	227	908
21	1763-23-1	Perfluorooctane sulfonate (PFOS)	2252	21	0.088	135	2	0.299	118	0.00061	83	0.21	44	924
22	2303-17-5	Triallate	1158	47	0.98			2.1	54	0.016	18	0.137	20	940
23	83905-01-5	Azithromycin	450	96	0.87			5.04	37	0.034	10	0.08	10	960
24	54-31-9	Furosemide	654	82	1.8			2.55	48	0.064	6	0.09	12	984
18	41859-67-0	Bezafibrate	215	124	39			86.9	9	0.009	27	0.071	8	992
25	135319-73-2	Epoxiconazole (BAS 480F)	2380	12	0.2			0.164	142			0.350	86	1032
26	198904-31-3	Atazanavir	12	227	0.23			38.7	13			0.040	5	1135
27	60207-90-1	Propiconazole	2404	9	0.082			0.152	146	0.00032	114	0.48	139	1251
28	375-73-5	Perfluorobutane sulfonate	1028	51	14			3.43	46			0.14	25	1275
29	1912-24-9	Atrazine	813	68	1.7	2.83	6	25	18	0.019	16	0.14	19	1292
30	15687-27-1	Ibuprofen	1585	38	1.1			1.09	71	0.0046	36	0.19	37	1406

Table 13b. Top 30 substance ranked by detection frequency corrected by integrated ecological hazard rank (e.g. detection frequency rank * integrated ecological hazard rank) for chemicals in the LC-MS surface water data-set (n. b. excludes substance detected in < 10 samples). Maximum concentration values reported in these tables must be considered in the context that they are based upon semi-quantitative data. For the purposes of this analysis, concentrations have been taken at face value, and therefore are assumed to demonstrate a worst-case scenario. However, comparisons against specific threshold levels, should be further validated using certified, fully quantitative methods. This is particularly true for some PFAS substances.

6.3 Consideration of usage categories to inform on potential sources

Analysis of the known usage categories for the ranked substances can aid in understanding the roles that different sources may play in groundwater and surface water pollution by different organic chemicals.

In both environments and for both detection methods, legacy or current use pesticides always contribute a major fraction of the top 30 ranked substances (Fig. 5). This reflects the widespread nature of pesticide use; the relatively high inherent hazard of these chemicals (which by their nature are designed for their activities against one or more groups of organisms: and the broader availability of hazard thresholds. A difference between the top 30 ranked pesticides in lists for groundwaters and surface waters, is the greater representation and generally higher ranking of legacy pesticides (e.g. triazines, phenylureas, the organophosphate diazinon) in groundwater. Given the long time-span that has elapsed since restrictions were placed on the use of these active ingredients (decades), their continued presence in the groundwater sample indicates a potential lower degradation potential and longer retention times in the sub-surface than the surface water environment.

In groundwater, there is a representation of chemicals associated with industrial processes and products, such as solvents, PAHs, industrial chemicals and plasticisers in the top 30 list (Fig. 5). The role of contaminated land as a reservoir of industrial pollutants that can transfer to groundwater is widely recognised and could partly account for the presence of some of these chemicals. For example, the prevalence and higher ranking of a greater number of PAHs in groundwater, where they are among the most frequently detected chemicals, may be linked to their presence in fossil fuel released to soils and groundwater through losses during processing, distribution and use. The role of industrial and domestic landfill as a source of pollution, especially for the older landfills built before the development of lining technologies, is indicated by the presence of consumer products and plastic associated chemicals in groundwater.

As many pharmaceuticals are polar in nature the total number detected is higher by LC-MS. A greater number of these pharmaceuticals are top 30 ranked in surface waters than in groundwater (11 surface water, 8 groundwater). This higher ranking for multiple pharmaceuticals is based on their higher ranking for frequency of detection in surface water compared to groundwater samples. The presence of pharmaceutical associated substances in surface waters may be linked to releases from wastewater discharges following human use (Gardner *et al.*, 2013; Heffley *et al.*, 2014). These represent largely pharmaceuticals ingested and excreted without biotransformation by patients that subsequently enter and pass through the sewage treatment system to be released in effluent. However, in addition to these human pharmaceutical uses, a number of the high ranked substances are also used as veterinary medicines. Entry of these chemicals into surface water and even groundwater following direct outdoor excretion to land and surface waters or after leaching from manures may provide routes for these substances to surface water bodies.
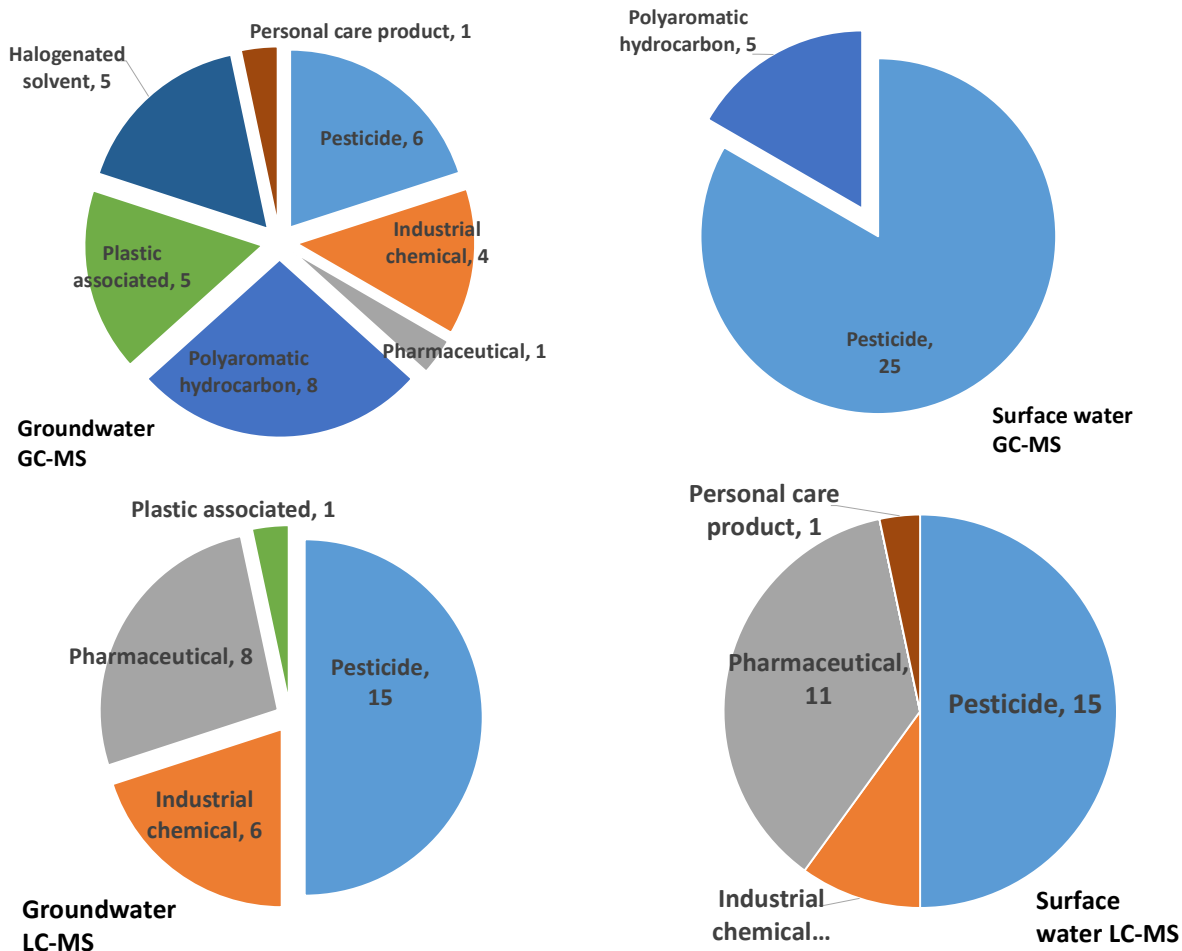
Fig. 5. Main use categories for the Top 30 integrated ecological hazard ranked chemicals detected by GC-MS (top) and LC-MS (bottom) in groundwater (left) and surface water (right).

7 Distribution of concentrations to assess the relevance of the highest measured value

The worst-case ranking approach was based on an assessment against the highest detected concentration for all chemicals. As discussed above, the use of the highest concentration for ranking was a pragmatic choice, selected as values more within the distribution, such as mean, median or 90th percentile, could not be calculated for the large majority of substances due to the high frequency of non-detects. Although a pragmatic best option, assessment based on the highest measured concentration is potentially liable to error in cases where the highest concentration corresponds to an outlier arising either from a short-term local case of intense pollution or by an analytical or data recording error. To assess whether there was any evidence of a high frequency of extreme outliers in the different measurement data-sets, an analysis was conducted to assess how the highest recorded concentration was related to the other measured concentrations. The aim was to assess whether the highest value was consistent with the other concentrations detected as part of an expected environmental distribution.

Given the limited project resources, a full assessment of all concentrations was not feasible for all of the different chemicals detected. Instead, a set of chemicals with a high worst-case HQ and high frequency of detection were chosen from both the GC-MS and LC-MS analytes. These assessments provided an assessment of concentration distributions for 40 substances which are shown in Appendix 4. **The analysis for two chemicals commonly detected in both sampled media by GC-MS (benzo[a]pyrene and fluoranthene) (Fig. 6) and LC-MS (PFOS and PFOA) (Fig. 7) are presented in this section of the report.** Graphical assessment for a further 20 GC-MS (atrazine, atrazine-desethyl, dimethenamid, benzo[a[anthracene, benzo[b]fluoranthene, benzo[g,h,i]perylene, pyrene, acetophenone, caffeine, 4-tert-octylphenol, di(2-ethylhexyl) adipate, di(2-ethylhexyl)phthalate, bisphenol A, diisobutyl phthalate, N-butyl-benzenesulfonamide, cyclohexanone, 1,4,-dioxane, tetrachloroethylene, tributyl acetylcitrate, trichloroethylene) and four LC-MS (atrazine, atrazine-desethyl, diuron, isoproturon) detected substances in groundwater and one GC-MS (rotenone) and one LC-MS (fipronil) detected pesticide and eight perfluorinated substances (perfluorobutane sulfonate, perfluoro pentanoic acid, perfluoro hexanoic acid, perfluorohexane sulfonate, perfluoro heptanoic acid, perfluoroctylsulfonamide (PFSOA), perfluoro nonanoic acid, perfluoro decanoic acid) in surface water are presented in Appendix 4.

All measured concentrations above the GC-MS and LC-MS detection limits (at the time of measurement) for all assessed substances were collated. Concentrations measured were plotted from lowest to highest and the number of samples below the detection limit also noted. This analysis allowed an assessment of the relative positioning of the highest measured concentrations in relation to all of the other concentrations detected. A highest concentration an order of magnitude greater than the next value was set as the criteria for outlier identification. To assess the hazard associated with the overall distribution of measured values, threshold values for three hazard metrics relating to human health (ADI/TDI) and ecological effects (WFD EQS and chronic SSD HC50) were (where available) also included in each plot to allow an assessment of limit exceedance across the full range of measured samples.

7.1 Benzo[a]pyrene and fluoranthene measured by GC-MS in groundwater and surface water

GC-MS measured concentrations of benzo[a]pyrene and fluoranthene above the detection limit represent only a small proportion of all samples quantified in groundwater (124 of 16,631, 0.7%, for benzo[a]pyrene; 1099 of 16,631, 6.7%, for fluoranthene) and surface water (548 of 23,023, 2.3%, for benzo[a]pyrene, 9006 of 23,040, 39.1%, for fluoranthene), with the remainder of samples being below the detection limit. In each case, the highest measured concentration was well within an order of magnitude of the other measurements made for these two compounds. This agreement indicates that the highest concentration was at the reasonable extreme of a distribution of environmental concentrations, rather than being a clear outlier. This supports the use of this highest value as a reasonable worst-case environmental concentration for ranking. Comparing the distribution of measured concentrations to substance relevant hazard values indicates that for benzo[a]pyrene, the WFD EQS is exceeded by all measured values, as the threshold value is lower than the limit of detection. The benzo[a]pyrene chronic SSD HC50 is exceeded in surface water but not groundwater, with multiple concentrations in addition to the highest value being above this threshold. For

fluoranthene, the highest measured concentration is closer to the next highest than is the case for benzo[a]pyrene (Fig. 6). Further, in cases where a fluoranthene hazard values (e.g. WFD EQS or chronic SSD HC50) is exceeded by the highest concentration, multiple further measurements also exceed this threshold (Fig. 6). Again this suggests that the use of the highest value for ranking represents a reasonable worst-case.
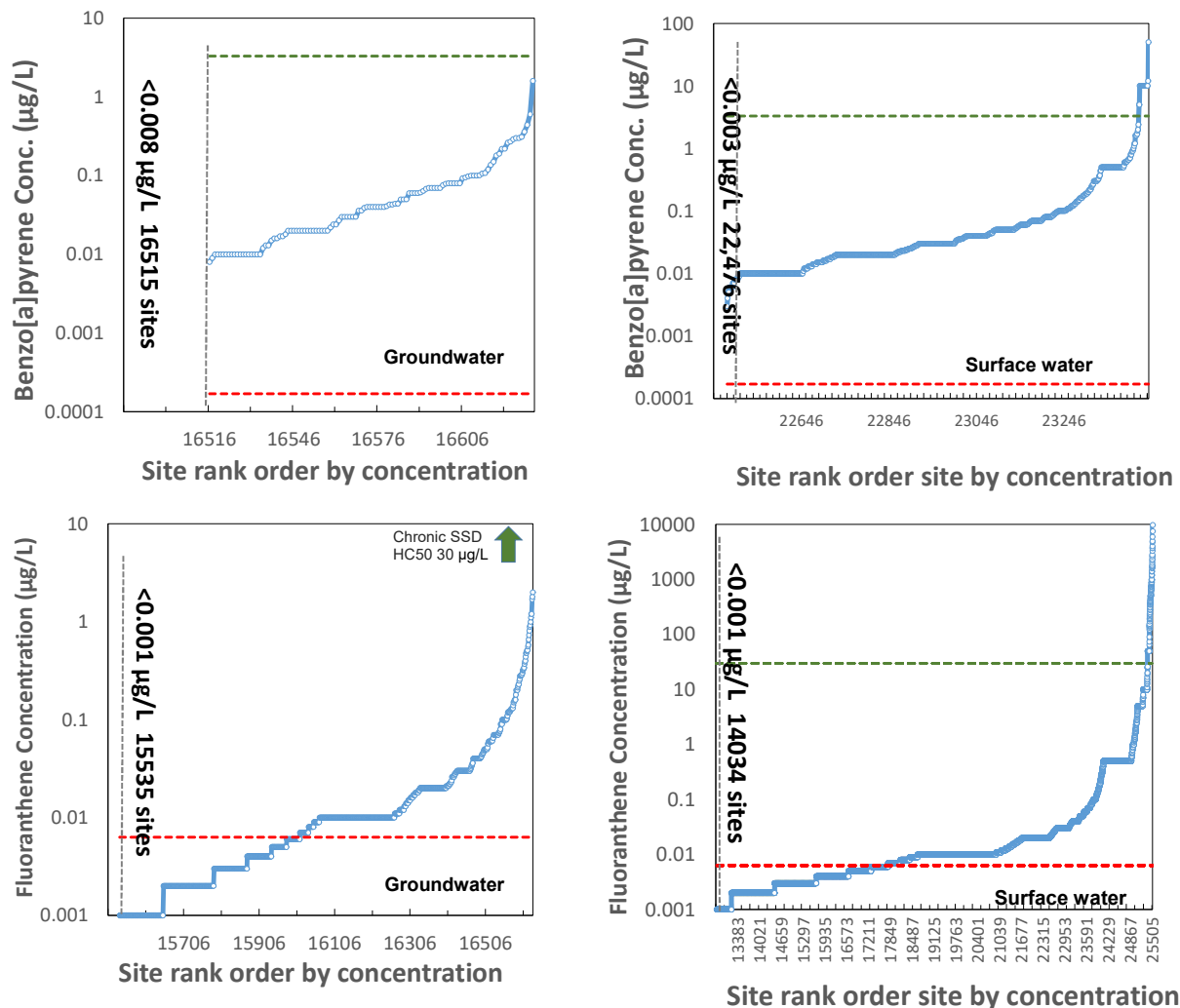
Fig. 6. Rank order of concentrations above the detection limit for benzo[a]pyrene (top) and fluoranthene (bottom) in groundwater (left) and surface water (right) samples; numbers of samples with concentrations below the detection limit are stated on the left-hand side of the plots; horizontal lines indicate WFD EQS (red), human ADI-TDI value (grey), chronic SSD HC50 (green) hazard values where available.

7.2 PFOS and PFOA measured by LC-MS in groundwater and surface water

The LC-MS method has lower detection limits than the GC-MS technique. Hence for PFOS and PFOA, the percentage of samples with measured concentrations above the detection limit in groundwater was higher (>26.5% in all cases) than for any GC-MS measured chemical. It

is, therefore, possible to gain a wider view of the range of concentrations for substances commonly detected using this method. The cumulative ranking of PFOS and PFOA concentrations in groundwater samples indicates that the highest measured concentrations are largely consistent with an expected distribution of environmental concentrations (Fig. 7). For PFOS, the highest measured concentration exceeds the next highest value by a factor of six, however, there are also further samples with concentrations within an order of magnitude of the highest value. Hence, while likely to be part of a range of environmental measurements, the highest PFOS concentration is certainly worst-case. This difference of highest PFOS value from further measured concentration means that, while the highest value exceeds the human ADI/TDI by a factor of ≥ 5, no other sample has a concentration above this threshold. This finding would be important to take into account when considering the nature and extent of any follow-up actions for this substance (as highlighted in Section 1). For PFOA, the highest concentration exceeds the next highest value by a factor of only 1.2 and a further 19 samples have concentrations within an order of magnitude of the top value. As a consequence, when a hazard value is exceeded by the maximum value, such as for the human ADI, further measurement also exceeds this criteria.
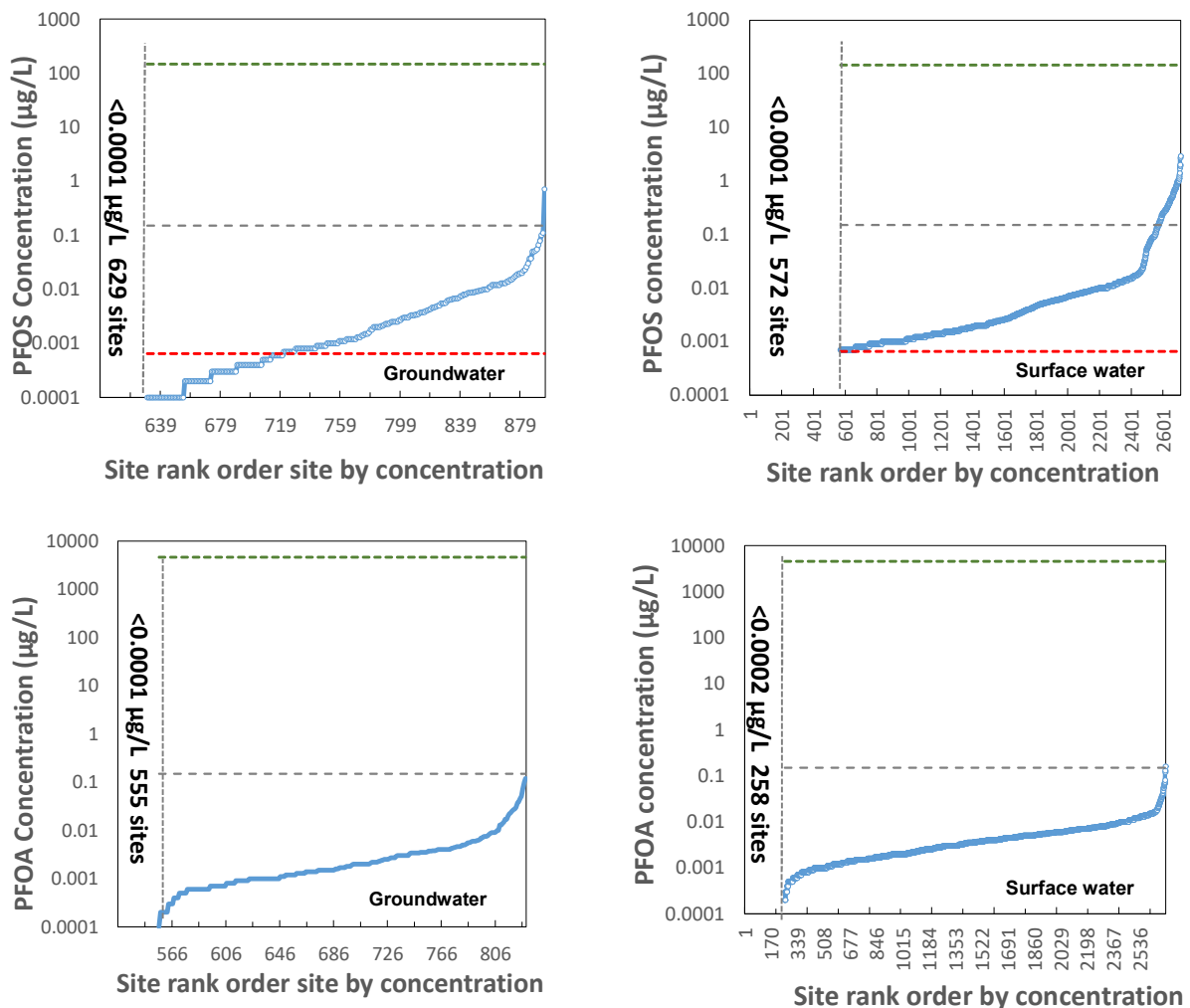
Fig. 7. Rank order of concentrations above the detection limit for PFOS (top) and PFOA (bottom) in groundwater (left) and surface water (right); numbers of samples with concentrations below the detection limit are stated on the left-hand side of the plots; horizontal

lines indicate WFD EQS (red), human ADI-TDI value (grey), chronic SSD HC50 (green) where available.

The highest measured PFOS and PFOA concentrations in surface waters are both consistent with being part of an expected environmental distribution. In both cases, the maximum value lies within a factor of two of the next highest value. For PFOS, a WFD EQS is available as well as a human TDI and a chronic SSD HC50. The WFD EQS of 0.00065 µg/L is at the detection limit achieved in the analysis for this substance. Hence all samples with detected PFOS concentrations (total 2,252 samples) exceed this hazard value. The human TDI of 0.15 µg/L is also similarly exceeded in multiple (138 of 2,252) measured samples. This suggests that the highest concentration provides a worst-case indication of a wider hazard. No sample measured has a PFOS concentration that exceeds the chronic SSD HC50 value. For PFOA, the only hazard metric available is a chronic SSD HC50. No measured concentration exceeds this value.

7.3 Further substances and overall conclusions of concentration distribution

Analysis of the range of maximum and further concentrations was also undertaken for a further 20 GC-MS and 4 LC-MS analytes assessments in groundwater and one GC-MS and 9 LC-MS analytes in surface water. These assessments are presented in Appendix 4. Across all substance specific assessments, there was no case in which the highest measured concentration exceeded the next highest measured value by a factor >10. The greatest difference between the maximum and next highest value (6.53 fold) was found for the insecticide fipronil measured by LC-MS in surface water. The only other substance where this difference was >5 fold was for PFOS in groundwater as discussed above. A further 7 GC-MS measured substances (atrazine-desethyl, dimethenamid, benzo[a[anthracene, benzo[g,h,i]perylene, 4-tert-octylphenol, N-butyl-benzenesulfonamid, bis(2-ethylhexyl) adipate) in groundwater and 2 (benzo[a]pyrene and fipronil) in surface water had difference between the maximum to next highest concentration of >3. All other substances (23) had a highest measured concentration within a factor of 3 of the next highest value.

The outlier analysis conducted for the total of 39 substance indicates that, while the use of only the highest value clearly provides a clear worst-case, there is no evidence for any of these substances that the highest measured concentration is a clear outlier. While of course not indicating that for any individual substance that the highest value may not be erroneous, this analysis does suggest that high value outliers are not common in the data-set. **As such, the use of the highest concentration is supported as a pragmatic approach for worst case ranking given the limitations of the data. For any chemical that is identified for further assessment, an analysis of the wider distribution of measured concentrations and their relationship with hazard limits should be undertaken to ensure that effort is not placed on assessing an individual substance on the basis of a top concentration that is not consistent with a wider distribution of values.**

8 Mixture effects prediction from site specific data for groundwater samples

The focus of (eco)toxicological research (and regulatory chemical management) remains predominantly on single substances. This does not take into account that real exposures are overwhelmingly to mixtures. The failure to consider the potential effect of mixtures has been recognised as a key gap in current approaches to chemical and natural resource management. For example, considering impacts on human health, a House of Commons select committee review of evidence on "Toxic Chemicals in Everyday Life" found that current UK regulations intended to protect people were inadequate because they failed to account for 'cocktail' effects. The committee called for any forthcoming Chemicals Strategy to consider the health implications of exposure to mixtures in a more routine, but evidence based manner (https://publications.parliament.uk/pa/cm201719/cmselect/cmenvaud/1805/180509.htm).

Multiple field studies in freshwaters have predicted mixture 'toxic pressure' using additive models and have further compared these predictions to observed diversity/species richness effects to identify mixture impacts. These assessments have found that observed impacts match mixture predictions (De Zwart *et al.*, 2008; DeZwart *et al.*, 2006; Kortenkamp *et al.*, 2019) and in some cases may even under-predict actual effects due either to chemical-chemical interactions or as a result of combined effects with other stressors (Schipper *et al.*, 2014; Stockdale *et al.*, 2010). Mixture analysis can, thus, support a more realistic risk assessment than a chemical by chemical approach as part of any risk assessment and management program.

The mixture effect assessments conducted for the groundwater and surface water organic chemical data-sets were undertaken based on the chemicals detected above the limit of detection in individual samples. It is widely accepted that chemical mixture assessment is a complex and challenging task. Any mixture assessment, by its nature, has specific features and limitations. This is the case with the technique adopted here. The mixture assessment method was based on the application of the concentration addition model. This model is particularly well suited for mixture assessments made against single value hazard thresholds, such as the chronic SSD HC50 (or ADI/TDI), because the mixture effects can be calculated without access to full concentration response relationship as needed for independent action analysis. The concentration addition model assumes that substances exert effects through a similar mode of action. Given the range of substances detected in samples, action through a common mechanism is rarely (if ever) likely to be applicable for the detected mixtures. This means that any assessment done using the concentration addition model may not accurately predict the true mixture effect. However, this model is generally accepted to result in a more conservative mixture effect prediction than the independent action model and so is well suited for initial screening and risk characterisation (Van Gestel *et al.*, 2010).

A further issue with the concentration addition approach is that the modelling assumes that all chemicals in the mixture act independently without interacting. As a consequence, synergistic or antagonistic effects are not accounted for. There is a widely accepted potential for synergism or antagonism to occur in a small, but potentially significant, number of mixture cases. Studies have shown that the effects of synergistic or antagonistic interactions can be cumulative, such that more complex mixtures may theoretically be characterised by a greater level of overall synergism. However, probability theory also means that when the number of substances in a

mixture rise, the probability for counteracting synergistic or antagonistic effects also increases. As a result, more complex mixtures may trend more to additivity than simpler mixtures in which a single dominant synergistic or antagonistic interaction may dominate.

The mixture assessment was conducted initially using the chronic SSD HC50 value, as the more robust of the two ecological hazard metrics with high substance coverage. To assess mixture risks in relation to a human health endpoint, an analysis was also conducted using the human ADI/TDI values. The ADI/TDI value has a much lower substance coverage (i.e. only around 1 in 3 detected substances have an ADI/TDI compared to more than 2 of 3 for the chronic SSD HC50). Therefore, the ADI/TDI analysis is less comprehensive than that for the ecological endpoint. Despite this difference the outcomes of the analysis were similar in regard to the overall patterns of mixture effect seen. The graphical outputs of this ADI/TDI analysis are provided in Appendix 5 for comparison with the chronic SSD HC50 assessment which is discussed in detail here.

The GC-MS and LC-MS data were used to assess the cumulative risk associated with the presence of the detectable mixture of chemicals in groundwater and surface water samples. A merger of calculated chronic SSD HC50 calculated HQs for the two analysis methods could potentially have been conducted in cases where samples were taken at the same time and from the same location. However, there are issues with such a merger. These include logistic issues such as the time need to identify temporally and spatially matched samples, which was beyond that available, and also technical issues, such as differences in the detection limits between the analysis methods. Such difference would result in a different number of chemicals being included in the analysis for each sample, meaning that detection limits would govern the contribution of chemicals to HQmix differently.

A final obvious limitation of the mixture analysis is that the assessments can only consider the effects of substances that are both detected above the LOD and that have an available hazard value (e.g. chronic SSD HC50). Even as one of the hazard metrics with the greatest coverage, only 80% of the substance detected have an available chronic SSD HC50 (only 30% of substances have an ADI/TDI). For any substance without a threshold value, the contribution of this substance to the mixture effect cannot be considered in HQmix calculation. This may mean that samples in which multiple chemicals are detected may have few substances that contribute to HQmix. Assessment of how HQmix varies in relation to the number of substances included was, therefore, made as a part of the mixture assessment.

Although there are challenges relating to the use and interpretation of mixture analyses conducted using a concentration addition model, the approach has an established history for pragmatic and conservative mixture assessment (DeZwart *et al.*, 2006; Piliere *et al.*, 2014; Schipper *et al.*, 2014). The approach used is comparable to that being developed by the Environment Agency and contractors for the assessment of pesticide mixture risks for freshwaters. The difference is that here we use the chronic SSD HC50 (and ADI/TDI) as the hazard value, while the pesticide assessment indicator approach uses a hazard value derived from a single species toxicity test (e.g. for *Daphnia magna*). The approach here benefits from assessing mixture effects against a hazard value derived based on a wider set of toxicity information, rather than for a single, species, as well as also indicating human health effects through the parallel ADI/TDI based assessments.

8.1 Overall distribution of HQmix values for each data-set

Substance HQs were calculated for all chemicals present above the LOD in a sample by comparison of the measured concentration for that substance in a sample to the chronic SSD HC50. This sample specific analysis was conducted separately for the GC-MS and LC-MS analysed groundwater and surface water samples. The individual substance HQ values were then summed assuming concentration addition to derive the overall hazard quotient for the mixture (HQmix). The distribution of HQmix values for all measured samples was plotted from lowest to highest to allow the distribution of HQmix values to be visualised.

In groundwater, HQmix values based on chronic SSD HC50 HQs indicate that, as would be expected, a greater number of samples that have a hazard quotient value ≥ 1 than was the case for any single chemical. Thus, the GC-MS HQmix was >1 in 64 groundwater samples (Fig. 8), indicating that at multiple locations GC-MS measured chemicals included in the mixture assessment may be expected to impact on 50% of species present in the community. For the LC-MS substance assessment, no sample has an HQmix ≥1, however, an HQmix of ≥ 0.1 was found for 89 of 878 assessed samples. This is greater than the number of samples showing this degree of risk for any single LC-MS measured chemical. A greater number of samples with HQmix values ≥1 or ≥0.1 for GC-MS and LC-MS measured chemicals indicate additional cumulative risk from the mixtures present than for any single chemical, illustrating the added value of the overall mixture assessment in identifying the potential for risk.
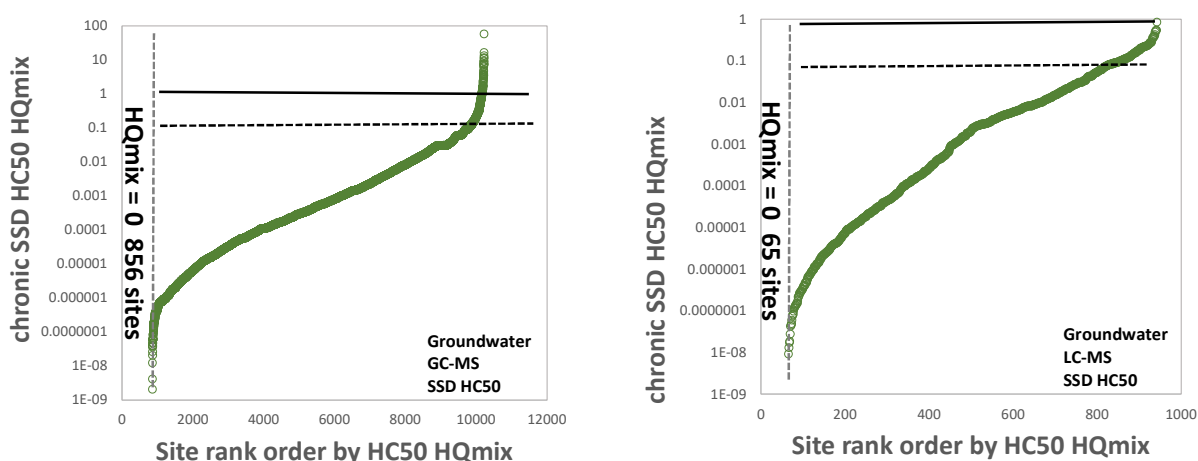
Fig. 8. Cumulative distributions of HQmix for the GC-MS (left) and LC-MS (right) measured analytes in groundwater

In surface water, the distribution of calculated values again indicated a greater number of samples with a chronic SSD HC50 based HQmix ≥ 1 than of samples with an HQ ≥ 1 for any single chemical. For the GC-MS data, HQmix ≥ 1 is found in 876 samples which is greater than the number of samples for any individual substance (Fig. 9). In the LC-MS data-set, values of HQmix ≥ 1 are found in a small number of samples, whereas for this method no single chemical has a chronic SSD HC50 HQ ≥ 1. A greater number of samples with an HQmix ≥ 0.1 are also found compared to the HQ values for any single chemical, illustrating a greater level of potential mixture risk. Compared to single substance HQs, the values of HQmix indicate that the mixture assessment identifies a greater scale of potential impacts due to the presence of multiple chemicals in samples analysed by GC-MS and LC-MS in groundwater and surface water.
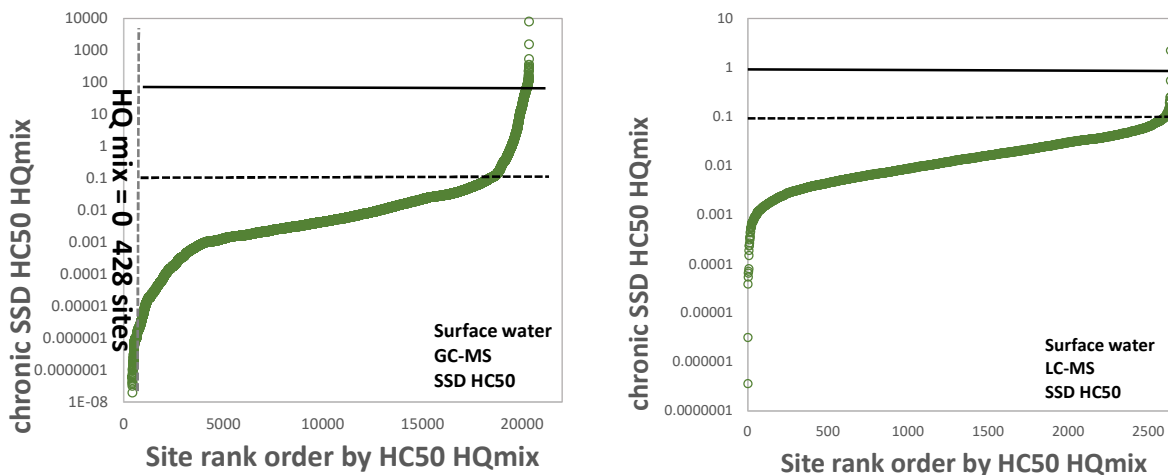
Fig. 9. Cumulative distributions of HQmix for the GC-MS (left) and LC-MS (right) measured analytes in surface water

The identification of a greater number of samples with HQmix ≥ 1 in the GC-MS data-set compared to LC-MS may simply be a product of the greater number of samples analysed by this technique (~16,000 for groundwater, ~22,000 for surface water) compared to by LC-MS (~800 for groundwater, ~2,200 for surface water). This greater sample analysis effort gives an order of magnitude or more potential to find locally high concentrations of one or more chemicals that will result in values of HQmix value >1. Additionally, the LODs are higher for the GC-MS than for the LC-MS analysis. Consequently, GC-MS detected chemicals will have high HQs when detected given they are found only at higher concentrations. Alternatively, substances that are detected by GC-MS may be more likely to exceed hazard thresholds because of their specific physicochemical characteristics and associated inherent hazard. Further work would be needed to tease apart the relevance of both of these issues and their role in determining risk.

8.2 Contribution of the most important single chemical to the overall mixture effect

To assess the importance of the most toxic chemical to the mixture, the cumulative distribution of the proportion contribution of the most toxic substance (expressed as the maximum individual substance HQ, hereafter HQmax) to HQmix was assessed (Fig. 10). The additional risk resulting from the presence of the mixture compared to the worst-case single substance can be calculated as HQmix / HQmax. This approach has been identified as a means to calculate a potential "Mixture Assessment Factor" (also termed the Maximum Cumulative Ratio) (Backhaus and Karlsson, 2014). If HQmix ≈ HQmax, then the most important (toxic) chemical in the mixture contributes all of the effect. In such cases, the evaluation is a single substance assessment and so no longer needs to consider mixtures. In those cases where HQmax = 0.5, then the most toxic substance contributes half of the mixture effects. This would be the default circumstance for cases where two chemicals are present and each has the same hazard quotient. Similarly where HQmax = 0.2 then the most important chemical provides one fifth of the total mixture effect.

- <u>GC-MS Groundwater</u>, the most important chemical (HQmax) contributes ≤ 20% to HQmix in 2 of 9,365 (0.02%) samples and ≤ 50% to HQmix in 516 samples (5.5%). This compares to 6,013 (62%) samples where HQmax between 0.5 and 1 indicating the highest risk substance contribute ≥ half of the mixture effect and 3,034 samples (32.4%) where HQmax = 1, indicating that the sample has only a single substance present and so represents only a single substance assessment (Fig. 10).

- <u>GC-MS Surface water</u>, there are 9 of 19,911 (0.05%) samples where HQmax contributes ≤ 20% to HQmix and 1,984 (10%) of samples where HQmax is ≤ 50% of HQmix (Fig. 10). This compares to 15,241 (76.5%) where HQmax is ≥50% of HQmix, but less <1, and 2,677 (13.4) samples where HQmax = 1 indicating the contribution of only a single chemical to the assessment in that sample.

- <u>LC-MS Groundwater</u>, HQmax always contributes ≥ 20% to HQmix and there are 55 of 818 (7.2%) samples were HQmax ≤ 0.5 indicating that the most toxic chemical contributes less than 50% to the mixture effect. This compared to 645 of samples (78.9%) where HQmax is ≥50% of HQmix, and only a single sample where HQmax = 1 indicating the contribution of only a single substance. Of the samples with values between 0.5 and 1, there are 433 (53.2% of all samples) where HQmax ≥ 0.9, indicating that one chemical in the mixture contributes a large proportion of the effect, despite the presence of other substances in the sample (Fig. 10). Cases where a single substance contribute a high proportion of the total effect are likely to be more common in mixtures with a smaller number of substances.

- <u>LC-MS Surface water</u>, there are 32 (1.2%) of samples in which HQmax contributed ≤ 20% to HQmix and 1,010 (38.2%) samples where the most "toxic" chemical contributes <50%. This compares to 1602 (60.6%) where HQmax is ≥50% of HQmix, but less <1, and only a single sample where HQmax = 1 indicating the presence of a single substance. Of samples between 0.5 and 1, 159 (6%) have an HQMax >0.9, indicating the dominant effect of a single chemical in the mixture.

For the GC-MS and LC-MS data-sets, assessment of the contribution of the most toxic chemical (HQmax) to the overall mixture effect (HQmix) always indicated that in < 50% of samples, the presence of further chemicals beyond the most toxic substance causes a > 2 fold increase in risk (i.e. > 50% of samples have an HQmax value that > 0.5 that of HQmix). In only a small proportion of samples (<1.5%), the presence of further chemicals results in a > 5 fold increase in risk compared to that for only the most toxic substance (i.e. an HQmax ≤ 0.2). Such information may be important in developing assessment factors that could account for mixture effects, as it represents the ratio between the highest risk compound and the total mixture risk.

The results from this analysis indicating that in >98% of all cases the ratio of HQmix / HQmax is <5. This level of additional risk is consistent with the conclusion of Backhaus and Karlsson (2014). These authors used a similar approach to calculate "Mixture Assessment Factors" for pharmaceuticals, concluding that a value of 4.3 was sufficient to scale from worst case single chemical effect to additive mixture effect of all detected chemicals in all cases. In the groundwater and surface water data-sets, this scale of assessment factor would be protective for mixture effects in ~98% of all cases.
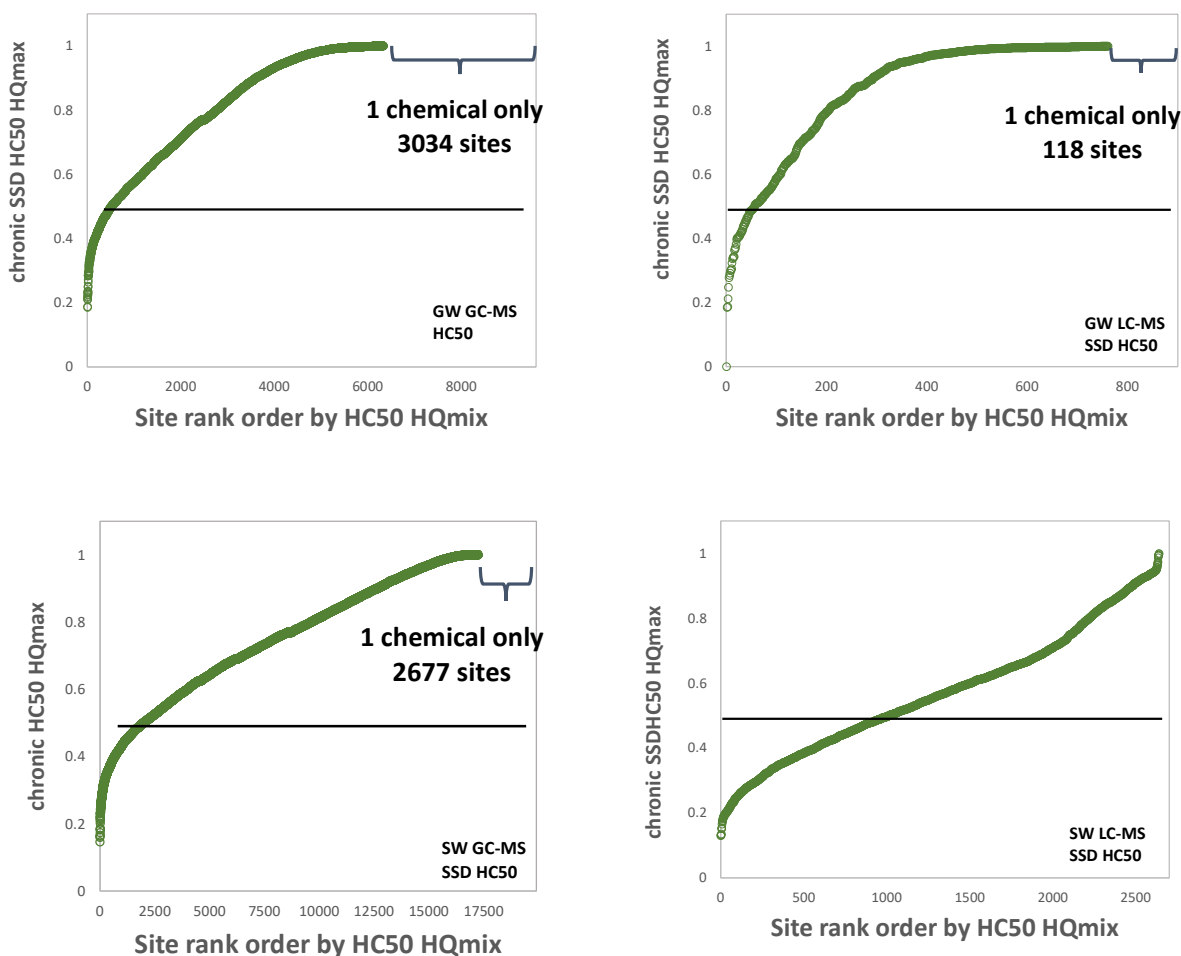
Fig. 10. Cumulative distribution of the contribution of the most toxic chemical (HQmix) to the overall mixture effects (HQmax) ordered by sample rank HQmax for GC-MS (left) and LC-MS (right) analysed samples for the groundwater (top) and surface water (bottom) data-sets.

8.3 Relationship of HQmix with the number of chemicals detected in the sample

As mixtures increase in complexity HQmix may be expected to increase as more chemicals contribute to the total effect. To test this hypothesis, HQmix values calculated using the chronic SSD HC50 HQs were plotted against the number of chemicals present in the mixture. Plots indicated that, as expected, an increase in the number of chemicals detected was (weakly) associated with an increase in HQmix (Fig. 11). There are, however, numerous samples at which high HQmix values are observed, even when the number of chemicals was low (<5). Thus, mixtures can show high HQmix values due to the effects of only two or three chemicals, especially in the GC-MS data. As mixture complexity increases, the number of samples with low HQmix values reduces, such that for mixtures of ≥10 substances, low values of HQmix are rarely found and mixtures of this complexity always present a relatively high mixture risk.
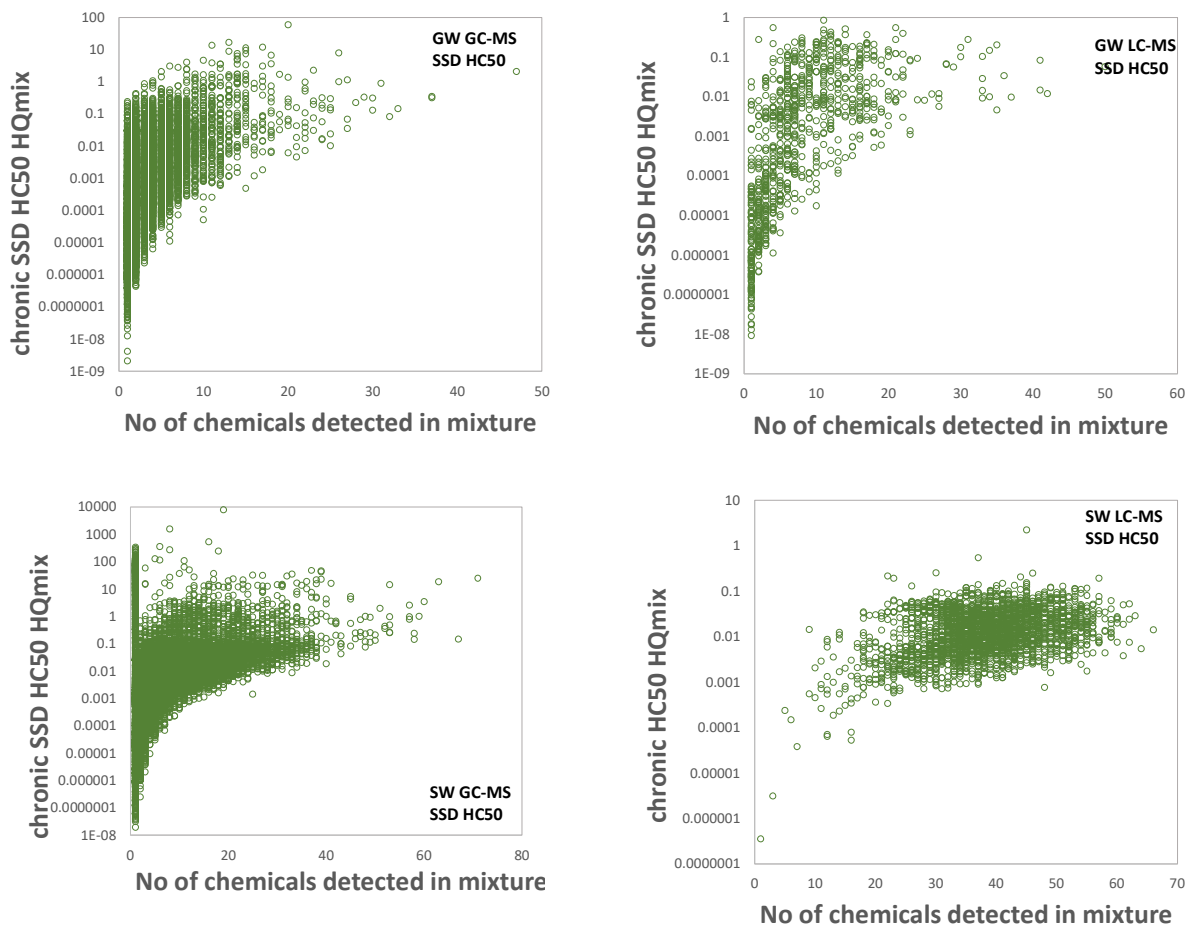
Fig. 11. Relationship between the number of chemicals detected above the limit of detection in a sample and the chronic SSD HC50 calculated HQmix values for that sample for GC-MS (left) and LC-MS (right) analysed samples for the groundwater (top) and surface water (bottom) data-sets.

8.4 Relationship of the number of chemicals detected in the sample and the contribution of the most toxic chemical (HQmax)

To assess how the contribution of the most toxic single chemical changes with mixture complexity, HQmax was plotted against the number of chemicals present in analysed samples (Fig. 12). Results indicated that even when there are relatively few chemicals present (≤ 3), there are cases where the most important chemical still only contributes ~40% to HQmix. These samples represent cases of substantial mixture effect at low mixture complexity. As the number of substances in the mixtures increases to > 10, there is a trend for HQmax to decrease, although this pattern is not strong. Indeed even when mixtures become complex (≥ 15 chemicals), there remains samples where the most important chemical still contributes ≥ 50% of HQmix in all data-sets.
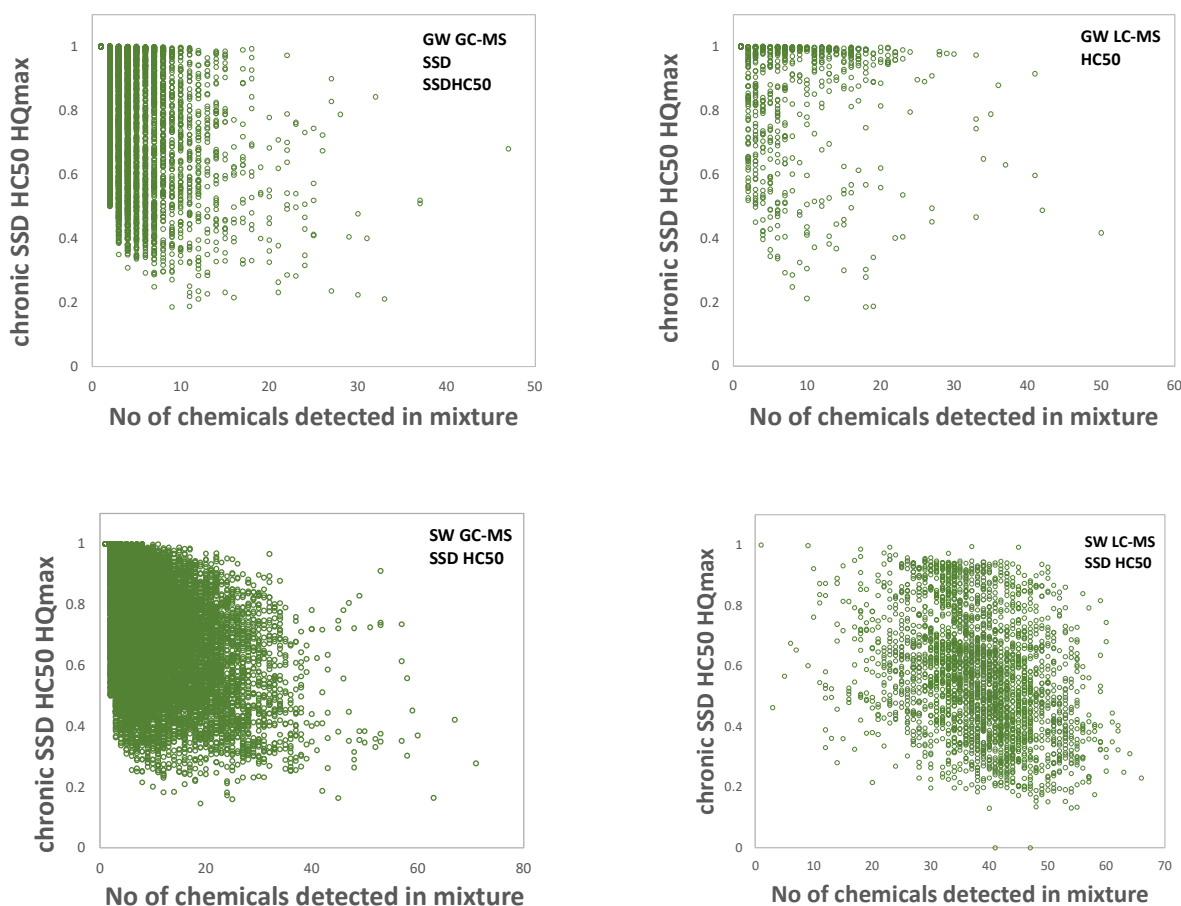
Fig. 12. Relationship between the number of chemicals detected above the limit of detection in any sample and the maximum single substance HQmax in that sample calculated for the GC-MS (left) and LC-MS (right) analysed samples for the groundwater (top) and surface water (bottom) data-sets.

9 Using hazard rankings to identify substances of interest for future assessment and research

9.1 Underlying assumptions and performance of the approach for ranking and mixture assessment

The ability to conduct large-scale semi-quantitative analysis of groundwater and surface water samples for an extensive range of chemicals provides significant insight into the diversity and concentration ranges of organic substances in these environments. Given the number of chemicals that may be present and that can be detected using the applied GC-MS and LC-MS techniques, an approach was needed to help rank substance for their potential risk as a step towards prioritisation for more detailed assessment. In this work, a relatively simple approach for worst case risk ranking has been developed that compares the highest concentration of detected substances to a set of readily available hazard metrics. Substances are ranked based on the hazard quotient (HQ) derived and also on their frequency of detection. This approach

has been used to generate ranked lists of substances that take into consideration both the potential risk of the chemical and also its potential to be present in groundwater and surface water samples. Separate assessments were made to allow ranking with respect to two human health focussed hazard metric (UK Drinking Water Standard and EFSA ADI/TDI values) and three ecological hazard metrics (WFD EQS, NORMAN PNEC, chronic SSD HC50). In developing the overall approach, a number of decisions and assumptions were made. Each of these has the potential to affect the outcome of the analysis as outlined below.

1) <u>Choice of hazard metrics.</u> The five hazard metrics selected for this study are not the only ones that could have been selected. Indeed, there remains the potential to add further metrics to the assessment. Examples include human health and ecological hazard risk and safety statements reported under the EU (& UK) Classification Labelling and Packaging (CLP) regulation and hazard information for human health and ecological endpoints in REACH registration documents. Such material is accessible in downloadable formats from the European Chemical Agency (https://echa.europa.eu), although a more detailed risk assessment would require extensive expert input to compile this data, and so would be resource intensive.

2) <u>Separate assessment of human health and ecological hazard metric.</u> Human and ecological hazard assessments are designed to address different protection goals. It was, therefore, considered appropriate to conduct separate assessments for worst case risk ranking in relation to human and ecological risk. For the human assessment, it was further decided to separate the assessments for the UK Drinking Water Standards from that for the EFSA ADI/TDI. This was done because the nature of the derivation of these two hazard values differs. Some UK Drinking Water Standard are based on analytical consideration relating primarily to historic limits of detection, while the EFSA ADI/TDI is more explicitly linked to toxicity data taken from mammalian testing. The three ecological hazard values are each derived through a common approach that bases the assessment on toxicity results derived from ecotoxicological testing. While the nature of the data differs between the three metrics (e.g. measured data for the chronic SSD HC50, QSAR model predicted toxicity for the NORMAN PNEC), they all have a common protection goal relating to toxicity for ecological species. Consequently, it was more justified and feasible to rank substances based on consideration of the three metrics together in an integrated manner.

3) <u>Weighting of the ecological hazard metrics for average ranking.</u> Equal weighting was given to each ecological hazard metric in the calculation of an average hazard rank. This was done even though the three hazard metrics differ in their input data (e.g. measured toxicity data, QSAR model predicted toxicity), level of regulatory acceptance (high for WFD EQS, none yet for the other two metrics) and application of assessment factor (included for WFD EQS and NORMAN PNEC, not included for chronic SSD HC50). Greater weight could, for example, have been given to those values that have higher regulatory acceptance (e.g. WFD EQSs) than those lacking regulatory approval and/or which have a higher associated uncertainty (e.g. NORMAN PNEC). However, substance specific regulatory values are available for only a relatively small proportion of the assessed substances. Hence, applying a weighting to the regulatory approved values would have skewed the analysis to already assessed substances favouring high ranking for these already prioritised chemicals. Equal weighting, in contrast, retains the possibility to identify emerging substances not yet a focus of regulatory action.

4) <u>Detection frequency correction.</u> The final substance ranking was weighted based on the detection frequency of the substances. This frequency correction had the effect of raising the overall ranking of substances with a lower HQ, but that are commonly detected and reducing the ranking of higher risk substances that are less frequently detected. This was considered appropriate for the overall ranking since inherent substance risk and also the potential for that risk to occur would both be relevant criteria in identifying substance for further assessment in schemes such as JAGDAG and PEWS.

5) <u>Choice of maximum concentration.</u> A major decision made was to use only the highest measured concentration for HQ calculation and subsequent ranking. The selection of this highest value has potential pitfalls in its interpretation. However as previously outlined (see Section 6), the use of values that are more embedded within the distribution of measured concentrations (e.g. mean, median, 90th percentile) was possible only for a relatively small number of chemicals and these mainly in surface waters. Thus, using an alternative concentration statistic would greatly restrict the number of chemicals that could be assessed. Analysis of the distribution of measured concentrations indicates that in all of the 40 assessed cases, the highest concentration was not an obvious outlier, supporting its generic use for worst case ranking (see Section 6, Appendix 4). For any wider assessment of potential risks, a fuller analysis of all concentrations and their distribution in time and space would be needed.

6) <u>Chemical use categories</u>. Major known use categories were used to provide an overview of the potential sources and associated routes of release for the highest ranked substances. Although the attribution of a substance to a single use class was sometimes difficult, clear patterns did emerge. Pesticides were common among the highest ranked substances found in both the groundwater and surface water environments. This reflects both the frequency for which hazard metrics were available for this class of substances, as well as their sometimes high hazard rank and relatively high frequency of detection. Groundwater showed a higher prevalence of high ranked industrial and plastic-associated chemicals, while in surface waters pharmaceuticals are more often identified. Further source apportionment would require a detailed spatial and temporal analysis to associate the concentrations present with different industrial, urban, domestic and agricultural uses. Such work would require significant resources and is outside of the scope of this project. For national or regional scale (e.g. Europe wide) assessments, it is possible to use a combination of usage volume information, Specific Environmental Release Category data and suitably scale environmental fate models to generate an estimate of predicted environmental concentrations for different environmental compartments (van de Meent *et al.*, 2020). Such an analysis could link release via different sources to groundwater and surface water concentrations.

7) <u>Mixture assessment approach.</u> A mixture assessment was conducted to assess the nature of hazards associated with the presence of the multiple organic chemicals frequently detected in groundwater and surface water. The overall approach was based on the use of the concentration addition model. There are recognised challenges with the use of this approach, notably that in most cases the assumption of a similar mode of action that underlie the CA model will not be met, that interactions causing synergism and antagonism will not be accounted for and that the contribution of chemicals present

at concentrations below the detection limit or that lack an available hazard value will not be included. However, despite these issues, the approach provides a pragmatic approach for mixture assessment that can be readily applied, especially when used with hazard metrics such as the chronic SSD HC50 that have a high substance coverage.

9.2 Use of the rankings to identify chemicals for further assessment

The final ranking of substance against the UK Drinking Water Standards and EFSA ADI/TDIs discussed in Section 5 and average ecological hazard values discussed in Section 6 can be used to generate lists of chemicals for further more detailed specific assessments. Such ranking lists can be generated for substances detected by GC-MS and LC-MS in groundwater, surface water, or both environments. From the overall ranking, a set of different ranking lists can be compiled that identify substances at different levels of assessment and regulatory status. For illustrative purposes, six rankings (each including a separate ranking for the GC-MS and LC-MS analytes) were developed by combing the top ranked chemicals in different environments (total 12 ranking lists) to identify the highest ranked substances at different specific levels of associated knowledge. These ranking lists are detailed separately below for GC-MS and LC-MS for each and both environments. In each case, a full ranking has been developed. However, for illustrative purposes only a specific sub-set of the top rank substance in each data-set are given, this number being set to provides a cut-off off but avoids highlighting substances with a low overall rank.

Human health prioritisation: Top 20 substances ranked for ecological effects that do not have an EFSA ADI/TDI

These substances represent a set of chemicals that could potential be considered for assessment for their potential risk to human health. Substances in this list are top 20 ranked substances for the average ecological hazard (Table 12 a-b, Table 13a-b), which at the time of writing do not have an EFSA reported ADI/TDI value. The ordering of the substances in this list reflects that for the average ecological hazard rank shown in Tables 12a-b, and 13a-b. However, as substances that have an ADI/TDI are excluded from this ranking, substance without an ADI/TDI take a higher rank (i.e. benzo[a]pyrene is 20th ranking in the GC-MS average ecological hazard for surface water, but is 12 ranked here because substances with an ADI/TDI ranking above it are removed from the list.

The high average ecological hazard ranking of these substances means that each may have relatively high toxicity for effect across a range of tested species. This is an indication of the potential for these chemicals to interact with biological processes to cause toxicity effects. High ranking on this list does not in itself indicate that a high potency of these substances for human health effects will necessarily be found. For example, some substances may be active against a biological endpoint and species not relevant to human health (e.g. effects on plants through inhibition of photosynthesis). However, high ranking across the average of different ecological metrics suggests that substances in this group may be the most relevant at least for initial screening level assessment for potential risks for human health endpoints.

Among the GC-MS measured substances identified in this list, 6 are common between groundwater and surface water. These include four PAH compounds (benzo[a]pyrene,

fluoranthene, dibenz[a,h]anthracene, pyrene) and two plastics associated chemicals (N-butyl benzenesulfonamide and triphenyl phosphate). Multiple further PAHs and halogenated solvent compounds are also included in this list for groundwater. There are also a small number of pesticides included in this list including atrazine in groundwater, and epoxiconazole, flufenacet, phenmedipham, rotenone and terbutryn in surface waters, that do not have a reported EFSA reported ADI/TDI even though the OpenFoodTox database. Plastics associated chemicals including phthalates and phosphate plasticisers (e.g. di-n-octyl phthalate and tri-(2-chloroethyl) phosphate) are included in this list for surface waters.

LC-MS chemicals in this list include seven that are top 20 ranked in both the groundwater and surface water samples (atrazine, boscalid, carbamazepine, clopidol, flufenacet, lamotrigine, perfluorobutane sulfonate)(Table 14). In addition, further pesticides, pesticide metabolites and pharmaceuticals are also top 20 ranked, especially in surface water. Industrial chemicals including perfluorobutane sulfonate are among the top those top ranked in groundwater.

GC-MS			
CAS Registry Number	Compound Name	Groundwater rank	Surface water rank
95-14-7	1H-Benzotriazole	8	
934-34-9	2(3H)-Benzothiazolone	6	
52315-07-8	2-Chlorophenyl isocyanate	14	
95-76-1	3,4-Dichloroaniline		18
56-55-3	Benz[a]anthracene	4	
3622-84-2	Benzenesulfonamide, N-butyl	5	
50-32-8	Benzo[a]pyrene	7	12
205-99-2	Benzo[b]fluoranthene	9	
191-24-2	Benzo[ghi]perylene	1	
21725-46-2	Benzophenone-3	19	
188425-85-6	Boscalid (Nicobifen)		10
58-08-2	Caffeine		6
84-74-2	Chlorodibromomethane	20	
117-81-7	Cyanazine (Fortrol)	16	
53-70-3	Dibenz[a,h]anthracene	3	4
60-57-1	Diisobutyl phthalate (DIBP)	12	
84-74-2	Di-n-butyl phthalate	17	15
135319-73-2	Epoxiconazole (BAS 480F)		3
142459-58-3	Flufenacet (Fluthiamide) (BAY FOE 5043)		8
206-44-0	Fluoranthene		17
193-39-5	Indeno[1,2,3-cd]pyrene	2	19
7085-19-0	MCPP / Mecoprop		11
84-69-5	N-Phenyl-1-naphthylamine	13	
556-67-2	Pentachlorophenol (PCP)	15	
2307-68-8	Pentanochlor		16
13684-63-8	Phenmedipham		2
1918-16-7	Propachlor		9
129-00-0	Pyrene	11	20
83-79-4	Rotenone		1
886-50-0	Terbutryn		14
77-90-7	Tributyl acetylcitrate	10	
87-86-5	Trietazine	18	
115-86-6	Triphenyl phosphate (TPPA)		13
13674-87-8	Tris (1,3-dichloroisopropyl) phosphate		7

LC-MS			
CAS Registry Number	Compound Name	Groundwater rank	Surface water rank
115-28-6	1,4,5,6,7,7-Hexachloro-5-norbornene-2	11	
1241-94-7	2-Ethylhexldiphenyl phosphate	12	
198904-31-3	Atazanavir		13
29122-68-7	Atenolol		14
1912-24-9	Atrazine	10	
6190-65-4	Atrazine-desethyl (Desethylatrazine)	4	
1007-28-9	Atrazine-desisopropyl (Deisopropylatraz	14	
83905-01-5	Azithromycin		20
41859-67-0	Bezafibrate		19
90357-06-5	Bicalutamide		18
188425-85-6	Boscalid (Nicobifen)	1	6
298-46-4	Carbamazepine		8
83881-51-0	Cetirizine		2
6339-19-1	Chloridazon-desphenyl	16	
17254-80-7	Chloridazon-desphenyl-methyl		1
81103-11-9	Clarithromycin		12
2971-90-6	Clopidol	8	17
50-36-2	Cocaine	3	
56-72-4	Coumaphos	17	
21725-46-2	Cyanazine (Fortrol)	9	
113096-99-4	Cyproconazole	18	
15307-86-5	Diclofenac	19	7
135319-73-2	Epoxiconazole (BAS 480F)		15
120067-83-6	Fipronil Sulfide	6	
120068-36-2	Fipronil sulfon (M & B 46136)	15	16
142459-58-3	Flufenacet (Fluthiamide) (BAY FOE 504	7	9
66108-95-0	Iohexol		10
84057-84-1	Lamotrigine		5
657-24-9	Metformin		11
375-73-5	Perfluorobutane sulfonate	13	
144701-48-4	Telmisartan		4
886-50-0	Terbutryn	5	
3380-34-5	Triclosan		3
1912-26-1	Trietazine	2	
115-86-6	Triphenyl phosphate (TPPA)	20	

Table 14. Table of the top 20 average ecological hazard ranked values by GC-MS (left) and LC-MS (right) in either or both of the groundwater and surface water surface water sample sets that do not have an EFSA reported ADI/TDI

Ecological effects prioritisation: Top 20 integrated ecological hazard ranked substances with no WFD EQS, but with a chronic SSD HC50 available.

Substances with a WFD EQS have already been the subject of regulatory oversight to derive a hazard based limit that can act as a protection goal for the management of risks to surface waters. As outlined above only a relatively small proportion (≤ 20%) of the top 30 integrated ecological hazard ranking substances detected by GC-MS and LC-MS in groundwater and surface water have an associated WFD EQS. Among the remaining substances, there is a significant number for which Posthuma *et al* (2019) were able to assemble sufficient

ecotoxicological data to parameterise a chronic SSD from which an HC50 could be derived. This list includes these substances with no WFD EQS, but that have a chronic SSD HC50. The substances in this list are, thus, highly risk ranked and have extensive toxicity data available. Such substances include multiple pesticides, including active ingredients in current use, as well as industrial chemicals (notably perfluorinated substances), plastics associated chemicals (notably phthalate and phosphate plasticisers) and consumer product chemicals and human and veterinary pharmaceuticals (Table 15).

For each of the substances in this list, the toxicity data that is available and used for SSD derivation could potentially be used to develop a more detailed assessment of potential ecological effects. This is a task that would require significant efforts and that may require regulatory development depending on the approaches to chemical management in place at a future given time.

GC-MS			
CAS Registry Number	Compound Name	Groundwater rank	Surface water rank
95-14-7	1H-Benzotriazole	13	
126-86-3	2,4,7,9-Tetramethyl-5-decyne-4,7-diol		11
6190-65-4	Atrazine-desethyl (Desethylatrazine)	7	
56-55-3	Benz[a]anthracene	3	18
3622-84-2	Benzenesulfonamide, N-butyl	4	15
191-24-2	Benzo[ghi]perylene	2	
131-57-7	Benzophenone-3	18	
80-05-7	Bisphenol A	1	
188425-85-6	Boscalid (Nicobifen)		13
75-27-4	Bromodichloromethane	17	
75-25-2	Bromoform	12	
106-65-0	Butanedioic acid, dimethyl ester	10	
58-08-2	Caffeine	15	2
298-46-4	Carbamazepine		10
124-48-1	Chlorodibromomethane	9	
218-01-9	Chrysene	20	
483-63-6	Crotamiton		14
53-70-3	Dibenz[a,h]anthracene	11	16
84-69-5	Diisobutyl phthalate (DIBP)	19	
117-84-0	Di-n-octyl phthalate		12
540-97-6	Dodecamethylcyclohexasiloxane (D6)		19
135319-73-2	Epoxiconazole (BAS 480F)		5
142459-58-3	Flufenacet (Fluthiamide) (BAY FOE 5043)		9
193-39-5	Indeno[1,2,3-cd]pyrene	6	
10543-57-4	N,N,N',N'-Tetraacetylethylenediamine		20
134-62-3	N,N-Diethyl-m-toluamide	16	7
13684-63-4	Phenmedipham		8
129-00-0	Pyrene	5	4
83-79-4	Rotenone		1
115-96-8	Tri-(2-chloroethyl) phosphate		17
77-90-7	Tributyl acetylcitrate	8	
115-86-6	Triphenyl phosphate (TPPA)	14	6
13674-87-8	Tris (1,3-dichloroisopropyl) phosphate		3

LC-MS			
CAS Registry Number	Compound Name	Groundwater rank	Surface water rank
115-28-6	1,4,5,6,7,7-Hexachloro-5-norbornene-2,3	20	
29122-68-7	Atenolol		15
6190-65-4	Atrazine-desethyl (Desethylatrazine)	1	
1007-28-9	Atrazine-desisopropyl (Deisopropylatrazin	4	
131860-33-8	Azoxystrobin	16	12
25057-89-0	Bentazone	7	4
188425-85-6	Boscalid (Nicobifen)	2	8
298-46-4	Carbamazepine	14	7
83881-51-0	Cetirizine		3
6339-19-1	Chloridazon-desphenyl	19	
17254-80-7	Chloridazon-desphenyl-methyl		2
81103-11-9	Clarithromycin		16
2971-90-6	Clopidol	8	17
210880-92-5	Clothianidin	15	
50-36-2	Cocaine	6	
15307-86-5	Diclofenac		9
135319-73-2	Epoxiconazole (BAS 480F)		20
120068-37-3	Fipronil	11	1
142459-58-3	Flufenacet (Fluthiamide) (BAY FOE 504:	12	11
66108-95-0	Iohexol		18
65277-42-1	Ketoconazole	18	
84057-84-1	Lamotrigine		5
307-24-4	Perfluoro Hexanoic Acid	17	
335-67-1	Perfluoro Octanoic Acid	13	14
375-73-5	Perfluorobutane sulfonate	10	
23950-58-5	Propyzamide (Pronamide)		10
56038-13-2	Sucralose	5	13
144701-48-4	Telmisartan		6
2303-17-5	Triallate	9	19
1912-26-1	Trietazine	3	

Table 15. Table of the top 20 integrated detection frequency corrected hazard ranked chemicals that lack a WFD EQS, but that have an available published chronic SSD HC50 indicating that there is a substantial amount of toxicity data available for those chemicals detected by GC-MS (left) and LC-MS (right) in either or both of the groundwater and surface water sample sets.

Ecological effects prioritisation: Top 20 integrated ecological hazard ranked substances with no WFD EQS or chronic SSD HC50, but with a NORMAN PNEC.

The development of a robust ecological assessment for chemicals that both lack an agreed WFD EQS and also a chronic SSD HC50 is problematic, because these substances lack sufficient ecotoxicological data for the derivation of an experimentally based hazard value. Hence, substances ranked high based on a NORMAN PNEC represent those for which further ecotoxicological research and assessment may be required. The substances in this list

includes industrial chemicals; specific PCB congeners; personal care product associated chemicals and pharmaceuticals (Table 8). The LC-MS list includes multiple pharmaceuticals, pesticide metabolites and perfluorinated compounds, other than PFOS and PFOA, that were all widely detected in a large number of samples, especially in surface water (Table 16).

The NORMAN PNEC value is generated by QSAR modelling. QSAR modelling can introduce uncertainties, especially for chemicals outside of the application domain of the relevant species models. To confirm the hazard associated with chemicals highly ranked by NORMAN PNEC HQ further work may be needed to identify any available toxicity data. Information submitted to the European Chemical Agency for REACH registration or documents held by the European Medicines Agency or US Food and Drug Administration could be mined on a case by case basis. Additionally, further research to confirm model predicted values in a range of relevant species could be warranted for the highest ranked chemicals.

GC-MS			
CAS Registry Number	Compound Name	Groundwater rank	Surface water rank
1025-15-6	1,3,5-Trially-1,3,5-triazine-2,4,6 (1H,3H,5	10	
934-34-9	2(3H)-Benzothiazolone	1	
127-51-5	alpha Isomethyl Ionone		9
1007-28-9	Atrazine-desisopropyl (Deisopropylatrazir	7	
1678-25-7	Benzenesulfonanilide	2	
108-60-1	bis(2-chloroisopropyl) ether	6	
50-36-2	Cocaine	9	
483-63-6	Crotamiton		3
15362-40-0	Diclofenac artifact		7
627-93-0	Dimethyl adipate	3	
117-84-0	Di-n-octyl phthalate		2
127-63-9	Diphenyl sulfone		4
135319-73-2	Epoxiconazole (BAS 480F)		1
60142-96-3	Gabapentin		6
544-76-3	Hexadecane		10
118-56-9	Homosalate	8	
137-58-6	Lidocaine (Diocaine)		8
87-41-2	Phthalide	5	
1912-26-1	Trietazine	4	

LC-MS			
CAS Registry	Compound Name	Groundwater rank	Surface water rank
115-28-6	1,4,5,6,7,7-Hexachloro-5-norbornene-2,3-	9	9
198904-31-3	Atazanavir		7
1007-28-9	Atrazine-desisopropyl (Deisopropylatrazin	2	
83881-51-0	Cetirizine		1
6339-19-1	Chloridazon-desphenyl	8	10
2971-90-6	Clopidol	5	3
50-36-2	Cocaine	4	
76-57-3	Codeine		8
135319-73-2	Epoxiconazole (BAS 480F)		5
66108-95-0	Iohexol		4
307-24-4	Perfluoro Hexanoic Acid	7	
2706-90-3	Perfluoro Pentanoic Acid	10	
375-73-5	Perfluorobutane sulfonate	6	6
56038-13-2	Sucralose	3	
144701-48-4	Telmisartan		2
1912-26-1	Trietazine	1	

Table 16. Table of the top 10 integrated ecological hazard ranking chemicals that have no WFD EQS or chronic SSD HC50 value available, but that is high risk ranked based on the NORMAN PNEC value indicating that these substances may be a priority for further assessment including through ecotoxicological studies for GC-MS (left) and LC-MS (right) detected chemicals in either or both of the groundwater and surface water sample sets.

Overall prioritisation: Substances detected in >10 groundwater or surface water samples that have no QSAR or toxicologically derived hazard value (e.g. WFD EQS, ADI/TDI, chronic SSD HC50, NORMAN PNEC) available.

A relatively small number of substances detected by GC-MS and/or LC-MS currently have no toxicologically or QSAR derived hazard value available. For some pesticides, the substance may have an HQ against the generic class specific UK Drinking Water Standard value. However this value is not hazard related, as assessment is against a common value derived from analytical limits, rather than from any experimental toxicological data. For assessment based on hazard, any substances that lack any human ADI/TDI or ecological hazard metric cannot be included in any ranking assessment, because they lack limit values from which HQs can be calculated for detection frequency correction and ranking. Capturing such substances without any hazard values identifies potential priory chemicals for further research and assessment. Substances identified in this list includes pesticide and biocide transformation

products, as well as some pharmaceuticals, cosmetic substances and a further group of lesser studied perfluorinated chemicals (Table 17).

Further research is needed to establish the hazard properties associated with these chemicals. Access to REACH registration, European Medicine Agency risk assessment documents and CLP submissions may provide a source of such information. However, additional experimental studies or expansion of QSAR model applications may also be needed.

GC-MS			
CAS Registry Number	Compound Name	Groundwater No. detects	Surface water No detects
4359-46-0	2-ethyl-4-methyl-1,3-dioxolane	48	
59-48-3	2H-Indol-2-one, 1,3-dihydro	19	11
36861-47-9	4-Methyl-benzylidene camphor	19	58
61592-45-8	Bentazone methyl derivative	12	
26444-49-5	Cresyl diphenyl phosphate	26	67
493-02-7	Decahydronaphthalene (trans)	49	81
3868-61-9	Endosulfan lactone	10	
19700-21-1	Geosmin	24	408
76-74-4	Pentobarbital	10	111
511-15-9	Totarol		17
4640-01-1	Triclosan-methyl		757

LC-MS			
CAS Registry	Compound Name	Groundwater No. detects	Surface water No detects
35079-97-1	10,11-Dihydroxycarbazepine		1075
100648-13-3	10,11-Dihydroxycarbamazepine	16	
188425-85-6	2-Phenoxypropionic acid	14	11
6303-58-8	4-Phenoxybutyric acid		303
98-95-3	Acesulfame (Acesulfame-K)	249	1099
59338-93-1	Alizapride		237
1912-26-1	Chloridazon-desphenyl-methyl	249	2322
125-73-5	Dextrorphan (Levorphanol - d form)		264
1861-32-1	Diphenhydramine	14	52
54143-55-4	Flecainide		933
38677-85-9	Flunixin		82
76-99-3	Methadone		209
17090-79-8	Monensin		66
77-53-2	Pentobarbital	20	133
5825-87-6	Perfluorohexane sulfonate	189	1025
175217-20-6	Silthiofam		79
76-74-4	Tramadol	93	2209

Table 17. Table of substances detected >10 times by GC-MS (left) and LC-MS (right) in either groundwater or surface water samples that have no available toxicological or QSAR based hazard value.

9.3 Use of the mixture assessment information for better management of mixture effects

Chemicals are generally present in the environment as mixtures. This is clearly shown from the results of the groundwater and surface water monitoring programs. For example, measurement by LC-MS almost always showed the presence of >5 chemicals and in some samples up to 70 different chemicals were present (see Fig. 12 and 13). Only when the detection limits are relatively high, as in the GC-MS analysis, is the ubiquitous presence of chemical mixtures not seen. However, this is almost certainly due to the inability of this method to detect chemicals at low concentrations, rather than a true absence of complex chemical mixtures at the sampled locations.

For the mixture assessment, the chronic SSD model parameters provided by Posthuma *et al*. (2019) could be used to generate the full SSD model fit to the available experimental data which could allow calculation of mixture effects considering both similarly acting and dissimilarly acting chemicals. The SSDs could, thus, be used to predict mixture hazard using both the concentration addition and independent action model or through a hybrid grouping approaches. It is recognised that the use of the concentration addition model has a number of limitations, such as the assumption made for mode of action, inability to include interactive effects, and issues with including chemicals that lack an available chronic SSD (and more frequently ADIs/TDIs). However, overall the approach offered a pragmatic and implementable approach to mixture assessment that was deliverable from the measurement data and hazard information available.

Mixture affects exceed those predicted for any single chemical, however, often the scale of this difference was not great. Even in cases of complex mixtures containing >20 substances, often only a small number of substances contribute a large proportion of the mixture effect. Thus, there were only $\cong$ 1% of samples at which the most important chemical contributed <20% to the overall mixture effect. This value being entirely consistent with values for the ratio of HQmax / HQmix between 1.2 and 4.2 identified by Backhaus and Karlsson (2014). For pragmatic purposes, a mixture assessment factor of five that is placed on the HQ of the most important chemical could adequately protect for possible mixture effects. However, as the process needed to identify the most important chemical matches that used to identify the additive mixture effect using concentration addition, the actual mixture effect can also be equally readily calculated to provide a more robust assessment than for any given sample.

10. Conclusions

1. Hazard values from literature sources have been collated into a single resource that can be used in combination with chemical concentrations to calculate hazard quotients. Hazard values from each of the five metrics were collated for the 1144 GC-MS and LC-MS detected substances included in the Environment Agency Groundwater and Surface Water Monitoring programs where available. Not all of these substances were detected in the analysed samples, however, the available metrics are available for future use. In total values for five metrics were collected, two human health (UK Drinking Water Standards and EFSA ADI/TDI values) and three ecological hazard metrics (WFD EQS, NORMAN PNECS, chronic SSD HC50s).

2. The hazard values from five sources: WFD EQSs, UK Drinking Water Standards, EFSA ADI/TDI values, NORMAN NETWORK PNECs and chronic SSD HC50s published by Posthuma et al. (2019), were collated and HQs for substances calculated against maximum measured concentrations for the GC-MS and LC-MS analytes in a worst-case assessment. Hazard quotient calculated for the two human health focussed metrics were used directly for subsequent ranking. The available HQs derived for the three ecological hazard metrics were used to calculate an average ecological hazard rank that was used for further analysis.

3. The ranking of substances by worst case HQ provides an indication of substance risk based on hazard and exposure information. However, for the final assessment, it was considered important to also included information on the frequency of detection of the substance in the monitoring data-set. To include detection frequency, the rank value of the specific chemical for each of the two human health assessments and the average ecological hazard value was multiplied by the rank of the substance by detection frequency. The product of this calculation (e.g. hazard rank * detection frequency rank) was used for the final assessment. Hence, a substance position in this list represents a combination of both the potential for hazard also the frequency of potential exposure.

4. The UK Drinking Water Standard assessment identified both pesticides and PAHs as the highest ranked chemicals. For almost all substances, the initial HQ calculations were made against class specific threshold values for pesticides and specific PAH compounds rather than against a specific chemical value. As such, the ranking for hazard identified the highest listing for substances with the highest measured concentration. Multiplication by detection frequency

ranked meant that final ranking generally highlighted substances that are commonly detected and/or occur at a high maximum concentration. Multiple herbicides and some fungicides are highly ranked in both groundwater and surface water against the UK Drinking Water Standard. In groundwater especially, multiple PAH compounds are also highly ranked.

5.   ADI/TDI values were available mainly for pesticides and biocide. Hence, substances within these two use classes are most often highly ranked. Some industrial chemicals are also identified in the GC-MS assessment. Examples include benzophenone and cyclohexanone, which are both highly ranked in both groundwater and surface water. Plasticisers are a further group of substances included in both environment ranking lists, examples include bisphenol A and phthalate compounds. In the LC-MS assessment, pesticides comprise the majority of the top ranked substances. However, some pharmaceuticals (e.g. carbamazepine) and food additive (sucralose) are also listed. The two perfluorinated chemicals with available ADI/TDI values (PFOS and PFOA) are both top 5 ranked in both environments.

6.   The ecological hazard ranking of the GC-MS detected chemicals in groundwater identifies multiple pesticides, PAHs, solvents, personal care products and industrial and plastics associated chemicals among the top 30 substances. The listing includes well-known historic pollutants including legacy pesticides, PAHs, halogenated solvents and the plastic associated chemicals (e.g. phthalates, bisphenol A). Not all of the top 30 highest ranked substances were legacy substances. Emerging chemicals, such as phosphate ester plasticisers and industrial chemicals (including multiple solvents) were also highly ranked.

7.   The ecological hazard assessment for the surface water data-set identified a set of top 30 GC-MS substances that differs substantially from those identified from the groundwater analysis. Highly ranked substances detected by GC-MS in surface water included a high number of current use pesticides, especially herbicides, multiple plastics associated chemicals and pharmaceutical compounds. Rotenone is highly ranked, but this the result of specific usage for invasive species control, indicating the need for further follow-up assessments after the initial ranking exercise.

8.   The LC-MS groundwater data-set analysis identified multiple pesticides and pharmaceuticals among the top 30 average ecological hazard ranked chemicals. The two highest ranked substances are the herbicide metabolite atrazine desethyl and fungicide boscalid. Other substances identified included three perfluorinated chemicals (n.b. other perfluorinated substances could not be ranked because they lack any hazard values, even though many were detected at high frequency in both groundwater and surface water.

9.   The top 30 average ecological hazard ranked LC-MS substances in surface water are dominated by pesticides, human and veterinary pharmaceuticals and industrial chemicals. The two highest ranked substances are the insecticide fipronil and herbicide bentazone. Pharmaceuticals (e.g. cetirizine, lamotrigine, telmisartan, carbamazepine, diclofenac) represent the majority of the remaining top 10 ranked chemicals. Perfluorinated chemicals are also identified among the top 30 chemicals in surface water samples, represented by three class members, PFOS, PFOA and perfluorobutane sulfonate.

10.   An analysis using the bulk set of raw sample measurement data was conducted to assess the highest value relative to other measured values. This allowed an assessment of whether there was evidence of a high frequency of extreme outliers values in the data-set that

could affect the validity of the data analysis based on the highest tested concentration. This outlier analysis was conducted for multiple substances and each sample analysis data-set. In all assessed cases, the analysis indicated that, while the use of the highest value clearly provides a worst-case, there is no evidence in any case that this maximum value is a clear outlier. While of course not indicating that any individual substance's highest value may not be an outlier, this analysis across multiple GC-MS and LC-MS substances does suggest that high value outliers are not common in either the groundwater or surface water data-sets. As such, the use of the highest value for worst-case ranking is supported as a pragmatic approach in either the groundwater or surface water data-set given the limitations of the data.

11. A concentration addition approach using the individual substances HQs was used to determine the nature of the risk associated with the presence of multiple chemicals in groundwater and surface water samples. The analysis indicated the extent of the additional risk that results when mixtures present in samples are taken into account when compared to that for any single chemical assessed through the standard one-by-one approach. Additional risk due to the presence of mixture was indicated, although the magnitude of this additional risk was not always large.

12. Comparing the HQ for any individual single substance in each sample with the HQmix for all substances that could be assessed in the mixture present in that sample (through the addition of all substance HQs), indicated that in 50% of cases, the most toxic substance contributed >50% of the mixture effects and in ~99% of case contributed >20% of the overall risk. This suggests that a Mixture Assessment Factor of five placed on the HQ for the highest risk substance would be sufficient to cover any potential mixture effect in the large majority of cases. However as an analysis for all chemicals is needed to identify the highest risk substance, a full mixture approach is no more challenging to conduct and benefits by providing a more complete analysis within any evidence based assessment.

13. The overall ranking was used to identify lists of substances for further substance specific consideration and assessment, including under programs such as JAGDAG and PEWS. For each substance, more detailed assessments may include reviews of regulatory documents associated with REACH registrations, regulatory pesticide assessments and medical product stewardship information; assessments of the primary research literature on hazard and occurrence; and, the review of further monitoring data to better understand the prevalence and concentrations of substances ranking as being of potential concern.

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Appendices

Appendix 1. Outline of resource potentially available for the download of hazard value lists

To enable risk assessment, available hazard values for the detected compounds were collated from a range of sources. The identified hazard values cover the major potential source of hazard reference values available. The metrics include major categories of regulatory limits values from the Water Framework Directive and Drinking Water Directive and values from new peer reviewed sources that provide information for a much greater number of chemicals. The collected values cover both human health and environmental hazard. The approach used for data collection and retrieval are detailed below (including screenshot of key web-sites for illustrative purposes where relevant).

Water Framework Directive environmental quality standards. The Water Framework Directive (WFD) was established as an EU policy to support the protection of inland surface waters, estuaries, coastal waters and groundwater. The WFD provides an approach for assessing the status of surface water bodies according to four main criteria: biological quality (fish, benthic invertebrates, aquatic flora); hydromorphological quality such as river bank structure, river continuity or substrate of the river bed; physical-chemical quality such as temperature, oxygenation and nutrient conditions and chemical quality. The assessment of chemical quality is conducted by comparing measured concentrations of chemicals to a set of environmental quality standards (EQSs) that specify Annual Averages or Maximum Allowable concentrations (in µg/L) for a given pollutant. The WFD currently stipulates EQSs for priority hazardous substances and priority substances. This list includes a range of metals and other cations and anions that are not quantified by the GC-MS or LC-MS approaches. Of the remaining values, the largest number are legacy pesticides, PAHs, solvents, PFOS and some biocides (e.g. triclosan). To extend the number of chemicals with an EQS, cases where values were provided as sums for compound groups, such as for hexachlorocyclohexane compounds, were used for the individual substances within the group. Further values for tetra- or tri- chlorinated solvents were used for all chemicals of the relevant type independent of the position of chlorination on the benzene ring. Because they have regulatory approval and are already widely used in decision making for assessing the quality of groundwater resources, the Water Framework Directive quality standard values have a high degree of regulatory acceptance. However as highlighted above, values are only available for a small number of organic substances (61). For this analysis, WFD EQSs expressed as Annual Averages were used.

UK/EU Drinking Water Standards. The UK/EU Drinking Water Directive (DWD) sets minimum quality standards for water intended for human consumption, including drinking, cooking and other domestic purposes). The current drinking water regulation included standards for 48 microbiological and chemical indicators. The chemical indicators include some substance specific values, as well as values covering whole classes of substances based on use (e.g. pesticides) and total concentration for substances from the same chemical class (e.g. PAHs, PCBs, dioxins). At time of writing, the DWD is currently under revision and this includes some proposal to change current regulatory limits for some substances (including for lead and some microorganisms) and also to add standards for further chemicals, such as for polyfluoroalkyl substances and bisphenol A (European Comission, 2018). The method used to calculate the

guideline standards for drinking water normally represents the concentration of a constituent that does not result in any significant risk to health over a lifetime of consumption. For most kinds of toxicity (the exception being genotoxic carcinogens), a threshold dose is used. For most chemicals this threshold is derived from the tolerable daily intake (TDI), based on an assumed consumption rate for water (2 L / individual / day) and an default assumption of an average adult body weight of 60 kg. An exception to this approach is for the presence of pesticides for each of which a generic threshold of 0.1µg/L has been set which was based on consideration of analytical capability to detect at the concentration rather than any specific hazard concern. Additionally, some substances have thresholds designed for aesthetic properties related to taste or discolouration.

EFSA data Tolerable Daily Intake (TDI) and Acceptable Daily Intakes (ADIs) for food additives and contaminants. The European Food Safety Authority (EFSA) produces risk assessment for pesticides and additives and contaminants applicable to food, feed and food contact materials. For individual substances, a summary of human health assessments has been collected and structured into EFSA's chemical hazards database. This OpenFoodTox resource provides a freely available source of information on substance characteristics; links to EFSA's outputs, background information on European legislation; and a summary of critical toxicological endpoints and reference values (see Appendix 1, Fig. 1 for screen shot of main pages). The database collects useful parameters that may be applicable for human health assessment including TDIs and ADIs. ADI and TDI are calculated as the amount of an agent, expressed on a body mass basis, to which an individual in a (sub)population may be exposed daily over its lifetime without appreciable health risk. To calculate the daily intake per person, a standard body mass of 60 kg is used. The ADI relates to intentionally added substances, while TDI is used for contaminant chemicals (Van Leeuwen and Hermens, 1995).

Additional to ADI/TDI values EFSA also calculates Threshold of toxicological concern (TTC) for substances that provide a value for hazard assessment. Three groups or classes of chemicals have been originally proposed and are classified: low toxicity (Group I: 30 µg/kg bw/day), intermediate (Group II: 9 µg/kg bw/day) and high toxicity (Group III: 1.5 µg/kg bw/day). Specifically for genotoxic carcinogens, a TTC of 0.0025 µg/kg bw/day is proposed and substances with a predicted anticholinesterase activity are allocated a TTC of 0.3 µg/kg bw/day. The ESA OpenFoodTox database can be interrogated to retrieve information from separate tabs including individual substance summaries (see Appendix 1, Fig. 1 top right for example for PFOS); lists of different reference values (see Appendix 1, Fig. 1 bottom left for example for TDIs and ADIs); and toxicological data (see Appendix 1, Fig. 1 bottom right for data for rat).
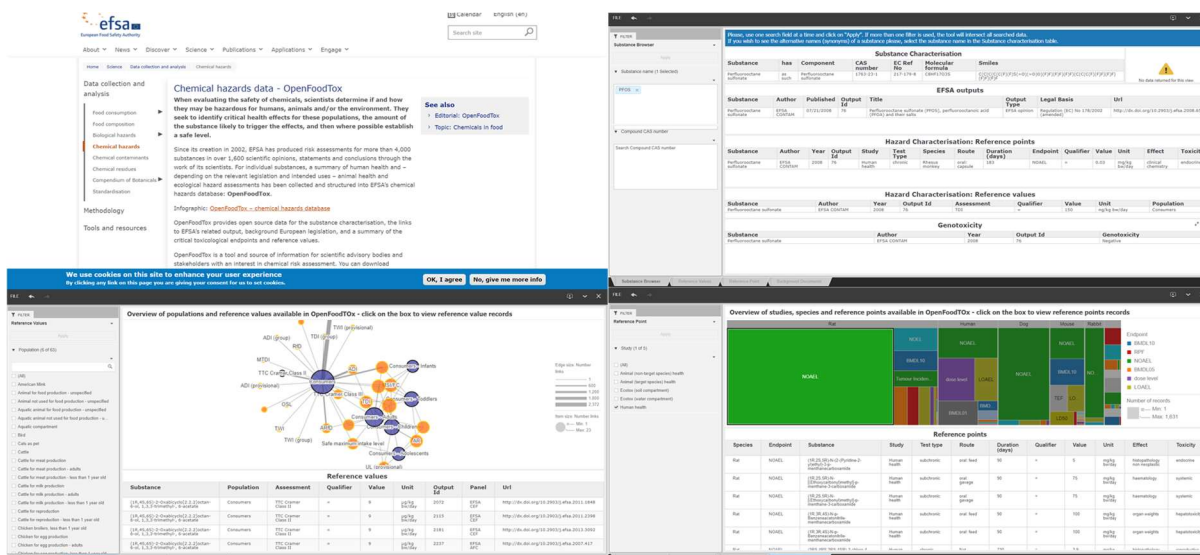
Appendix 1, Fig. 1. Example screenshots taken from the EFSA OpenFoodTox database web site, showing the Launch page (top left, http://www.efsa.europa.eu/en/data/chemical-hazards-data), substance summary for PFOS (top right, http://www.efsa.europa.eu/en/microstrategy/openfoodtox), reference values page for TDIs and ADIs (bottom left) and toxicological NOAEL values for rat (bottom right).

NORMAN network database (see https://www.norman-network.com/nds/). The Network of reference laboratories, research centres and related organisations for monitoring of emerging environmental substances (aka the NORMAN Network). The NORMAN ecotoxicology database collates the lowest PNEC values either predicted by QSAR or obtained experimentally. Screenshots of the login pages for the NORMAN main site and Ecotoxicology pages are shown in Appendix 1, Fig. 2. Derived PNEC are periodically reviewed by members of the NORMAN network to classify them as 'verified'. Hence, within the data resources, individual PNEC can have different levels of certainty (QSAR derived-unverified; QSAR derived-verified; experimental-unverified; experimental-verified). The PNECs currently within the database include values for ≥ 40,000 substances. The vast majority of these relate to values derived from QSAR models. To generate the reported PNEC value, for each substance the available or QSAR modelled NOEC is divided by an assessment factor of 1000. For many of the compounds for which PNECs are presented, values for four different species from different taxonomic groups are provided, these being a protist (*Tetrahymena*), vertebrate (fish), aquatic plant (algae) and invertebrate (*Daphnia*), as well as the lowest PNEC from the four species. The model derived PNECs are reported at different levels of certainty relating to whether the QSAR covers the chemical space in which the substance exists. For this assessment, the lowest PNEC values was selected for the worst-case ranking. All species are, however, provided in the supporting data file to allow bespoke receptor based analyses to be undertaken.

Appendix 1, Fig. 2. Example of the launch page for the NORMAN database resources (left panel, https://www.norman-network.com/nds/) and resources summary for the NORMAN Network ecotoxicology database (right panel, https://www.norman-network.com/nds/ecotox/).

Estimated HC$_{50}$ values recalculated from published species sensitivity model fits from Posthuma et al. 2019. Environ. Toxicol. Chem. 38:905–917. To address the gap in SSD availability, Posthuma *et al* (2019) published a study that used a comprehensive assembled set of ecotoxicity data (see below) to derive distribution models for 12,386 compounds, each with an associated quality score. The HC50 values derived from these SSDs and the quality score are available for this study. The data-set includes SSDs that have been calculated using both acute and chronic input data. Here we have focussed on the use of the chronic SSD and associated HC50 values. The HC50 was selected for this assessment for two reasons. Firstly, these values are readily available from the primary paper published by Posthuma *et al*. (2019) where they are reported in the Supplementary information. Second, the HC50 value is placed in the middle of the distribution and, hence, its calculation has a much higher certainty making the assessment more robust compared to values more at the extreme of the distribution, such as an HC5. The use of the HC50 is, however, potentially under precautionary, as in general an HC5 would be used when using SSD for EQS development along with an assessment factor.

The number of species data points that are used in the derivation of the HC50 for each chemical was used to assign an assessment of certainty to the resulting value. SSDs built from a greater amount of experimental data obtained for a greater number of species have a higher certainty that these containing few toxicity data. From the information provided by Posthuma *et al*. (2019), it is possible to categorise each substance HC50 according to the amount of data from which it was generated. Categories were High: The SSD was based on chronic NOEC data for 10 or more species; Medium: The SSD was based on chronic NOEC data for 5 or more species or on chronic NOEC data extrapolated from Acute EC$_{50}$ values for 10 or more species or some combination of these data; Low: The SSDs was based on chronic NOEC data for 2 or more species or on chronic NOEC data extrapolated from Acute EC$_{50}$ values for 5 or more species or some combination of these data.

Appendix 2. Approaches used for mixture risk assessment

To assess mixture hazard, assessment is based on concentrations measured in each individual sample. There are two prevailing models that can be used to make predictions of mixtures risk. Concentration addition (CA) assumes that chemicals act on the same biological target (similar mode of action), while Independent Action (IA) assumes that chemicals act independently on the same endpoint (dissimilar mode of action) (see Box 1). Of the two models, CA generally predicts slightly greater effects for a given mixture than IA, except when response curves are shallow in which case the toxic units used for CA calculation scale lower than the proportion increase in actual effects used for IA. Although often used as stand-alone tools, CA and IA can also be used within more complex models. These include 1) Combined CA and IA models that use CA initially to predict the joint effects of sets of similarly acting chemicals and IA to combine effects predictions for these groups (Kim *et al.*, 2014; Qin *et al.*, 2011); 2) Multi-substance potentially affected fraction (msPAF) models which use CA (and IA) to predict the fraction of species affected by a mixture from individual chemical species sensitivity distribution.

Box 1. Basic mixture model concept and formulations

Concentration addition: For mixtures of chemicals with the same mode of action. First formulated by Loewe (1926) according to Equation 1;

$$\sum_{i=1}^{n} \frac{c_i}{EC x_i} = 1 \qquad \text{(Eqn. 1)}$$

Where c_i gives the concentration of the *i*-th component in an *n*-compound mixture which elicits x% total effect and ECx_i is the concentration provoking an x% effect singly. The fraction c_i/ECx_i - commonly known as "toxic unit" (TU) - scales chemical concentration by potency. A TU of 1 indicating a mixture effect at the effect level used for scaling (e.g. 50% when an EC_{50} is used).

Independent action: For chemicals with different modes of action acting independently (Bliss, 1939) as in Equation 2.

$$Y = u_0 \prod_{i=1}^{n} q_i(c_i) \qquad \text{(Eqn. 2)}$$

where *Y* is the measured response, u_0 denotes either control response for endpoints decreasing with concentration or maximum response for endpoints increasing with concentration, and $q(c_i)$ probability of non-response (i.e. unaffected fraction), related to concentration *c* of compound *i*.

Appendix 3. Worst-case risk assessment of groundwater and surface water GC-MS and LC-MS measurements for extracted hazard values
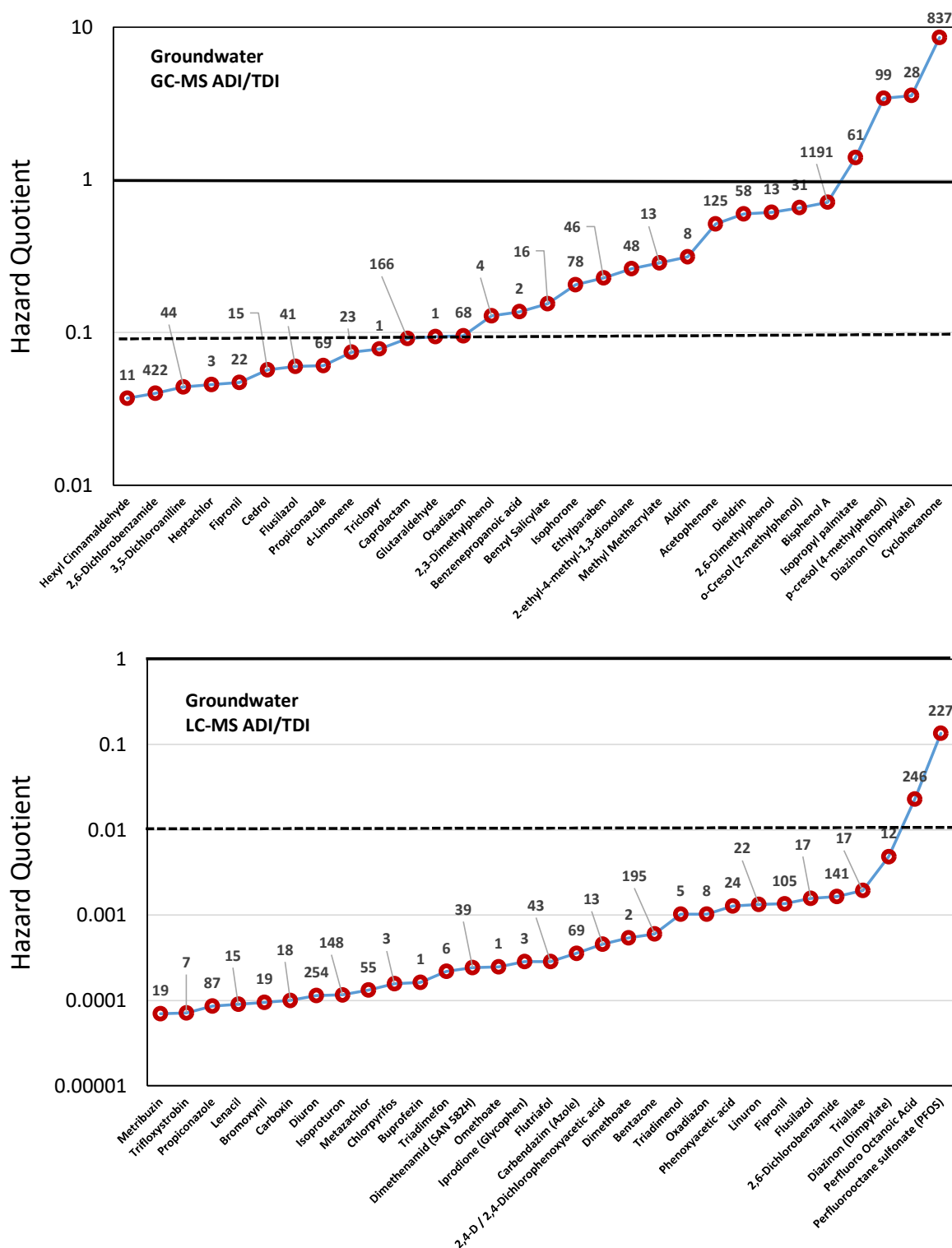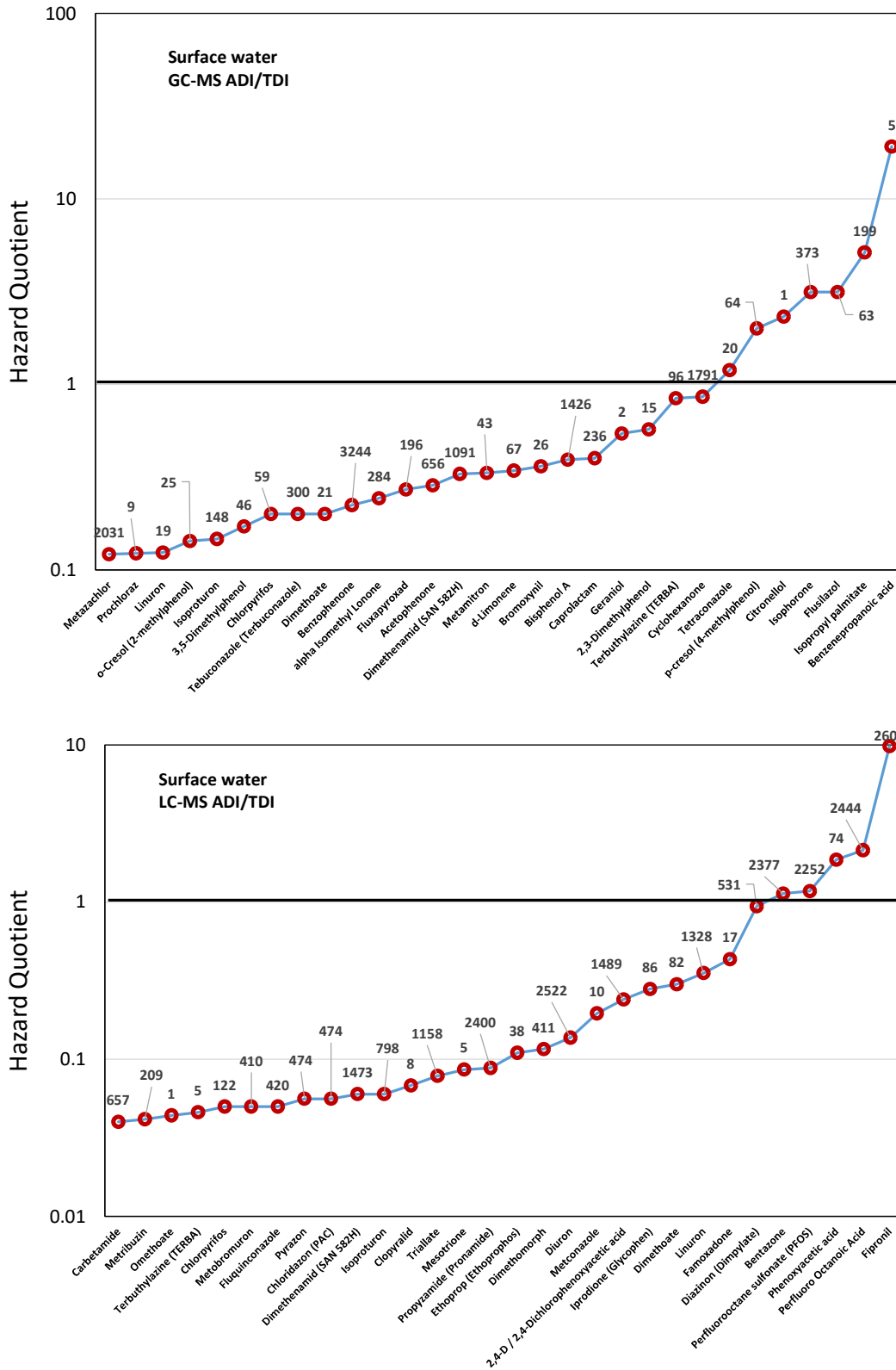
Water Framework Directive environmental quality standards
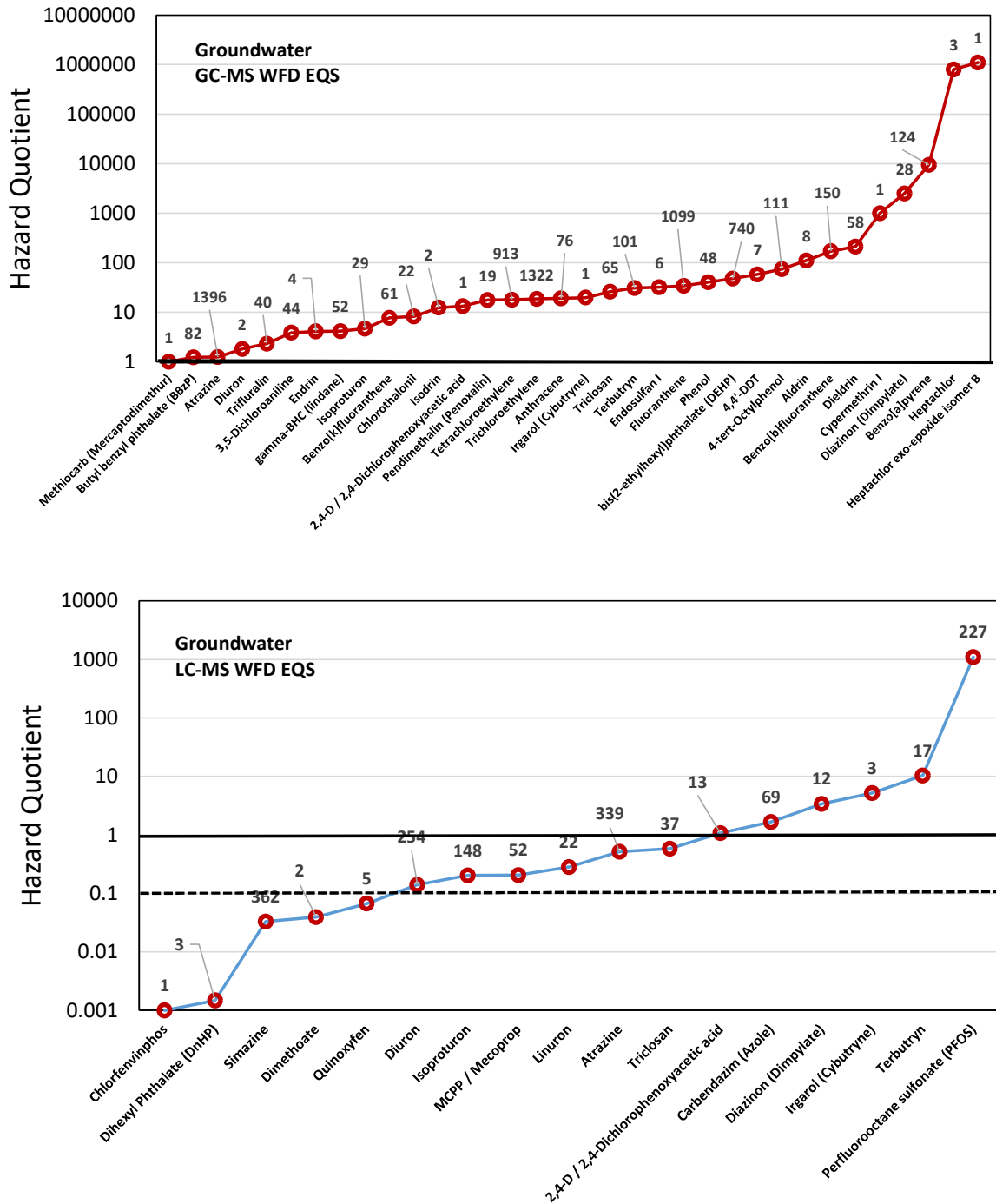
Appendix 3. Figure 1. Rank order of HQs for all substances in the GC-MS (top) and LC-MS (bottom) groundwater data-sets for which the maximum measured concentrations exceeds the relevant WFD EQS (HQ≥1) for the GC-MS data and for all substances for the LC-MS data. The numbers associated with each data-point are the numbers of samples with detections above the LOD for the individual substance.
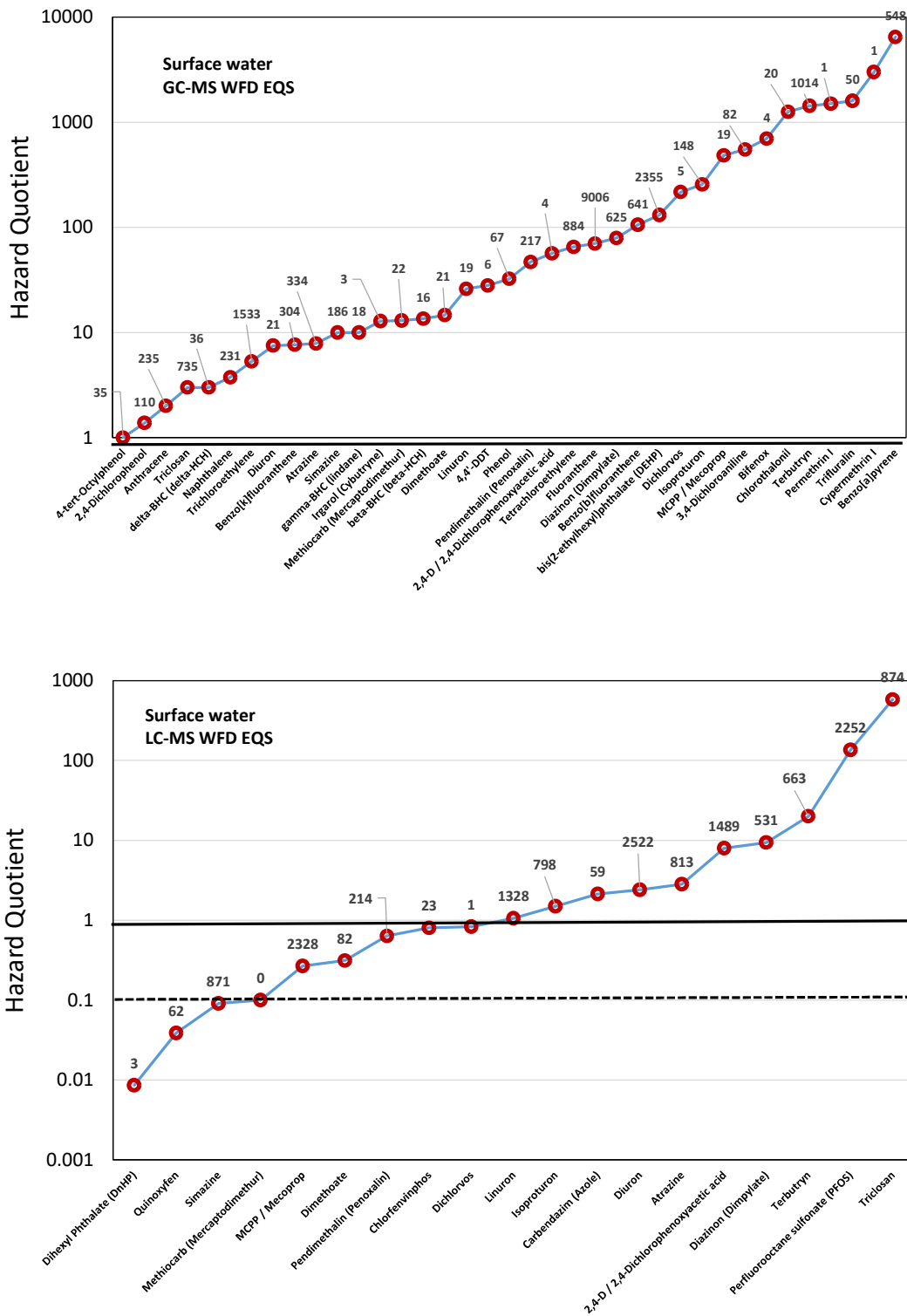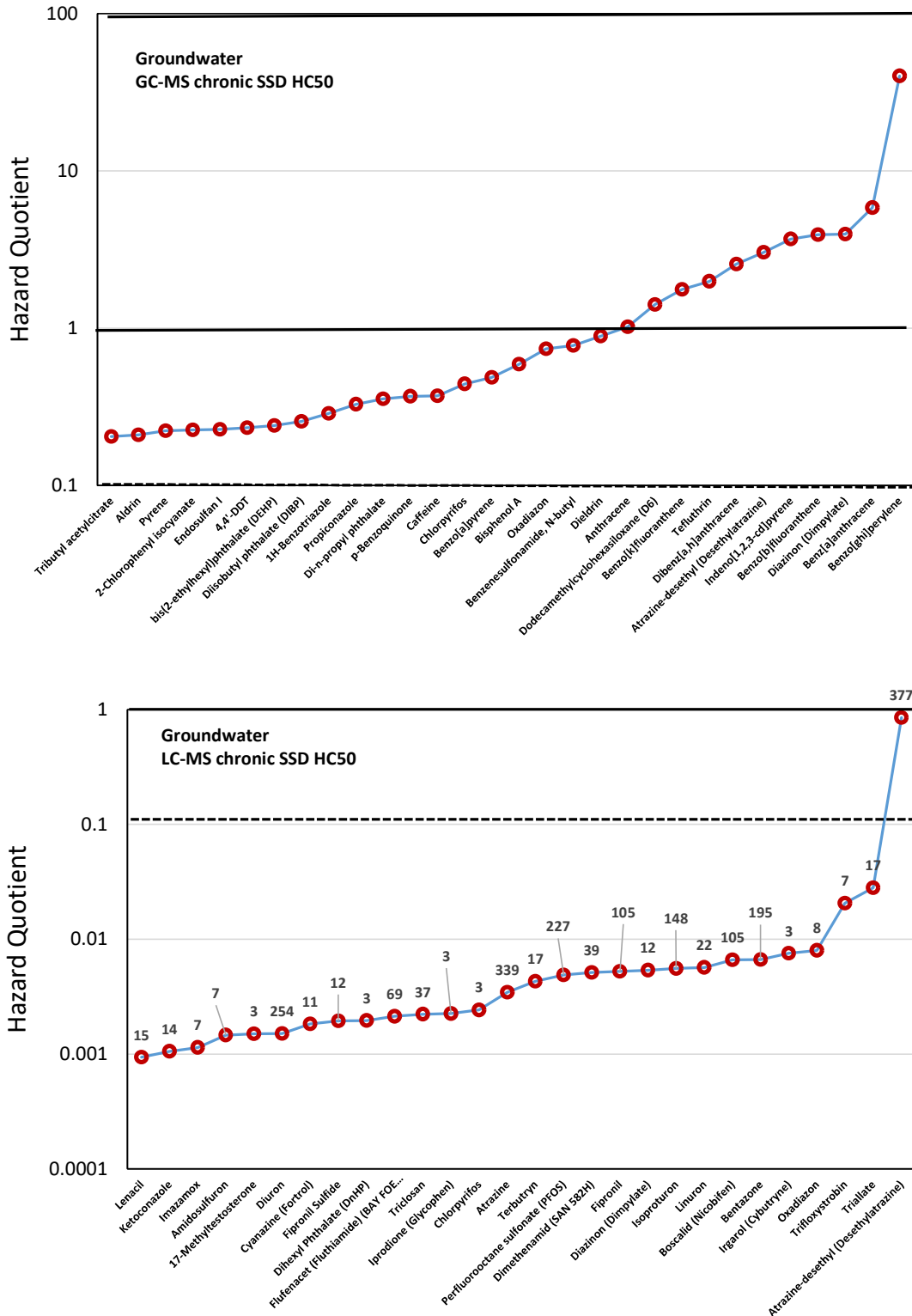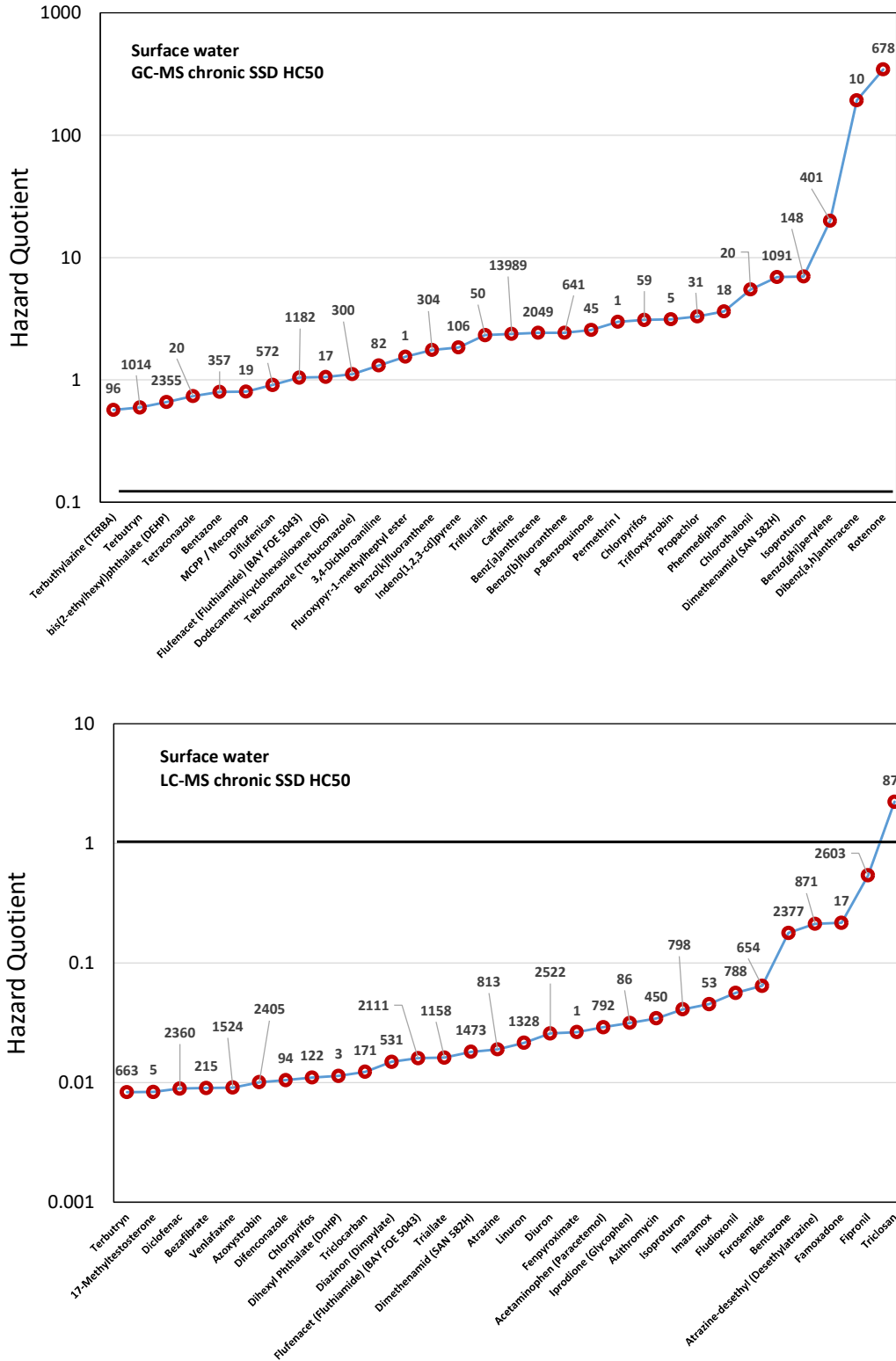
Appendix 3. Figure 2. Rank order of HQs for all substances in the GC-MS (top) and LC-MS (bottom) surface water data-sets for which the maximum measured concentrations exceeds the relevant WFD EQS (HQ≥1) for the GC-MS data and for all substances for the LC-MS data. The numbers associated with each data-point are the numbers of samples with detections above the LOD for the individual substance.

UK Drinking Water Standards values
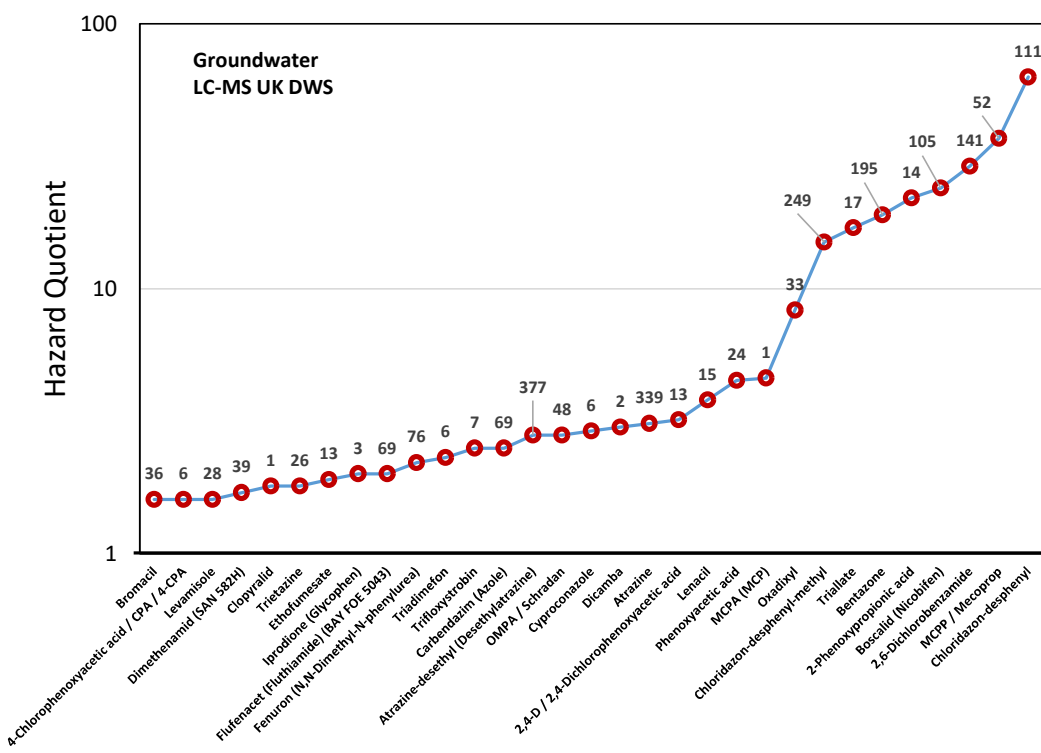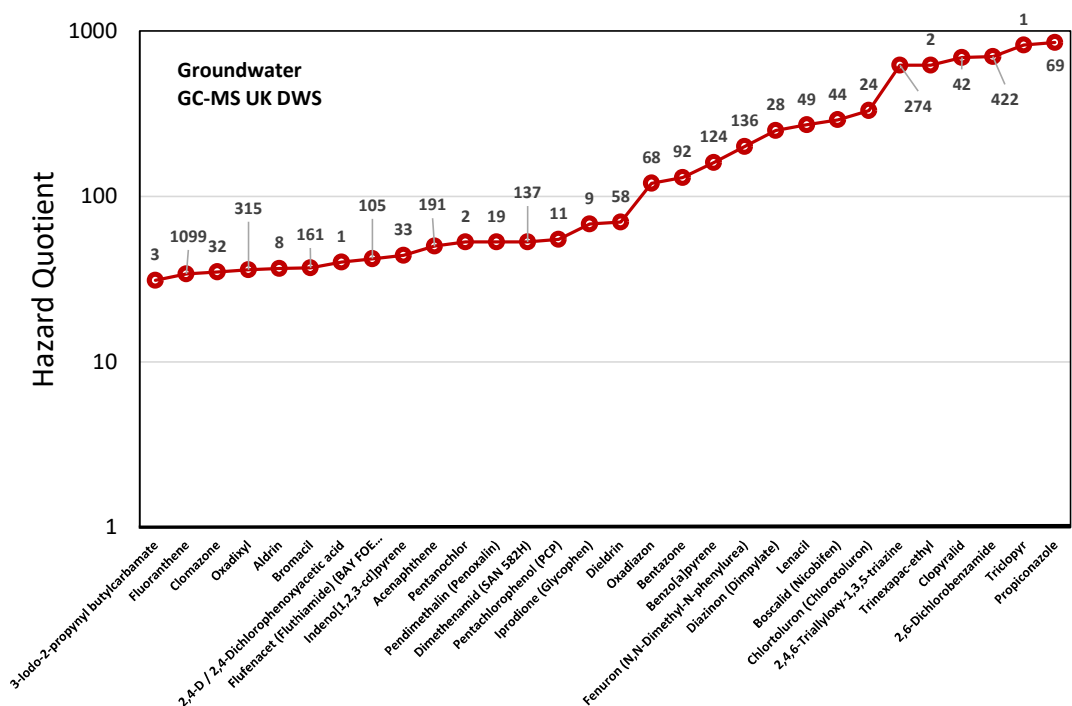
Appendix 3. Figure 3. Rank order of HQs for the top 30 substances in the GC-MS (top) and LC-MS (bottom) groundwater data-set for which the maximum measured concentrations exceeds the UK Drinking Water Standard (HQ≥1). The numbers associated with each data-point are the numbers of samples with detections above the LOD for the individual substance.
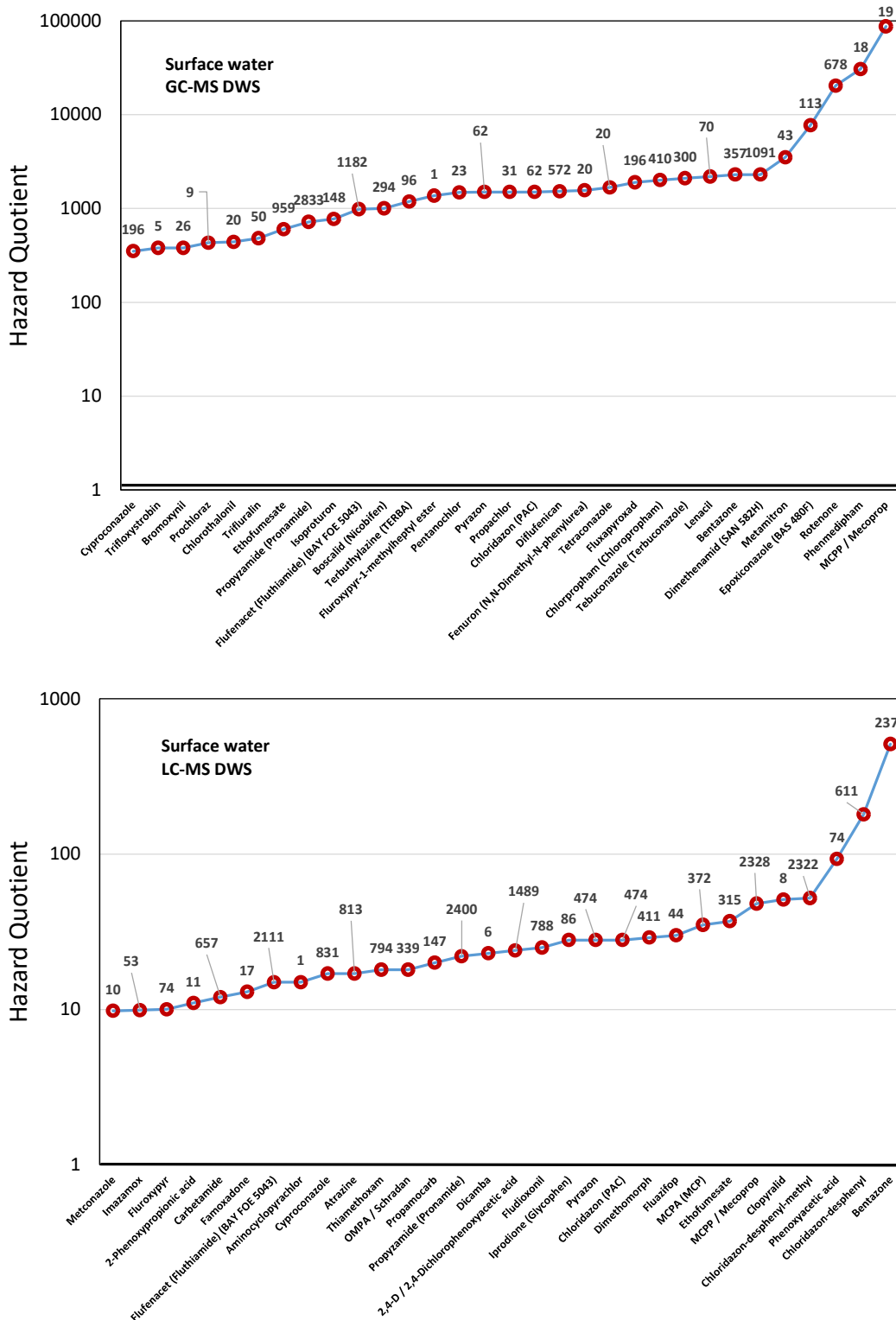
Appendix 3. Figure 4. Rank order of HQs for the top 30 substances in the GC-MS (top) and LC-MS (bottom) surface water data-set for which the maximum measured concentrations exceeds the UK Drinking Water Standard (HQ≥1). The numbers associated with each data-point are the numbers of samples with detections above the LOD for the individual substance.

Human Acceptable Daily Intake and Tolerable Daily Intake values

Appendix 3. Figure 5. Rank order of HQs for the top 30 substances in the GC-MS (top) and LC-MS (bottom) groundwater data-sets for which the maximum measured concentrations exceeds the available ADI/TDI (HQ≥1). The numbers associated with each data-point are the numbers of samples with detections above the LOD for the individual substance.

Appendix 3. Figure 6. Rank order of HQs for the top 30 substances in the GC-MS (top) and LC-MS (bottom) surface water data-sets for which the maximum measured concentrations exceeds the available ADI/TDI (HQ≥1). The numbers associated with each data-point are the numbers of samples with detections above the LOD for the individual substance.

NORMAN Network PNEC value
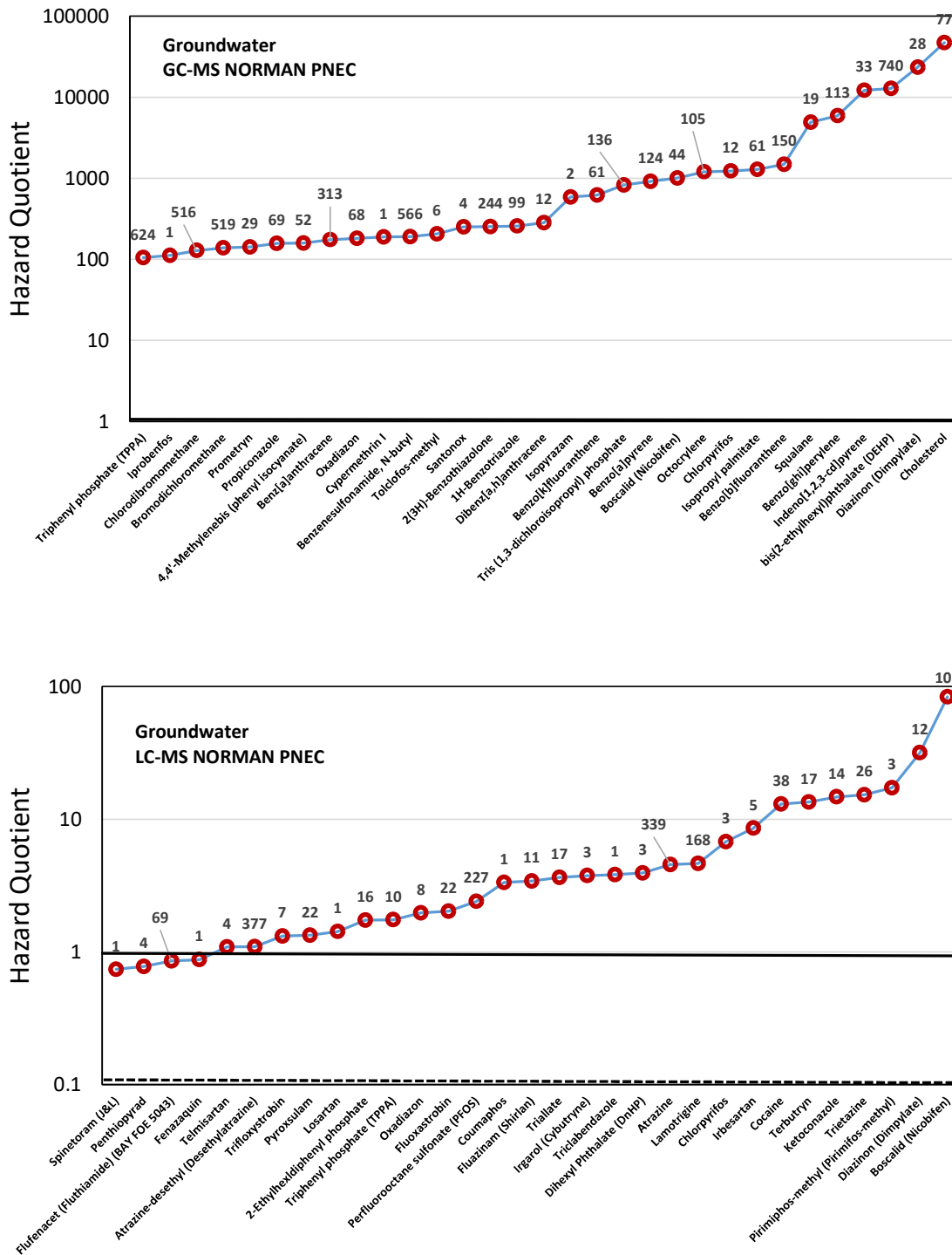
Appendix 3. Figure 7. Rank order of HQs for the top 30 substances in the GC-MS (top) and LC-MS (bottom) groundwater data-set for which the maximum measured concentrations exceeds the available NORMAN PNEC (HQ≥1). The numbers associated with each data-point are the numbers of samples with detections above the LOD for the individual substance.
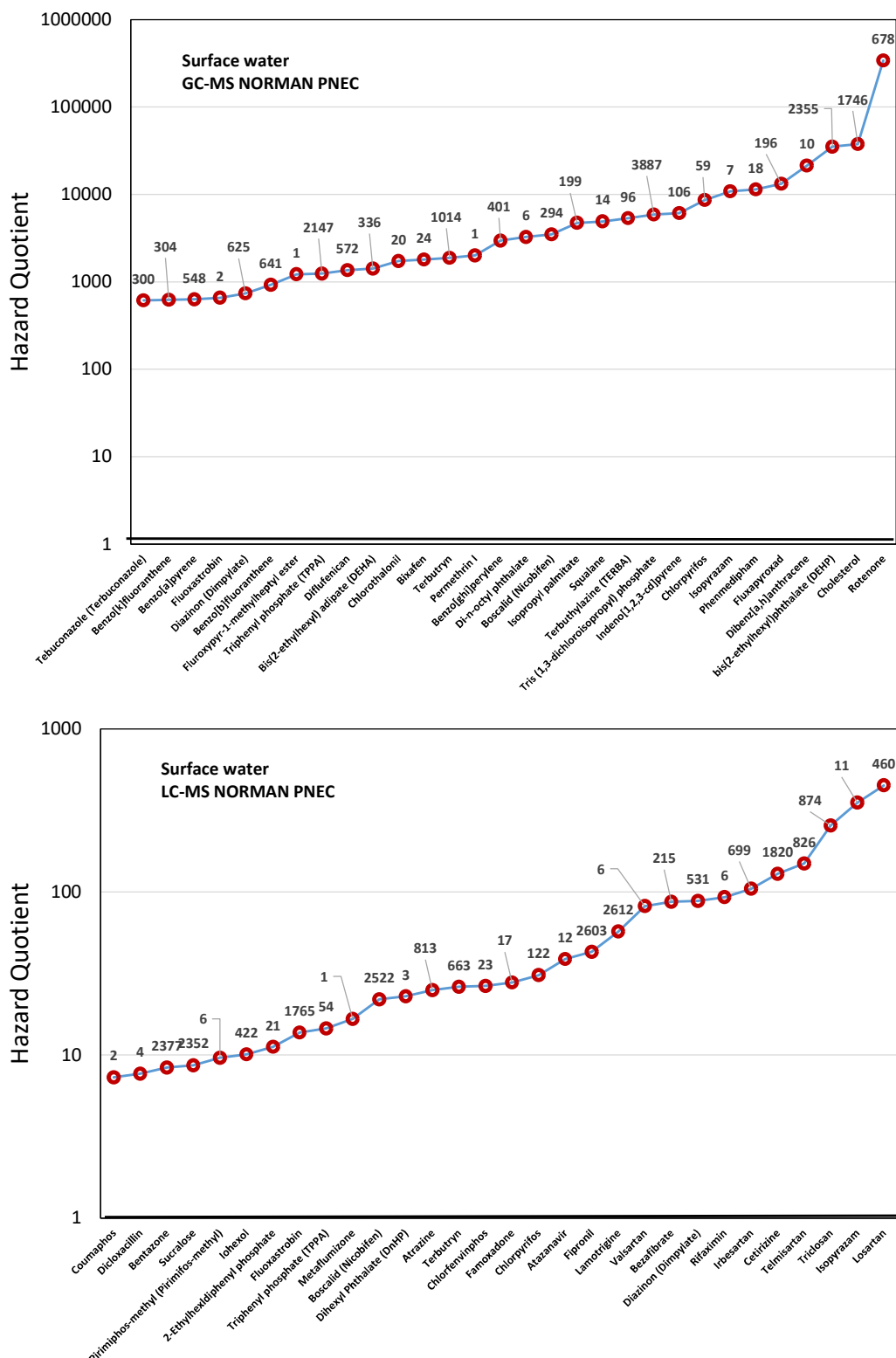
Appendix 3. Figure 8. Rank order of HQs for the top 30 substances in the GC-MS (top) and LC-MS (bottom) surface water data-set for which the maximum measured concentrations exceeds the available NORMAN PNEC (HQ≥1). The numbers associated with each data-point are the numbers of samples with detections above the LOD for the individual substance.

Appendix 3. Figure 9. Rank order of HQs for the top 30 substances in the GC-MS (top) and LC-MS (bottom) groundwater data-set for which the maximum measured concentrations exceeds the available chronic SSD HC50 (HQ≥1). The numbers associated with each data-point are the numbers of samples with detections above the LOD for the individual substance.

Appendix 3. Figure 10. Rank order of HQs for the top 30 substances in the GC-MS (top) and LC-MS (bottom) surface water data-set for which the maximum measured concentrations exceeds the available chronic SSD HC50 (HQ≥1). The numbers associated with each data-point are the numbers of samples with detections above the LOD for the individual substance.

# *Appendix 4. Worst-case risk assessment of groundwater and surface water GC-MS and LC-MS measurements for extracted hazard values*
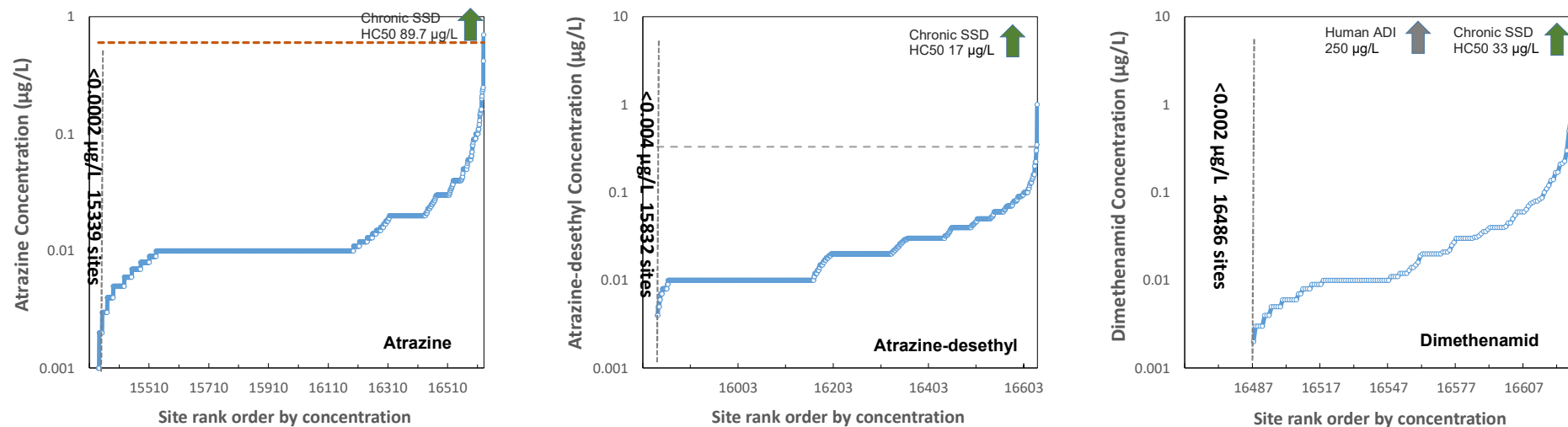
Appendix 4. Figure 1. Rank order of measured concentrations above the detection limit for selected pesticides detected in groundwater samples by GC-MS; number of samples with level below the limits of detection are stated on the left-hand side of the plots; horizontal lines indicate WFD EQS (umber), human ADI-TDI value (grey), SSD chronic HC50 (green) where these values are available (not the case for all chemicals).
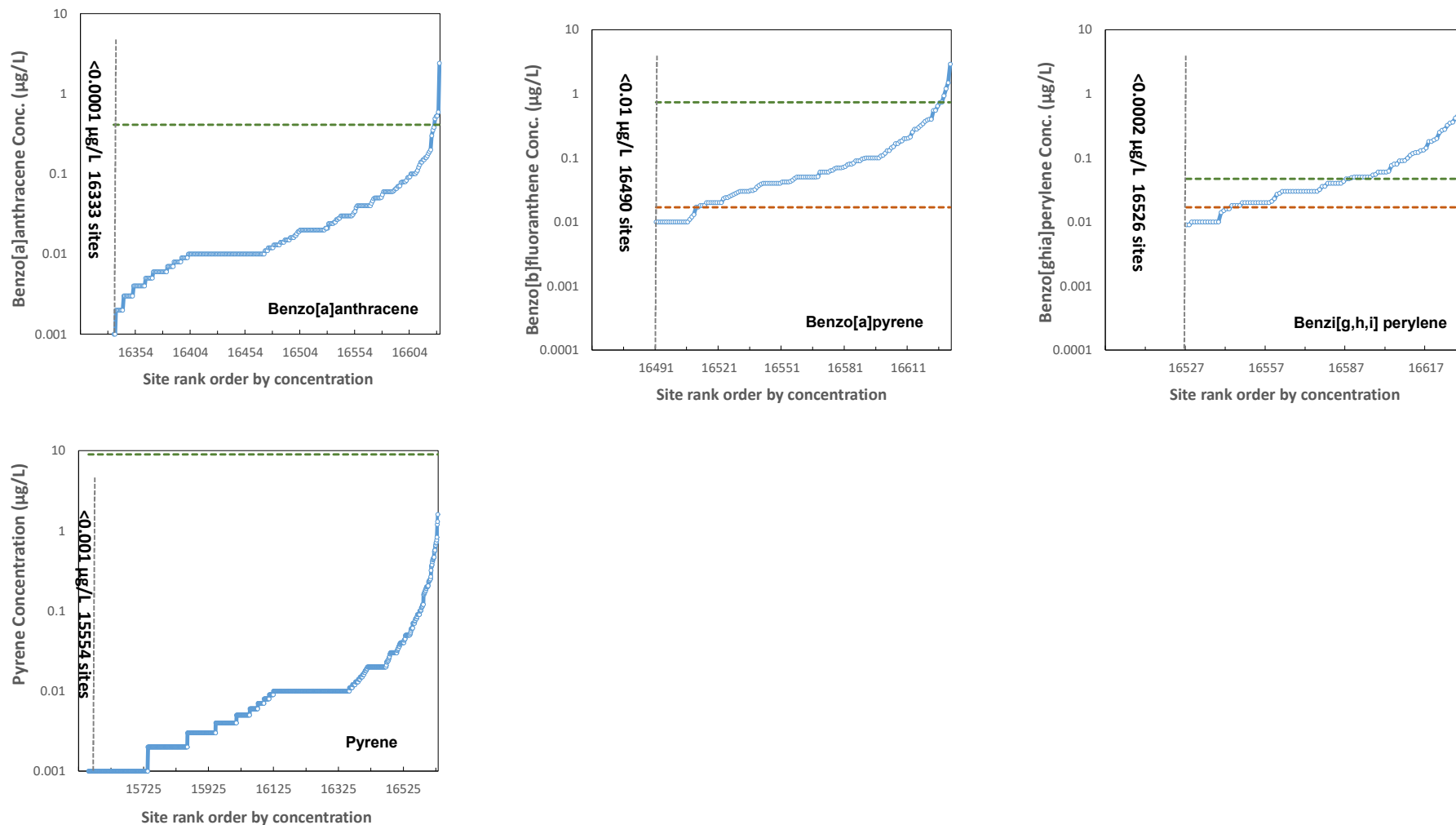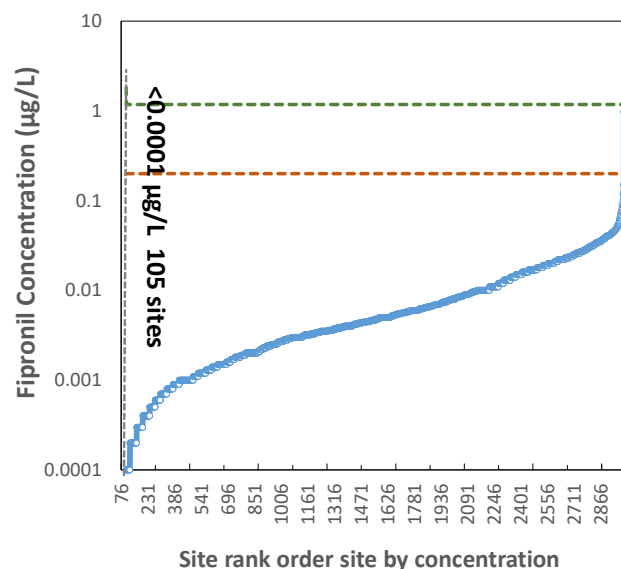
Appendix 4. Figure 2. Rank order of measured concentrations above the detection limit for selected PAHs detected in groundwater samples by GC-MS; number of samples with level below the limits of detection are stated on the left-hand side of the plots; horizontal lines indicate WFD EQS (umber), human ADI-TDI value (grey), SSD chronic HC50 (green) where these values are available (not the case for all chemicals).
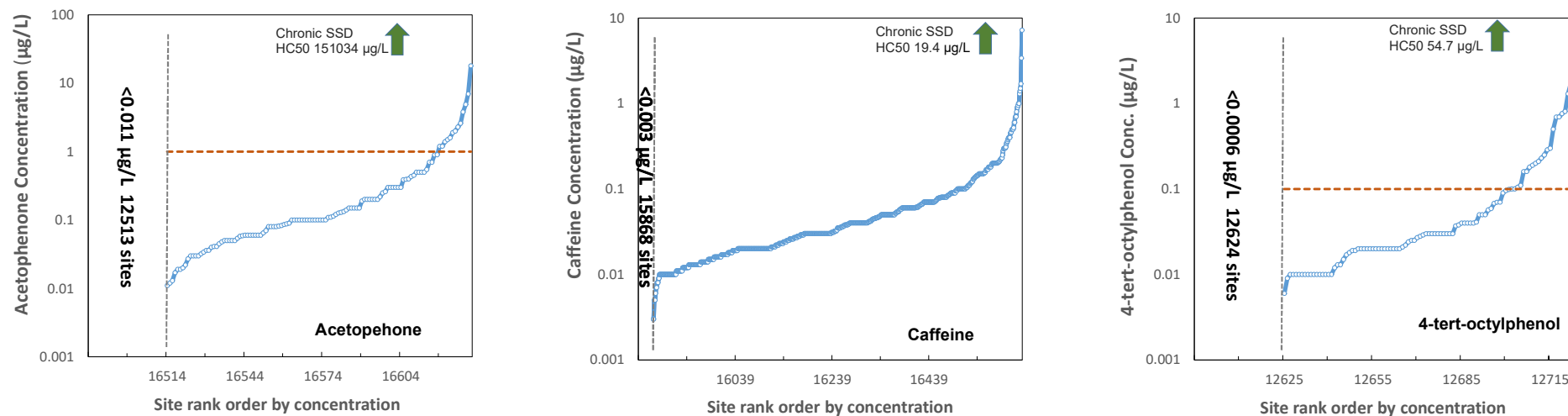
Appendix 4. Figure 3. Rank order of measured concentrations above the detection limit for selected consumer product associated chemicals detected in groundwater samples by GC-MS; number of samples with level below the limits of detection are stated on the left-hand side of the plots; horizontal lines indicate WFD EQS (umber), human ADI-TDI value (grey), SSD chronic HC50 (green) where these values are available (not the case for all chemicals).
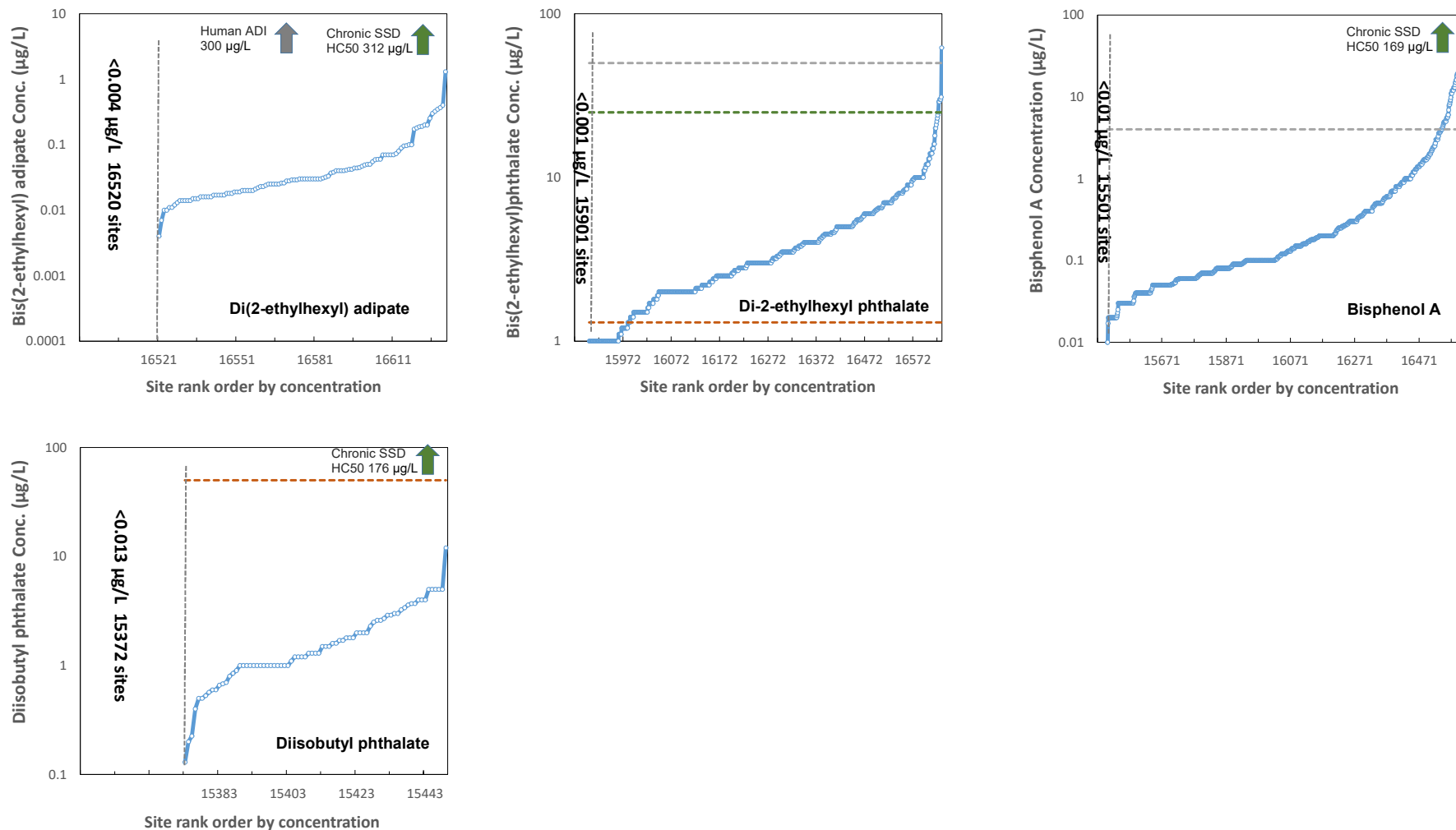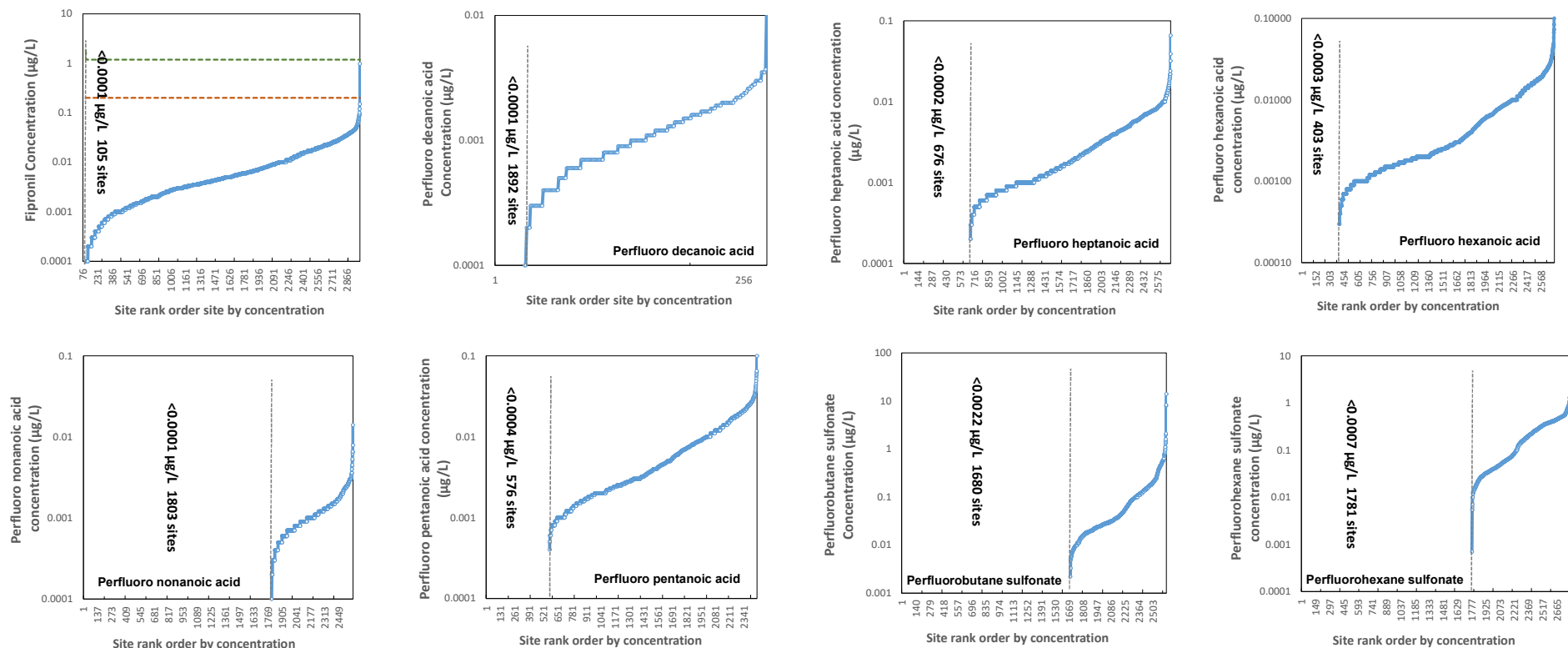
Appendix 4. Figure 4. Rank order of measured concentrations above the detection limit for selected plastics associated chemicals detected in groundwater by GC-MS; number of samples with level below the limits of detection are stated on the left-hand side of the plots; horizontal lines indicate WFD EQS (umber), human ADI-TDI value (grey), SSD chronic HC50 (green) where values are available (not the case for all chemicals).
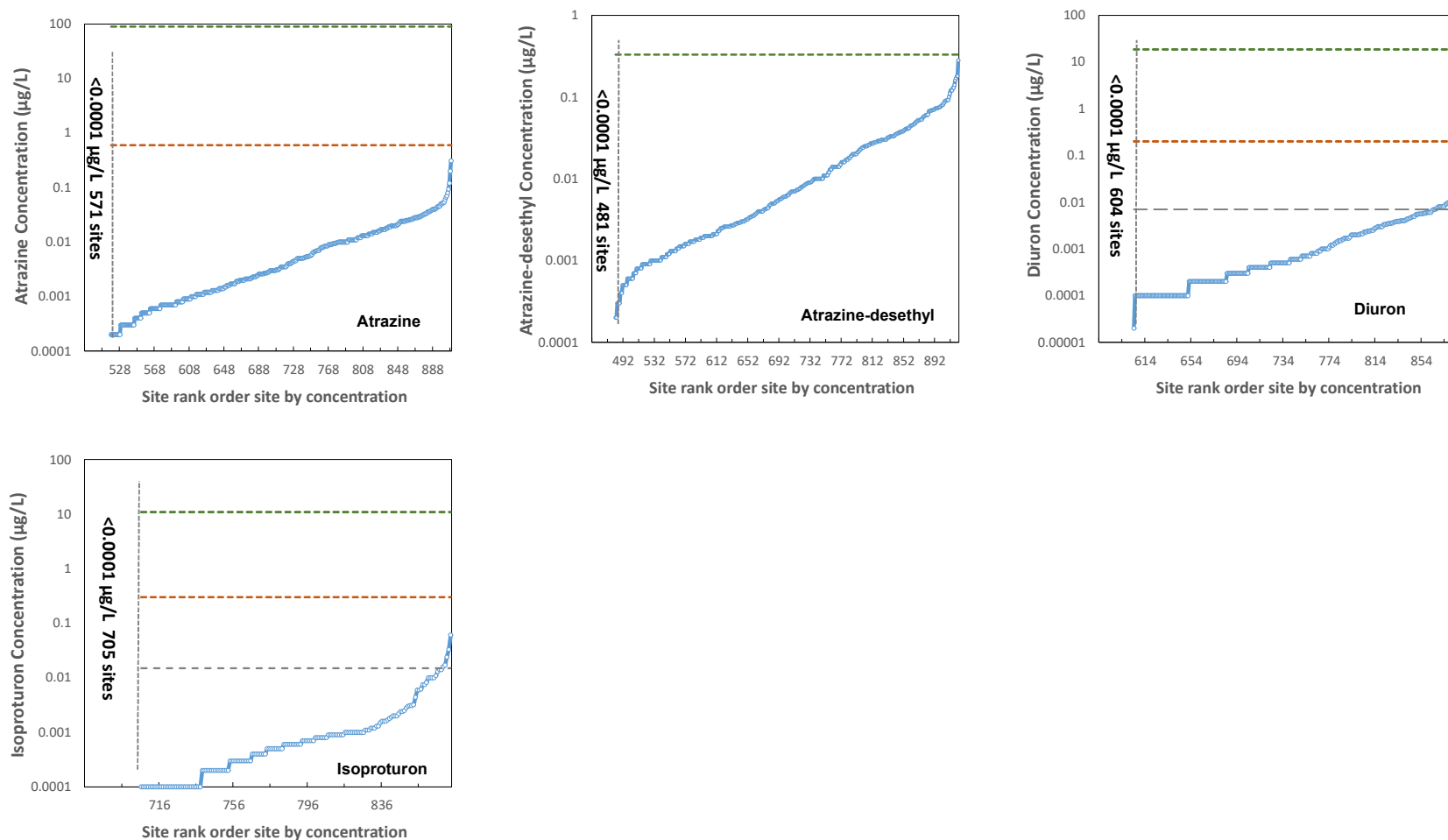
Appendix 4. Figure 5. Rank order of measured concentrations above the detection limit for selected pesticides detected in groundwater samples by LC-MS; number of samples with level below the limits of detection are stated on the left-hand side of the plots; horizontal lines indicate WFD EQS (umber), human ADI-TDI value (grey), SSD chronic HC50 (green) where these values are available (not the case for all chemicals).

Appendix 4. Figure 6. Rank order of measured concentrations above the detection limit for selected pesticides detected in surface water samples by GC-MS; number of samples with level below the limits of detection are stated on the left-hand side of the plots; horizontal lines indicate WFD EQS (umber), human ADI-TDI value (grey), SSD chronic HC50 (green) where these values are available (not the case for all chemicals).
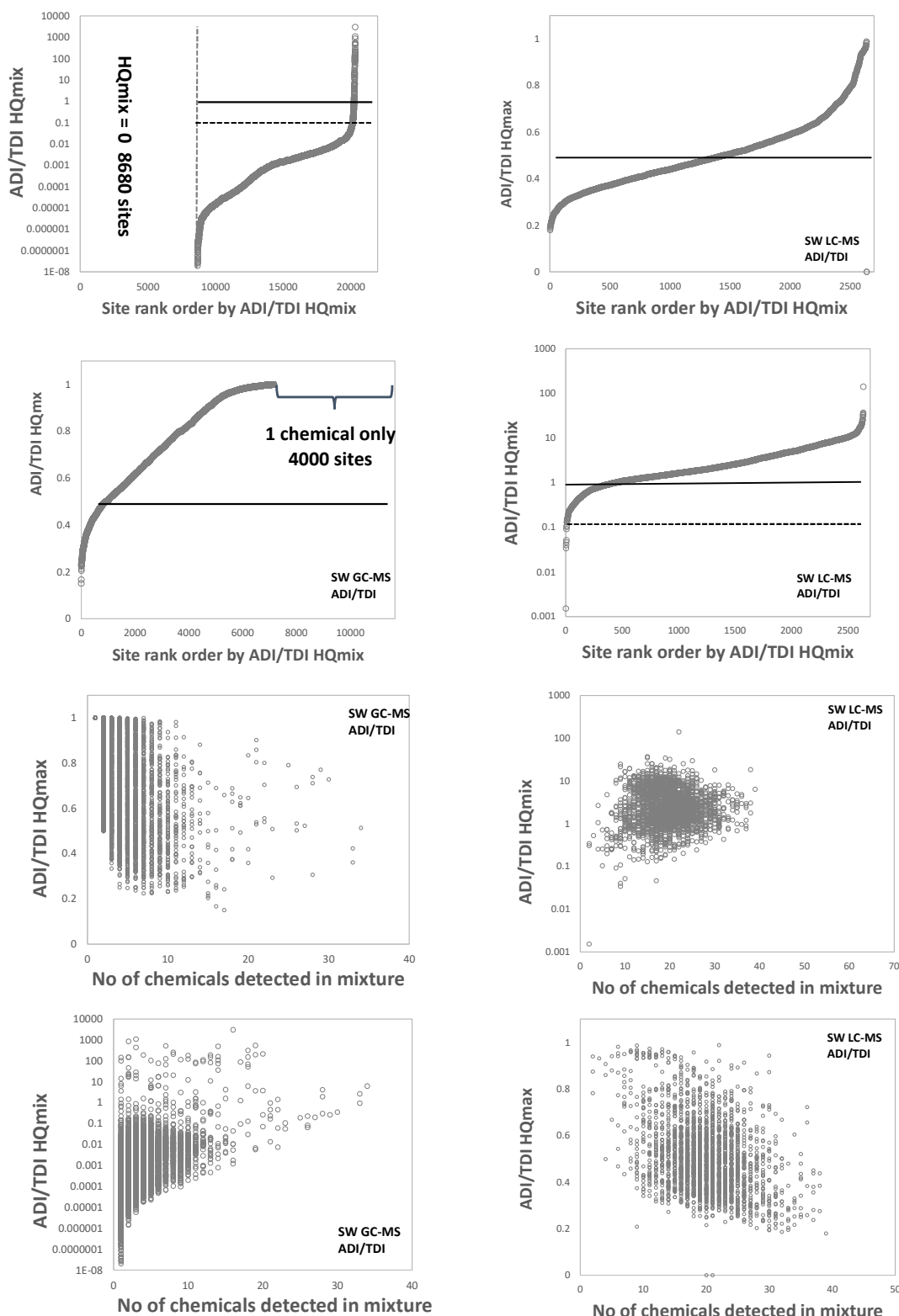
Appendix 4. Figure 7. Rank order of measured concentrations above the detection limit for selected industrial chemicals (including perfluorinated substances) detected in surface water samples by LC-MS; number of samples with level below the limits of detection are stated on the left-hand side of the plots; horizontal lines indicate WFD EQS (umber), human ADI-TDI value (grey), SSD chronic HC50 (green) where these values are available (not the case for all chemicals).

Appendix 5. Mixture analysis for ADI/TDI hazard values
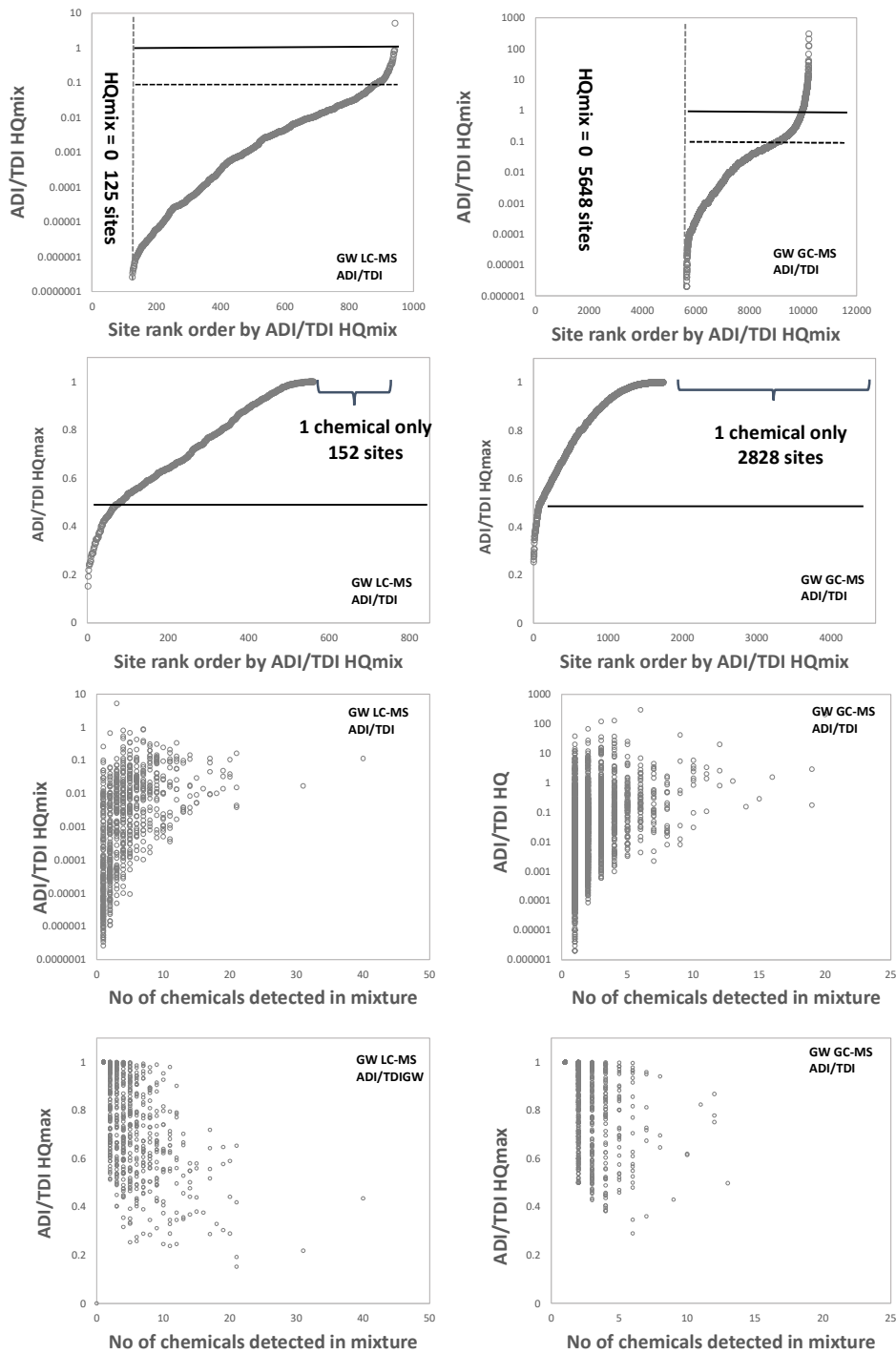
Appendix 5. Fig. 1. Mixture analysis based on ADI/TDI values for GC-MS (left) and LC-MS (right) in groundwater showing cumulative distribution of HQmix (top), HQmax (moddle top), HQmax in relation to number of detected chemicals (middle bottom) and HQmix in relation to number of detected chemicals (bottom)

Appendix 5. Fig. 2. Mixture analysis based on ADI/TDI values for GC-MS (left) and LC-MS (right) in surface water showing cumulative distribution of HQmix (top), HQmax (middle top), HQmax in relation to number of detected chemicals (middle bottom) and HQmix in relation to number of detected chemicals (bottom).