PFAS – Evaluating the economic burden of remediating high-risk sites

Document no: B2382404/REP/001
Version: 1.0

Environment Agency
ecm_66074

PFAS Risk Screening Project - Phase 4 - Work Package 4 Economic Appraisal
July 2023

PFAS – Evaluating the economic burden of remediating high-risk sites

Client name:	Environment Agency		
Project name:	PFAS Risk Screening Project - Phase 4 - Work Package 4 Economic Appraisal		
Client reference:	ecm_66074	**Project no:**	B2382404
Document no:	B2382404/REP/001	**Project manager:**	[REDACTED]
Version:	1.0	**Prepared by:**	[REDACTED]/[REDACTED]
Date:	6 July 2023	**File name:**	PFAS WP4 Phase 4 - Report Rev0.docx

Document history and status

Version	Date	Description	Author	Checked	Reviewed	Approved
1.0	6/7/2023	Rev 0	[REDACTED]	[REDACTED]	[REDACTED]	[REDACTED]

Jacobs U.K. Limited

160 Dundee Street
Edinburgh, EH11 1DQ
United Kingdom

T +44 (0)131 659 1500
F +44 (0)131 228 6177
www.jacobs.com

Executive summary

The purpose of this work (PFAS Risk Screening Project Phase 4 WP4) is to report on the nature of the PFAS problem across England through the development and use of a model to highlight the financial scale and burden of the problem. Our evidence gathering and modelling of different scenarios provides insight into the potential scale of PFAS in England, both in terms of the number and distribution of sites across sectors and financial cost: between £31 billion and £121 billion of remediation costs for between 2,900 and 10,200 high-risk sites.

An evidence-review was carried out which covered both academic and grey literature, focussing on unit costs and case studies of land based remediation as well as impacts relating to PFAS (health, environmental, and economic) and the regulatory context. The evidence review was augmented by expert elicitation to gather and validate cost information on remediation activities from specialist contractors [REDACTED].

The GIS-based PFAS Risk Explorer web application (PFAS Risk Screening Project Phase 4 WP1) was used to identify potential PFAS source sites and attribute a potential risk score based on its location, environmental setting, water quality data, and site type. These scores were then used to model scenarios by setting a threshold score to determine which sites are deemed high-risk and therefore more likely to require remediation. The potential scale of the PFAS problem was explored through three different scenarios, reflecting different levels of remediation: Scenario 1 being 'comprehensive' and Scenario 2 being potentially more practical by addressing a smaller number of sites. Scenario 3 represents a different approach whereby the full extent of the PFAS challenge is addressed in part by a centralised wastewater treatment works (WwTW) 'end of pipe' intervention.

The modelling for each of these scenarios involved multiple estimates of cost for different remediation measures, taken from our evidence review and expert elicitation. The most robust estimates were utilised and applied to the different site types and the steps required, or 'treatment trains'. The modelled costs involve a mixture of soil and groundwater remediation in Scenarios 1 and 2, and wastewater treatment methods in Scenario 3. The table below shows the following:

- Estimated cost per site and aggregated sector totals of remediating different types of sites in England.
- Average costs per site are estimated to range from £400,000 to £29 billion; this is due to the different remediation required for different site types and the range in size of the different sites.
- Historic landfills, wastewater treatment works, and COMAH/Chemicals/Refineries are estimated to cost significantly more than other site types due to the size of the sites and complex remediation required to address PFAS contamination.
- Scenario 1 has a higher cost because it reflects a lower risk threshold, meaning more sites are deemed "high risk". This represents a more comprehensive scenario where more airports, landfills and wastewater treatment works are remediated.

Scenario 3 presents a different approach to Scenarios 1 and 2 by treating PFAS contamination entering the sewage and wastewater system. This represents a comparatively more feasible intervention at a national scale than a programme of site-based remediation; however it would leave soil and groundwater contamination largely in-situ with further opportunities for PFAS to be transported and contaminate other environmental media. This scenario therefore represents an additional, rather than an alternative intervention to Scenarios 1 and 2, with an estimated cost of £28bn to address 95% of WwTW in England.

Site type	Per site cost – average (£m)		Total cost – average (£m)	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Air Transport Sites/Military	£8	£8	£3,400	£1,700
Fire Stations	£2	£3	£3,000	£1,700
Permitted Landfill	£5	£6	£3,500	£800
Historic Landfill	£7	£9	£27,100	£6,300
Wastewater Treatment Works	£13	£26	£28,100	£17,200
COMAH/Chemicals/Refineries	£23	£29	£27,000	£18,600
Nuclear Permitted Site	£4	£4	£115	£22
TULAC/Metals/Pulp and Paper	£7	£7	£1,400	£161
Oil and Gas	£0.40	£0.40	£0.30	£0.00
	Weighted Average	Weighted Average	Sum	Sum
All	£9	£16	£93,400	£46,400

The potential benefits of removing PFAS from the environment are reduced impacts (avoided costs) on human health, the economy, and the wider environment, as well as avoided legal/reputational damage. PFAS are associated with serious health effects including decreased response of the immune system to vaccination, increased risk of some cancers and various conditions associated with endocrine disruption, among others. A reduction in exposure through any of modelled scenarios is likely to result in human health benefits. Key potential economic benefits of remediation include secure drinking water supplies (avoiding more costly alternatives), avoided loss in property value around sites of known contamination as well as the development potential and associated economic benefits from remediating individual sites. There is some evidence linking PFAS exposure to impacts on key species of birds, fish, and mammals and whilst it can be inferred that the overall effect on habitats and ecosystems is likely to be positive from reducing the level of PFAS in the environment, the specific nature of impacts and their scale are not as clearly understood. PFOS (a PFAS) is one of the uPBT (ubiquitous, persistent, bioaccumulative, toxic) substances causing widespread failure of English surface water bodies to meet Good Chemical Status and removal of PFAS from the environment will help achieve targets.

There are other limitations and uncertainties within the PFAS cost estimation model (and associated datasets) that affect the accuracy of results and in turn recommendations: definition of "high risk site" is open to interpretation, each datapoint of PFAS cost remediation data is context specific, and modelling has assumptions that can significantly influence results (eg the depth of soil excavation). What is important to understand is that the results reflect data, learning and methods from an emerging field and therefore should be treated with caution. In order to quantify the potential benefits of remediation associated with reduced PFAS levels, further understanding of source apportionment and the contribution to overall risk/exposure is needed. As such, it has not been possible to present monetised benefits that are comparable to the estimated scenario costs.

The complexity of the PFAS challenge in terms of the number of affected sites, the multi-pronged nature of remediation required, and the range of receptor and impact pathways necessitates an inter-departmental approach. Recommended next steps include further analysis to quantify wider impacts (health, environmental, and economic) and investigate the relative contribution of different PFAS sources to the overall issue (impact pathways and source apportionment).

Important note about this report

The work undertaken herein is in accordance with the scope of services set out in the contract between Jacobs and the Environment Agency (EA) (ref: ecm_66074 dated 18th October 2022). That scope of services, as described in this report, was developed with the Client.

A number of the findings and conclusions presented in this report are based on information provided by third parties and / or historical records, which Jacobs has relied on in good faith. Jacobs accepts no responsibility for any deficiency, misstatements, or inaccuracy contained in this report as a result of errors, omissions or misstatements of said third parties or from information obtained from these.

Jacobs derived the data in this report from information sourced from a range of sources including academic journals, public domain, and direct data collection from named sources. The passage of time, manifestation of latent conditions or impacts of future events may require further examination of the project and subsequent data analysis, and re-evaluation of the data, findings, observations and conclusions expressed in this report. Jacobs has prepared this report in accordance with the usual care and thoroughness of the consulting profession, for the sole purpose described above and by reference to applicable standards, guidelines, procedures and practices at the date of issue of this report. For the reasons outlined above, however, no other warranty or guarantee, whether expressed or implied, is made as to the data, observations and findings expressed in this report, to the extent permitted by law.

No liability is accepted by Jacobs for any use of this document, other than for the purposes for which it was originally prepared and provided.

A separate disclaimer is set out in the associated spreadsheet used to produce the results presented and discussed in this report. That disclaimer also applies to the relevant content within this report.

This report should be read in full and no excerpts are to be taken as representative of the findings. No responsibility is accepted by Jacobs for use of any part of this report in any other context.

Contents

Tables

Figures

Acronyms and abbreviations

General Abbreviation	Definition
AFFF	Aqueous Film-Forming Foam
CBA	Cost-Benefit Analysis
COMAH	Control Of Major Accident Hazards
Defra	Department for Environment, Food, and Rural Affairs
DoD	Department of Defence
DoE	Department of Environment
EA	Environment Agency
EPA	Environmental Protection Agency
EPR	Environmental Permitting Regulations
FFF	Fire-Fighting Foam
GAC	Granular Activated Carbon
GDP	Gross Domestic Product
GIS	Geographical Information System
HSE	Health and Safety Executive
IX	Ion Exchange
LFD	Landfill Directive
MoD	Ministry of Defence
OECD	Organization for Economic Cooperation and Development
PFAS	Perfluoroalkyl and Polyfluoroalkyl Substances
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonic acid
PRB	Permeable Reactive Barrier
QALY	Quality Adjusted Life Year
REACH	Registration, Evaluation, Authorization and Restriction of Chemicals
TULAC	Textiles, Upholstery, Leather, Apparel and Carpets
UK HSA	United Kingdom Health Security Agency
UK RMOA	UK Regulatory Management Options Analysis
UK WIR	United Kingdom Water Industry Research
WELLBY	Wellbeing Adjusted Life Year
WwTW	Wastewater Treatment Works
WP	Work Package

1. Introduction

1.1 Purpose of this report

This report presents the methodology and findings from developing a model for estimating the cost of remediating high-risk sites contaminated with PFAS (Per and polyfluoroalkyl substances) in England.

This builds on previous phases of work undertaken for the Environment Agency, primarily the PFAS Risk Explorer web application which can be used to estimate the number and size of contaminated sites across England by sector/site type and assigns them a risk score. This report describes the approach or "mechanism" for estimating the financial scale of dealing with these contaminated sites. For each site type, we describe the approach to estimating remediation costs including the limitations and uncertainties around the estimates. We then present aggregated results across sectors and for England as a whole according to three different policy scenarios. This provides an indication of the cost of land contamination liability for different groups (e.g. MOD, Industry etc.)

The intended audience for the report is Central Government economists and policy makers and its purpose is to help them to understand the potential technologies and associated costs for land-based treatment as a component of addressing the PFAS challenge in its totality. Note that the discussed technologies do not represent an exhaustive list, and commentary on their relative efficacies sits largely outside the scope of this work. We discuss approaches to remediation and how these can be combined into multi-step "treatment trains", the costs and benefits of remediation, and key findings from our rapid evidence review including international examples of economic appraisals of addressing the PFAS challenge. Whilst results are presented, the key findings focus on the approach to constructing a PFAS remediation cost estimate.

1.2 Project background

This project forms part of the PFAS Risk Screening Project currently being delivered to the Environment Agency as a series of work packages by multiple contractors. The PFAS Risk Screening Project aims to assess and tackle the risks arising from a group of "forever chemicals" which are contaminating soil, groundwater and surface waters and also pose a risk to human health. These chemicals are causing a global pollution problem - and the nature and scale of the problem in the UK is only now being fully realised.

PFAS are a broad group of more than 12,000 synthetic fluorinated organic chemicals which are extremely persistent in the environment. Some are bio-accumulative and toxic, and/or highly mobile. The two most well-known PFAS are perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS).

PFAS are used in a wide variety of consumer products and industrial applications because of their unique chemical and physical properties, including oil, water and stain repellence, temperature and chemical resistance, and surfactant properties. These properties mean they are also persistent in the environment and some PFAS are bio-accumulative, toxic, and/or highly mobile.

Increasing coverage and awareness of the widespread presence of PFAS in environmental media has heightened regulatory concerns about their potential risks to human health and the environment. In order to ensure effective actions are implemented the Environment Agency needs to better understand the sources of PFAS, the pathways and the relative significance of these substances in surface waters and groundwater.

The PFAS Risk Screening Phase 1 project (Jacobs UK Ltd., 2020) proved the concept of the viability of using a GIS approach based on readily available datasets, using spatial analysis techniques to undertake initial risk prioritisation using a multi-criteria analytical approach to evaluate risk. The predictive model allocates scores based on respective weightings applied to key criteria – all designed around the source-pathway-receptor type strategy. PFAS Phase 2 enhanced and provided a more robust prioritisation approach with additional functionality focussed on needs and priorities. PFAS Phase 3 included further validation and enhancement of the underpinning model and datasets and development of a more user-friendly and accessible GIS portal (The

PFAS Risk Explorer) with additional focused studies to enhance understanding of significant PFAS sources to the water environment in England.

Phase 1 and Phase 2 demonstrated that there is potentially an extensive PFAS pollution problem across England. With any such pollution, there is associated liability and an associated economic impact relating to the various costs involved with investigating and possibly remediating identified problem sites. Phase 3 included activity to start to evaluate the potential scale of the PFAS pollution problem across England in order to help the Environment Agency to evaluate the cost burden associated with remedying the situation. The aim was to identify the sites with the highest pollution potential in the locations of the highest environmental sensitivity presented as a land area which could inform economic evaluation. The information was presented in the form of numbers of sites of different types, and individual and combined land area, which could then be used as the basis for future preliminary economic evaluation.

The plan for Phase 4 (2022–25) has been to build on the outputs of these preceding stages. Phase 4 has been broken down into a series of six discrete but interlinked work packages (WP):

- WP1 GIS Model Refinement & Application
- WP2 Development of Good Practice Guidance
- WP3 Detailed Assessment of Potential PFAS Problem Sites
- WP4 Economic Appraisal (this project)
- WP5 Landfill Assessment
- WP6 Background Concentrations in Soil

1.3 Project aim and scope of work

This work builds on the outputs of previous phases of the PFAS research programme (specifically Phase 3 Task 9 – see Section 1.4 for further detail), using the results generated by the GIS-based predictive PFAS Risk Explorer web application, which aimed to categorise and quantify the number of potential high-risk PFAS sites. Further to the recommendations from the Phase 3 activity, the aim of this work is to develop an approach and ultimately deliver a report, detailing the nature of the PFAS problem across England together with a mechanism for deriving costs to highlight the financial scale and burden of the problem.

This is therefore as much about deriving an approach or “mechanism” for estimating costs which can be updated and refined over time, as it is about presenting preliminary results.

The key objectives are:

- Compare and appraise approaches to economic appraisal of PFAS globally. Through our rapid evidence review, liaison with other Work Packages in this phase of the research programme, and expert elicitation we have gathered and assessed international approaches to economic appraisal of PFAS generally, with a focus on contaminated land remediation.
- Derive a mechanism for estimating costs of PFAS remediation at potential high-risk sites. We have gathered and synthesised information from our rapid evidence review both on how costs have been derived as well as data points themselves, through unpublished/confidential information gained through expert elicitation, as well as consideration of selected non-PFAS remediation case-studies (e.g. other emerging contaminants). For each site type, we have considered both bottom up, and top-down estimates to generate a sensitivity range that can be updated as new data points emerge.
- Construct a model to estimate the financial burden. Our Excel-based model takes the outputs of the existing PFAS Risk Explorer and produces estimates for each site type as well as facilitating scenario analysis, whereby total costs are estimated depending on the threshold risk score and/or level of intervention assumed. This Excel-based model will be provided to the Environment Agency (EA).

- Produce a clear and unambiguous report. This report outlines the approach to modelling and key findings, with the intention of informing regulatory decisions taken in future. Assumptions, limitations and caveats are clearly stated, along with recommendations for further refinement.
- Collaborate and share information with others under Phase 4. We have worked with the teams delivering the other work packages in this research phase (see Section 1.4 for further detail), specifically WP1 for the enhanced PFAS Risk Explorer GIS Model, the WP2 Good Practice Guidance literature review (Jacobs, 2023a) was used to supplement/enhance our rapid evidence review and WP5 Landfill Assessment (Jacobs, 2023b) provided a case study which was incorporated as a data point to generate cost estimates for landfill site remediation.
- Recommendations for further iterations of economic appraisal. This work has identified gaps in knowledge both around the costs and benefits of PFAS land remediation. We have prioritised these for further research based on the sensitivity of results to these gaps/areas of uncertainty.

As the number of PFAS remediation projects in the UK increases, information is likely to become more publicly available and consideration should be given to means of gathering and analysing data to refine the level of cost, methods of remediation being adopted and other criteria useful in understanding the scale of the challenge. This will allow the robustness of the estimate of the overall financial burden to increase over time. Further iterations of the literature review are recommended to maintain the contemporaneous nature of the appraisal, providing evidence on regulatory practice, national policy development and remediation activity.

1.4 General Limitations

Defining the scope or boundary of appraisal was challenging, due to the far-reaching impacts of PFAS contamination. The focus of this work is on direct (primarily capital or one-off) costs of remediating contaminated sites. There are numerous elements to consider around the total economic cost of dealing with the PFAS challenge. This appraisal has not considered the following:

- Affordability / who will pay
- Legal / reputational costs
- Regulatory costs
- Site investigations, ongoing monitoring
- Wider environmental and social impacts of treatment (e.g. greenhouse gas emissions, landfill capacity, and traffic and noise disturbance from the bulk transport of materials).
- Other sources of PFAS contamination and treatment e.g. water and wastewater treatment, human exposure through use of consumer products, and ambient PFAS/atmospheric dispersion.
- Economic/regulatory costs associated with restricting or banning PFAS and eradicating them from the supply chain/ use of alternative substances.

Where possible, we have included a qualitative discussion of these elements as well as an indication of how to prioritise effort for quantifying these aspects going forward.

This analysis does not include a monetised estimate of the benefits of land-based remediation activity; rather we discuss the benefits (largely avoided human health damages) qualitatively, as well as provide recommendations for valuing the benefits which would underpin policy decisions and/or clearly state the case for change.

2. PFAS background

2.1 Introduction

Per- and Poly-Fluoroalkyl Substances (PFAS) are a large family of man-made organic compounds, including at least 12,000 manufactured fluorinated organic chemicals used since the 1940s. The understanding of these compounds is rapidly developing and there is no universally accepted definition of PFAS. OECD has attempted to consolidate the definition of PFAS (OECD, 2021):

PFASs are defined as fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), i.e. with a few noted exceptions, any chemical with at least a perfluorinated methyl group (-CF3) or a perfluorinated methylene group (-CF2-) is a PFAS.

The definition of PFAS is important when it comes to remediating sites where there is PFAS contamination, and to what level a site or substrate could be considered 'remediated'. It is plausible that different jurisdictions will adopt different definitions of PFAS for regulatory purposes, and indeed the UK Health and Safety Executive Regulatory Management Options Analysis (HSE, 2023) uses a more limited definition. Various grouping strategies for the compounds have been proposed and published (Cheng, et al., 2022) (OECD, 2021) (OECD, 2022) which can be based on intrinsic properties or the level of risk posed by a group of compounds i.e. grouping of PFAS with similar toxicity.

Contamination of soil and water systems by PFAS is a widespread issue and can lead to significant human health and environmental impacts. Remediation of these sites will reduce the overall burden of PFAS on society, minimising risks of exposure by eliminating key hotspots or point sources.

The wider use and often uncontrolled release of PFAS containing substances began around the 1960s and is still widespread across Europe despite restrictions on some operations having been introduced in recent years. 'High risk' sites include those where firefighting foams are present/widely used such as military facilities, airports and fire stations, industrial manufacturing sites such as chemical works, refineries, textiles and metals, as well as various landfills where the diffuse contamination from consumer products is accumulated (Jacobs, 2023c).

PFAS transport and accumulation in environmental media varies depending on the physicochemical properties as well as environmental conditions but generally short-chain PFAS are more water soluble and therefore mobile, while long-chain PFAS tend to adhere more to soil particles and also accumulate in the food chain (Lewis, et al., 2022). There are numerous impact pathways leading to human exposure – primarily through drinking water; however, the soil in hotspot areas can result in leaching into groundwater, contaminating nearby surface water and ultimately affecting drinking water supplies (Dickman & Aga, 2022). It is therefore important to address all sources of PFAS contamination and human/animal exposure pathways in combination.

In order to prioritise interventions and direct resources in a proportionate manner towards addressing the risks, it is important to estimate site-specific costs of remediation and the collective benefit of actions/regulatory responses.

2.2 Impacts associated with PFAS

PFAS exposure has multiple detrimental impacts, primarily involving those on human health. These include increased risk of cancer, multiple diseases, and development complications. See more detail of these in Section 5.2.1. Humans are exposed to PFAS through varied contamination sources such as point source pollution, consumer products, drinking water and the food chain.

The most recent European assessment of the risks to human health related to PFAS in food (EFSA, 2020) concluded that effects on the immune system, as shown by decreased antibody response to vaccines, were the most critical for risk assessment. The UK RMOA (HSE, 2023) acknowledged that while there is limited evidence on the human health hazard for many PFAS, there are toxicology data for a limited number of well-regulated

PFAS. The UK RMOA identified that the primary concern with PFAS is to the environment, driven by their extreme persistence, as well as mobility and potential for bioaccumulation.

As for environmental impacts, when passing through soil and waterbodies, PFAS can have highly detrimental impact to ecosystems, including toxic effects on aquatic animal species and a reduction in soil bacterial biodiversity (see Section 5.2.2).

2.3 PFAS remediation approaches

As emerging contaminants, remediation approaches to immobilise, remove or destroy PFAS are in varying stages of development with some being regularly used in the field and others being trialled in controlled conditions; few destructive approaches are available at field scale. The characteristics of PFAS are such that when ground becomes contaminated, surface waters, groundwater, soil and any capping, paving or drainage materials can all be affected, with the liquid and solid phases requiring different remedial approaches. Consequently, a combination of multiple technologies known as 'treatment trains' may be required to fully remediate a site (this is assumed in our analysis here). Some of the most widely reported remediation technologies for the soil and other solid materials are:

- Stabilization with a range of treatment additives, some of which are cement-based. The PFAS compounds become bound to the additive material and are no longer free in the environment. However, they are neither destroyed nor removed.
- Thermal treatment including incineration off site. High temperatures (>900°C) are needed to destroy PFAS compounds.
- Soil washing on-site but ex situ.
- Excavation and landfilling at an off-site disposal facility.
- Phytoremediation (nature-based solutions using plants, bacteria, fungi) either in situ or ex situ.

For contaminated waters removal of PFAS compounds can be achieved through the use of ion-exchange resins (IX) and/or activated carbon filtration media which entrain the PFAS compounds as the water passes through. These approaches can be applied in the ground (in situ) or above ground (ex situ) in a treatment facility where water extracted from the ground or from surface water can be dealt with. In situ treatments are commonly in the form of permeable reactive barriers (PRBs) which are 'curtains' or walls of treatment media which allow groundwater to flow through them, installed in the ground in locations which capture the flux of contaminated groundwater removing the contaminants as it passes through. It should be noted that PRBs do not destroy PFAS, but bind the PFAS so they are no longer free in the environment.

The size (length, depth and thickness) of the barrier wall is designed to capture the plume of contaminated water and to provide a residence time sufficient for the fixing of the contaminants within the barrier media to take place. The design of the barrier must respond to the site conditions, geology, soil properties, contaminant concentrations and other constraints such as buried utilities.

The PFAS compounds will be captured in the filter media which will eventually lose its capacity to absorb the compounds and will need to be replaced. The longevity of stabilisation techniques for PFAS is not yet proven. Some types of the filter media used in the ex-situ filtration of water can be regenerated but others need to be treated, by thermal means to destroy the PFAS, or disposed of to landfill.

In developing the cost model, evidence of recently completed or active remediation schemes has been used as far as possible.

2.4 Costs and benefits of remediation

The costs of remediation are the main focus of the modelling exercise, as outlined in the scope. Costs which could be incurred include remedial works on both soil and groundwater, capital expenses, monitoring/operational costs, centralised water treatment costs and any miscellaneous costs such as finance/consultancy/site inspection/administrative/regulatory. Due to the nature of the literature, the most reliable values primarily revolve around soil and groundwater remediation costs, thus these are what the majority of the modelling is focussed on. There are wider costs from the remediation of PFAS, such as legal costs of action against polluters or the cost of transitioning away from PFAS use in production, however these are not further explored in this analysis.

The benefits of PFAS remediation are as vast as they are hard to assess. There is a clear economic benefit from both the improvement of quality of life and increased lifespans brought by the removal of contamination.

There are also unintended consequences associated with remediation, which depending on the technique can be carbon / resource intensive. Excavation and disposal of material would generate noise and transport emissions – both of which should be captured as costs (negative externalities). Whilst these impacts are important, these sustainability concerns fall outside of the scope of this work at this stage.

2.5 Economic appraisals of PFAS interventions

There are a handful of economic appraisals of PFAS interventions and none of them are comprehensive. In 2019, the Nordic Council of Ministers' report presents the potential effects of PFAS and avoided negative health impacts from reducing PFAS concentrations (Goldenman, et al., 2019). The US EPA recently published their analysis on the economic impacts of introducing a more stringent PFAS concentration level for water quality (EPA, 2023). These are explored in more detail in 5.2.3, with a more rounded discussion of the potential benefits of PFAS in section 5. Overall, there are benefits to intervening with PFAS (health, economic, and environment) but the net impact when considered with the cost of intervention is not yet known due to significant uncertainties with the quantification of benefits.

3. Methodology

3.1 Introduction

Building a methodology to estimate the cost of existing PFAS contamination remediation is complex, both due to its widespread nature and the lack of historic research on the issue. On the lack of research, whilst there have been an increasing number of papers released, only a small proportion of these provide estimated costs. Thus, this analysis aimed to construct a robust yet flexible methodology for PFAS remediation appraisal. This involved looking at the specific site types identified in the PFAS Risk Explorer and assigning bespoke treatment trains to each, based on evidence review and expert elicitation.

3.2 Evidence Review

3.2.1 Purpose

The aim of this evidence review was to search for data on PFAS remediation (types, effectiveness, and cost), the potential impacts of PFAS (health, environmental, and economy), and different regulatory approaches to PFAS. The information gathered from this review would then feed into the model, discussed in sections 3.2.5 onwards, that estimates the scale and burden of PFAS in England; the information is also used within this report to provide context around the potential impacts of PFAS and remediation of PFAS. The evidence review searched through academic literature and grey literature, as well as consulting experts for PFAS information and recommendation of further sources of information.

3.2.2 Academic literature search

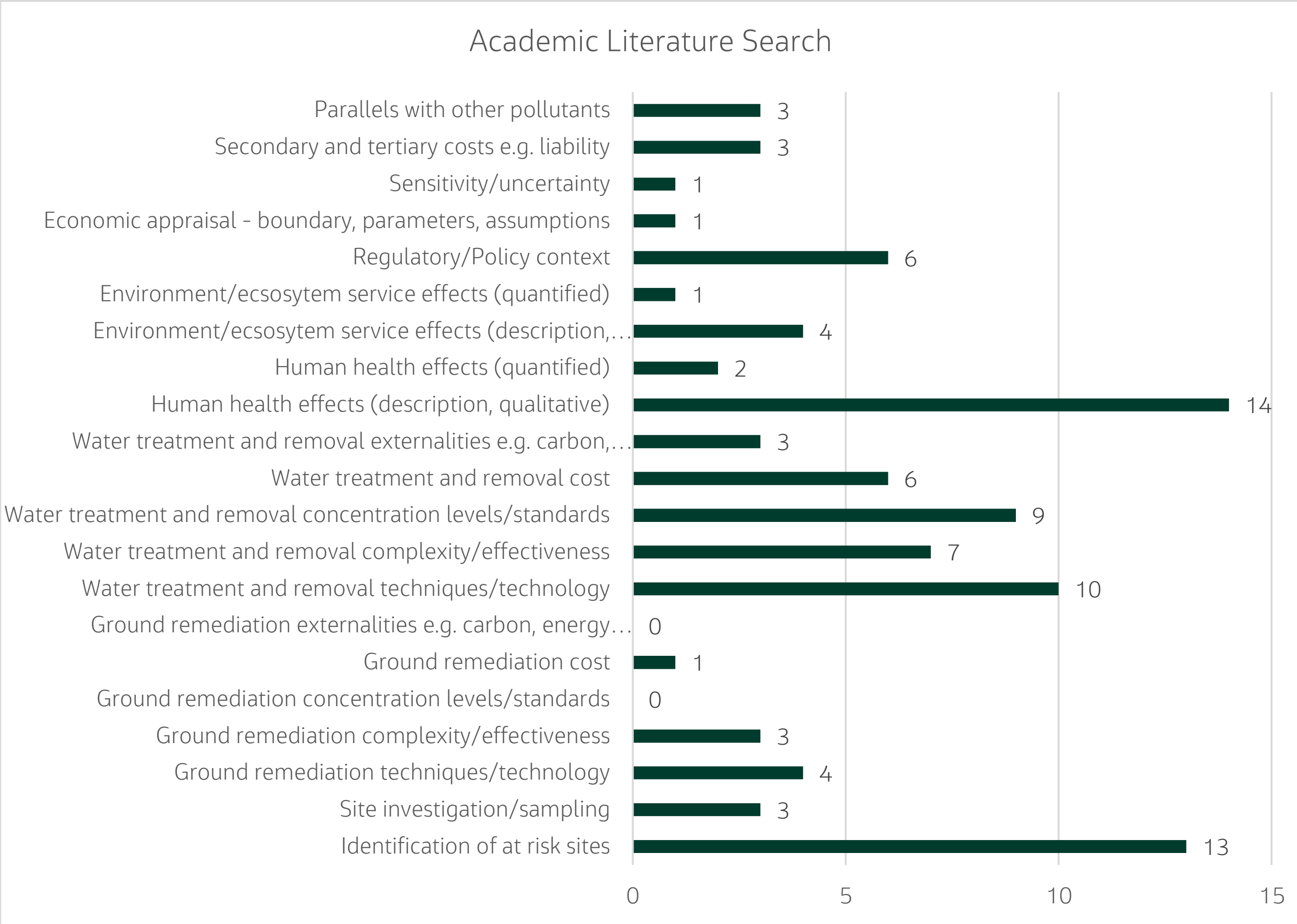
A list of search terms (Appendix A) was produced using the Jacobs team's expertise in economics and PFAS remediation. These terms covered the main topic areas: health impacts, environmental impacts, PFAS regulation, PFAS remediation techniques, and cost of PFAS remediation techniques. Originally this search included economic appraisals of cost of PFAS remediation but the conclusion was quickly reached that useful case studies were limited and therefore the search instead focussed on individual elements of an economic appraisal (cost data, potential impacts etc). When this project commenced (November 2022) the only useful publication was the article by the Nordic Council of Ministers (Goldenman et al., 2019), falling under the grey literature search; this is covered in section 5.2.3.

Jacobs has access to Elsevier's academic journal search engine Science Direct. Initially, we collected the first 100 articles associated with each search but after the first 50 articles, there was a significant drop in relevance and quality of articles. Therefore, we opted to collect the first 50 articles of each search and collate a list of articles. Some articles were collected multiple times by different search terms, these duplicates were removed, producing a list of 1,331 articles to be reviewed.

The title and abstract of each article was reviewed and relevance to the topic areas covered above was assessed. Three colleagues conducted this process, marking articles that were considered relevant and if an article was marked as relevant by two colleagues, it would then be shortlisted for further, more detailed investigation.

This produced a shortlist of 46 articles which were examined in more detail (Appendix B). The findings of these shortlisted articles were summarised in terms of identification of risk, site identification, water treatment, ground remediation, health impacts, environmental impacts, regulation, cost, assumptions, and economic impacts. Overall, the data were used in the modelling of PFAS cost remediation. See the Figure 3-1 below demonstrating the coverage of the topics relevant to the evidence review in the shortlisted articles.

Figure 3-1: Academic Literature Search



3.2.3 Grey literature

This search aimed to achieve the same objective as the academic literature search, to find information on PFAS remediation techniques (type, effectiveness, and cost) and regulatory approaches. The grey literature search investigated governmental, regulatory and non-governmental organisations that may publish data, research or regulation on PFAS; these organisations are mostly health, environmental, or water focused. Relevant information was collected and utilised within the modelling and production of this report.

3.2.4 [SECTION REDACTED]

3.2.5 [SECTION REDACTED]

3.3 Overview of analysis

The objective of this work is to provide a model which the EA can use to estimate the cost burden of PFAS remediation, on both a site-by-site and a sector basis. The key input into the model is the output of the WP1 PFAS Risk Explorer, which maps potential PFAS contamination source sites throughout England, whilst assigning a risk score to them. Most importantly to our modelling methodology, these are categorised by site types, allowing bespoke modelling of the varying remediation costs for different sites depending on their size and anticipated treatment methods.

We have constructed the model to be highly flexible, allowing for different scenarios to be assessed. These scenarios are based on two factors, firstly, the number of sites remediated, depending on a varying Risk Explorer score threshold, and secondly, the level of effort applied in the remediation. A low effort scenario could be to assume no on-site remediation of groundwater whilst the high effort scenario could encompass soil extraction, remediation/incineration, and on-site water treatment. Further detail on these scenarios can be found later in section 3.6.

Cost estimates are built up either on a bottom-up basis (for example per volume of soil treated) or a top-down basis per-site. When observing previous studies, top-down estimates have been more readily available, and closer to real-world costs from case study sites than their bottom-up counterparts; thus, the majority of the modelled costs are produced from top-down inputs. For each site type, various specific cost estimates are presented, from different sources. Bottom-up estimates are multiplied by the Risk Explorer factored area whilst top-down ones are multiplied by the number of factored sites. The estimate that is assessed to be most appropriate for the scenario is taken forward as the overall remediation cost for that site type. Most of these estimates will be presented as a range, to indicate the uncertainty of the value.

3.4 PFAS Risk Explorer inputs from Work Package 1

3.4.1 Risk Explorer overview

The economic model uses outputs from the PFAS Risk Explorer as the basis for estimating the number and area of different site types in England. The PFAS Risk Explorer used for this phase of the project is described in the PFAS Risk Explorer Handbook (Jacobs, 2023c) which provides further detail on the development of the GIS tool, the origin of the datasets, and the scoring system. The content of the PFAS Risk Explorer continues to evolve as improvements are introduced by activities under WP1.

The approach of the PFAS Risk Explorer is to identify the types of sites which may be potential sources of PFAS contamination ('site types', e.g. fire stations, Wastewater Treatment Works), and then to map the locations of these potential sites using a variety of information sources. Where possible, sites have been mapped as polygons based on the site boundary or the building extent. Where this has not been possible a judgment has been made to apply a circular buffer of a set distance. This is further explained in the PFAS Risk Explorer Handbook (Jacobs, 2023c). Mapping of a site as a potential PFAS source site does not mean that PFAS releases have occurred on the site, or even that PFAS has been used on the site. It simply indicates that the site has been identified from the data sources used, as a site where activities may have been undertaken that could have resulted in PFAS release to the ground. The mapping also does not include all sites where activities which might result in the loss of PFAS have been undertaken, but only those identified from the data sources detailed in the PFAS Risk Explorer Handbook (Jacobs, 2023c), however concern for this uncertainty is partially mitigated by the inclusion of the factoring process (Section 3.4.3). Potential limitations of the datasets are discussed further in the PFAS Risk Explorer Handbook (Jacobs, 2023c).

Potential source sites mapped in this process are then scored using the methodology described in the PFAS Risk Explorer Handbook (Jacobs, 2023c). There are three aspects used in the development of the scoring system: Site Type (source potential), Environmental Setting, and Water Quality Data. Scores have been developed for each of these aspects on a generic basis and using national datasets. Site type scores reflect the anticipated PFAS source potential of identified subject sites, based on a generic understanding of potential site activities. Site type scores are solely based on source potential and are not geographically dependent.

The purpose of the environmental setting scores is to allow risk ranking of sites based on their environmental setting, both for groundwater and surface water receptors. For each receptor type, generally available national datasets have been used, considering pathway and receptor information which can inform likely risks to surface water and groundwater. Spatial analysis is used to derive environmental setting scores for surface water and groundwater for each source site location.

The risk scoring methodology has been designed to also take into account existing water quality monitoring data when assigning site scores to potential source sites. A score has been calculated for each water monitoring point for which data are available, and spatial analysis is used to derive water quality scores for each source site location.

An overall site score (‘Final Score’, potentially between zero and 100) has been developed for each source site that has been identified, using the site type score, the environmental setting scores for the location, and the water quality scores for the location. The overall site score provides an indication of the relative risk ranking for the site.

It should be noted that identification of a specific site in the Risk Explorer only indicates the potential for the site to be a source of PFAS loss to the environment, specific assessment is required on a site-by-site basis to assess whether the site has been or is an actual user of PFAS, whether there are plausible pollutant pathways and whether there is any recorded PFAS impact on the environment.

There remains substantial uncertainty with regard to the threshold at which remediation for PFAS is likely to be required at any particular site, related in part to ongoing uncertainty with regard to future regulation and remediation standards required for PFAS, and the practicality and technical challenges of delivering beneficial remediation.

3.4.2 Site Types

The PFAS Risk Explorer outputs used in the economic model encompass a list of individual sites, with data entries for the following categories: SourceID, Site Type, Final_score (risk score), and SHAPE_Area (site footprint). These inputs are taken directly from the PFAS Risk Explorer (Work Package 1 of Phase 4, data exported 11/4/23), ensuring continuity with previous work. Note that the dataset has been refined since commencement of Work Package 1, and may be subject to further change as the model is enhanced as the project progresses. Depending on the scenario, a subset of the total list of sites is assumed to be remediated based on the selected Final Score Threshold. For example, Scenario 1 assumes all sites with a Final Score of 50 or greater undergo remedial works (see Section 3.6).

The Site Type classifications are as follows: Air Transport Sites, Military, Fire Stations, Permitted Landfill, Historic Landfill, Wastewater Treatment Works, COMAH sites, Chemicals, Refineries, Nuclear Permitted Site, TULAC (Textiles, Upholstery, Leather, Apparel and Carpets), Metals, Pulp and Paper, and Oil and Gas (see the PFAS Risk Explorer Handbook (Jacobs, 2023c) for details of these site types). These site types will have different environmental factors and intensity of PFAS contamination, thus different remediation methodologies are likely appropriate for each, with different final remediation cost estimates. Several of these site types are grouped, bringing multiple sites with similar attributes together under the same remediation methodology. The reasoning for grouping is as follows:

- Air Transport Sites/Military: Air transport sites and military sites are roughly comparable to each other. Firstly, they are of a similar scale, being some of the largest sites modelled in terms of footprint. Secondly, they have a similar land formation, with large paved areas such as runways, as well as more permeable zones such as grass and soil. Thirdly, contamination comes from a similar source and intensity, mainly the use of Aqueous film forming foams (AFFF) in fire training activities.

- COMAH/Chemicals/Refineries: These sites are of a similar scale, being smaller but having a higher intensity of contamination. The main source of PFAS on these sites is likely to be use of AFFF in fire suppression systems (including accidental loss), in fire training and demonstration of emergency systems, and in incident response. PFAS may also be used in some industrial processes. PFAS may have been lost to ground through deliberate past flushing of fluids, through loss of containment and through cracks in the largely paved environment, or any grassy areas.

- TULAC/Metals/Pulp and Paper: All of these are industries where PFAS may be used for specialist applications within the manufacturing process, for example for surface treatments and coatings or as a mist suppressant. PFAS loss to the environment may occur through for example accidental spillage and discharge of process fluids.

The output from the PFAS Risk Explorer used in this phase of work is summarised in Appendix D; this summary includes histograms showing the distribution of both site area and risk score for all site types.

3.4.3 Factoring

Whilst the outputs from the PFAS Risk Explorer can provide the numbers of these respective sites and their cumulative area footprint, as described above there are known limitations within the mapping and the model which will affect the accuracy of estimates based simply on the sites and scores in the model. The work in Phase 3 Task 9 included initial development of simple factors which were applied to the estimated land area and site count to provide a better overall estimate of impacted land area and site numbers. This has been developed further for this study, with the modified approach presented below also taking into account updates to the PFAS Risk Explorer since Phase 3.

The factors and the rationale behind them are detailed in Appendix E. These factors have been developed using professional judgment and current understanding of PFAS use in England. They provide an indicative assessment and should be treated with caution. Each site is therefore assigned six factors, between 0 and 1, as informed by Jacobs Land Quality team. The factors used are as follows:

- A – Proportion of mapped site area likely to be impacted: this is applied to the area footprint and accounts for the fact that contamination will only cover a certain percentage of the site area.

- B – Proportion of sites likely to have PFAS impact: this accounts for the fact that not all sites identified will have PFAS contamination.

- C – Proportion of current English sites likely mapped in PFAS Risk Explorer: some existing sites may have been missed due to the level of data quality (completeness of data set).

- D – Proportion of historical English sites likely to be mapped in PFAS Risk Explorer: some historical sites may have been missed due to the level of data quality (completeness of data set).

- E – Proportion of missing historical sites likely to have PFAS impact: this is linked to factor D, and accounts for the proportion of missed historical sites where PFAS contamination is actually possible i.e. the older the site, the more likely it was in operation before PFAS were commonly used.

- F – Double Counting: within the PFAS Risk Explorer, different sites may overlap each other, for example, a COMAH site may intersect a Nuclear Permitted Site. This factor removes these overlaps from the aggregate.

As factor C applies to only current sites, and factors D and E apply to only historical sites, they cannot both be directly applied to the total sites/area numbers from the Risk Explorer output. These numbers must therefore be split into the number of sites/area of both current and historic sites, based on proportions derived from the Risk Explorer mapping (Appendix E). Once these separate values are calculated, the factors are applied using the following equations.

Figure 3-2: Factoring Calculation Method

$$Risk\ Explorer\ Factored\ Sites = \left(\frac{Current\ Sites * B}{C} + \frac{Historic\ Sites * B}{\left(D + (1 - D) * (1 - E)\right)}\right) * F$$

$$Risk\ Explorer\ Factored\ Area = \left(\frac{Current\ Sites * A * B}{C} + \frac{Historic\ Sites * A * B}{\left(D + (1 - D) * (1 - E)\right)}\right) * F$$

Note that the calculation for factored sites and area differs only in that the area is subjected to a further factor in A. From this factoring process, more realistic site/area estimates are produced for each individual site type. These estimates can be taken forward into the cost modelling stage. See Appendix E for the factor values used at this stage, as well as the justifications behind them. Also see Section 4.2 for the unfactored and factored site/area figures.

3.5 Identification of potential high-risk sites

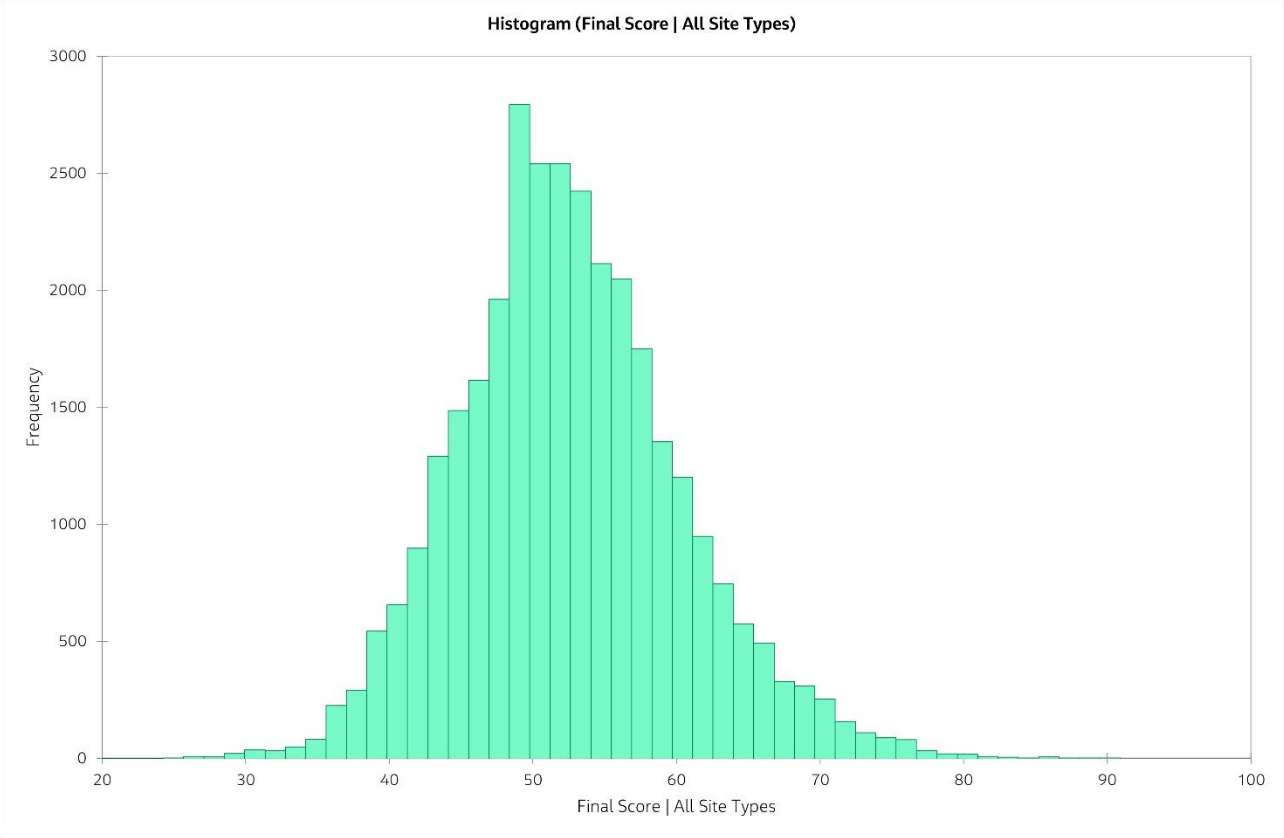
While the output of the PFAS Risk Explorer includes all sites mapped as potential source sites, the objective of this task is to assess the costs of remediation of high-risk sites, that is sites with the highest pollution potential which are in locations of highest sensitivity.

The overall site scores (Final Score) derived using the PFAS Risk Explorer provide an indication of the relative risk ranking for individual sites, however there is no absolute measure of what constitutes a ‘high-risk site’, and where the cut-off should be placed when identifying high-risk sites to be included in the economic model.

Figure 3-3 shows the distribution of Final Scores for all sites in the PFAS Risk Explorer, which shows a generally normal distribution with a median around a score of 50. Appendix D includes further charts illustrating the distribution of Final Score by site type.

As PFAS are emerging contaminants, there is not yet a robust case record demonstrating the types of sites and settings which have required remediation, and therefore a level of professional judgment has had to be used in assessing what may constitute a ‘high-risk’ site for the purpose of this study. Based on review of known sites, it is considered that sites with a Final Score of 60 or above meet the criteria for ‘high-risk’ sites. However, there are also known sites with Final scores between 50 and 60 where remediation has been required, and therefore a lower threshold of 50 would provide a more precautionary cut-off for the definition of ‘high-risk’ sites. Figure 3-3 shows that more than half of all the mapped sites in the PFAS Risk Explorer have a Final Score of greater than or equal to 50.

Figure 3-3: Distribution of PFAS Final Score for all sites



3.6 PFAS remediation modelling – scenario definitions

Three scenarios are modelled, each addressing a different number of sites and using different remediation methodologies. These scenarios are defined as follows:

- Scenario 1 – Comprehensive
    - Final Score Threshold is set at 50, relatively low, therefore more sites are considered as requiring remediation.
    - Comprehensive remediation suggested is to immobilise/remove a significant amount of PFAS from the soil and environment for each site type. This largely involves on-site remediation of both soil and groundwater.
    - The estimates are presented as a range, to reflect both the uncertainty in results, and the varying levels of effort that may be required in remediating the site type.
- Scenario 2 – Practical
    - This scenario recognises that there is likely to be a limit to public and private expenditure on this issue. Whilst we assume that not all costs will come out of the public purse, and polluters may be made liable, total expenditure will likely be somewhat limited. Thus, the Final Score Threshold is set at 60, reducing the number of sites considered to only those which present the highest risk.

- Similar to Scenario 1, there is comprehensive remediation of the sites above the Final Score Threshold. On-site remediation of soil and groundwater is used, with site-specific techniques being employed.
- The estimates are presented as a range, to reflect both the uncertainty in results, and the varying levels of effort that may be required in remediating the site type.

- Scenario 3 – Wastewater Treatment
  - Centralised remediation scenario, no on-site remediation of ground or surface water. Historical contamination which has reached ground and surface water bodies can be recovered and conveyed to sewer where it is then treated by an 'end of pipe' solution at wastewater treatment works rather than at a site-specific treatment plant on site.
  - This scenario presents remediation that is additional to Scenarios 1 and 2. It does not recommend on-site remediation.
  - As all sewage and wastewater flows are aggregated, there is no way to apportion the costs of this option to individual sectors or sites, thus the Final Score Threshold is set to 0. However, in terms of the build-up of the cost estimate, this threshold is of no consequence, as modelling is instead based on the cost of PFAS treatment of all flows into wastewater treatment works (WwTW).
  - The range in the reported cost estimate is primarily driven by uncertainty in both the unit cost of remediation (per WwTW) and the volumes of waste treated independent of their source.

The definition of "high-risk" has an influence on the scenarios and results. Section 4.6 explores other assumptions and features of modelling that influence the results.

3.7 PFAS remediation modelling – Scenarios 1 and 2

This section outlines the specific methodology used for the cost estimates of each site type, under Scenarios 1 and 2, including detailed discussion of the estimates used from the evidence review. The information presented in this section is also available in the Excel-based model provided to the EA. Both Scenarios 1 and 2 are discussed simultaneously here, as the primary difference between them is the number of sites/area treated. See below an overview of the remediation methodologies for each site type:

Table 3-1: Site Type Remediation Method Summary

Site Type	Remediation Method				
	Soil remediation (excavation and treatment)	Install permeable reactive barrier for on-site groundwater to pass through	On-site water treatment	Install low permeability cap on site to reduce effluent generation	Nominal per site value
Air Transport Site/ Military		High			
Fire Station		High			
Permitted Landfill					
Historic Landfill				High	
Wastewater Treatment Works		High			
COMAH/Chemicals Sites/Refineries		High			
Nuclear Permitted Site					
TULAC/Metals/Pulp and Paper		High			
Oil and Gas					

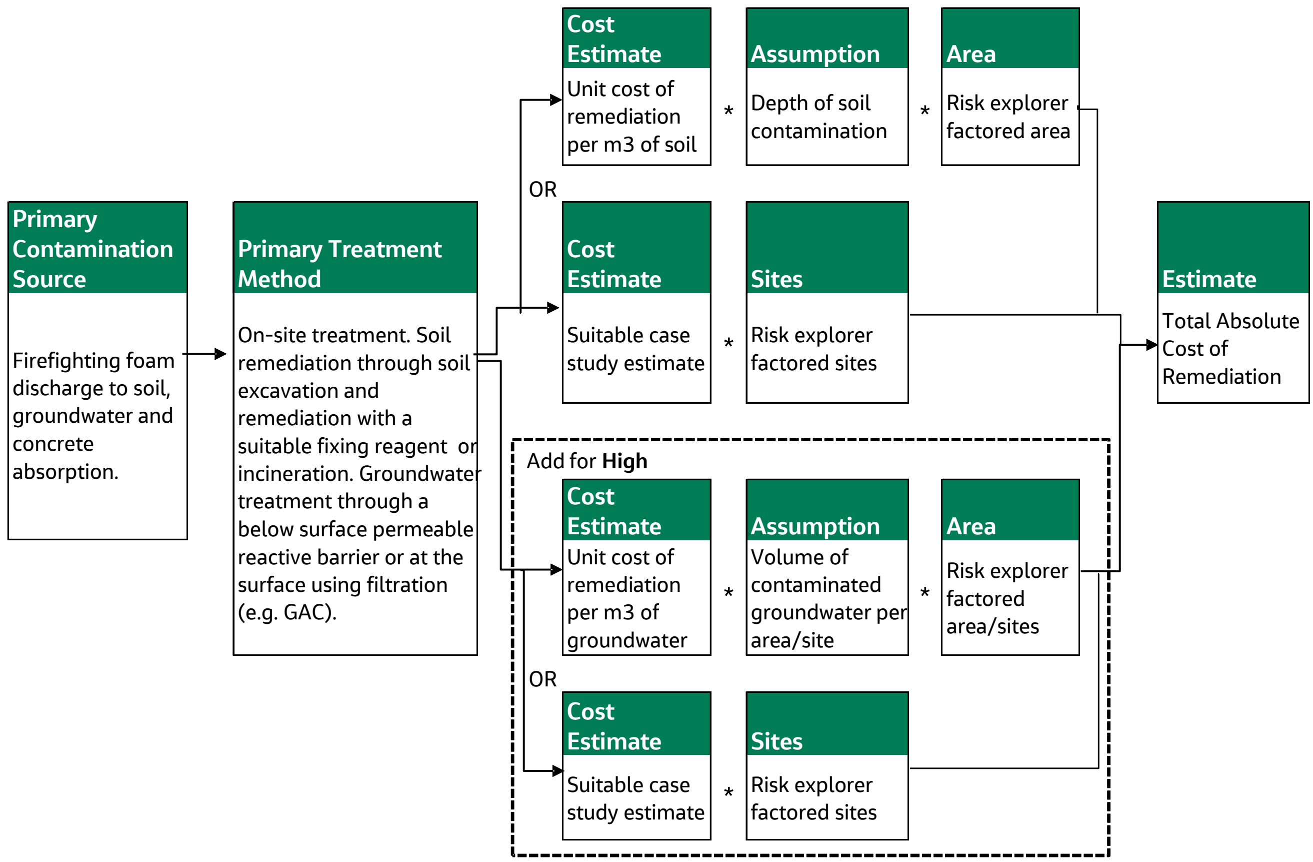
In the above, a black box indicates the assumed minimum level of remediation. Thus, this is included in both the low and high end of the range. Grey 'high' boxes indicate an additional, comprehensive remediation stage which could be employed. The cost of this is included in the high (upper end of the range), under both Scenarios 1 and 2.

Whilst the specific remediation methods for each site type are discussed in the following sections, a few general observations can be made at this stage. For almost all sites, apart from landfills, some form of soil remediation is assumed, with additional groundwater treatment in the high scenario. This can be interpreted as treating the sites' existing contamination as a minimum, with the upper end of the cost range including the limiting of lingering contaminants seeping into the surrounding area. For landfills, due to their inherent nature, soil remediation is not feasible. Therefore, on-site water treatment is assumed as the minimum, due to the large amounts of landfill leachate generated from sources such as rainwater. Finally, specifically for Nuclear Permitted Sites and Oil and Gas sites, the calculation process simply involves a total estimated cost being applied to each site (i.e. a 'top-down' approach). This is due to the expected low number of these sites and the complexity of separating PFAS treatment from existing remediation activities.

3.7.1 Air Transport/Military sites

The logic chain below demonstrates the various possible methods employed in building up a cost estimate for remediating Air Transport/Military sites. The assumed treatment method is soil remediation with the addition of the cost of installation of an on-site Permeable Reactive Barrier (PRB) for the high end.

Figure 3-4: Air Transport/Military Site Calculation Framework



When creating a bottom-up estimate of the cost of soil remediation, the case studies outlined in The Cost of Inaction (Goldenman et al., 2019) have been used. As discussed in Section 3.2, the evidence review identified multiple key papers, one of the primary papers on this topic is the Cost of Inaction report and is significantly referred to in this analysis. For the bottom-up estimate, we refer to the Schiphol Airport case study, in which a cost of €30-40 million was incurred to remediate 50,000 m^3 of PFAS contaminated soil (Goldenman et al., 2019). Using the centre of this range, and applying a GDP deflator and currency conversion, produces an estimated remediation cost of £700/m^3. This is multiplied by a depth assumption (currently at 4m) and the Risk Explorer factored area, to produce a total absolute cost of remediation of £412bn in Scenario 1 and £305bn in Scenario 2. These estimates are deemed as highly unrealistic and unachievable, due to their scale, which stems from the one-off nature of the Schiphol intervention. Thus, a set of per-site, top-down estimates are applied.

The Cost of Inaction report also states a best estimate of "*€5 million/case is taken, with a range for the main cost of €300,000 to €50 million*". Taking forward this €5 million per site estimate, and again applying GDP deflation, currency conversion and multiplication by the Risk Explorer factored sites, produces a much lower total absolute cost estimate of around £2.10bn in Scenario 1 and £1.04bn in Scenario 2.

Another key source which is employed multiple times throughout this exercise is the Environmental Business Journal paper titled *PFAS Waiting Game Continues in 2022* (EBJ, 2022). This article provides average site remediation costs for three different types of US airport: Major ($20 million), Regional ($7.5 million) and Commercial/Private ($6 million). Considering that in the US, regional airports are very large, being comparable in size to a UK major airport. Thus, a weighted average of the three is taken, with a high weighting on the regional estimate. When applying GDP deflation and currency conversion, and multiplying by the Risk Explorer factored sites, this produces a total absolute cost estimate of £3.88bn in Scenario 1 and £1.92bn in Scenario 2.

To provide a third cost estimate, the Jersey Airport case study is used from Appendix XIII in *The Global PFAS Problem: Fluorine-Free Alternatives as Solutions* (Bluteau et al., 2019). A detailed cost breakdown of the site's remediation is provided, with the total being £7.37 million. When applying GDP deflation, and multiplying by the Risk Explorer factored sites, this produces a total absolute cost estimate of £3.44 bn in Scenario 1 and £1.70bn in Scenario 2. This could potentially be an overestimate as this cost includes the installation of an impermeable concrete barrier, which is an unrealistic remediation step to be applied at scale. This estimate does, however, fall within the range of the previous two per-site cost estimates.

[REDACTED]

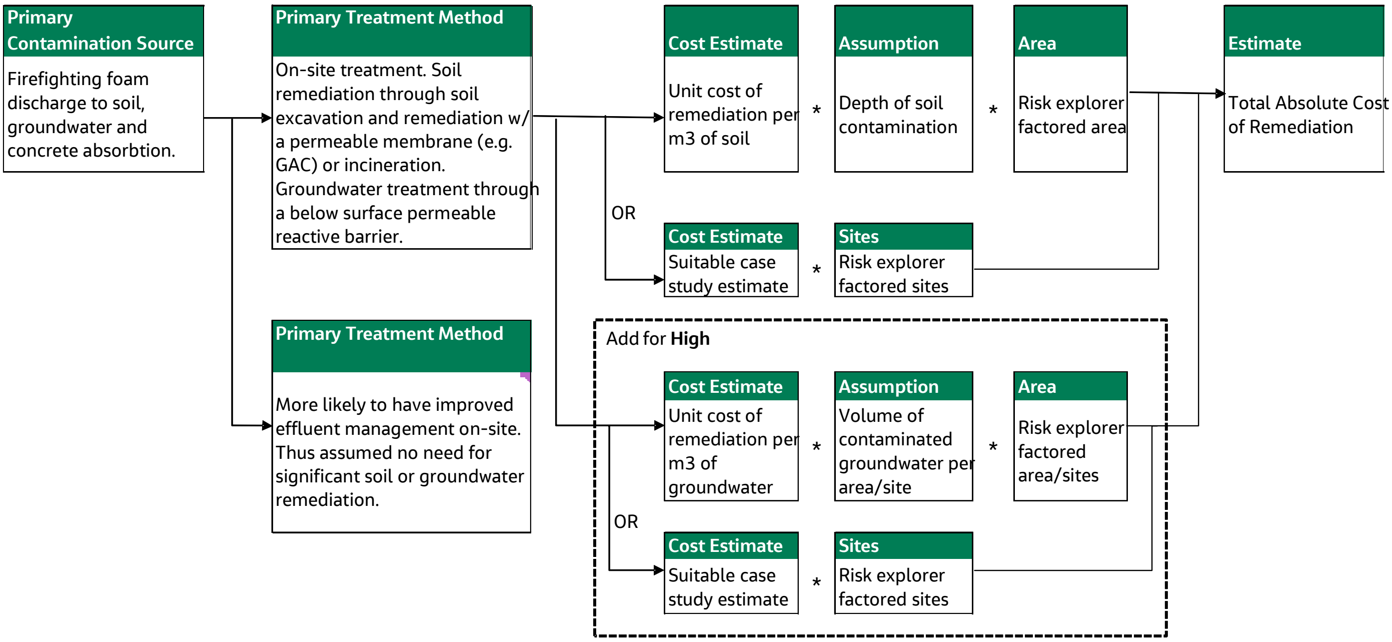
[REDACTED]

[REDACTED]

3.7.2 Fire Stations

See below an example logic chain, demonstrating the alternative methods available for building up a cost estimate for remediating contaminated fire stations. Similar to Air Transport/Military sites, this includes both the treatment of soil using a binding additive or incineration, and of groundwater in the high end of the range, likely using a PRB. A combination of bottom-up and top-down cost estimation methods are explored.

Figure 3-5: Fire Station Site Calculation Framework



The first set of groundwater cost estimates are based on the Wood paper, which was prepared for the ECHA to estimate the unit costs of firefighting foam remediation (Wood et al., 2020). This presents per tonne cost estimate ranges for the remediation of contaminated soil, for both excavation with offsite disposal, and for excavation with incineration. Note that neither of these estimates explicitly involves remediation with binding additives, which is the default assumed for most site types. However, remediation of soil with additives is in general more expensive than off-site disposal and less expensive than incineration, thus the cost of remediation with binding additives will fall within any modelled estimate ranges, reducing the concern regarding its omission. The Wood estimate ranges are averaged for both remediation techniques, and subjected to currency conversion, GDP deflation and a conversion from a per tonne unit cost to a per m3 unit cost. This is then multiplied by both the Risk Explorer factored area and a depth assumption to produce total absolute remediation cost estimates. These are £1.07bn to £2.97bn in Scenario 1 and £0.76bn to £2.11bn in Scenario 2.

The second cost estimate for soil remediation presented is based on site values provided by the European Chemicals Agency (ECHA, 2022), which in themselves are based on the previous Wood report for the ECHA (Wood et al., 2020). These estimates are for sites predominantly contaminated through the use of firefighting foams and are therefore suitable for application to the fire station site type. The values have a very broad range, stemming from the fact that they encompass the costs for multiple site types. For example, the cost of soil excavation and off-site disposal is said to range from €500,000 to €18,000,000. As fire stations are smaller, being in municipal areas, the cost estimates brought forward are heavily weighted towards the lower end of the presented ranges The specific treatment techniques relevant to this analysis are soil excavation with off-site disposal, and soil excavation with incineration. As outlined by the paper, the low estimate assumes off-site disposal, whilst the high estimate assumes incineration. Based on this derivation, currency conversion and GDP deflation, per site remediation costs are estimated at £3.92 million to £9.41 million. Applying these to the Risk Explorer factored sites, low and high-cost estimates are produced, namely, £6.22bn to £14.94bn in Scenario 1 and £2.00bn to £4.79bn in Scenario 2.

[REDACTED'

[REDACTED]

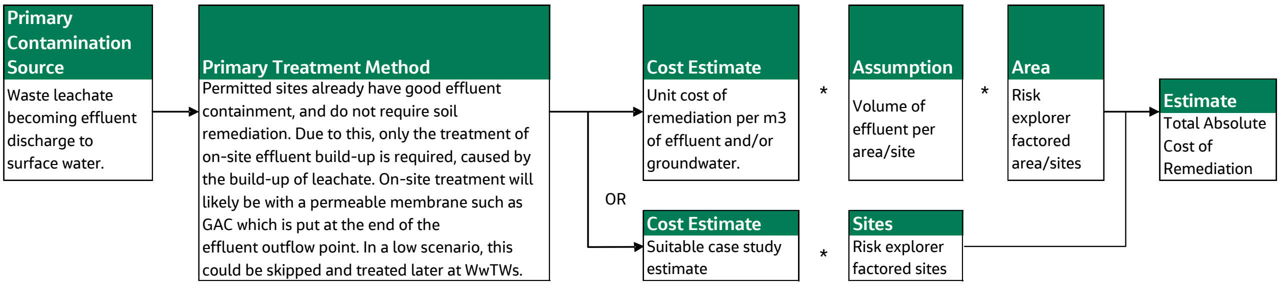
A final groundwater remediation estimate comes again from the Wood paper (Wood et al., 2020), in which a detailed breakdown of cost estimates for the onsite ‘Pump and Treat’ remediation method is provided. These include low and high estimates for both capital and annual operational expenses. In the lower range, remediation takes place over 10 years with annual costs of €85,000, whilst in the high, it spans 30 years with annual costs of €950,000. As this paper considers all sites contaminated by firefighting foams and fire stations are some of the smallest of these sites, the low value has been taken forward. Once subjected to currency conversion, GDP deflation and multiplied by the Risk Explorer factored sites, this produces total absolute cost estimates of £1.87bn in Scenario 1 and £0.60bn in Scenario 2.

[REDACTED]

3.7.3 Permitted landfill

For landfills, the most commonly referred to remediation methods are largely different to what has been previously discussed. This is because the PFAS source comes from the waste deposited within the contained landfill therefore soil remediation is not required. Secondly there is in most cases limited potential to redevelop the land, thus the risk of potential human contact with PFAS contamination is reduced. As a result, the primary contamination concern is the liquid leachate which accumulates from the waste stored in these sites. For Permitted Landfills, this leachate is assumed to be well contained, with adequate barriers preventing it from contaminating the surrounding groundwater. Consequently, the primary remediation method is on-site leachate remediation, using some form of ion exchange (IX) or GAC filtration treatment. See below an example logic chain for how a cost estimate could be constructed.

Figure 3-6: Permitted Landfill Site Calculation Framework



The predominant leachate remediation cost estimates used come from the paper Feng et al. (2021), which presents cost estimates on a unit cost and per-site basis, allowing for both bottom-up and top-down estimates. Starting with bottom-up, annual onsite and offsite remediation costs per m^3 of leachate are provided. In this case, onsite is cheaper than offsite, thus onsite methods are assumed for the low end of the range and offsite for the high end of the range (Feng, 2021). For these estimates to be comparable to the Risk Explorer factored area, they must be converted to m^2. The Feng et al. (2021) paper provides an example site area, with a daily leachate volume generated, allowing for calculation of annual leachate per m^2. However this single data point produced unreliable results, thus an additional estimate was sourced from another paper (Kanchanapiya, 2022) and the two were averaged to estimate leachate volume per m^2. This average was applied to the existing onsite/offsite remediation costs to produce an annual cost per m^2. This is then multiplied by a currency conversion, GDP deflator, the assumed intervention duration of 15 years (as used by the paper due to the lifespan of equipment used) and the Risk Explorer factored area in order to produce total absolute cost estimate. These range from £3.29bn to £4.19bn in Scenario 1 and £0.79bn to £1.01bn in Scenario 2. The large difference in cost between scenarios is due to many Permitted Landfills falling between 50 and 60 on the Risk Explorer score range.

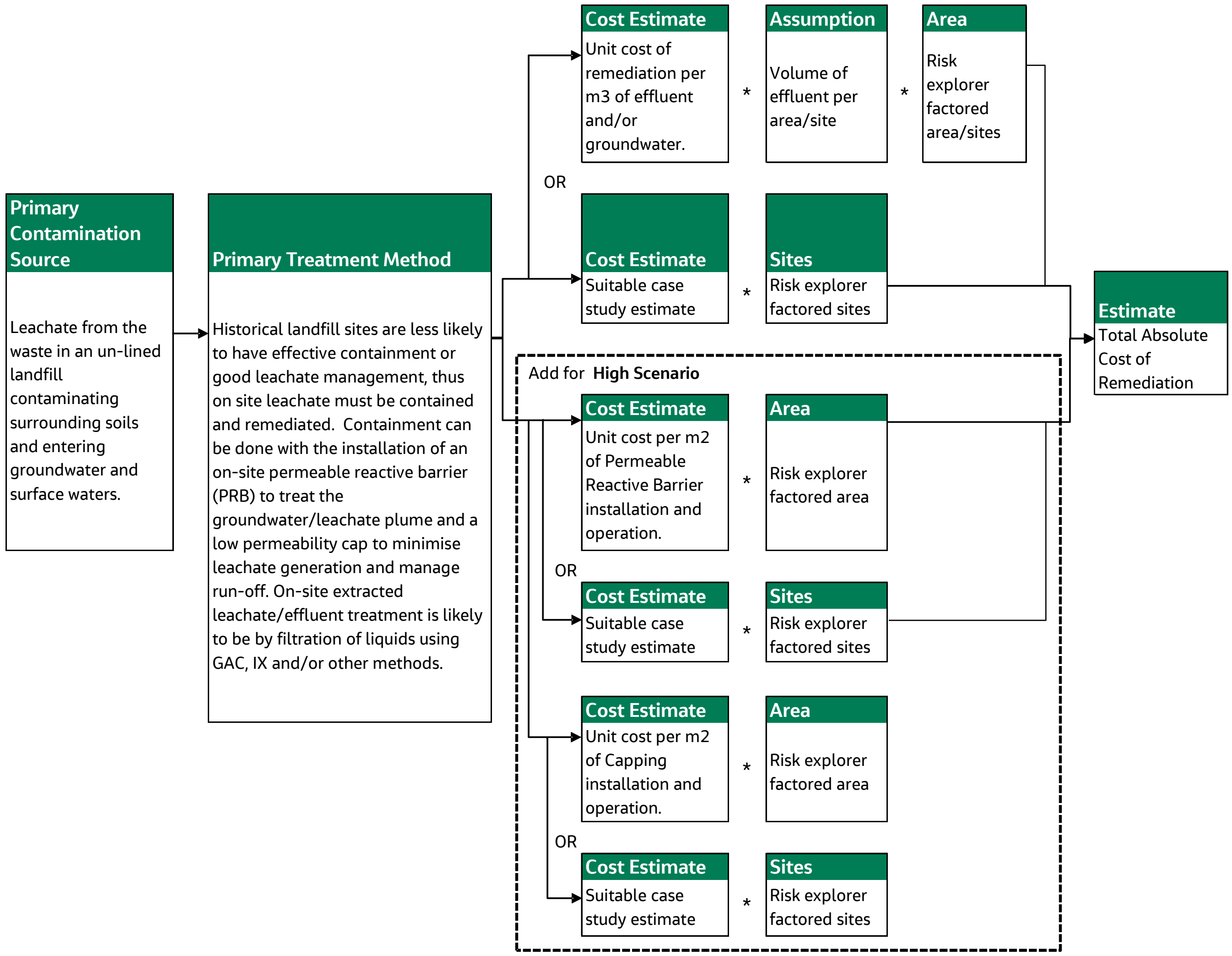
As for the top-down estimate based on the Feng paper, a case study with a range of costs is provided. These include one-off costs (construction), annual operation costs (electricity and chemical) and periodic maintenance costs (replacement of membrane bioreactor, nanofiltration and reverse osmosis). When factoring the annual operational costs and the periodic maintenance costs by the assumed 15-year intervention period, a final per-site cost estimate is produced for leachate remediation. This is subjected to currency conversion, GDP deflation and multiplied by the Risk Explorer factored sites to produce a singular total absolute cost estimate of £2.75bn in Scenario 1 and £0.51bn in Scenario 2. Again, there is a large decrease in the estimate between scenarios, with this being amplified by the fact that the sites which remain in Scenario 2 tend to be the largest sites in terms of area, thus the bottom-up estimate sees less of a decrease than the top-down one.

In terms of which estimate is used for the low-end of the range, the top-down per-site estimate is used, as it is the lowest whilst still at a similar magnitude to alternatives. As for the high end of the range, the bottom-up estimates were selected due to their adaptability to the large size of some Permitted Landfills. Specifically, the high end of the effluent treatment cost range is used.

3.7.4 Historic landfill

Historic landfills differ from Permitted Landfills in that they are less likely to be contaminated with PFAS due to the age of material waste deposited (this is addressed through the factoring). However, they are also unlikely to have adequate effluent containment, with a lack of barriers allowing leachate to contaminate surrounding groundwater and poor-quality capping allowing the ingress of rainwater into the waste mass. Thus, the majority of Historic Landfills that are impacted with PFAS would require the installation of some form of effluent containment infrastructure. Here, this is assumed to be done using capping on top of the site to prevent excessive effluent generation, as well as a perimeter PRB to hold PFAS contamination within the site. This method is deemed to be the most feasible with least impact on existing groundwater flows. An alternative was explored around installation of an impermeable concrete barrier to completely contain effluent, however this was deemed to be an unrealistically costly method. See an example logic chain of the costing methodology below.

Figure 3-7: Historic Landfill Site Calculation Framework



For leachate remediation, the methodology to estimate costs is identical to that used for Permitted Landfills. See the above section '3.7.3 Permitted Landfills'. Using this methodology, both bottom-up and top-down total absolute cost estimates are produced. For bottom-up, these are £5.44bn to £6.93bn in Scenario 1 and £1.40bn to £1.78bn in Scenario 2. For top-down, these are £17.15bn in Scenario 1 and £2.89bn in Scenario 2.

As for the installation of a concrete barrier, this comes from the Jersey Airport case study (Bluteau et al., 2019). This outlines a range of various costs incurred in the remediation, concrete capping and reinstatement of the training ground. Not all these costs are relevant to Historic Landfill barriers, thus a subset of these is taken forward, leading to a per site estimate of around £6 million. An estimate of the area of this training ground is also taken in order to calculate a cost per m^2 which is then adjusted by the GDP deflator and multiplied by the Risk Explorer factored area to produce total absolute cost estimates. Note, that as Scenario 1 represents comprehensive remediation, the total Risk Explorer factored area is assumed to have a barrier installed. However in Scenario 2 it is assumed that only 50% of the total factored site area would undergo the additional step of concrete barrier installation. This leads to less variance between the low and high in Scenario 2. As for the total absolute capping estimates themselves, these are £107.31bn in Scenario 1 and £13.81bn in Scenario 2.

[REDACTED]

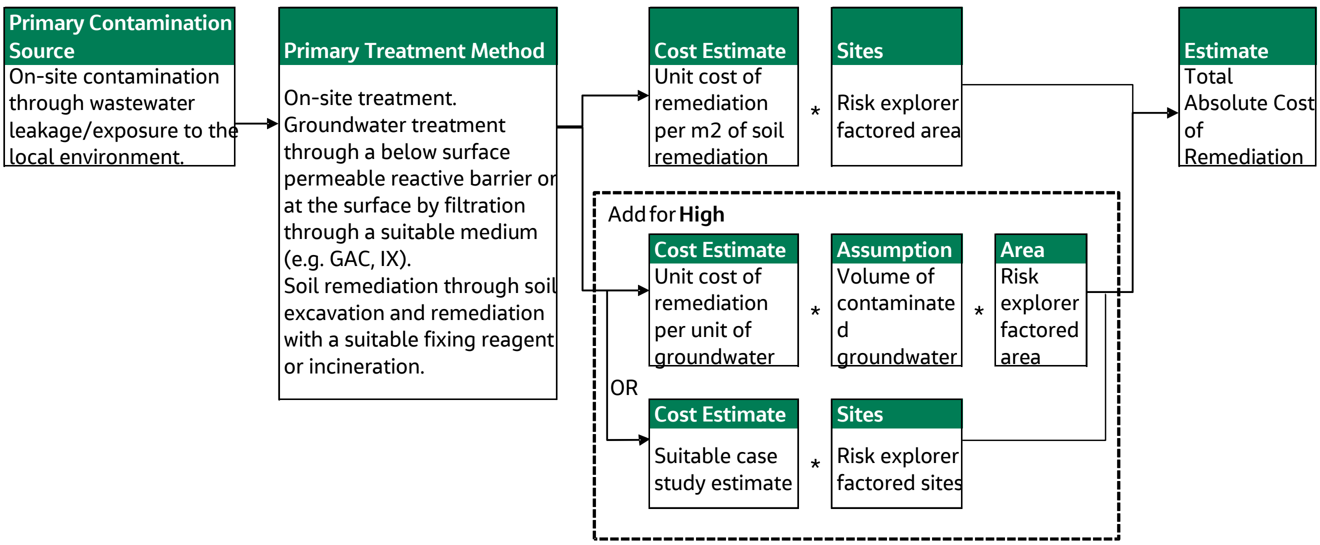
As for capping, the Wood paper provides a unit cost estimate per m^2 for this ranging from €75 to €150 (Wood et al., 2020)). The average is taken on the basis that there is nothing to indicate that a Historic Landfill unit will be towards the bottom or top of this range. This is then subjected to currency conversion, GDP deflation and multiplied by the Risk Explorer factored area to produce total absolute cost estimates of £24.83bn in Scenario 1 and £6.39bn in Scenario 2.

In terms of which estimates were taken forward, for effluent remediation, the upper end of the bottom-up estimate was used in both the low and high end of the range. This is due to the top-down estimate seeming unrealistically high, however, this leads to the high bottom-up estimate being used even for the low end of the range, to reflect a precautionary approach. As mentioned previously, PRB containment and capping was selected over concrete barrier installation. PRB containment is included in both the low and high whilst capping is added to the high end of the range.

3.7.5 Wastewater Treatment Works (WwTW)

Wastewater Treatment Works sites have been identified as high risk due to the potential for untreated PFAS contaminated water to come into contact with soil and groundwater. This means that remediation would be required to address both potential transmission routes of PFAS to the environment. The primary remediation method used at these sites is assumed to be soil excavation and treatment using a mix of off-site disposal and incineration, as well as groundwater treatment using a PRB. An alternative option has been explored where a modified clay is used to chemically immobilise PFAS in the ground, therefore preventing further soil damage and stopping potential groundwater damage. See an example logic chain for the calculation of the cost of remediation for Wastewater Treatment Works.

Figure 3-8: Wastewater Treatment Works Site Calculation Framework



For soil remediation, the primary estimates come from the Wood paper, which presents a low and high unit costs per ton for soil excavation and offsite disposal, soil excavation with incineration, and capping. Whilst estimates for capping are explored within the model, capping is assumed not to be necessary in the context of WwTW remediation (surface will be paved etc) and is therefore not taken forward. The low and high costs for both offsite disposal and incineration were averaged and subjected to a conversion from weight (ton) of soil to volume (m^3). A currency conversion and GDP deflation was then applied to produce unit costs per m^3 of soil of £375 and £1,041 for offsite disposal and excavation respectively (Wood et al., 2020). This demonstrates that incineration is a more costly method, however, as off-site disposal is likely to be limited by national landfill capacity, it is assumed that a mix of the two methods will be used. Based on consultation with Jacobs Land Quality team, it is assumed that between 10% and 30 % of the treated soil will be treated using incineration. This allows low, medium, and high expected per m^2 unit cost estimates to be produced of £441, £508 and £575 respectively. To generate the total absolute cost estimates, these unit cost estimates are multiplied by the Risk Explorer factored area as well as a remediation depth assumption of 3 metres (as informed by the Wood paper itself). This produced final soil remediation cost estimates of £23.38bn to £30.43bn in Scenario 1 and £14.63bn to £19.04bn in Scenario 2.

[REDACTED]

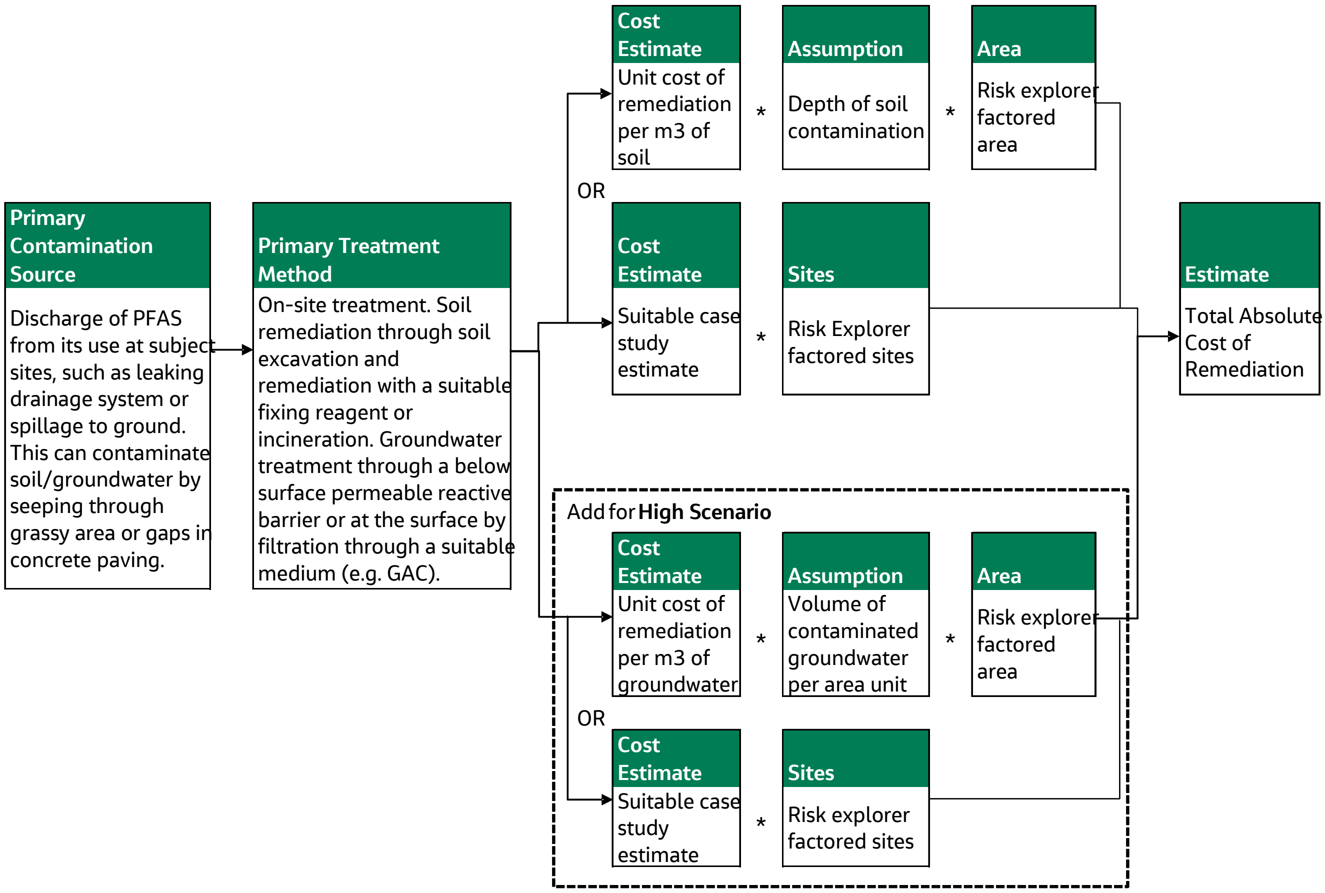
[REDACTED]

[REDACTED]

3.7.6 COMAH, chemical and refineries

For the group of sites encompassing COMAH, chemical and refineries, see the below logic chain. The method for deriving cost estimates is largely aligned with the other site types, with soil remediation plus on-site groundwater remediation in the high end of the range and soil remediation only in the low end. Note that the potential area of contaminated land is very large for these sites. Whilst the PFAS Risk Explorer applies a scaling factor to estimate the proportion of the total site area that is likely to require remediation, the cost estimates generated per site remain large.

Figure 3-9: COMAH/Chemical/Refineries Site Calculation Framework



The EBJ paper was used as a top-down estimate, which presents a per-site remediation cost of $20 million for refineries (EBJ, 2022), which is, as outlined earlier, also applicable to COMAH and Chemicals sites. When applying currency conversion and GDP deflation, this estimate comes to £17.7 million. When multiplied by the number of Risk Explorer factored sites, this produces a total absolute cost estimate of £20.83bn in Scenario 1 and £11.29bn in Scenario 2.

[REDACTED]

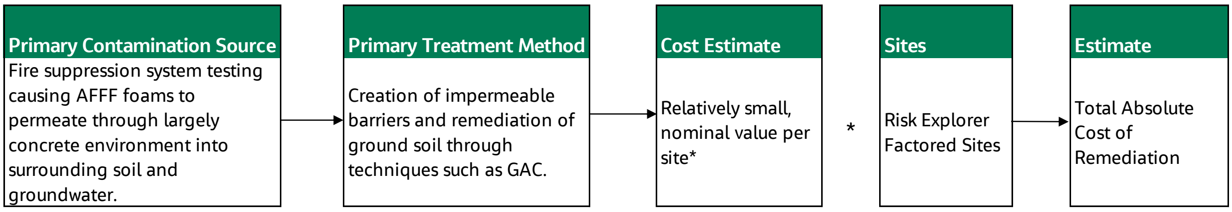
[REDACTED]

[REDACTED]

3.7.7 Nuclear permitted site

The below logic chain demonstrates the methodology used to calculate the cost of remediation of Nuclear Permitted sites. Whilst we assume that there would be a combination of soil and groundwater remediation, using methods such as GAC and PRB, instead a flat nominal value is applied to each site. The reasoning for this is that, due to the nature of nuclear plants, any wastewater will already have extensive remediation processes to account for nuclear waste. Similarly, ground remediation issues at nuclear licenced sites are likely to be dominated by radiological contaminants and the end state requirements for each site. If PFAS contamination remains, dedicated remediation may be too disruptive to an operating plant to be feasible. Thus, remediation is most likely to be considered within decommissioning strategies far into the future. This cost will likely be small when compared to the overall strategy, as well as only being applied to a small number of sites. Thus, a general nominal figure is attached.

Figure 3-10: Nuclear Permitted Site Calculation Framework

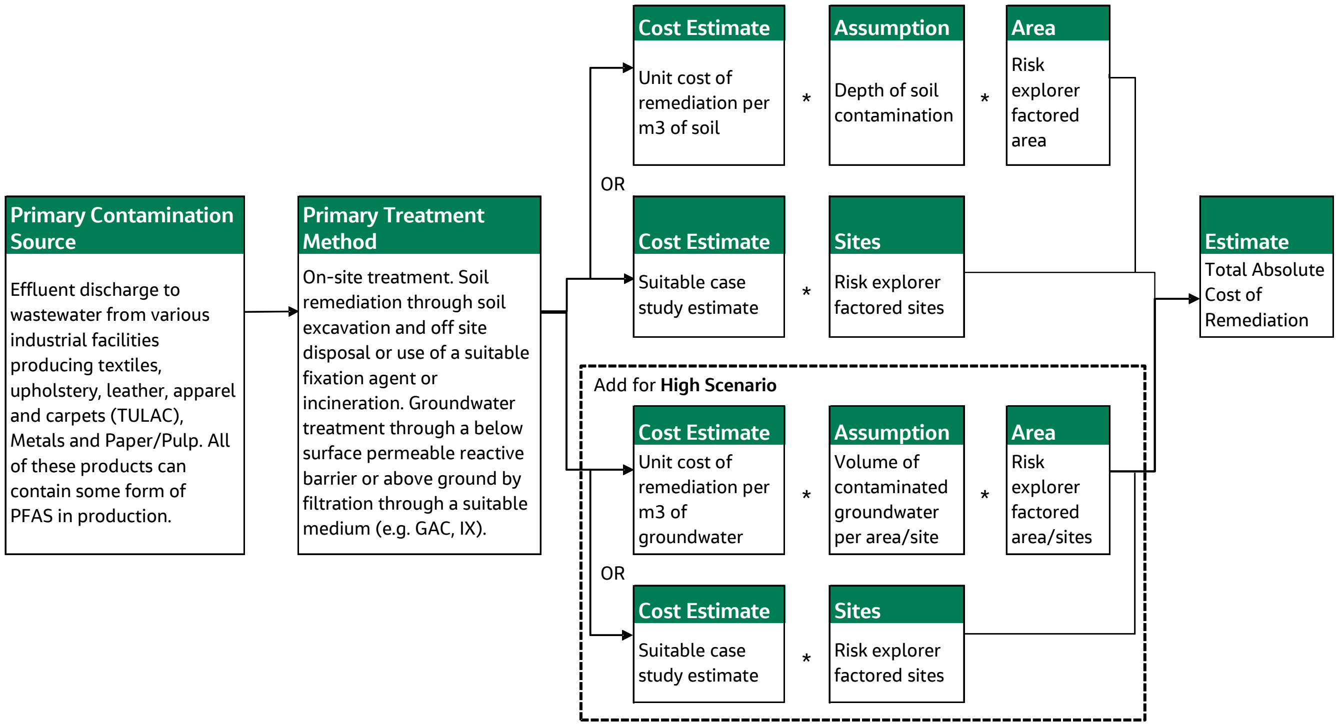


The nominal estimate used is informed by the EBJ paper, which estimates that the cost of remediation per US Department of Energy (DOE) site is $5 million (EBJ, 2022). As many of these DOE sites will be nuclear related, and this estimate aligns with professional judgment of the Jacobs Land Quality team, this value is seen as a suitable proxy. When applying currency conversion and GDP deflation, this per site cost becomes £4.4 million. When multiplying this by the Risk Explorer factored sites, this produces a total absolute cost estimate of £115 million in Scenario 1 and £22 million in Scenario 2.

3.7.8 TULAC, metals and pulp/paper

The methodology of the cost build-up for TULAC, Metals and Pulp and Paper sites is largely consistent with what has been demonstrated for previous site types, namely, soil remediation with on-site groundwater remediation in the high part of the cost range. See an example logic chain below:

Figure 3-11: TULAC/Metals/Pulp and Paper Site Calculation Framework



The first estimate for soil remediation comes from the EBJ paper, which outlines a group of sites entitled 'manufacturing sites using PFAS', remediation costs of $7.5 million per site (EBJ, 2022). This aligns with TULAC, Metals and Pulp and Paper sites, firstly, as they are all manufacturing sites involving PFAS, and secondly, as this estimate seems reasonable based on Jacobs Land Quality team's professional judgement. When applying currency conversion, GDP deflation and multiplying by the Risk Explorer factored sites, this produces total absolute cost estimates of £1.25bn in Scenario 1 and £0.15bn in Scenario 2.

An alternative bottom-up soil remediation estimate is also explored, using the Wood unit values from Section 3.7.2, due to the lack of literature on the costs of remediating these manufacturing sites and the fact that fire stations are the closest comparison in terms of size distribution. When multiplied by the Risk Explorer factored area and subjected to a depth assumption of 4m, this leads to total absolute cost estimates of £11.25bn to £31.24bn in Scenario 1 and £0.78bn to £2.17bn in Scenario 2. The large difference in bottom-up estimates is due to the increased risk threshold score removing some significantly large area sites. These estimates are clearly unrealistic, due to the large area of some of these sites, thus they are not taken forward.

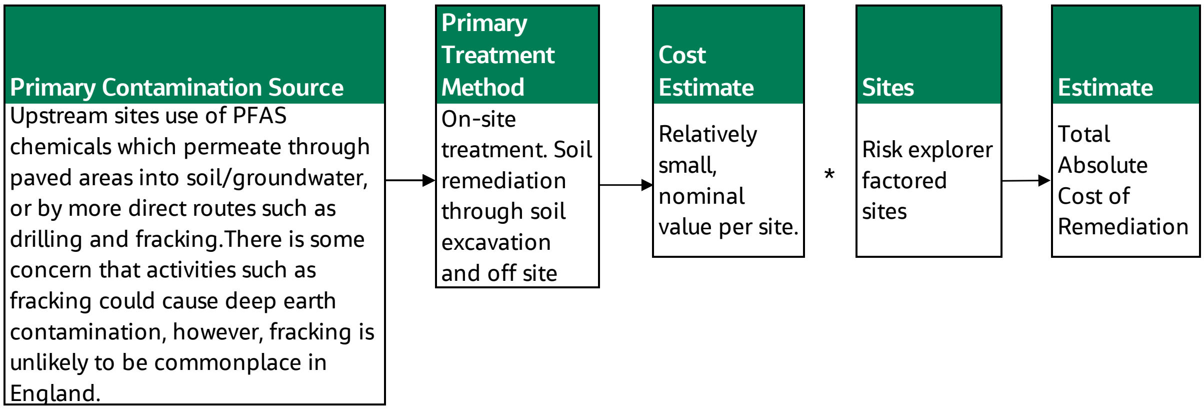
[REDACTED]

[REDACTED]

3.7.9 Oil and gas

As detailed in the PFAS Risk Explorer Handbook (Jacobs, 2023c) the 'Oil and Gas' site type refers to oil and gas exploration and production sites which require an environmental permit. There is only a relatively small number of such sites in England, however they have been included in the economic model as a separate site type as they are included in the PFAS Risk Explorer output and have characteristics different to the other site types considered. Note that downstream oil and gas sites are included under refineries and/or COMAH sites. See below the logic chain of the methodology in building up an Oil and Gas site cost estimate. Similar to Nuclear Permitted sites, a simple nominal per site value is applied which encompasses all remediation. The main reasoning for this is primarily, the small number of sites and the lack of high-risk sites, leading the impact on the overall national remediation cost being minor, as well as other factors such as the lack of literature available on the topic.

Figure 3-12: Oil and Gas Site Calculation Framework



The nominal estimate used is informed by the EBJ paper, which estimates that the cost of remediation per US 'Other Manufacturing' site is $0.5 million (EBJ, 2022). Whilst 'Other Manufacturing' is a very broad, unspecified category, Oil and Gas sites would come under this classification. Thus, this is seen as a suitable proxy. When applying currency conversion and GDP deflation, this per site cost becomes £0.44 million. When multiplying this by the Risk Explorer factored sites, this produces a total absolute cost estimate of £309,000 in Scenario 1 and £0 in Scenario 2 (all Oil and Gas sites come under the Risk Explorer threshold of 60).

3.8 PFAS remediation modelling – Scenario 3 – wastewater treatment

As explained above in section 3.6, this scenario presents a centralised solution through end of pipe PFAS remediation at Wastewater Treatment Works (WwTW). This scenario could be seen as the more realistic of the scenarios given its use of existing infrastructure, use of known technologies, and feasible scale of implementation.

This scenario is based on an estimate from UK Water Industry Research (Campitelli, et al., 2022) into the cost of remediating PFAS. The research covers the current regulatory approach and potential changes to it, identification of sources of PFAS, effective treatment options for WwTW, and costs of treatment. Campitelli et al. presented three different scenarios of intervention with Scenario 1 being the most intensive and costly in reducing PFAS concentrations and Scenario 3 being the least intensive and costly. They presented figures at a national level, therefore it is possible to derive the cost for England relative to the rest of UK and Ireland.

The UKWIR estimate for the installation of PFAS removal equipment to treat the effluent flows in 95% of WwTWs in England is £14.8bn in 2021 prices, discounted over 20 years. Assuming an equal distribution over the 20 years and a discount rate of 3%, this equates to £28bn undiscounted. They estimated how many WwTW sites required a pre-treatment stage (Rapid Gravity Filter), normal treatment (GAC), then incineration and sludge production. The operating and capital cost of GAC treatment utilised Tehrani and Haghi's (2015) formula of investment and annual cost relative to WwTW site capacity, converting this to 2021 British Pounds.

Section 4.5 presents the results of Scenario 3 and further discussion of the impacts of this centralised remediation approach.

4. Results

4.1 Summary

Based on the methodology outlined in the above Section 3, remediation cost estimates are generated under Scenarios 1 and 2 based on inputs from the PFAS Risk Explorer. The results focus on Scenarios 1 and 2; however, a discussion of Scenario 3 based on the UKWIR report is presented as an alternative to considering land remediation on a site by site basis.

While results are presented for each category of site both individually (per average site) and aggregated, it is important to note that there remains a significant level of uncertainty around the figures, and that they are subject to change as the PFAS Risk Explorer inputs change. The emphasis here is to provide an example of how the model can be used as a tool for generating cost estimates, rather than viewing these as definitive results. The information presented here is also available in the Excel-based model provided to the EA. Discussion on the sensitivity of these estimates to assumptions made is included in Section 4.6.

4.2 Factored sites and areas

Table 4-1 below shows the impact of the factors applied in reducing the number of sites and total area assumed to require remediation under Scenario 1 and 2. See Appendix E for the justification behind the factors which drive the variations between unfactored and factored sites/areas. In both scenarios, all categories, apart from TULAC/Metals/Pulp and Paper, experience a significant decrease in area, largely driven by factor B, which applies an adjustment for the proportion of each site likely to have PFAS contamination present.

Table 4-1: Unfactored and Factored Sites/Areas

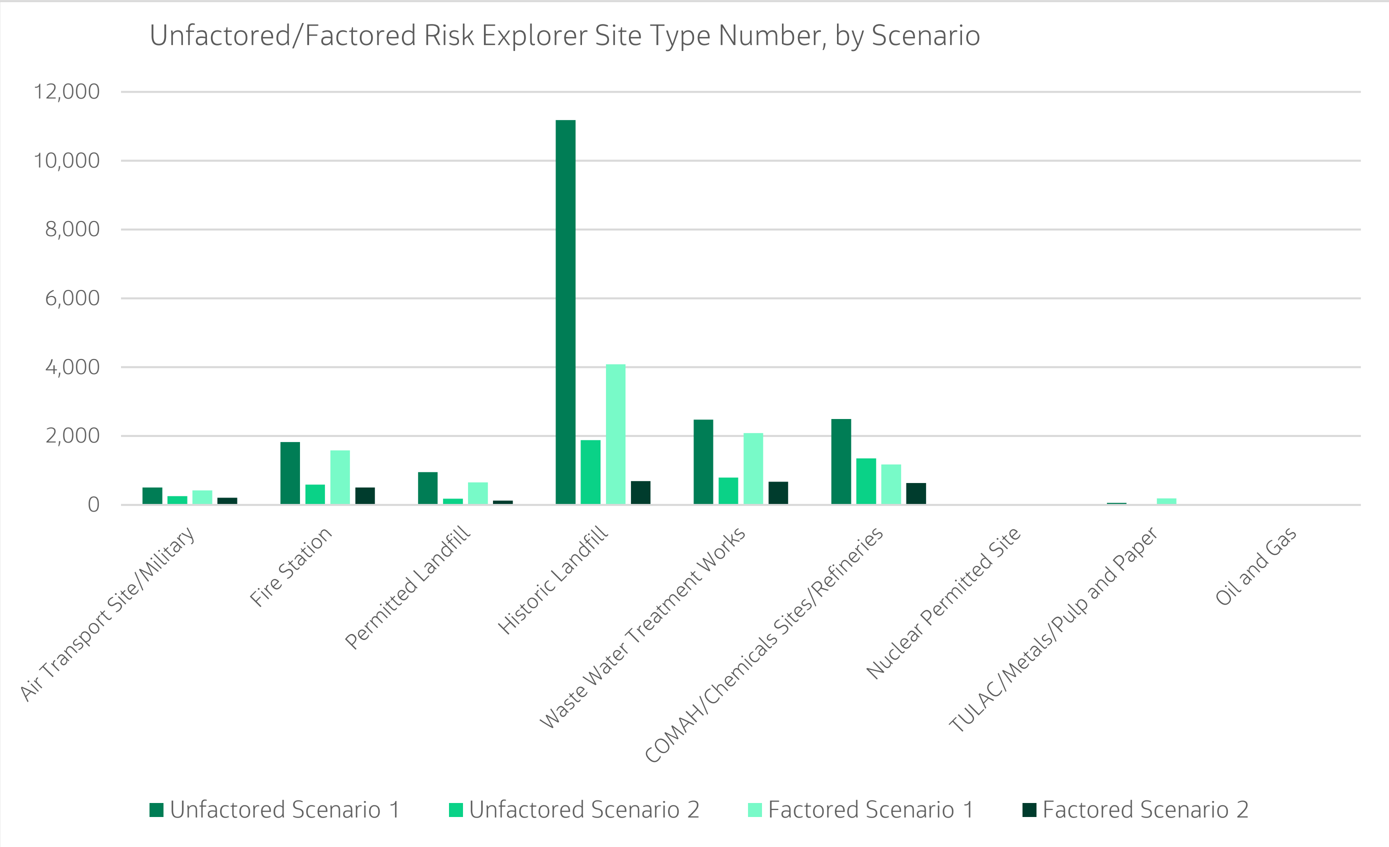
Site Types	Scenario 1				Scenario 2			
	Unfactored		Factored		Unfactored		Factored	
	Sites	Area (m2)	Sites	Area (m2)	Sites	Area (m2)	Sites	Area (m2)
Air Transport Sites/ Military	511	597,555,000	419	147,005,000	253	442,691,000	207	108,907,000
Fire Stations	1,827	2,738,000	1,588	714,000	586	1,940,000	509	506,000
Permitted Landfill	954	198,003,000	656	136,226,000	178	47,620,000	122	32,763,000
Historic Landfill	11,180	615,843,000	4,089	225,223,000	1,884	158,466,000	689	57,953,000
Wastewater Treatment Works	2,474	69,678,000	2,089	17,652,000	793	43,604,000	670	11,046,000
COMAH/Chemical /Refineries	2,501	468,126,000	1,180	132,493,000	1,356	365,380,000	640	103,413,000
Nuclear Permitted Site	26	16,124,000	26	4,837,000	5	5,000,000	5	1,500,000
TULAC/Metals/Pulp and Paper	59	4,688,000	189	7,501,000	7	325,000	22	520,000
Oil and Gas	7	1,227,000	1	123,000	0	0	0	0

As for the number of sites, both Historic Landfills and COMAH/Chemicals/Refineries experience the largest decrease as a result of factoring. For Historic Landfills, this is driven by factor E which accounts for the proportion of missing historical sites likely to have PFAS impact (due to decreasing likelihood of PFAS presence the older the sites are). For COMAH/Chemicals/Refineries, this is largely due to the high potential for overlapping with other site types within the PFAS Risk Explorer (factor F). However, in both scenarios, Historic Landfills remain the most significant site type in terms of number of sites assumed to require remediation. Note that in Scenario 2, Oil and Gas sites completely fall out of the analysis, as none of them are assigned a risk score above 60 in the PFAS Risk Explorer.

TULAC/Metals/Pulp and Paper are an outlier, in that across both scenarios, there is an increase in both the number of sites and area when comparing the unfactored versus factored inputs. The reasoning behind this is that current data on contamination is highly limited for these industries, particularly for TULAC site. Thus the potential number of sites could be much larger than that currently captured within the Risk Explorer, which only includes sites in these categories that are currently regulated under the Environmental Permitting Regulations (2016) Schedule 1. Factor C attempts to account for this limitation but there remains very large uncertainty with regard the overall number of TULAC/Metals/Pulp and Paper sites in the UK where there is or has been substantial use of PFAS within process treatments.

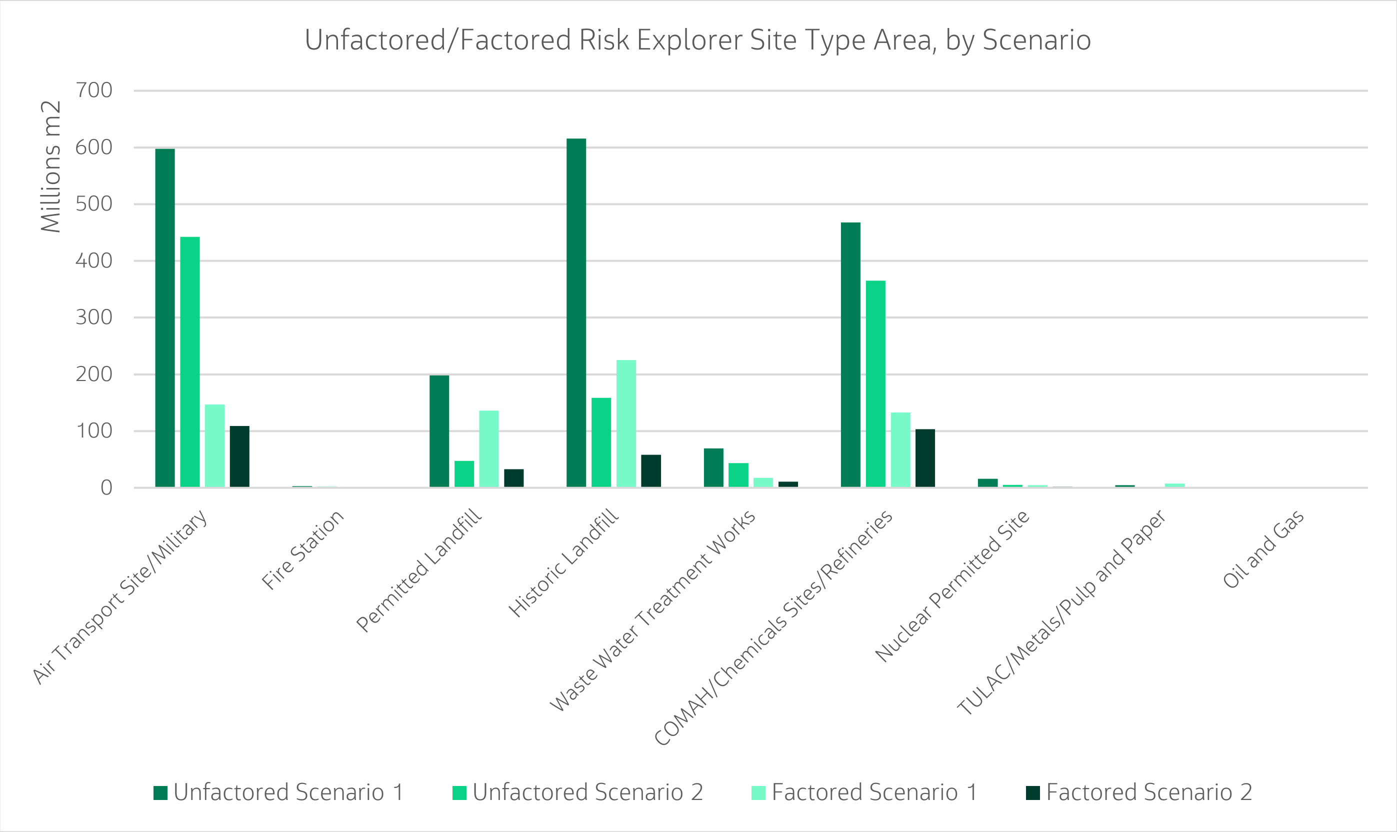
Figure 4-1 below presents the relative number of sites under each type, and Appendix D includes more detailed graphs showing the distribution of risk scores and site area for the different site types. In particular, Figure 4-1 shows the large decrease in Historic Landfill sites between Scenarios 1 and 2. On the other end of the spectrum, it illustrates the low numbers of Nuclear Permitted, TULAC/Metals/Pulp and Paper, and Oil and Gas sites present, even before factoring.

Figure 4-1: Risk Explorer Sites by Scenario



In terms of total site area, this is dominated by a few site types as shown by Figure 4-2. Note that, despite Fire Stations being high in number under both scenarios, due to each site being relatively small, they barely register in terms of total area footprint. Wastewater treatment works also have a relatively small area compared to the overall number of sites.

Figure 4-2: Risk Explorer Area by Scenario



4.3 Scenario 1

Table 4-2 below presents the results for Scenario 1. Whilst this provides some useful context for beginning to examine remediation costs – both in terms of orders of magnitude per site and by sector, as well as comparing across site types – the emphasis here is not on the final numbers. Rather, these tables are illustrative of the outputs generated by the economic appraisal and are expected to be refined over time as further data emerges.

Table 4-2: Scenario 1 Cost Estimate Outputs

Site type	Per Site (£ millions)			Total (£ millions)		
	Low	High	Average	Low	High	Average
Air Transport Sites/Military	£5.0	£11.2	£8.1	£2,096.4	£4,678.3	£3,387.4
Fire Stations	£0.7	£3.0	£1.9	£1,070.2	£4,839.7	£2,955.0
Permitted Landfill	£4.2	£6.4	£5.3	£2,753.0	£4,193.9	£3,473.5
Historic Landfill	£3.6	£9.7	£6.6	£14,702.3	£39,529.7	£27,116.0
Wastewater Treatment Works	£11.2	£15.7	£13.4	£23,376.1	£32,731.1	£28,053.6
COMAH/Chemicals/Refineries	£17.7	£28.1	£22.9	£20,828.2	£33,123.2	£26,975.7
Nuclear Permitted Site	£4.4	£4.4	£4.4	£114.8	£114.8	£114.8
TULAC/Metals/Pulp and Paper	£6.6	£7.7	£7.2	£1,249.9	£1,457.6	£1,353.8
Oil and Gas	£0.4	£0.4	£0.4	£0.3	£0.3	£0.3
	Weighted Average	Weighted Average	Weighted Average	Sum	Sum	Sum
All	£6.5	£11.8	£9.1	£66,191.2	£120,668.7	£93,429.9

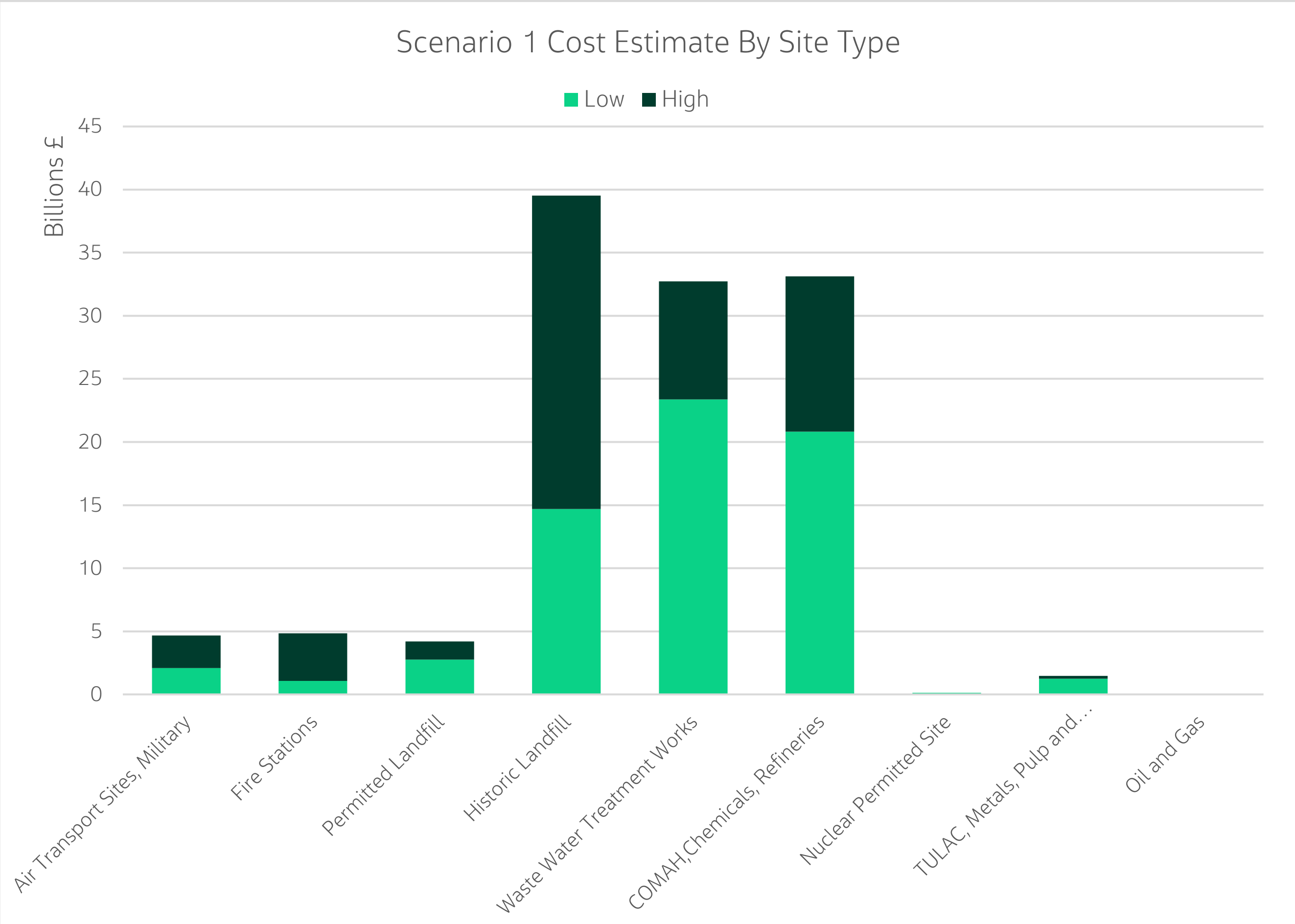
Under Scenario 1, the model estimates that the total cost in remediating all identified sites with a risk score above 50 will be between £66.19-120.67bn, with a central estimate being £93.43bn. These estimates are large, however deemed realistic, due to the inherent nature of Scenario 1 being a comprehensive clean-up of all high-risk sites.

As can be seen, the key cost drivers are Historic Landfills, Wastewater Treatment Works, and COMAH/Chemicals/Refineries. This is largely driven by the number of factored sites captured by the PFAS Risk Explorer and included in Scenario 1. COMAH/Chemicals/Refineries are also estimated to have the highest per site remediation cost with a central estimate of £22.87 million. This is reflective of their large overall size and the proportion that is assumed to be contaminated.

The sites with the lowest estimated cost are Nuclear Permitted, TULAC/Metals/Pulp and Paper and Oil and Gas. Oil and Gas sites contribute by far the smallest total cost, largely due to the low per site cost, and the low number of factored sites.

The below Figure 4-3 presents low and high aggregated cost estimates, thus illustrating the sensitivity range for each site type. Fire Stations and Historic Landfills have the largest range, with the high estimate being more than double the low estimate. In contrast TULAC/Metals/Pulp and Paper, and to a lesser extent, Permitted Landfills, show a lower degree of variance between the low and high.

Figure 4-3: Scenario 1 Cost Estimates by Site Type



4.4 Scenario 2

Figure 4-3 below presents the results for Scenario 2. Whilst this provides some useful context for beginning to examine remediation costs and comparing two plausible policy scenarios, the same caveats apply as per Scenario 1.

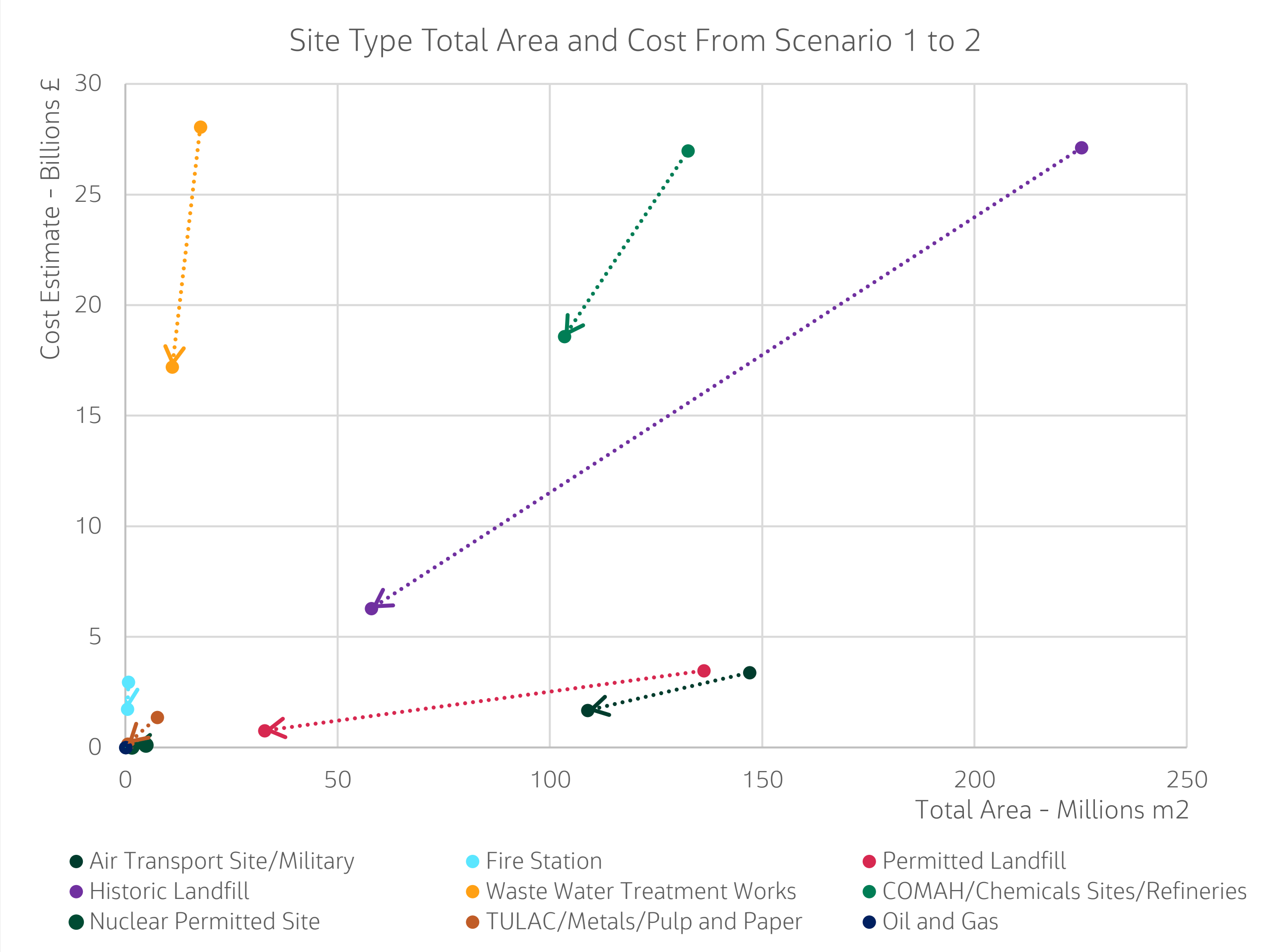
Table 4-3: Scenario 2 Cost Estimate Outputs

Site type	Per Site (£ millions)			Total (£ millions)		
	Low	High	Average	Low	High	Average
Air Transport Sites/Military	£5.0	£11.2	£8.1	£1,037.9	£2,316.3	£1,677.1
Fire Stations	£1.5	£5.3	£3.4	£758.3	£2,705.1	£1,731.7
Permitted Landfill	£4.2	£8.2	£6.2	£513.7	£1,008.6	£761.2
Historic Landfill	£4.5	£13.8	£9.1	£3,093.3	£9,481.8	£6,287.5
Wastewater Treatment Works	£21.8	£29.5	£25.7	£14,628.7	£19,781.5	£17,205.1
COMAH/Chemicals/Refineries	£17.7	£40.4	£29.0	£11,292.7	£25,853.2	£18,573.0
Nuclear Permitted Site	£4.4	£4.4	£4.4	£22.1	£22.1	£22.1
TULAC/Metals/Pulp and Paper	£6.6	£7.7	£7.2	£148.3	£172.9	£160.6
Oil and Gas	£0.4	£0.4	£0.4	£0.0	£0.0	£0.0
	Weighted Average	Weighted Average	Weighted Average	Sum	Sum	Sum
All	£11.0	£21.4	£16.2	£31,494.9	£61,341.6	£46,418.3

Under Scenario 2, the model estimates that the total cost of remediating sites with a risk score above 60 ranges from £33.49bn to £61.34bn, with a central estimate of £46.42bn. This central estimate is around half of that of Scenario 1, which appears realistic considering this represents a lower level of intervention, on a smaller number of high-risk sites.

Whilst the cost estimates have decreased for all site types compared to Scenario 1, the largest decrease come from Historic Landfills, due to the large decrease in the number of sites assumed to require remediation under Scenario 2. Note that the highest risk (risk score >60) Historic Landfills which remain, also tend to be the largest, thus the average per site remediation cost has increased from Scenario 1. With the exception of Historic Landfills, the other site types all experience a similar proportional decrease between Scenarios 1 and 2 in terms of total aggregated costs as illustrated in Figure 4-4. In general, all site types move towards the origin from Scenario 1 to 2 due to the reduction in the number of sites and total area assumed to be remediated.

Figure 4-4: Change in Site Type Total Area and Cost Between Scenarios



4.5 Scenario 3

The UKWIR estimate for the installation of PFAS removal equipment to treat the effluent flow in England is £14.8bn, discounted over 20 years. Assuming an equal distribution of cost over the 20 years and a discount rate of 3%, this equates to £28.0bn undiscounted. This model is based on 1,913 WwTW sites.

Given this relates to the relatively intensive scenario which assumes 95% (1,817) of WwTW utilising PFAS treatment without mixing, it represents the most expensive of the WwTW scenarios from the Campitelli et al research (Campitelli, et al., 2022) . The other scenarios presented in the Campitelli et al paper are relatively cheap but less effective at removing PFAS from effluent. Comparing it with the site-based remediation costs explored in Scenarios 1 and 2 above, it is relatively inexpensive. However, Campitelli et al highlighted that current incineration infrastructure would not be able to accommodate the estimated 610,000 tonnes of GAC per annum that would require incineration in this scenario. The cost of constructing additional incineration facilities has not been considered financially or environmentally, and given the scale of their estimate, these could be significant.

It is difficult to ascertain the degree to which this Scenario 3 alternative interacts or overlaps with Scenario 1 or 2. However, as mentioned in section 3.5, Scenario 3 would tackle PFAS in wastewater whereas Scenarios 1 and 2 focus on addressing PFAS at source. It is presumed that contaminated land sites contribute to PFAS contamination in the wastewater system primarily through overland flows; however, the level of contribution relative to other sources is not known. It would be overly simplistic to assume that the majority of the impact of PFAS from contaminated land sites could be dealt with by waiting for the substances to be transported to a WwTW and treated in some centralised system firstly due to the uncertainty around how much ends up in wastewater versus remaining in situ and/or is transported to other environmental receptors (ground and surface water, air). Secondly, the total impact on human and ecological health and the various pathways that contribute to the overall impact are not understood (see sections 5.2 and 6.2 for further detail). In other words, if centralised treatment at WwTW was pursued in isolation (lacking any land-based remediation) exposure risks would remain.

For these reasons it is not suggested that Scenario 3 represents a plausible alternative to Scenario 1 or 2; rather that to address the PFAS challenge comprehensively will require a combination of Scenario 1 or 2 and 3, as well as multiple other policy and regulatory interventions.

If it could be inferred that the primary impact pathway linking high risk contaminated sites to human health impacts was via the wastewater system, there would be benefits to pursuing a centralised approach. Reliance on large WwTW treating PFAS entering the sewer system instead of remediating individual high-risk sites would transfer the burden of cost from individual operators to water treatment companies. The efficiency of this transfer (effect on taxpayers, avoidance of business closures, etc.) may be an area for further consideration. It maximises the use of existing infrastructure and the capital cost of installing treatment facilities would be borne by a small number of water companies (presumably under the direction of Ofwat) rather than a significantly larger number of smaller operators with varying levels of regulation. Water companies could recover the cost through existing charging arrangements; however, this again raises the question of source apportionment and who should pay. Finally, a centralised WwTW approach as an alternative to site-based remediation would avoid significant material transport from excavation plus offsite treatment which can pose a significant cost (both in financial and environmental terms) as highlighted by (Feng, 2021).

This form of remediation intervention has the potential to avoid business closures where the cost of installing site-specific treatment plant is too high and the easiest option is to walk away. This avoids the risk of the creation of orphan sites and was observed when the enforcement of Part 2A of the Environmental Protection Act 1990 came into force in April 2000 (UK, 1990). There are both environmental and economic problems created by this: a potential polluter has walked away from environmental issues created, potential contamination of site will remain in place, loss of productive capacity of land, employment/skills/economic capacity/economic activity of business, and the taxpayer may have to indirectly pay for PFAS remediation of orphaned site. This highlights the needs for updated legislation.

4.6 Sensitivity of cost estimates

Several assumptions were made throughout the methodology to generate preliminary estimates, largely due to the limited research/data available. Whilst for the most part these assumptions are based on existing precedents, there remains a level of judgement in their selection which impacts significantly on the results. Thus, the sensitivity of results to input values should be explored to understand how the cost estimates could change with different inputs.

4.6.1 Factoring

Factoring is perhaps the most important element in this sensitivity discussion as it includes 54 variables ranging from 0 and 1 which were selected and applied based on professional judgment. Note the factors have been developed to address limitations in the mapping of sites within the PFAS Risk Explorer, the economic appraisal model has been constructed to allow the user to overwrite any of the factors to understand their implication on the results.

Factors A (proportion of mapped site area likely to be impacted), B (proportion of sites likely to have PFAS impact) and F (double counting) have the most influence on aggregated results as they apply to both current and historical sites. As factor A only impacts the Risk Explorer Factored Area figures, final cost values which are calculated based on a bottom-up (area) basis are the most sensitive to the factoring. Such values include the estimates for Fire Stations, Permitted Landfill, Historic Landfill, Wastewater Treatment Works, and COMAH/Chemicals/Refineries. Whilst significant uncertainty remains, it is assumed that as more information becomes available on site-specific PFAS contamination, the factoring can be refined.

4.6.2 Site type sensitivity

Air Transport/ Military

- The remediation estimate is based on a weighted average between three different estimates provided by the EBJ paper (EBJ, 2022). This includes a 60% weighting towards regional airports, based on best judgement of the comparability of UK and US airports. This weighting is a key parameter in constructing the high end of the overall per-site cost estimate; thus the results are highly sensitive to the weighting used.

Fire Stations

- The bottom-up soil remediation cost estimate, based on the Wood paper, makes up the majority of the low and high end of the cost range (Wood et al., 2020). The calculation of this estimate includes an assumption of the depth of soil to be treated. This is assumed as 4 metres based on expert judgement; however, this could vary depending on individual site geology and topography. The final cost estimate is directly linked to this estimate, thus making it highly sensitive to this assumption.
- Whilst not used in the final results, the top-down ECHA (ECHA, 2022)approach provides a feasible alternative to the previously mentioned Wood estimate (Wood et al., 2020), however, it is also sensitive to assumptions made. The ECHA paper provides a low and high site cost estimate for two different remediation methods (ECHA, 2022). A weighted average is calculated based on 80% weighting towards the lower end of the range, with the justification being that fire station sites have a small area and thus will be closer to the low end in cost.

Permitted Landfill

- The final cost estimate for Permitted Landfills has a high degree of sensitivity to the assumption of intervention duration, as this affects both the bottom-up and top-down Feng et al estimates (Feng, 2021). This is assumed as 15 years, having been informed by the paper itself, therefore there is less concern over this assumption being incorrect.

Historic Landfill

- As historic landfills are assumed to use the same leachate remediation methodology as permitted landfills, they are subject to the same sensitivity that is outlined above.
- Whilst not used in the final results, the estimated cost of an impermeable concrete barrier is sensitive to the breakdown of expenditure types sourced from the Jersey airport case study and the assumed area of the Jersey sites (IPEN, 2019).

Wastewater Treatment Works

- The soil remediation estimate used in both the low and high end of the WwTW costs is sensitive to two key assumptions. The first is the assumed proportion of incinerated soil, which dictates the low, medium, and high estimates. The second is the assumed depth of soil treated, which is currently set as 3 metres. Whilst both assumptions affect the final estimate, the second is particularly impactful to the final result being directly proportional to it.

COMAH, Chemicals, Refineries

- This estimate is not sensitive to particular assumptions, with the low and high end of the range being directly informed by the EBJ paper and expert elicitation respectively.

Nuclear Permitted Sites

- As this estimate is based on an assumed average per-site value, it is inherently highly sensitive to the value chosen. This concern for sensitivity is reduced however due to the chosen value aligning with that indicated by the EBJ paper.

TULAC, Metals, Pulp and Paper

- For this site type, neither of the estimates used for the low and high ends of the range rely significantly on assumptions. However, despite not being used, the second soil remediation estimate, which is based on the methodology for Fire Stations, is sensitive to the assumed depth of contaminated soil. The total cost is directly proportional to this assumption.

Oil and Gas

- Similar to Nuclear Permitted Sites, the Oil and Gas estimate is based on an assumed average per-site value and is thus highly sensitive. However, again this concern for sensitivity is reduced due to the selected value's alignment with the EBJ paper.

Scenario 3

- The Scenario 3 cost estimate from the UKWIR report is relies on reversing or 'un-discounting' present value costs. This relies on an assumption of expenditure being equally spread across the time period. It is likely that there will be up-front plant installation costs which would deviate from the assumed cost profile and increase the overall cost.

5. Benefits of PFAS remediation

5.1 Introduction

This section discusses the potential benefits associated with PFAS remediation both generally and specifically regarding land remediation of high risk sites, which is the focus of the costing exercise presented above. In doing so, this highlights the difficulty in quantifying and attributing cause/effect to interventions – with particular reference to the paucity of studies that present robust quantified estimates of benefits of PFAS remediation. Finally, there is discussion of alternative approaches to benefits estimation including public surveys which, if deployed at the appropriate scale/context, could be used to quantify the benefits of remediation given the scarcity of empirical data at present.

5.2 Summary of evidence review

As discussed in 3.2, the evidence review collected knowledge and understanding on remediation techniques and the effects of PFAS. The methodology section (3.7) outline how we have synthesised data on remediation techniques, associated costs, and high risk site data to derive a mechanism for estimating remediation costs per site and per sector (section 44.1). This analysis was enabled by the data found within the evidence review. This review also captured information on the impacts of PFAS which are discussed in presented in the following sections 5.2.1, 5.2.2, 5.2.3, and 5.5.

5.2.1 Health impacts

The list of PFAS-related health impacts includes among others:

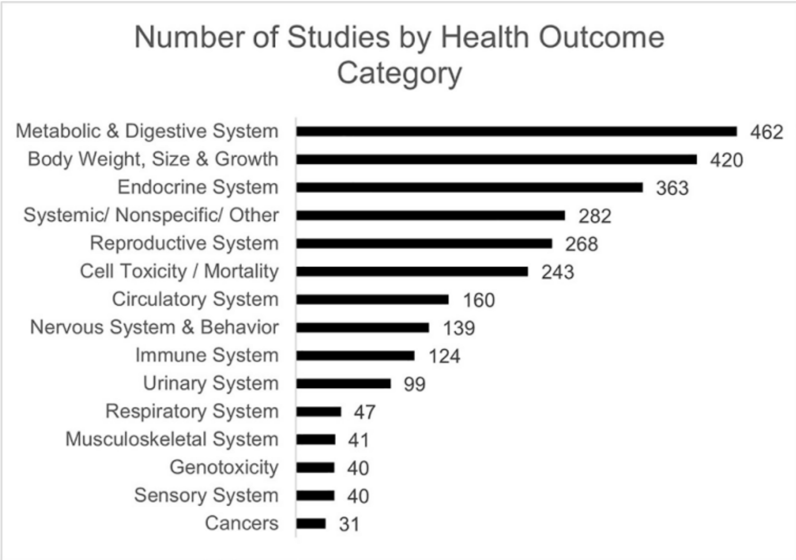
- Increase in risk of heart attack or other cardiac events
- Increase in risk of respiratory diseases (eg asthma)
- Increased risk of cancers
- Changes to reproductive system (eg infertility and increased risk of disease)
- Changes to endocrine system (increased risk of diabetes)
- Changes in body weight, size & growth
- Changes in bone mineral content and density
- Changes to nervous system & behaviour
- Changes to immune system
- Changes to Metabolic & digestive system
- Sensory changes
- Cell toxicity/mortality

However, full epidemiological studies in relation to PFAS exposure and these health impacts have not been carried out in all cases. More impacts may also be identified in the future.

In order to quantify benefits of remediation, evidence is required linking exposure levels to occurrence of disease and the effect must be able to be modelled across a population. There is significant uncertainty in this given the number of PFAS compounds and their individual/in-combination effect on health. Similarly, we would need to understand the contribution of contaminated sites to total exposure levels. There are multiple impact pathways exposing humans to PFAS – remediating high risk sites would reduce overall exposure levels but to what degree or proportion is not known.

The database (pfastoxdatabase.org) of journal articles on PFAS (Pelch, et al., 2022) covers 27 PFAS chemicals, 15 health outcomes (across humans, animals, and in vitro) and 1,067 articles, underlining the complexity of modelling the health impacts from reduced exposure. The database focusses on PFAS variants other than the two most prolific (PFOS and PFOA) due to the fact that PFOS and PFOA effects are well researched and regulated, therefore finding information on the effects of other variants can be challenging. Figure 5-1 shows the distribution of articles in the database organised by health outcome. Despite the volume of papers, this database is likely to be a partial representation of the full impact – not least as it covers 27 of the 15,000 known PFAS compounds.

Figure 5-1: Health Outcome Studies (Pelch, et al., 2022)



In addition to disease morbidity and mortality, there is a link between PFAS and mental health that has been explored through various interview-based studies. Interviewees living near contaminated sites in an Australian study perceive PFAS causing harm in a number of ways: concern for physical health, strain on mental health through worrying about negative impacts on housing, negative impacts on surrounding environment and lack of resolution by the government (Legg, et al., 2022). An American study interviewing six community members and three public health department employees concluded similar negative impacts associated with PFAS contamination (Calloway, et al., 2020). These included health issues, loss of trust in governmental institutions, financial burden, and general stress caused by uncertainty, frustration and lack of control. Community experience was related to unexpected illness and deaths in the community causing further stress and uncertainty; lack of recognition of the situation and government intervention leading to further loss of trust and stress. These health impacts in turn create financial burden for individuals that lead to worsening mental health. Calloway et al's study focused on drinking water contamination which is not the focus of this economic appraisal; however the presence of PFAS in contaminated land sites can impact on drinking water supplies. Further, it can be inferred that communities in proximity to high-risk sites could experience many of the same mental health effects.

As highlighted by the number of articles and diversity of PFAS variants explored within academic literature, the complexity of human health impacts associated with PFAS makes informing decision making challenging. An independent panel of 12 experts on PFAS (Anderson, et al., 2022) said that meaningful analysis should:

- avoid grouping PFAS together under one heading, splitting out effects and impacts to separate chemicals when possible;
- not assume equal toxicity for different PFAS chemicals; and
- adopt a tiered approach of grouping some PFAS together to ease/support decision making.

5.2.2 Environmental impacts

Previous health studies (such as those in PFAStox database) noted impacts on humans as well as animals. Any impact on animal health (life expectancy, size of population etc.) links to biodiversity which could be considered a wider environmental impact due to the role of animal biodiversity on ecosystem services and natural capital assets. Therefore, a negative impact on animal health resulting from PFAS, could be interpreted as a negative environmental impact as well. Schultes et al. (2020) examined concentrations of various PFAS in Baltic cod between 1981 and 2013; this had two general conclusions, firstly, an increase in concentrations of PFAS found in liver tissue of cod over the period, with a slower increase from 2000 to 2013. Secondly, there were significant negative correlations between some PFAS and the condition of cod, defined as a condition factor which reflects weight and length (Schultes, et al., 2020) . This second correlation can indicate stress in fish as they react to pollutants. Linking to the wider ecosystem impact discussion, it was acknowledged that the PFAS concentrations observed in Baltic cod align with trends of other Baltic wildlife – increased concentrations in herring gull eggs and Swedish peregrine falcon eggs.

There is a lack of evidence/data looking at the impact of PFAS concentrations on plant life and non-animal life (e.g. bacteria present in soil). Studies focus on human health, animal health, or in vitro but few look at environmental impacts in the sense of plant or soil health and the effect this may have on ecosystems or other ecological indicators. There is consensus that the accumulation of PFAS in organisms causes toxicity, inhibits growth, and causes ill-health (cancers or disrupting reproductive systems) – although there is a lack of studies as to the impact on plants, it is possible that presence of PFAS causes similar negative effects. There is a wealth of studies that report on concentrations of PFAS in different environmental media (Wang, et al., 2023) but they lack a discussion of the impacts on plants or soils themselves.

5.2.3 Landmark studies – monetisation of health impacts

The evidence review undertaken as part of this work (see Section 3.2) highlighted that in general, there is a lack of published articles that attempt to quantify the health impacts of PFAS in monetary terms. This remains a key research gap; however there are two landmark studies discussed here, namely the Nordic Council of Ministers, 2019, and United States Environmental Protection Agency (EPA), 2023.

5.2.3.1 The cost of inaction – Nordic Council of Ministers (2019)

This was a socioeconomic analysis (Goldenman et al., 2019) of environmental and health impacts linked to exposure to PFAS with two aims:

1. *"to establish a framework for estimating costs for society related to negative impacts on health and the environment associated with PFAS exposure; and*
2. *to provide monetary values for those societal costs, documented by case studies."*

Five case studies were used to demonstrate the different impact pathways whereupon PFAS can impact upon people, the environment, and the economy. Different methodologies were used to model health costs and environmental costs, but both demonstrate the scale of the problem.

Health related costs

The report noted that in 2019, no other research had monetised health related costs of PFAS due to a lack of global consensus on the specific health impacts. More importantly it also cited a lack of understanding on the level of PFAS exposure or concentrations required to trigger certain health effects; this knowledge is essential to accurately model different scenarios for remediation and monetising the benefits (avoided costs). Recent research provides more detail on the relationship between specific PFAS concentrations and associated health impacts (see 5.2.1) but this report was one of the first to amalgamate the most widely known health impacts. The methodology involved three steps: modelling the marginal impact of different levels of PFAS exposure on various health conditions, quantifying the impacts in economic terms using the value of a statistical life, and aggregating the impacts across the relevant population.

Th health impacts considered included:

- Metabolic disease

    - Liver damage
    - Ulcerative colitis
    - Increased serum cholesterol levels
- Immunotoxicity
    - Decreased immune response
    - Increased risk of asthma
- Endocrine disruption
    - Increased risk of thyroid disease
    - Elevated sex hormones
    - Decreased fertility
    - Pregnancy induced hypertension
    - Delayed menstruation/early menopause
- Developmental outcomes
    - Lower birth weight
- Carcinogenicity
    - Cancer (testicular and kidney)

It is highlighted that these health impacts are not comprehensive and more can be included as further evidence on exposure-response relationships emerges.

Although the relationship with PFAS is evidenced for each of these health impacts, it is then necessary to quantify the link between the level of exposure and risk of disease. The health impacts in terms of deaths brought forward are then combined with value of statistical life (€3.5 million) to monetise the impact. Aggregating exposure to PFAS in populations across Europe and combining with modelled change in life expectancy allows an estimate of cost in terms of inaction; without the presence of PFAS, a certain number of excess deaths would be avoided (see Figure 5-2 below).

Figure 5-2: Value of Life Impacts

There are three scenarios modelled in the study which reflect different levels of PFAS exposure: high exposure through working with PFAS (manufacturing), medium exposure through being in close proximity to PFAS contaminants such as living near a PFAS-using manufacturing facility, and low level exposure through use of general products that may contain PFAS such as cosmetics or eating food products that have come into contact with PFAS. In each of these scenarios, an exposure level for the population was estimated, based on a combination of case studies and on wider evidence. The exposure level is then combined with health impacts and resulting deaths which are then monetised as previously described. Table 5-1 below summarises the monetised health impacts presented in the Nordic study.

Table 5-1: Annual cost of health impacts from PFAS exposure

Level of PFAS exposure	Health impact	European population	Annual cost of PFAS to life
High (working at PFAS using production facility)	Kidney cancer	84,000 – 273,000	€12.7m – €41.4m
Medium (community exposure – PFAS in drinking supply)	Mortality	12.5m	€41bn – €49bn
	Low birth weight	156,000	3,354 low birth weights
	Infection	785,000	1.5m additional days of fever
Low (using products that have contain PFAS – cosmetics etc)	Hypertension	207.8m	€10.7bn – €35bn

Environmental costs

These were separated into environmental remediation and loss of ecosystem services. The costs of environmental remediation largely reflect the costs captured and estimated in this Phase 4 WP4 project: survey work, monitoring, and treatment of soil/water. The use of terminology where the Nordic paper refers to these as "environmental costs" is potentially confusing – whereas in the context of this WP4 economic appraisal report we refer to such costs as land-based remediation or remediation of high-risk sites.

The Nordic paper noted the uncertainty in estimating such costs, with the variation in site conditions and reliance on a small number of case studies driving large sensitivity ranges. This conclusion is similar to the findings of the evidence review and cost modelling undertaken as part of this work package. It was also noted that use of Monte Carlo analysis could address some concerns about uncertainty but could still give a false impression of the quality of data.

The estimated cost of treatment is based on assumed scenarios of:

- Percentage of population exposed to PFAS in drinking water
- Duration of remediation/maintenance programme
- Cost per water treatment site

Results for these remediation costs (screening, monitoring, water treatment, soil remediation and health assessment) for the Nordic countries are shown in Table 5-2 below, noting these are discounted present-value costs based on the assumed duration of the programme.

Table 5-2: Nordic Paper Results

	Number of affected people (3%)	Screening and monitoring (€m)	Health assessment (€m)	Upgrade treatment work and maintenance (€m)	Soil remediation (€m)	Total (€m)
Denmark	169,791	0.07-8.3	0.28-27	7.4-274	0-798	8-1,106
Finland	164,153	0.25-22	0.27-26	7.2-265	2.2-2,081	10-2,393

Iceland	10,102	0.01-0.9	0.02-1.6	0.4-1.6	0.1-86	1-105
Norway	154,995	0.17-20	0.26-25	6.8-250	1.6-1,887	9-2,181
Sweden	292,421	0.48-47	0.49-46	13-472	4.3-4,497	18-5,061
Nordic	791,462	-	-	-	-	46-10,846

The range in total costs is significant (€46m - €10,846m), again reflecting uncertainty of PFAS concentrations and the costs involved in remediation.

Loss of ecosystem services was not quantified in this report due to lack of quality data (ecosystem impact pathways and PFAS) and the uncertainties associated with using the available data (based on willingness to pay or WTP). WTP estimates can be assumed to reflect societal preference for avoidance of environmental harm instead of a total damage cost of PFAS. There was potential to quantify the impacts through two WTP estimates; however the authors deemed the level of uncertainty associated with the WTP estimates to be unacceptable.

Overall conclusions

In general, the health costs of PFAS exposure exceed the costs of intervention (termed environmental costs) in Nordic countries: €2.8bn- €4.6bn in benefits (avoided health costs) per annum versus intervention costs of €0.046bn - €10.8bn over 20 years.

Although this appears to suggest a net positive outcome in economic terms, it is not a clear comparison of costs and benefits. The health benefits reflect complete removal of PFAS exposure to humans whereas the costs of intervention would only partially address human exposure.

Links to our analysis

The Nordic paper underlines the uncertainty involved in estimating the costs of PFAS in health terms, in environmental terms and the costs of remediation. It presents monetised health impacts that could potentially be transferred to estimate similar avoided costs in England; however this would require multiple adjustments and assumptions not least to account for the relative population sizes of the Nordic countries, land area, etc. Further, the Nordic paper is focused on general population exposure to PFAS via drinking water which as acknowledged is not the focus of this WP4 economic appraisal.

There are however elements of the methodology that could be used to form the basis of an approach to monetising benefits of PFAS remediation in England. These include case studies linking PFAS exposure to the burden of disease, the approach to monetising human health impacts across a national population, as well as WTP values for avoiding environmental harm.

The overall cost for remediating PFAS across the Nordic countries (€46m - €10,846m) is significantly lower than our range of estimates (£66m to £120,669m for Scenario 1). The difference between the studies is the scale of remediation being proposed – the PFAS Risk Explorer identifies significantly more sites in England (over 10,000 in Scenario 1) for remediation than the Nordic Council of Ministers analysis (1,426). The Phase 4 WP4 cost modelling is also more detailed in terms of the range of cost estimates used and different forms of remediation proposed.

5.2.3.2 US EPA report

The US EPA proposed a reduction in the legal limit for PFAS concentrations in drinking water and accompanied this with economic analysis of the benefits and costs of various options (EPA, 2023). It focused on six different forms of PFAS in drinking water:

- perfluorooctanesulfonic acid (PFOS)

- perfluorooctanoic acid (PFOA)
- perfluorononanoic acid (PFNA)
- hexafluoropropylene oxide dimer acid (HFPO-DA or HFPO-DA)
- perfluorohexanesulfonic acid (PFHxS)
- perfluorobutanesulfonic acid (PFBS).

The report proposes a range of limits, conceding that "maximum contaminant level goal (MCLGs) of 0 ppt for PFOA and 0 ppt for PFOS" is a goal to aim for whereas "enforceable maximum contaminant levels (MCLs) for PFOA and PFOS at 4.0 ppt each" is more feasible. Other PFAS variants will be subject to the same MCL. This reflects the "proposed option" with other options setting high levels, therefore allowing high concentrations of PFAS in drinking water and demanding less intervention.

Annualised benefits and costs (as shown in Table 5-3) indicate an overall positive net outcome in economic terms, although the discount rate plays a significant role, with higher rates creating generating a negative net present value.

Table 5-3: Total national annualised benefits and costs ($Millions, 2021 prices)

	3% discount rate		7% discount rate	
	Benefit	Cost	Benefit	Cost
Proposed option	$1,232.98	$771.77	$908.11	$1,204.61
Option 1a	$1,216.08	$755.82	$895.36	$1,177.31
Option 1b	$1,046.91	$611.01	$773.33	$942.28
Option 1c	$548.80	$292.57	$436.24	$430.87

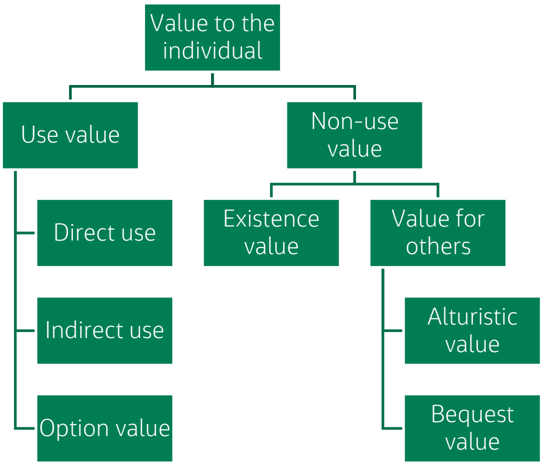
The quantified benefits are exclusively human health related, whereas the costs include the implementation of the new standards (agency costs) and public water system costs. Other categories of benefits associated with PFAS remediation are not quantified in the US EPA analysis.

5.3 Value framework

Prior to considering the potential application of different approaches to valuing PFAS remediation, it is useful to first consider the different elements of value that individuals may hold with regard to any non-market 'good'[1]. A framework for considering such value is set out in Figure 5-3.

[1] The use of the term 'good' does not necessarily imply a positive value. The good may be pollution or other such value-destroying phenomenon. Regardless, an individual may hold a value (positive or negative) with respect to the good in question for the different reasons set out.

Figure 5-3 Total Economic Value Framework



This framework highlights two key elements of the value that someone may hold regarding a good: use and non-use value.

The former refers to the value the individual derives from their experience of the good in question. This may be through direct interaction (e.g. through reduced health impacts from remediation) or indirectly (e.g. through enhanced value of their housing assets as a result of remediation). For some forms of asset (e.g. heritage or cultural assets) there may also exist an option value related to the option to use the asset in the future. Such a concept does not readily translate to the topic at hand.

Non-use value reflects a value that someone can place on a good even if they do not directly benefit. They may just value something because of its existence (e.g. because a reduction in pollution is morally the right thing to do) or because it will yield use values to others, either to those currently alive or for future generations.

Given the long-term and non-exclusivity of the benefits PFAS remediation, it is clear that consideration of the value of PFAS remediation should, if possible, look to account of both use and non-use elements to be complete.

5.4 Comparison of valuation approaches

When considering the impact of issues such as pollution on individuals/society, HM Treasury's Green Book highlights three key methodologies for valuing such non-market impacts: stated preference, revealed preference and wellbeing valuation. Stated preference techniques also underpin the Quality Adjusted Life Year (QALY) based approach to valuing health outcomes including both changes in mortality and morbidity which can be considered as a further option.

The relative advantages and disadvantages of the different approaches is set out in supplementary government guidance (Fujiwara & Campbell, 2011). These are summarised in Table 5-4. In short, stated preference provides the most flexible approach but are costly and are subject to a range of biases, while wellbeing-based approaches are cost effective but cannot cover future-looking scenarios or non-use value. QALY-based approaches are relatively easy to apply but cannot capture all aspects of value.

Table 5-4 Relative advantages and disadvantages of non-market valuation approaches

Approach	Advantages	Disadvantages
Stated preference	Can be applied to a wide range of scenarios including hypothetical issues	Costly

	Can provide evidence for different elements of value including non-use value	Subject to a range of biases including anchoring, hypothetical effects as well as protest valuations Requires ability to clearly define scenario and convey key attributes
QALY-based valuation	Existing value for changes in length of life and/or quality health Can be applied to hypothetical situations without need for a survey	Can only capture health-mediated impacts
Revealed preference	Based upon actual choices made by individuals Relatively cost-effective	Limited application to issues that are revealed through a linked secondary market (e.g. housing or labour market) Non-use value not captured
Wellbeing-based valuation	Highly cost-effective Based upon actual lived experience Few biases	Non-use value not captured Difficulties in establishing causal estimates of key impacts Limited to existing conditions that are captured within relevant datasets

Within stated preference approaches, different options can be considered. Whereas the most common approach (a contingent valuation study) asks participants to directly state their willingness to pay for a scenario that is presented, a more complex discrete choice experiment approach seeks to understand individual's willingness to trade off specific attributes of the scenario in question. As such, the latter can provide more nuanced understanding of what is driving the assessed value and provide some level of counterweight to the potential hypothetical bias[2].

5.5 Benefits mapping and valuation approaches

As indicated in the evidence review, the current evidence base for quantifying and monetising PFAS impacts focuses on human health in terms of morbidity and mortality. It is possible to value these human health impacts in economic terms, however this requires data, and in the absence of such data, assumptions to be made that are beyond the scope of this study. Quantification of avoided health costs using a QALY approach would be a plausible next step and is discussed further in Section 5.6.

The difficulties in valuing human health impacts also extend to other categories of benefits arising from PFAS remediation which are likely to be further away from a robust method for quantification and monetisation. Table 5-5 below presents an outline for how to conceptualise benefits and the valuation approaches that may be applicable.

[2] By forcing individuals to make choices between scenarios, the discrete choice experiment forces some consideration of the reality of trade-offs in the real world. However, it remains the case that the choices are hypothetical and, as such, people may not accurately consider their genuine willingness to pay.

Table 5-5: Benefit Category Valuation Approaches

Category of benefit	Impact	Indicator	Valuation approach
Human health	Reduced morbidity and mortality	Change in levels of disease and mortality.	Quality-adjusted life year Value of a statistical life
Wellbeing	Reduced anxiety from real and perceived PFAS risk	Change in stated level of quality of life	WELLBY
Development land	Unlocking development land	Change in number of industrial residential, commercial and industrial units	Number of properties Market value per unit/floorspace
Property values	Avoided reduction in property house price or rental value. Applies to residential, commercial and industrial units.	Change in market value of properties Change in number of properties in proximity to high risk sites	Hedonic pricing using % change in observed sale prices. Generally not included in economic appraisal at a national scale but could be considered regionally
Species	Avoided deaths of animals affected by PFAS	Change in number of animals (birds, fish etc.)	Market value of livestock or foodstuff. Wild species contribution to overall biodiversity could be captured using the Biodiversity Metric but is not monetised.
Habitats/Ecosystem services	Avoided degradation of habitats and associated ecosystem services. Quality of surface water and drinking water is an important strategic aim of multiple organisations.	Change in natural capital assets (extent and condition of habitats) and resulting change in ecosystem services. This is a current research gap.	Natural Capital Assessment provides a range of approaches to valuing the loss or gain in ecosystem services in economic terms.
Legal dispute	Avoided legal disputes (e.g. gross negligence and/or nuisance cases)	Change in number of legal disputes	Settlement costs[3]
Public perception & behaviour change	Increased public awareness leading to change in consumer choices – both in terms of PFAS free products and greener products generally.	Change in products purchased/services used	Multiple depending on the life cycle impacts

[3] Such as recent settlements by Solvay of $393m (https://www.jdsupra.com/legalnews/nj-pfas-alert-solvay-enters-393-million-9747620/?origin=CEG&utm_source=CEG&utm_medium=email&utm_campaign=CustomEmailDigest&utm_term=jds-article&utm_content=article-link) and 3M of $10.3bn (https://www.theguardian.com/environment/2023/jun/22/3m-settlement-municipal-water-systems-pfas-contamination).

5.6 QALY – feasible method for human health impact valuation

Given that remediation of land-based sites has not yet occurred on a significant scale, revealed preference and wellbeing valuation are not viable options. While there could theoretically be potential to assess the cost of PFAS pollution using one of these techniques, in reality it is unlikely that individuals are currently sufficiently aware of the risks and impacts associated with PFAS for their effect to be measurable either in stated wellbeing values or in the property market.

The question is then whether a stated preference approach (contingent valuation or discrete choice experiment) is preferred to a narrower valuation approach which would capture health outcomes only using QALYs. Previous studies have reasoned that a QALY-based approach may be preferable in situations of non-fatal health risks where individuals are often seen to express inconsistent willingness to pay to avoid illness of varying length and severity, often being insensitive to the length of the illness while simultaneously being relatively over-sensitive to changes in probability (Hammitt, 2016).

While stated preference methods could, in theory be used to capture the full value (beyond health outcomes) that individuals attribute to PFAS remediation, there are significant challenges in implementing such an approach. While issues of anchoring, hypothetical bias and protest valuations can be overcome through good survey design[4], the key issue is the ability of any survey to effectively convey the likely benefits of PFAS remediation in such a way as to elicit and accurate understanding of an individual's willingness to pay. Given the relative paucity of understanding of the long-term impacts of PFAS or the potential impacts of remediation, it will be difficult to frame a scenario for valuation within such as survey that can be accurately interpreted and valued by those taking it.

Changes in risk are particularly difficult to value. Any PFAS remediation is inevitably only going to be partial and hence will only shift the degree to which the hazard remains rather than eliminating it completely.

It is possible that, in the future, with greater scientific clarity and public awareness, a stated preference approach may be viable. However, at this stage, our view that the best alternative would be to use a QALY-based approach to valuing the health impacts. Despite the issues in quantification and monetisation of human health impacts, it is still easiest relative to other types of impact, partially due to the significantly developed research base. Therefore, we recommend that this is first form of monetised impact relating to PFAS.

5.7 Benefits of Scenarios

Scenarios 1 and 2 focus on remediation of PFAS contaminated soil and groundwater at a number of individual high-risk sites across the England. As shown in the logic chains in Section 3.7, each site type has a different combination of primary contamination sources and proposed remediation methods. Table 5-6 describes the potential benefits of these interventions, providing a basis for future work and adding quantitative detail where possible.

[4] For example, the use of so-called 'cheap talk' scripts has been shown to reduce hypothetical bias and randomisation can help to reduce anchoring impacts

Table 5-6: Potential benefits of PFAS remediation in Scenario 1 and 2

Issue and Remediation	Impact	Logic chain	Benefits
Groundwater contamination – PRB Soil contamination – Excavation and treatment	Reduced PFAS dispersion in groundwater and soil	Decreased PFAS dispersion in groundwater and soil that otherwise could contaminate drinking water and in turn cause human health impacts.	Decreased morbidity and mortality associated with avoided negative human health impacts. Could be monetised via QALY approach. Security of drinking water supply could be quantified and monetised using average incremental cost of alternative supply.
		Decreased PFAS dispersion in soil allows site to return to use (industrial, commercial, or domestic/residential).	Potential future use of site for economic activity (industrial, commercial, residential units/floorspace), creates jobs, expenditure and multiplier effects. Avoided reduction in house prices or site value (commercial/industrial) for sites in proximity.
		Research (Legg, et al., 2022) shows that people who are aware of PFAS contamination near their homes perceive negative harm on their physical health and this gives rise to mental health impacts.	Improvement (or avoided reduction) in quality of life. This could be quantified and monetised using a WELLBY approach.
		Decreased PFAS dispersion in groundwater and soil reduces exposure and consequential impact on animal health including domestic and wild species.	Avoided animal deaths/loss of species. This remains a research gap however the impact could be monetised according to the market value of reared/domestic animals. Wild species contribution to biodiversity could be captured by the Biodiversity Metric (non-monetised) and in theory through natural capital assessment; however the contribution of species to ecosystem service provision is not widely understood.
		Decreased PFAS dispersion in groundwater and soil prevents ecosystem degradation including crop cover and plant life.	Impact of PFAS on plant-life, soil health and agricultural productivity has not been researched and remains a gap. However the impact could be monetised based on improvement (or avoided loss) of crop yields, timber production and other ecosystem goods. Contribution to the overall health of ecosystems could be captured by the Biodiversity Metric (non-monetised) and in theory through natural capital assessment; however effect on plant and soil health on ecosystem service provision is not widely understood
		Decreased PFAS in surface waters. This is a strategic target for the EA (For example, PFOA presence causing surface water bodies to fail "Good Chemical Status").	Perception of PFAS contamination has an impact on individuals (see (Legg, et al., 2022) and WELLBY discussion above). If PFAS in surface waters decreases then individuals will be more likely to utilise surface water bodies for activity.

		PFAS remediation prevents future legal disputes such as gross negligence cases, reduction in property value, lost productivity, mitigation costs, lost revenue (tourism dissuaded, seafood not consumed etc.) (Ashurst, 2020).	Potential avoided legal costs for polluters, local authorities and regulators.
Groundwater contamination – On-site water treatment	Reduced PFAS concentration in groundwater	Decreased PFAS in groundwater contamination achieves same benefits as above interventions. On-site water treatment is used instead of off-site water treatment that involves use of road transport.	Same benefits as above. Lower transport costs an associated externalities. Potentially lower operating costs associated with on-site treatment.
Effluent contamination – Permeable cap	Reduced PFAS concentration in leachate	Less PFAS flux in wider surface waters and groundwaters	Human health and environmental benefits of decreased PFAS in surface waters and groundwaters.

Table 5-6 shows that Scenarios 1 and 2 potentially generate significant benefits by reducing PFAS concentrations in the environment. Further research is needed to robustly estimate the scale of these benefits at various national, regional, sectoral and individual case study levels. The greatest societal benefits are likely to associated with:

- Human health (avoided morbidity and mortality)
- Environment (animal health, biodiversity, habitats, surface water quality, livestock/market value)
- Economy (existing property/rental value, drinking water supply, development land value, employment, expenditure, and multiplier effects skills)

Other categories of benefits discussed in Table 5-6 such as avoided legal costs and reduced operating costs represent a potential benefit to some agents/organisations but a cost to others – therefore would not necessarily be captured in a national economic assessment.

Scenario 3 proposes a different type of intervention (centralised end of pipe solution at WwTW) that does not address PFAS contamination at individual sites as in Scenarios 1 and 2. Scenario 3 should therefore be considered an additional intervention instead of an alternative to Scenarios 1 and 2. That being said, Scenario 3 would alter the remediation choice of on-site water treatment for landfill and other small industrial operations.

As described in Section 4.5, Scenario 3 would result in reduced concentration of PFAS in treated wastewater, with knock on benefits to surface waters receiving effluent discharge. This larger scale intervention to tackle PFAS at a national level mirrors the scenarios analysed in the landmark studies by the Nordic Council of Ministers and the US EPA. Estimating the human health benefits would be possible using a similar approach to the two landmark studies, given an ability to make assumptions of purported change in PFAS concentrations and health outcomes for the population. Other aspects of Scenario 3 that would potentially favour it over other interventions are its relative ease to implement, making use of existing assets and services. These include sewage infrastructure, charging mechanisms for water companies and an existing regulator (Ofwat).

Remediation of high-risk sites as reflected in Scenarios 1 and 2 could give rise to higher overall societal benefits than Scenario 3; however until further work is done to explore source apportionment and the concentration/flux across all environmental receptors + impact pathways it is not possible to draw any firm conclusions. Overall, more work is required to robustly quantify the effects of all scenarios at a meaningful level and suggestions are made in Section 6.2.

6. Conclusions

6.1 Summary of overall conclusions

The aim of this work package is "*develop an approach and ultimately deliver a report, detailing the nature of the PFAS problem across the Country together will a mechanism for deriving costs to highlight the financial scale and burden of the problem.*"

This report uses a cost estimation model, that could be developed to add further utility, to provide perspective on the financial scale and burden of the problem. The three scenarios of PFAS remediation costs provide insight into the scale of the problem and a robust dynamic model with significant evidence base forms the foundation that can be adjusted to a rapidly changing landscape of PFAS. The model is flexible and allows the incorporation of better cost data and new remediation approaches as relevant information becomes available.

The PFAS Risk Explorer indicates the potential for the existence of a large number of high risk sites in England as a result of historic and ongoing use of PFAS, (although the number of high risk sites depends upon the threshold score used to define 'high risk'), even after accounting for relative importance of different types of sites. Scenario 1 estimating 10,236 sites and 672,000,000 m^2 of affected area; scenario 2 estimating 2,865 sites and 317,000,000 m^2 (see section 4.2).

As shown in Table 6-1 below, the cost of PFAS remediation at these sites is significant and underlines the scale of PFAS contamination and the complexity and difficulty of removing them from the environment.

Cost estimates for PFAS remediation at different sites are based on an extensive evidence review involving academic, grey literature and expert elicitation. The range of these estimates underlines the scale and complexity of PFAS contamination and remediation; a "one-size-fits-all" approach will not work at a national level. Scenarios 1 and 2 contain a degree of feasibility with chosen remediation for each site type and effort/cost levels but the scale and cost at a national level is still potentially infeasible.

Table 6-1: Summary of remediation cost totals for Scenarios 1 and 2

Site type	Scenario 1 Total (£ millions)			Scenario 2 Total (£ millions)		
	Low	High	Average	Low	High	Average
Air Transport Sites/Military	£2,100	£4,700	£3,400	£1,000	£2,300	£1,700
Fire Stations	£1,100	£4,800	£3,000	£800	£2,700	£1,700
Permitted Landfill	£2,800	£4,200	£3,500	£500	£1,000	£800
Historic Landfill	£14,700	£39,500	£27,100	£3,100	£9,500	£6,300
Wastewater Treatment Works	£23,400	£32,700	£28,100	£14,600	£19,800	£17,200
COMAH/Chemicals/Refineries	£20,800	£33,100	£27,000	£11,300	£25,900	£18,600
Nuclear Permitted Site	£100	£100	£100	£22	£22	£22
TULAC/Metals/Pulp and Paper	£1,200	£1,500	£1,400	£148	£173	£161
Oil and Gas	£0.30	£0.30	£0.30	£0.00	£0.00	£0.00
All	£66,200	£120,700	£93,400	£31,500	£61,300	£46,400

PFAS remediation interventions bring about the following potential benefits:

- Health benefits
    - Reduced morbidity and mortality
    - Increased wellbeing for individuals
- Economic benefits
    - Avoided blight of residential, commercial and industrial properties.
    - Opportunity for sites to be used for future residential, commercial and industrial activities. Potential jobs, skills, and taxation benefits from this.
    - Drinking water security enables economic activity.
    - Avoided legal action.
- Environmental benefits
    - Animal health is negatively affected by PFAS, this has been proven in scientific terms but not quantified/monetised in economic terms. It is noted as a potential research gap in sections 5 and 6.2
    - Surface water quality is a strategic aim of the EA and this will be positively affected by PFAS remediation interventions.

For the reasons set out in section 5, these potential benefits have not been quantified and monetised in this report but it is possible to conduct further research (see following section 6.2).

Scenarios 1 and 2 show that addressing PFAS contamination at sites has benefits but also significant financial costs. Scenario 3 shows that addressing PFAS using a centralised WwTW based approach will have a positive effect on PFAS concentrations in the environment but still allows PFAS to remain at high risk sites identified in scenarios 1 and 2. The landmark studies (Nordic Council and EPA) show that interventions similar to scenario 3 have positive effects on human health, potentially creating a net positive effect when only focussing on human health and financial cost.

Scenario 3's centralised approach also is relatively feasible compared to the interventions set out in scenarios 1 and 2 given 3's use of existing infrastructure and regulatory powers in the water sector. Again though, it should be noted that scenario 3 is additive to scenarios 1 and 2, not an alternative. The problem of PFAS has to be tackled by a range of organisations, it cannot be tackled solely by ground specialists in the EA, Defra, Ofwat, other industry bodies and private firms must also act.

6.2 Research gaps identified

Short term research gaps that could be addressed in the immediate future:

- Impact pathways of PFAS
    - To what extent do different sources of PFAS contribute to overall PFAS in the environment?
        - In turn, to what extent does this lead to PFAS in other receptors such as humans.
    - This discussion of source apportionment of PFAS would allow progress towards prioritising which areas should be focussed on first, where funding should be allocated, and where the burden of cost is.
    - What is a bigger issue: PFAS in ground at a fire station that may make it's away into a river and eventually drinking water or PFAS in textiles, pizza-boxes and makeup?
- Microeconomic Cost Benefit Analysis (CBA) analysis of site based PFAS remediation – case study of the site types in detail. Reference new research paper that includes cost of inaction (Drenning, et al., 2023).
    - This would entail a detailed economic examination of one of the site types, looking at the potential impacts, both positive and negative; This would move beyond the discussion of financial cost, looking at the economic impacts similar to a business case. The example mentioned above by Drenning is recent and sets out an approach for airports.
- Quantify/monetise impacts discussed in section 5.5 – health, economic, and environmental impacts.
    - This would focus on human health initially as this has the most research behind it. Using similar approaches to The Nordic Council of Ministers, US EPA or a QALY approach.
        - QALY based human health benefit assessment to assess and monetise evidence on human health benefits of reduced PFAS contamination. This would require a review of the evidence on health impacts and modelling of the QALY changes and hence value associated with reduction in risk of a range of conditions.
    - As discussed in section 5, quantifying/monetising all elements relating to PFAS is not possible with current levels of research therefore some of these will be longer term, potentially requiring data collection.
- Utilise Monte Carlo simulation to manage range of figures more effectively within cost data. This could produce more robust ranges of cost estimates and associated uncertainty for the different site types.
- Transition costs in replacing PFAS in industrial processes. Nappies, cosmetics, food packaging and storage, fertiliser (PFAS contaminated sewage sludge), firefighting foams etc. Other concurrent research is being conducted on this but there will still be gaps in specific areas.
- In some areas of industrial activity, notably TULAC, pulp and paper and metals, the amount of available information about PFAS use, historically and currently, is limited compared with other sectors. Further work is needed to provide more robust cost estimates on these groups. Investigating separate industry sub-groups and further examination of PFAS use in each, the number, size and distribution of sites, types and quantities of PFAS use, exposure pathways to receptors including humans, etc. To determine the significance of each sub-group in current and historic PFAS use. This will be subject to the availability of useable datasets of relevant information and may require research to gather the required information.
- Investigate feasibility and potential economic impact of scenario 3.

  - Scenario 3 – centralised approach of water companies addressing PFAS in wastewater is potentially preferable to a significantly larger number of smaller companies implementing remediation.
  - Economic efficiency of this type of centralised intervention – smaller operators remain in business (Part 2A examples), increased compliance rates, jobs retained, one regulator instead of multiple across individual business sectors/EA and Defra.
    - This would be a step towards addressing the question 'who bears the burden of the cost of dealing with PFAS?' that was originally intended to be explored at within this study.
- There are potential impacts on the insurance market and implications of any change in insurers' willingness to cover risks associated with PFAS in the future. This could be investigated through expert elicitation with lawyers and insurance companies.
- Investigation costs for sites with limited data should be researched further.

Long term research gaps:

- Environmental impacts of PFAS appear to be a research gap, specifically effect on soil health, plant/vegetation growth. There has been research into negative effect on animal health of PFAS but the potential impact of this in a wider ecosystem context has not been investigated. It has also not been quantified in economic terms such as a Natural Capital Assessment or BNG. This could be investigated via a case study or proposal of a bespoke methodology of assessment or logic chain of effect.
- Potential dynamic effects of PFAS regulation and remediation interventions being adopted globally and within the UK.
  - Economies of scale for materials and technologies
  - Supply and demand pressure lead to significant changes in price
  - Unintended consequences – for example, significant increase in demand for GAC incineration outstrips current supply. There is not enough activated carbon either.
- Research on national landfill capacity to indicate potential feasibility of off-site disposal of PFAS contaminated soils and on the capacity for the disposal of spent GAC filter media either by incineration or disposal to landfill.
  - UKWIR identified, see 4.5, that there is currently not enough incineration capacity to deal with the remediation proposed in Scenario 3 (Campitelli, et al., 2022). To address the PFAS issue nationally, more remediation and GAC filter media is required therefore the problem is significant.
- Maintain watching brief on the development, viability and market readiness of full-scale remediation techniques.

7. Bibliography

Anderson, J. et al., 2022. Grouping of PFAS for human health risk assessment: Findings from an independent panel of experts.. *Regul Toxicol Pharmacol,* p. 134.

Ashurst, 2020. *PFAS and Property: Valuation, Litigation, Remediation.* [Online] Available at: https://www.ashurst.com/en/news-and-insights/insights/pfas-and-property-valuation-litigation-remediation/

Bluteau et al., 2019. *The Global PFAS problem: Fluorine-Free Alternatives as Solutions,* s.l.: IPEN Expert Panel.

Calloway, E. et al., 2020. Exploring Community Psychosocial Stress Related to Per- and Poly-Fluoroalkyl Substances (PFAS) Contamination: Lessons Learned from a Qualitative Study.. *Int J Environ Res Public Health,* p. Nov 24; 17 (23).

Campitelli, A., Georges, K., Newton, C. & Piekarniak, L., 2022. *PFAS and wastewater - prevalence, reduction options and costs.* [Online] Available at: https://ukwir.org/new-object-159

Cheng, B. et al., 2022. Per- and polyfluoroalkyl substances exposure science: current knowledge, information needs, future directions. *International Journal of Environmental Science & Technology (IJEST),* 19(10), pp. 10393-10408.

Dickman, R. & Aga, D., 2022. A review of recent studies on toxicity, sequestration, and degradation of per- and polyfluoroalkyl substances (PFAS). *Journal of Hazardous Materials.*

Drenning, P. et al., 2023. Comparison of PFAS soil remediation alternatives at a civilian airport using cost-benefit analysis. *Science of The Total Environment,* p. https://www.sciencedirect.com/science/article/pii/S0048969723022842.

EBJ, 2022. PFAS Waiting Game Continues in 2022. *Environmental Business Journal.*

ECHA, 2022. *ANNEXES TO ANNEX XV RESTRICTION REPORT,* s.l.: European Chemicals Agency.

EFSA, 2020. Risk to human health realted to the presence of perfluoroalkyl substances in food- Scientific Opinion. *EFSA journal.*

EPA, U. E. P. A., 2023. *Economic Analysis for the Proposed Per- and Polyfluoroalkyl Substances.* [Online] Available at: https://www.epa.gov/system/files/documents/2023-03/Proposed%20PFAS%20NPDWR%20EA_final_03_09_2023_0.pdf

Feng, D. S. C. &. M. W., 2021. *Environmental, human health, and economic implications of landfill leachate treatment for per- and polyfluoroalkyl substance removal,* s.l.: Journal of Environmental Management.

Fujiwara, D. & Campbell, R., 2011. *Valuation Techniques for Social Cost-Benefits Analysis - A Discussion of the Current Issues.* [Online] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/209107/greenbook_valuationtechniques.pdf

Goldenman et al., 2019. *The Cost of Inaction: A Socioeconomic Analysis of Environmental and Health Impacts Linked to Exposure of PFAS,* s.l.: Nordic Council of Ministers.

Goldenman, G. et al., 2019. *THE COST OF INACTION: A socioeconomic analysis of environmental and health impacts linked to exposure to PFAS,* Copenhagen, Denmark: Nordic Council of Ministers.

Hammitt, J., 2016. *Valuing Non-fatal Health Risks: Monetary and Health Utility Measures.* [Online] Available at: https://www.tse-fr.eu/sites/default/files/TSE/documents/doc/wp/2017/wp_tse_757.pdf

HSE, 2023. *Analysis of the most appropriate regulatory management options (RMOA),* s.l.: HSE.

IPEN, 2019. *The Global PFAS Problem: Fluorine-Free Alternatives as Solutions,* s.l.: IPEN Expert Panel.

Jacobs, 2023a. *WP2 Good Practice Guidance Liternature Review,* s.l.: s.n.

Jacobs, 2023b. *WP5 Landfill Assessment,* s.l.: s.n.

Jacobs, 2023c. *PFAS Risk Explorer Handbook,* Reading: s.n.

Kanchanapiya, P. a. T. T., 2022. *Analysis of the additional cost of addressing per- and polyfluoroalkyl substance contamination from landfill leachate by reverse osmosis membranes in Thailand,* s.l.: Journal of Water Process Engineering.

Legg, R., Prior, J., Adams, J. & McIntyre, E., 2022. A geography of contaminated sites, mental health and wellbeing: The body, home, environment and state at Australian PFAS sites,. *Emotion, Space and Society,,* p. Volume 44.

Lewis, A., Yun, X., Spooner, D. & Marie J. Kurz, E. R. M. C. M. S., 2022. Exposure pathways and bioaccumulation of per- and polyfluoroalkyl substances in freshwater aquatic ecosystems: Key considerations. *Science of The Total Environment.*
Li, M. et al., 2017. Isomers of perfluorooctanesulfonate (PFOS) in cord serum and birth outcomes in China: Guangzhou Birth Cohort Study. *Environment International,* pp. 102. 1-8..
OECD, 2021. *Reconciling Terminology of the Universe of Per- and Polyfluoroalkyl Substances: Recommendations and Practical Guidance.* [Online]
Available at: https://one.oecd.org/document/ENV/CBC/MONO(2021)25/En/pdf
[Accessed June 2023].
OECD, 2022. *Synthesis Report on Understanding Side-Chain Fluorinated Polymers and Their Life Cycle.* [Online]
Available at: https://www.oecd.org/chemicalsafety/portal-perfluorinated-chemicals/synthesis-report-on-understanding-side-chain-fluorinated-polymers-and-their-life-cycle.pdf
[Accessed June 2023].
Pelch, K. E. et al., 2022. The PFAS-Tox Database: A systematic evidence map of health studies on 29 per- and polyfluoroalkyl substances,. *Environment International,* p. Volume 167.
Schultes, L. et al., 2020. Temporal Trends (1981-2013) of Per- and Polyfluoroalkyl Substances and Total Fluorine in Baltic cod (Gadus morhua). *Environ Toxicol Chem,* pp. 300-309.
UK, P., 1990. Environmental Protection Act 1990. *UK Parliament.*
Wang, Y., Munir, U. & Huang, Q., 2023. Occurrence of per- and polyfluoroalkyl substances (PFAS) in soil: Sources, fate, and remediation. *Soil & Environmental Health.*
Wood et al., 2020. *The use of PFAS and fluorine-free alternatives in fire-fighting foams,* s.l.: ECHA.

8. Appendices

Appendix A. Literature Review Search Terms

Key documents / areas	Economic impact key search words	Other relevant key words
Public Health Agencies	Impact assessment	Regulation
Environment Agency Publications	Monitoring and Reporting	Insurance industry response
PFAS Firefighting Foams – fluorinated aqueous film-forming foams (AFFFs)	Mitigation techniques and their cost	Orphan sites
Commercial application of PFAS	Property value	Forever Chemicals
International Environment Agencies (e.g. US EPA)	Asset value	PFOA/PFOS/PFCs
The Nordic government's 2018 Report 'The Cost of Inaction'	Disruption to business operation. Lost revenue. Lost production.	Air Transport sites (civil and military)
Homes & Communities Agency's Remediation Cost Guidance	Cost to water industry operations	Landfills (permitted and historical)
National Institute of Environmental Health Sciences (US)	Health impact	Utilities, including Waste Water Treatment Works (WWTWs)
Chemicals Policy	Social cost	COMAH Sites
	Population impact	Fire Stations & Fire-fighting Training Sites
	Socio-economic impacts	Textiles, Upholstery, Leather, Apparel and Carpets (TULAC)
	Respiratory impact	Remediation
	Environmental impact	Toxicology Research
	Natural capital impact	Environmental incident economic impact
	Biodiversity	Remediation
	Habitats[5]	Water contamination
	Ecosystem services (provisioning, regulating, cultural) based on Enabling Natural Capital Approach (see footnote 1)	Public health event or disaster
	Productivity	Investigation
	Land-use	Consultancy cost
	Employment or jobs	Reputational damage
	Water quality	
	Wildlife	
	Businesses	
	Output	

[5] UK Government, 2021, https://www.data.gov.uk/dataset/3930b9ca-26c3-489f-900f-6b9eec2602c6/enabling-a-natural-capital-approach

UK Government, 2021, https://www.gov.uk/government/publications/enabling-a-natural-capital-approach-enca-guidance/enabling-a-natural-capital-approach-guidance#economic-valuation

	Export	
	Stress, anxiety, mental health	
	Life expectancy or mortality	
	Illness or sickness	
	Costs and benefits (including social cost)	
	Economic appraisal of environmental incident	
	Economic appraisal of public health incident	
	Externalities	

Appendix B. Shortlisted Papers

Author(s)	Title	Publication year	
Sivagami K,Sharma P,Karim AV,Mohanakrishna G,Karthika S,Divyapriya G,Saravanathamizhan R,Kumar AN	Electrochemical-based approaches for the treatment of forever chemicals: Removal of perfluoroalkyl and polyfluoroalkyl substances from wastewater	2022	https://www.sciencedirect.com/science/article/pii/S0048969722075428
Garrett KK,Brown P,Varshavsky J,Cordner A	Improving governance of "forever chemicals" in the US and beyond	2022	https://www.sciencedirect.com/science/article/pii/S2590332222004936
Wang Q,Ruan Y,Zhao Z,Zhang L,Hua X,Jin L,Chen H,Wang Y,Yao Y,Lam PK,Zhu L,Sun H	Per- and polyfluoroalkyl substances (PFAS) in the Three-North Shelter Forest in northern China: First survey on the effects of forests on the behavior of PFAS	2022	https://www.sciencedirect.com/science/article/pii/S0304389421031277
Zhang M,Zhao X,Zhao D,Soong TY,Tian S	Poly- and Perfluoroalkyl Substances (PFAS) in Landfills: Occurrence, Transformation and Treatment	2023	https://www.sciencedirect.com/science/article/pii/S0956053X22005141
Li M,Zeng XW,Qian Zmin,Vaughn MG,Sauvé S,Paul G,Lin S,Lu L,Hu LW,Yang BY,Zhou Y,Qin XD,Xu SL,Bao WW,Zhang YZ,Yuan P,Wang J,Zhang C,Tian YP,Nian M,Xiao X,Fu C,Dong GH	Isomers of perfluorooctanesulfonate (PFOS) in cord serum and birth outcomes in China: Guangzhou Birth Cohort Study	2017	https://www.sciencedirect.com/science/article/pii/S016041201630592X
Feng D,Song C,Mo W	Environmental, human health, and economic implications of landfill leachate treatment for per- and polyfluoroalkyl substance removal	2021	https://www.sciencedirect.com/science/article/pii/S0301479721006204
Moeini M,Modaresahmadi K,Tran T,Reddy KR	Sustainability assessment of PFAS adsorbents for groundwater remediation	2022	https://www.sciencedirect.com/science/article/pii/S2214785322013037
Kassotis CD,Vandenberg LN,Demeneix BA,Porta M,Slama R,Trasande L	Endocrine-disrupting chemicals: economic, regulatory, and policy implications	2020	https://www.sciencedirect.com/science/article/pii/S2213858720301285
Mahinroosta R,Senevirathna L	A review of the emerging treatment technologies for PFAS contaminated soils	2020	https://www.sciencedirect.com/science/article/pii/S0301479719316147
Legg R,Prior J,Adams J,McIntyre E	A geography of contaminated sites, mental health and wellbeing: The body, home, environment and state at Australian PFAS sites	2022	https://www.sciencedirect.com/science/article/pii/S1755458622000421
Longpré D,Lorusso L,Levicki C,Carrier R,Cureton P	PFOS, PFOA, LC-PFCAS, and certain other PFAS: A focus on Canadian guidelines and guidance for contaminated sites management	2020	https://www.sciencedirect.com/science/article/pii/S2352186419308168
Pelch KE,Reade A,Kwiatkowski CF,Merced-Nieves FM,Cavalier H,Schultz K,Wolffe T,Varshavsky J	The PFAS-Tox Database: A systematic evidence map of health studies on 29 per- and polyfluoroalkyl substances	2022	https://www.sciencedirect.com/science/article/pii/S016041202200335X

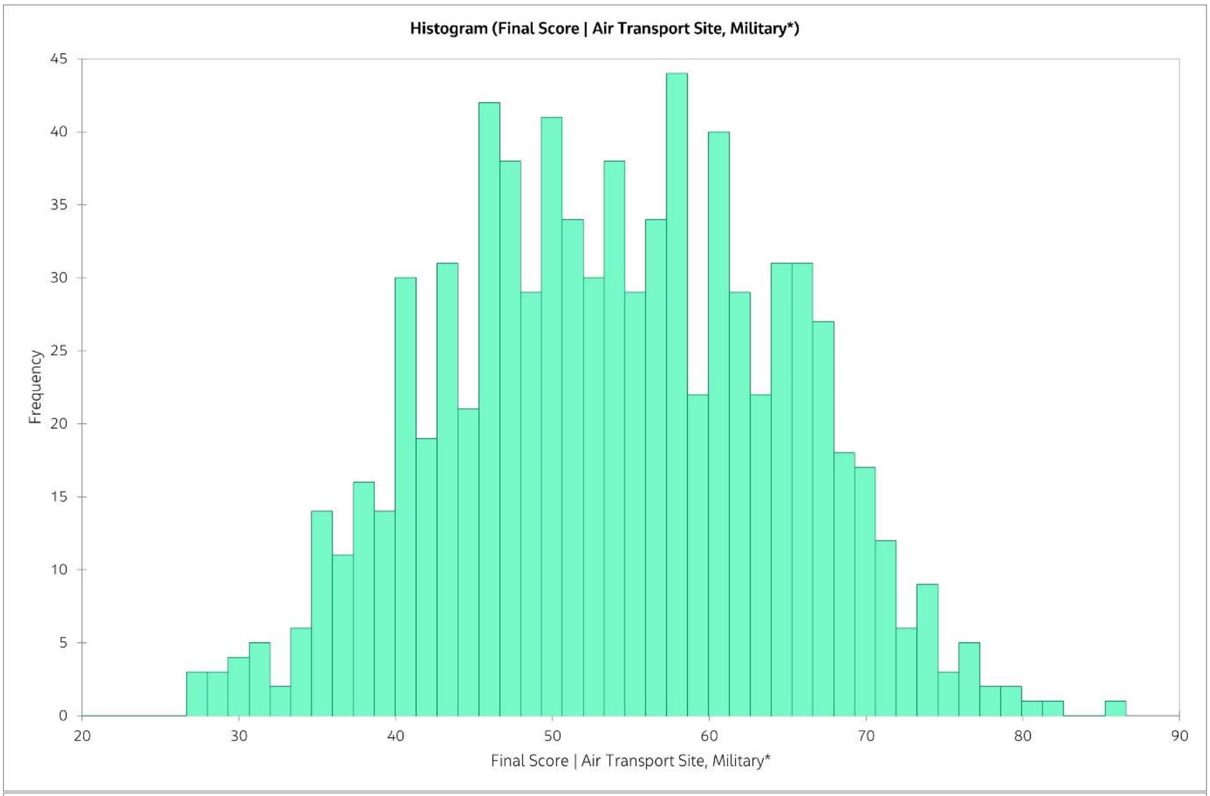
Stoiber T,Evans S,Naidenko OV	Disposal of products and materials containing per- and polyfluoroalkyl substances (PFAS): A cyclical problem	2020	https://www.sciencedirect.com/science/article/pii/S0045653520318543
DeLuca NM,Angrish M,Wilkins A,Thayer K,Cohen Hubal EA	Human exposure pathways to poly- and perfluoroalkyl substances (PFAS) from indoor media: A systematic review protocol	2021	https://www.sciencedirect.com/science/article/pii/S0160412020322637
O'Connor J,Bolan NS,Kumar M,Nitai AS,Ahmed MB,Bolan SS,Vithanage M,Rinklebe J,Mukhopadhyay R,Srivastava P,Sarkar B,Bhatnagar A,Wang H,Siddique KH,Kirkham MB	Distribution, transformation and remediation of poly- and per-fluoroalkyl substances (PFAS) in wastewater sources	2022	https://www.sciencedirect.com/science/article/pii/S0957582022004839
Vendl C,Taylor MD,Bräunig J,Gibson MJ,Hesselson D,Gregory Neely G,Lagisz M,Nakagawa S	PFAS exposure of humans, animals and the environment: Protocol of an evidence review map and bibliometric analysis	2022	https://www.sciencedirect.com/science/article/pii/S0160412021005985
Anderson JK,Brecher RW,Cousins IT,DeWitt J,Fiedler H,Kannan K,Kirman CR,Lipscomb J,Priestly B,Schoeny R,Seed J,Verner M,Hays SM	Grouping of PFAS for human health risk assessment: Findings from an independent panel of experts	2022	https://www.sciencedirect.com/science/article/pii/S0273230022001131
Awad J,Brunetti G,Juhasz A,Williams M,Navarro D,Drigo B,Bougoure J,Vanderzalm J,Beecham S	Application of native plants in constructed floating wetlands as a passive remediation approach for PFAS-impacted surface water	2022	https://www.sciencedirect.com/science/article/pii/S0304389422001145
Dickman RA,Aga DS	A review of recent studies on toxicity, sequestration, and degradation of per- and polyfluoroalkyl substances (PFAS)	2022	https://www.sciencedirect.com/science/article/pii/S0304389422009104
Yadav S,Ibrar I,Al-Juboori RA,Singh L,Ganbat N,Kazwini T,Karbassiyazdi E,Samal AK,Subbiah S,Altaee A	Updated review on emerging technologies for PFAS contaminated water treatment	2022	https://www.sciencedirect.com/science/article/pii/S0263876222001733
Wanninayake DM	Comparison of currently available PFAS remediation technologies in water: A review	2021	https://www.sciencedirect.com/science/article/pii/S0301479721000396
Garg S,Wang J,Kumar P,Mishra V,Arafat H,Sharma RS,Dumée LF	Remediation of water from per-/poly-fluoroalkyl substances (PFAS) – Challenges and perspectives	2021	https://www.sciencedirect.com/science/article/pii/S2213343721007612
Cooper K,Burdon D,Atkins JP,Weiss L,Somerfield P,Elliott M,Turner K,Ware S,Vivian C	Can the benefits of physical seabed restoration justify the costs? An assessment of a disused aggregate extraction site off the Thames Estuary, UK	2013	https://www.sciencedirect.com/science/article/pii/S0025326X1300461X
Mohamed BA,Li LY,Hamid H,Jeronimo M	Sludge-based activated carbon and its application in the removal of perfluoroalkyl substances: A feasible approach towards a circular economy	2022	https://www.sciencedirect.com/science/article/pii/S0045653522002004

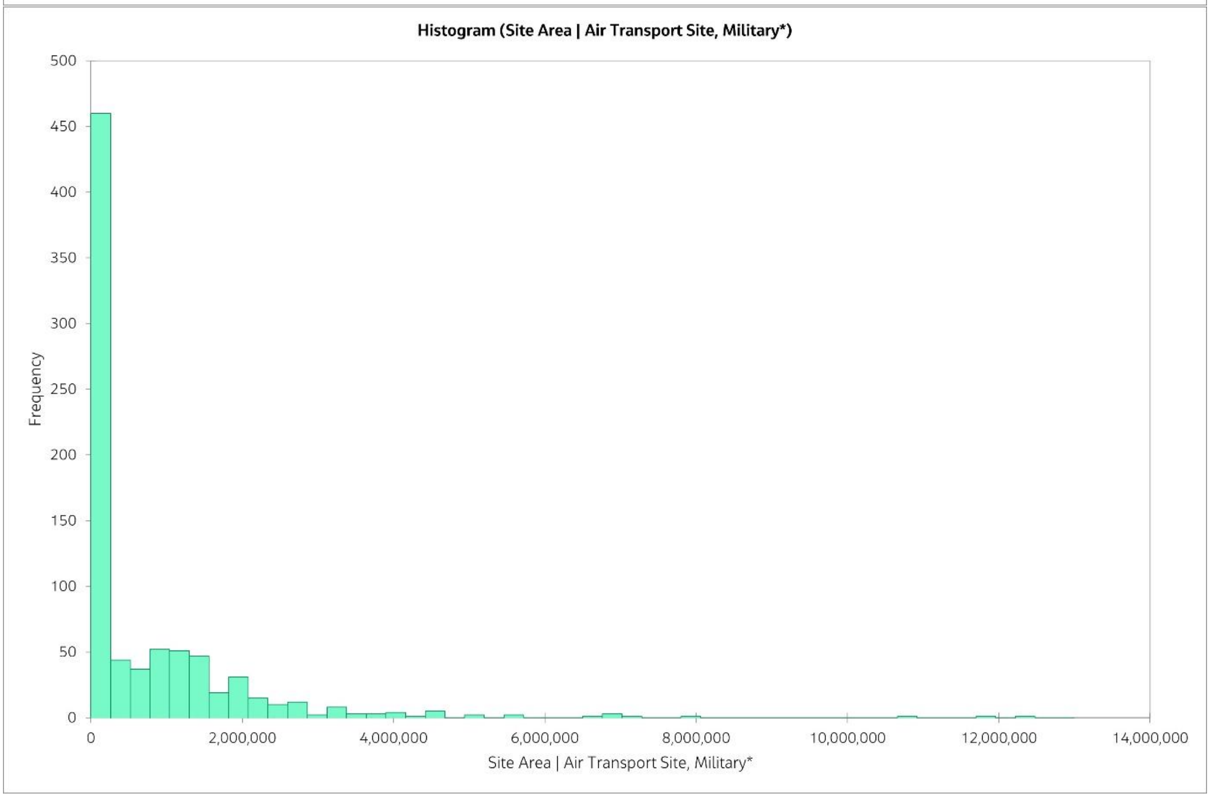
Bell EM,De Guise S,McCutcheon JR,Lei Y,Levin M,Li B,Rusling JF,Lawrence DA,Cavallari JM,O'Connell C,Javidi B,Wang X,Ryu H	Exposure, health effects, sensing, and remediation of the emerging PFAS contaminants – Scientific challenges and potential research directions	2021	https://www.sciencedirect.com/science/article/pii/S0048969721014674
Podder A,Sadmani AH,Reinhart D,Chang NB,Goel R	Per and poly-fluoroalkyl substances (PFAS) as a contaminant of emerging concern in surface water: A transboundary review of their occurrences and toxicity effects	2021	https://www.sciencedirect.com/science/article/pii/S030438942101325X
Hou D,O'Connor D	Chapter 1 - Green and sustainable remediation: concepts, principles, and pertaining research	2020	https://www.sciencedirect.com/science/article/pii/B978012817982600001X
Kurwadkar S,Dane J,Kanel SR,Nadagouda MN,Cawdrey RW,Ambade B,Struckhoff GC,Wilkin R	Per- and polyfluoroalkyl substances in water and wastewater: A critical review of their global occurrence and distribution	2022	https://www.sciencedirect.com/science/article/pii/S0048969721060812
Lenka SP,Kah M,Padhye LP	A review of the occurrence, transformation, and removal of poly- and perfluoroalkyl substances (PFAS) in wastewater treatment plants	2021	https://www.sciencedirect.com/science/article/pii/S0043135421003857
Pelch KE,Reade A,Wolffe TA,Kwiatkowski CF	PFAS health effects database: Protocol for a systematic evidence map	2019	https://www.sciencedirect.com/science/article/pii/S0160412019305380
Verma S,Varma RS,Nadagouda MN	Remediation and mineralization processes for per- and polyfluoroalkyl substances (PFAS) in water: A review	2021	https://www.sciencedirect.com/science/article/pii/S0048969721040596
Barhoumi B,Sander SG,Driss MR,Tolosa I	Survey of legacy and emerging per- and polyfluorinated alkyl substances in Mediterranean seafood from a North African ecosystem	2022	https://www.sciencedirect.com/science/article/pii/S0269749121019801
Lewis AJ,Yun X,Spooner DE,Kurz MJ,McKenzie ER,Sales CM	Exposure pathways and bioaccumulation of per- and polyfluoroalkyl substances in freshwater aquatic ecosystems: Key considerations	2022	https://www.sciencedirect.com/science/article/pii/S0048969722006532
Anderko L,Pennea E	Exposures to per-and polyfluoroalkyl substances (PFAS): Potential risks to reproductive and children's health	2020	https://www.sciencedirect.com/science/article/pii/S1538544220300201
Öberg M,Schenk L	Toxicology brought to justice: Risk assessments and liability assessments related to high levels of PFAS	2021	https://www.sciencedirect.com/science/article/pii/S0378427421007347
Ahmadireskety A,Da Silva BF,Townsend TG,Yost RA,Solo-Gabriele HM,Bowden JA	Evaluation of extraction workflows for quantitative analysis of per- and polyfluoroalkyl substances: A case study using soil adjacent to a landfill	2021	https://www.sciencedirect.com/science/article/pii/S0048969720374751
Tian S,Xu T,Fang L,Zhu Y,Li F,Leary RN,Zhang M,Zhao D,Soong TY,Shi H	A ‘Concentrate-&-Destroy’ technology for enhanced removal and destruction of per- and polyfluoroalkyl substances in municipal landfill leachate	2021	https://www.sciencedirect.com/science/article/pii/S0048969721031958

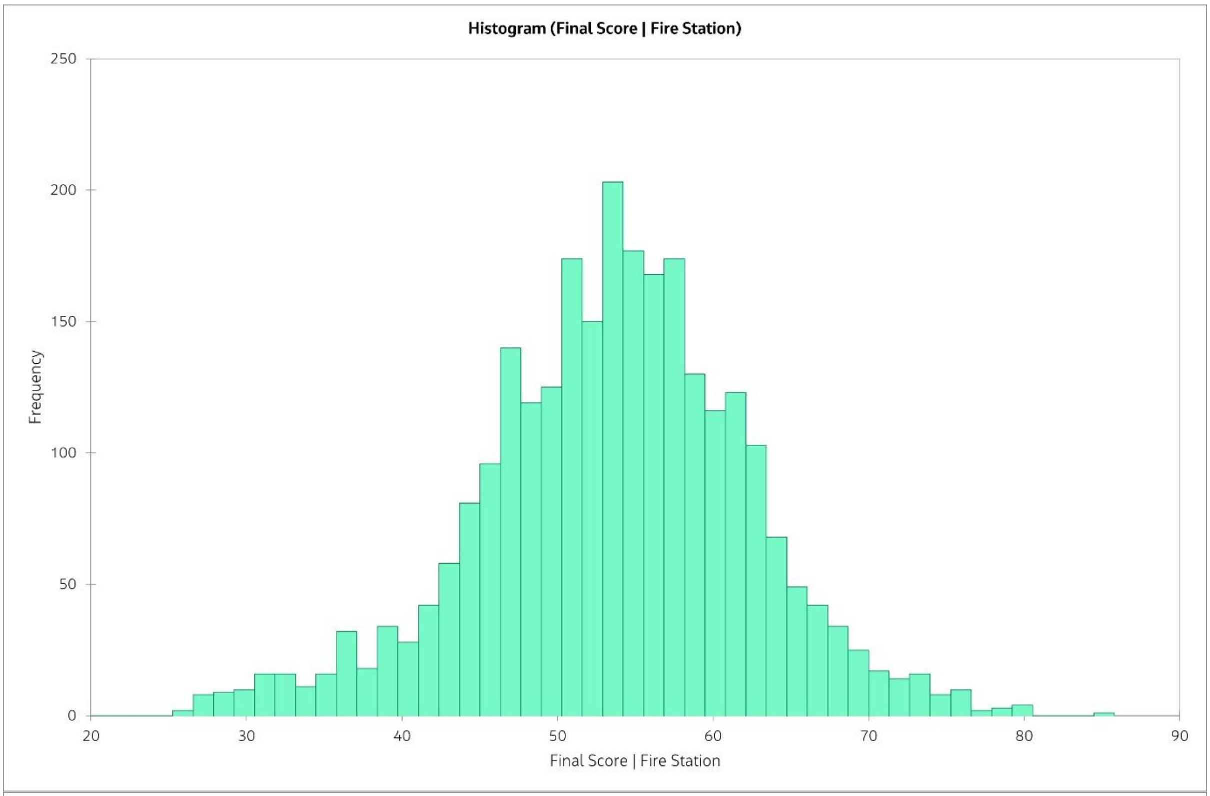
Xu C,Liu Z,Song X,Ding X,Ding	Legacy and emerging per- and polyfluoroalkyl substances (PFASs) in multi-media around a landfill in China: Implications for the usage of PFASs alternatives	2021	https://www.sciencedirect.com/science/article/pii/S0048969720352967
Marchiandi J,Green MP,Dagnino S,Anumol T,Clarke BO	Characterising the effects of per- and polyfluoroalkyl substances (PFASs) on health and disease: An opportunity for exposomics?	2020	https://www.sciencedirect.com/science/article/pii/S2468584420300398
Blake BE,Fenton SE	Early life exposure to per- and polyfluoroalkyl substances (PFAS) and latent health outcomes: A review including the placenta as a target tissue and possible driver of peri- and postnatal effects	2020	https://www.sciencedirect.com/science/article/pii/S0300483X20302043
Popovic J,Thorn JR,Jones AR,Kornuc JJ	Evaluation of a drop-in waste volume reduction method for liquid investigation derived waste containing per- and polyfluoroalkyl substances	2021	https://www.sciencedirect.com/science/article/pii/S0301479720314274
Gardener H,Sun Q,Grandjean P	PFAS concentration during pregnancy in relation to cardiometabolic health and birth outcomes	2021	https://www.sciencedirect.com/science/article/pii/S0013935120311841
Liu H,Hu W,Li X,Hu F,Liu Y,Xie T,Liu B,Xi Y,Su Z,Zhang C	Effects of perfluoroalkyl substances on root and rhizosphere bacteria: Phytotoxicity, phyto-microbial remediation, risk assessment	2022	https://www.sciencedirect.com/science/article/pii/S0045653521036092
Grimison C,Knight ER,Nguyen TM,Nagle N,Kabiri S,Bräunig J,Navarro DA,Kookana RS,Higgins CP,McLaughlin MJ,Mueller JF	The efficacy of soil washing for the remediation of per- and poly-fluoroalkyl substances (PFASs) in the field	2023	https://www.sciencedirect.com/science/article/pii/S030438942202235X
Phong Vo HN,Ngo HH,Guo W,Hong Nguyen TM,Li J,Liang H,Deng L,Chen Z,Hang Nguyen TA	Poly - and perfluoroalkyl substances in water and wastewater: A comprehensive review from sources to remediation	2020	https://www.sciencedirect.com/science/article/pii/S2214714420302713
Chaudhry AK,Sachdeva P	Microplastics' origin, distribution, and rising hazard to aquatic organisms and human health: Socio-economic insinuations and management solutions	2021	https://www.sciencedirect.com/science/article/pii/S2352485521004102

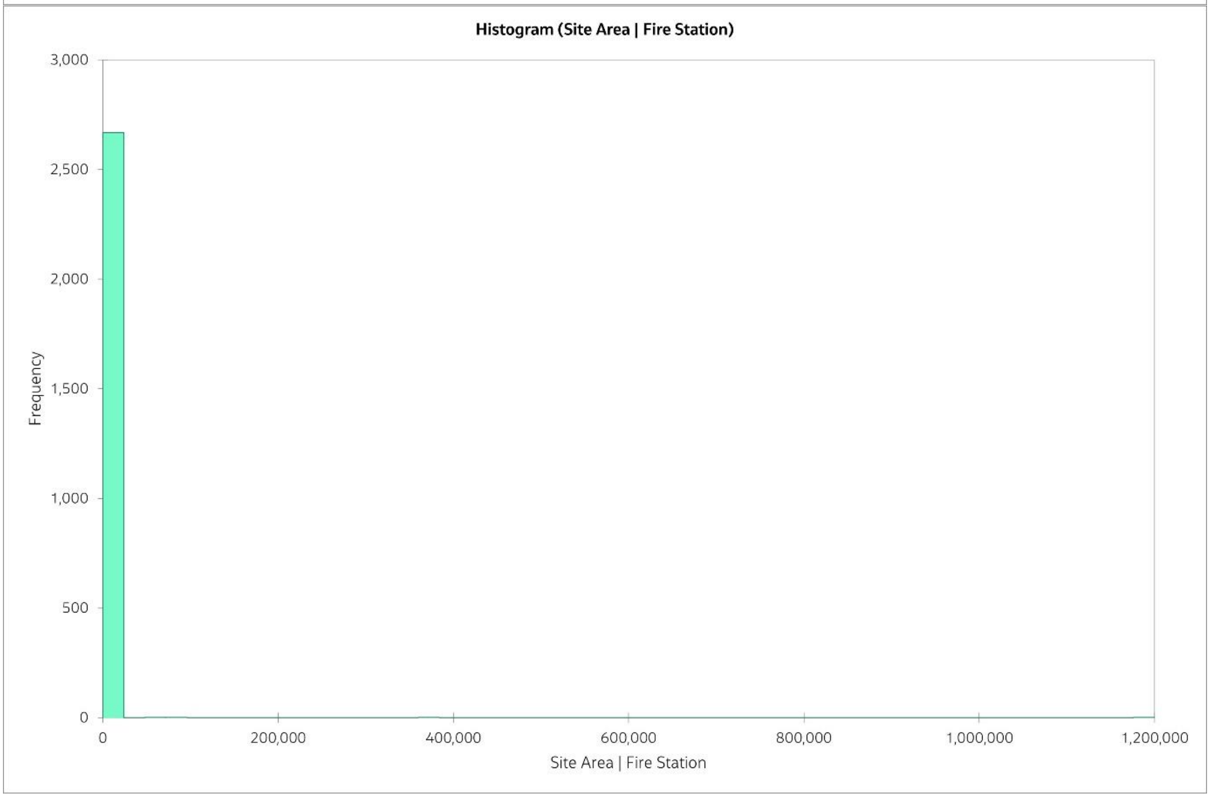
[APPENDIX REDACTED]

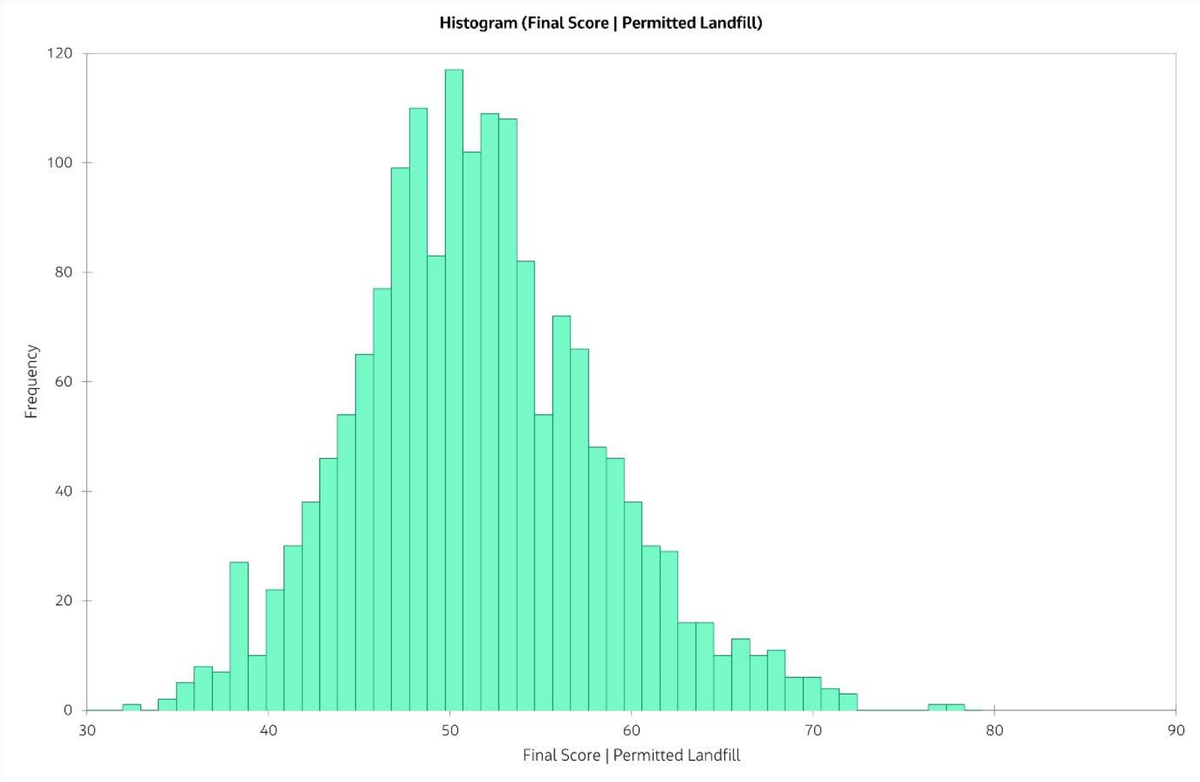
Appendix D. Site Type Histograms

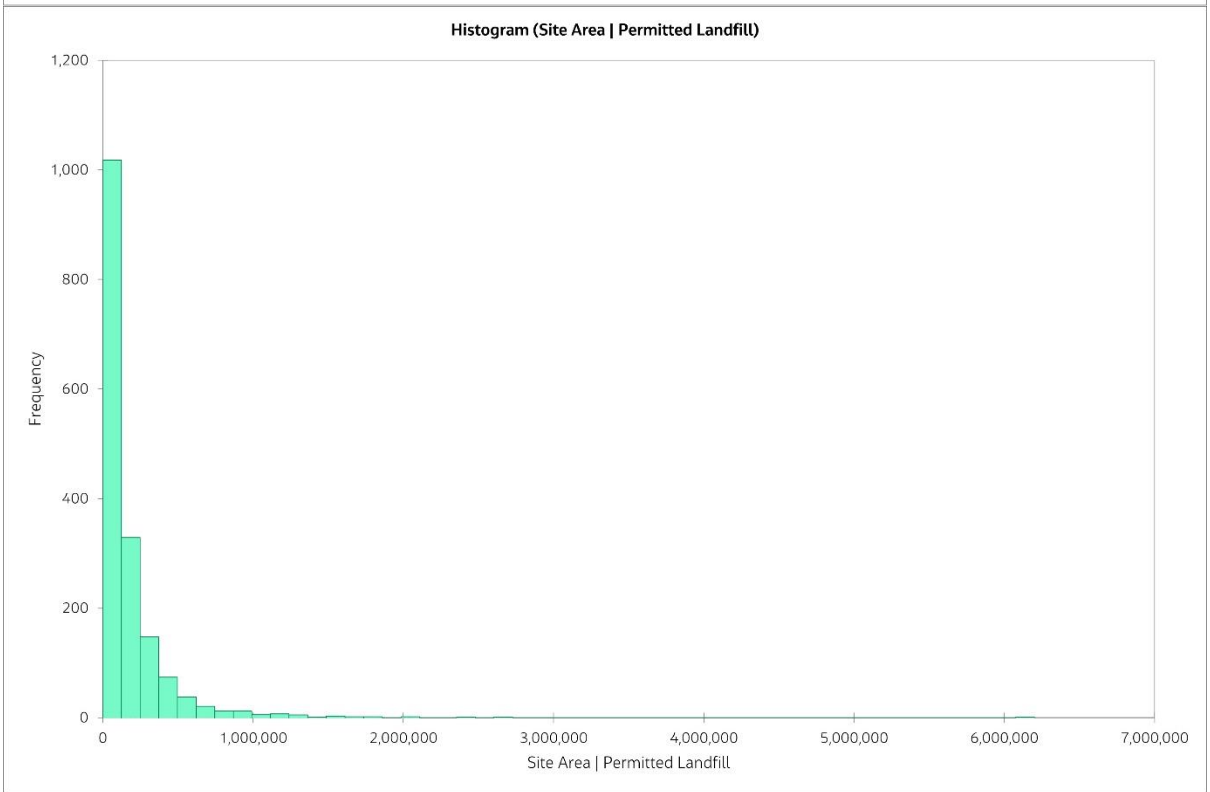


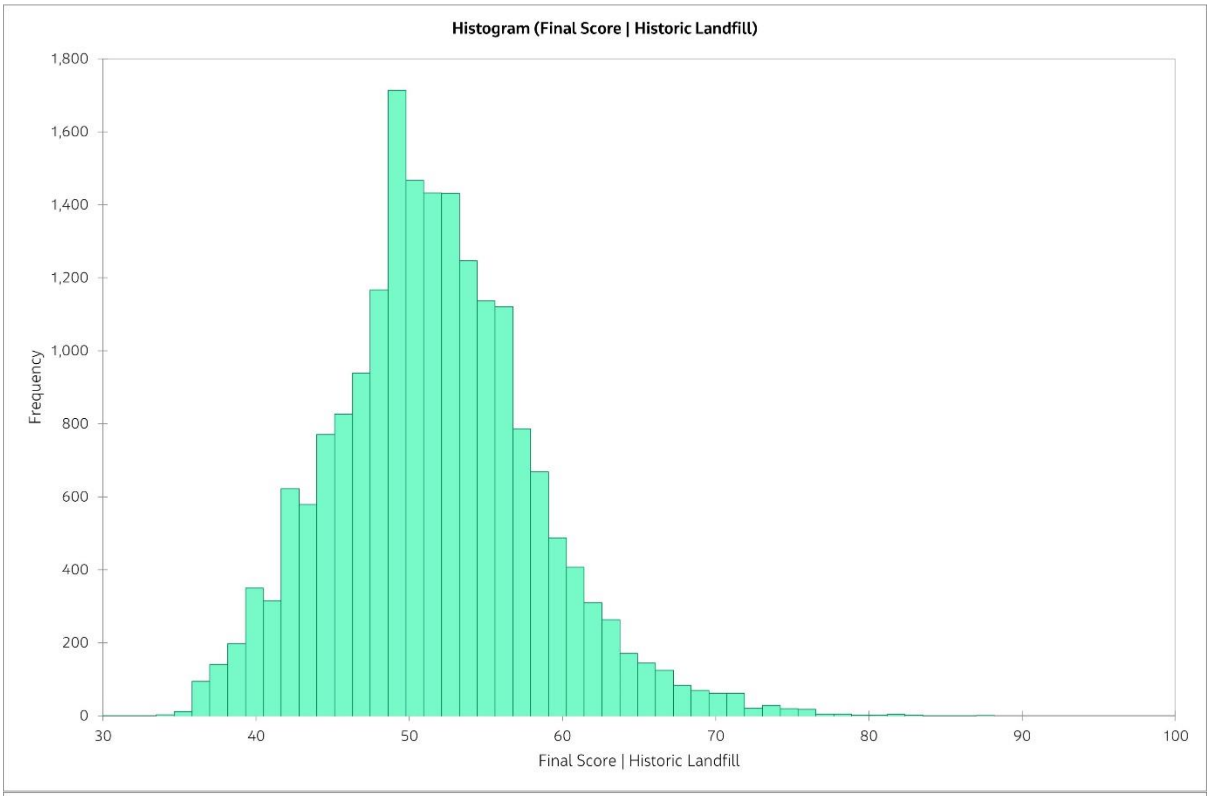


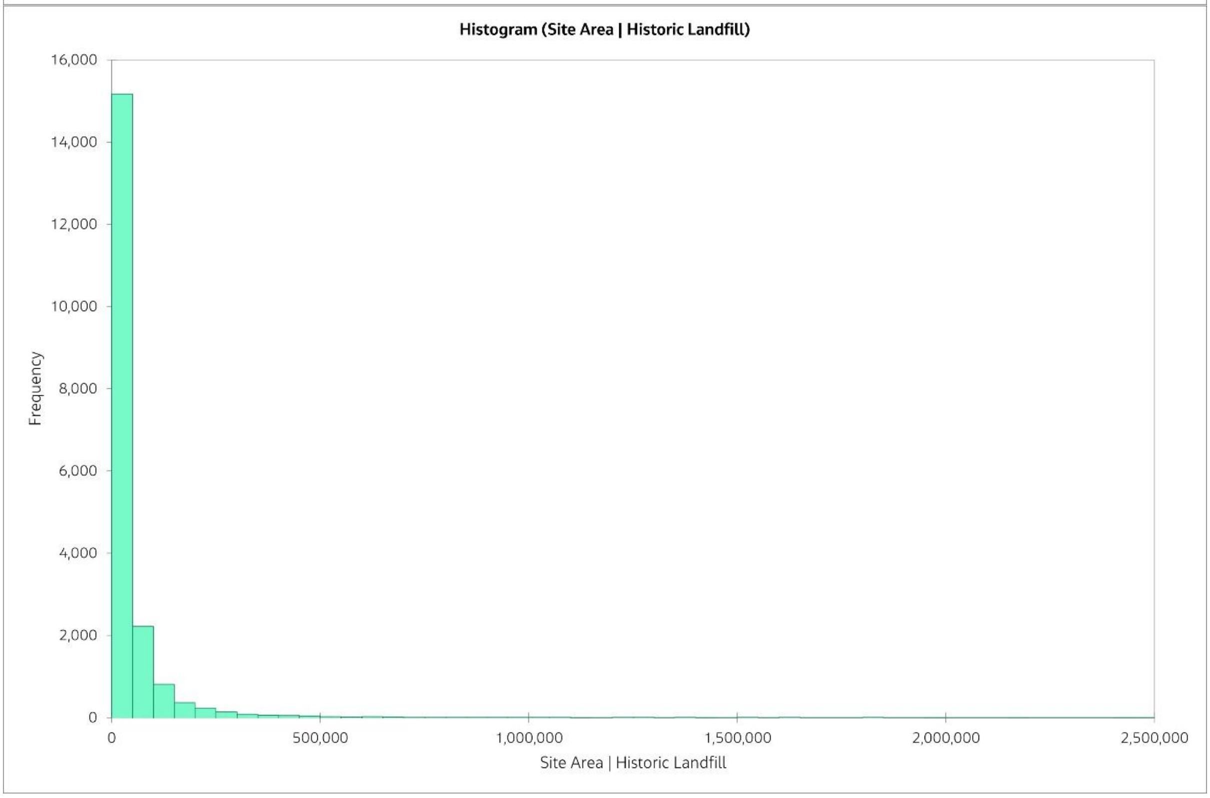

Histogram (Final Score | Fire Station)
Frequency
250
200
150
100
50
0
20
30
40
50
60
70
80
90
Final Score | Fire Station

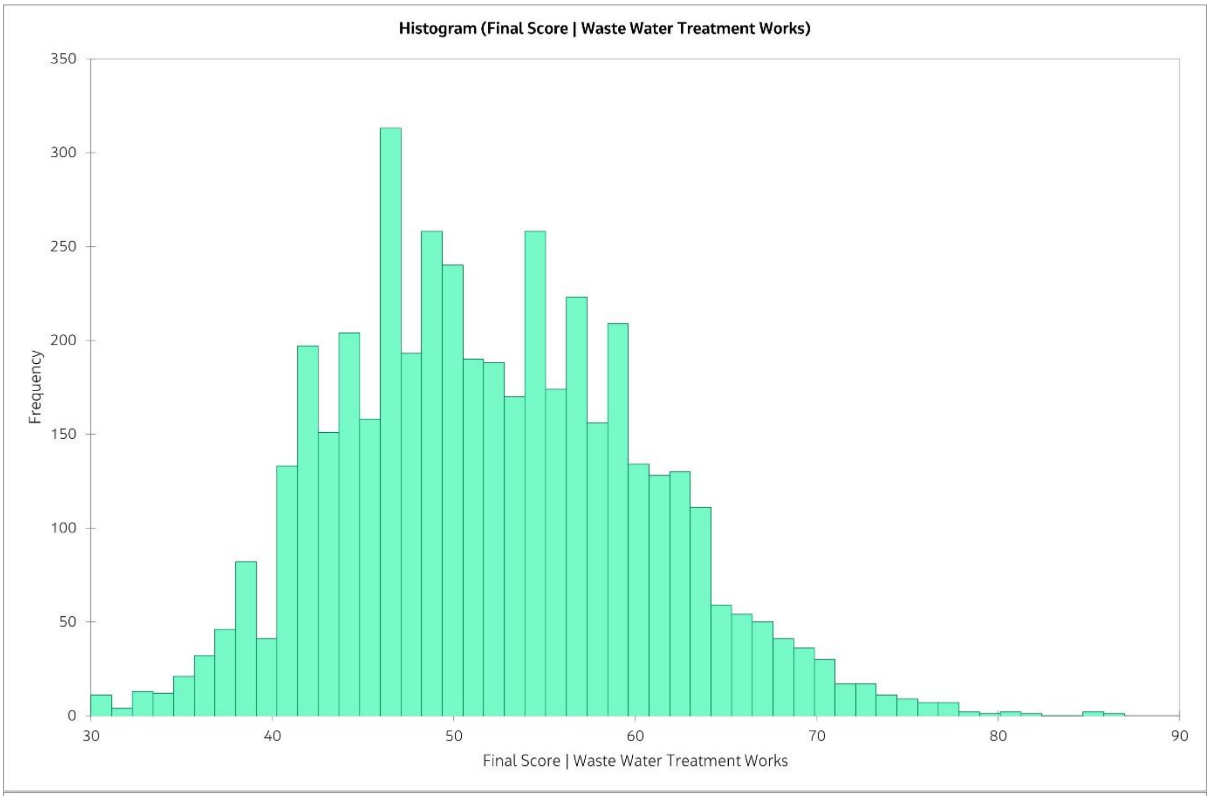

Histogram (Site Area | Fire Station)
Frequency
3,000
2,500
2,000
1,500
1,000
500
0
0
200,000
400,000
600,000
800,000
1,000,000
1,200,000
Site Area | Fire Station

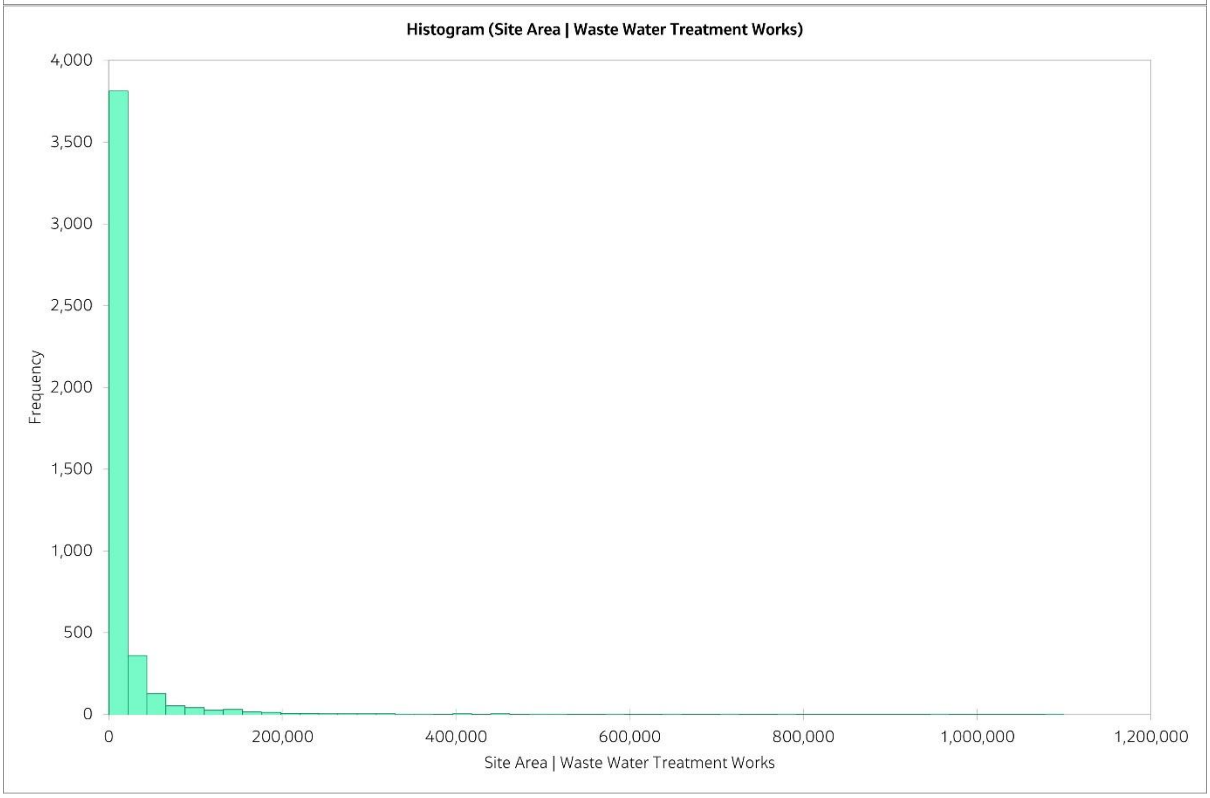

Histogram (Final Score | Permitted Landfill)
Frequency
Final Score | Permitted Landfill

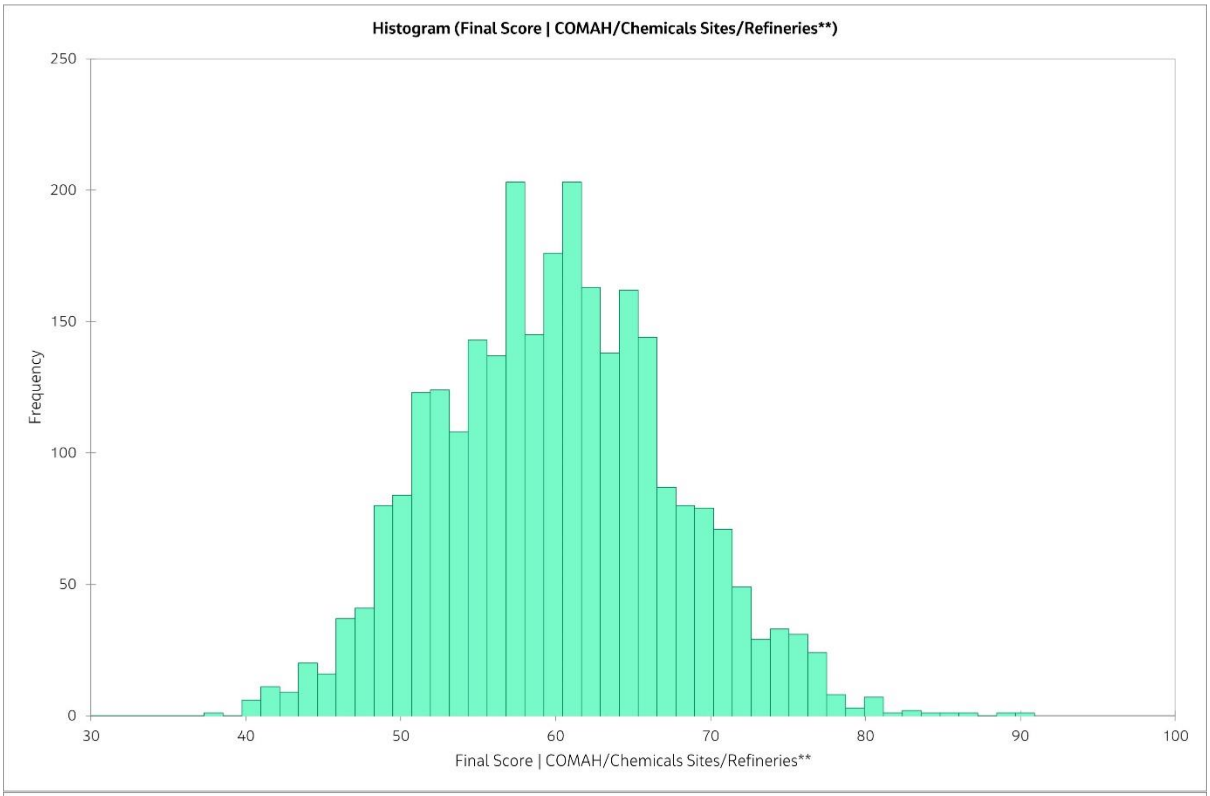

Histogram (Site Area | Permitted Landfill)
Frequency
Site Area | Permitted Landfill

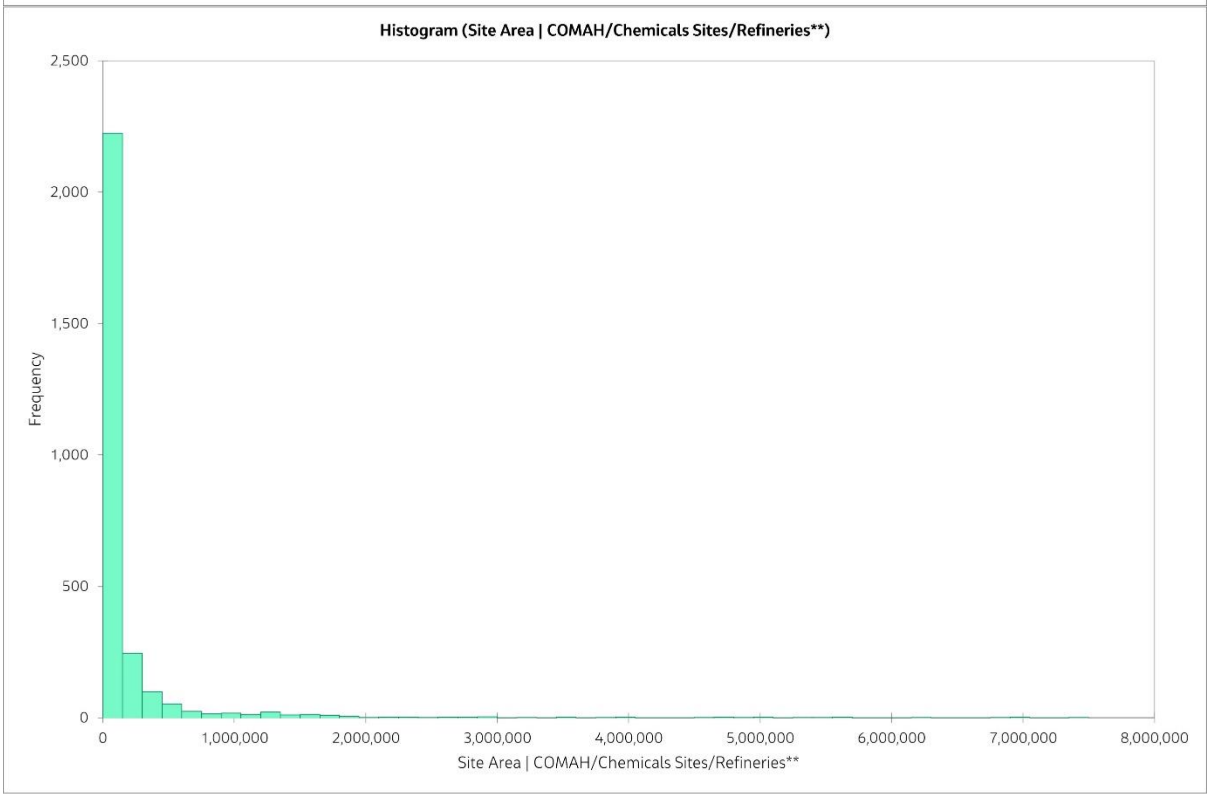

Histogram (Final Score | Historic Landfill)
Frequency
1,800
1,600
1,400
1,200
1,000
800
600
400
200
0
30
40
50
60
70
80
90
100
Final Score | Historic Landfill

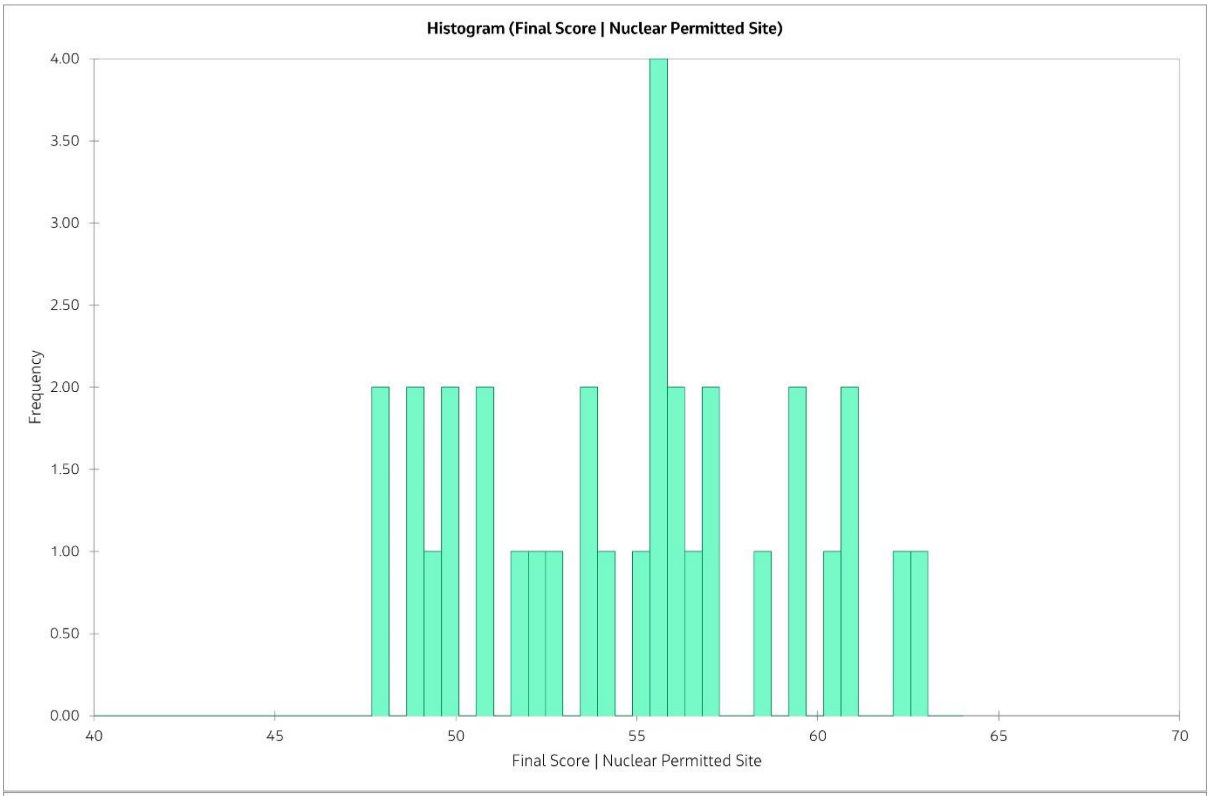

Histogram (Site Area | Historic Landfill)
Frequency
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
0
500,000
1,000,000
1,500,000
2,000,000
2,500,000
Site Area | Historic Landfill

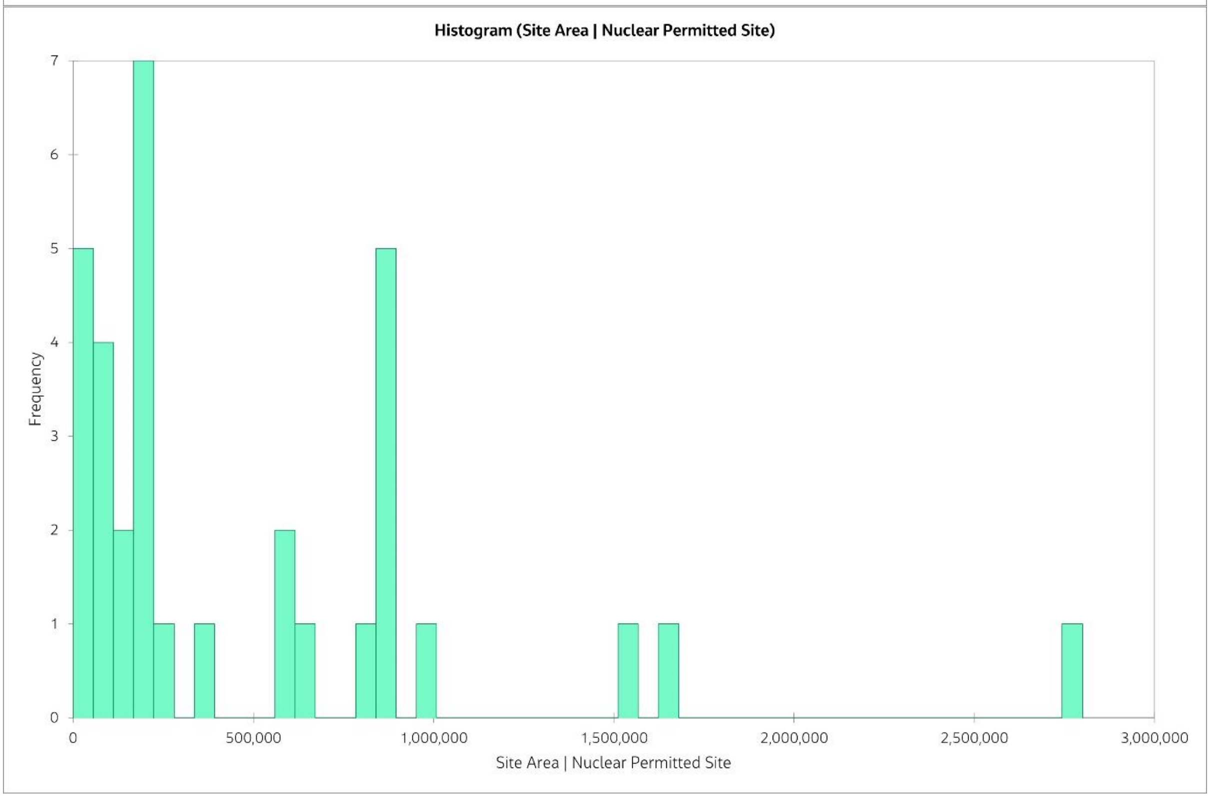

Histogram (Final Score | Waste Water Treatment Works)
Frequency
0
50
100
150
200
250
300
350
30
40
50
60
70
80
90
Final Score | Waste Water Treatment Works

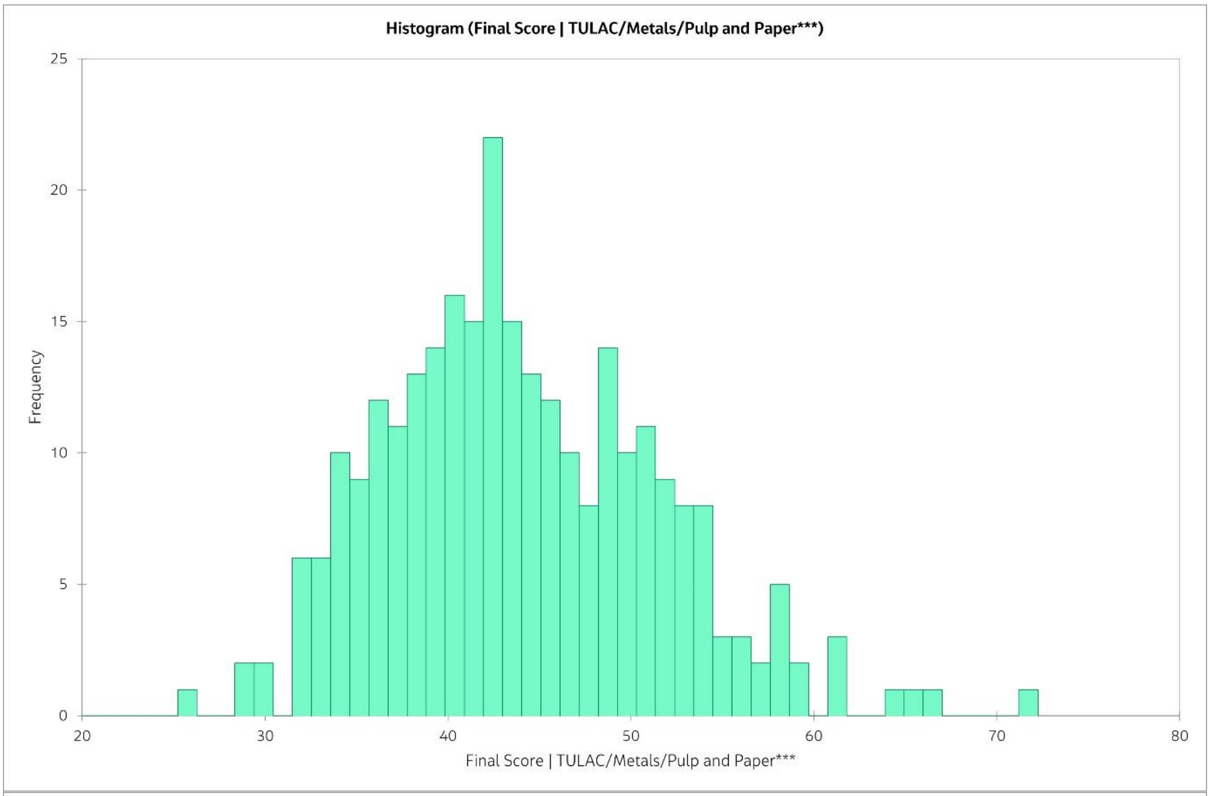

Histogram (Site Area | Waste Water Treatment Works)
Frequency
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
0
200,000
400,000
600,000
800,000
1,000,000
1,200,000
Site Area | Waste Water Treatment Works

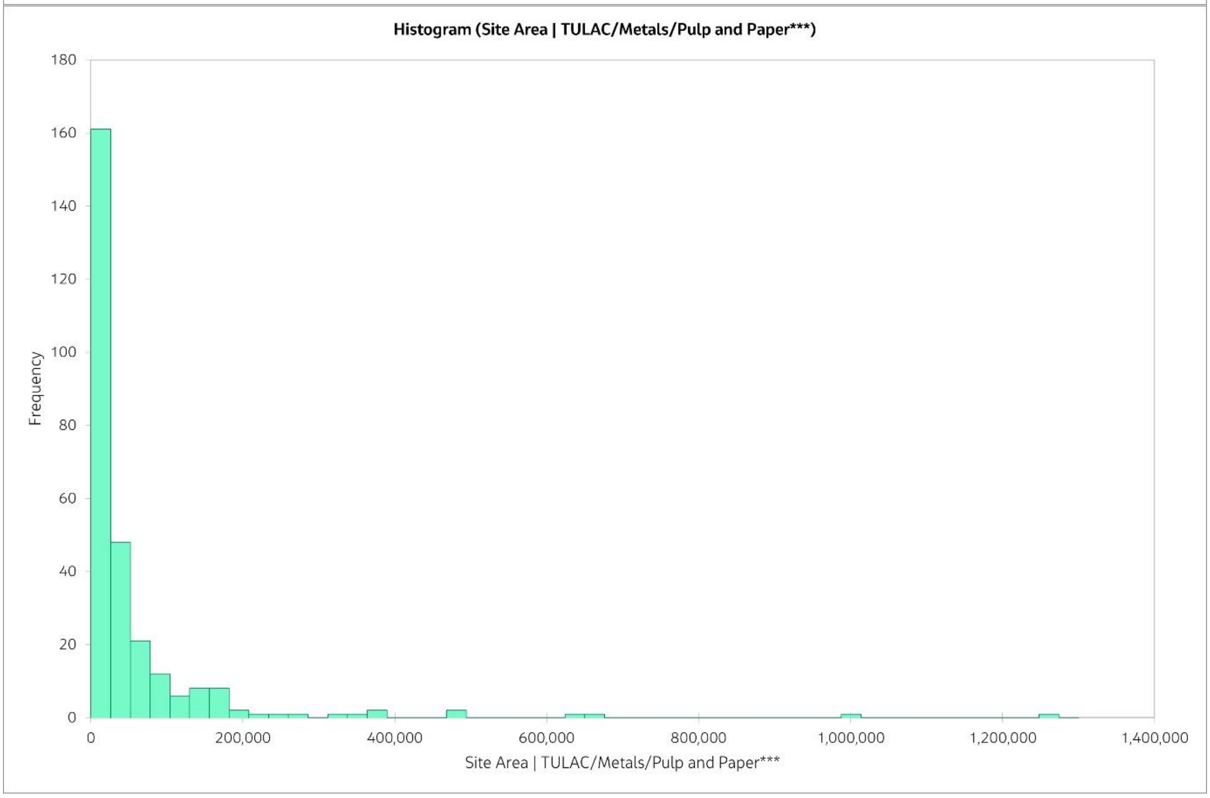

Histogram (Final Score | COMAH/Chemicals Sites/Refineries**)
Frequency
0
50
100
150
200
250
30
40
50
60
70
80
90
100
Final Score | COMAH/Chemicals Sites/Refineries**

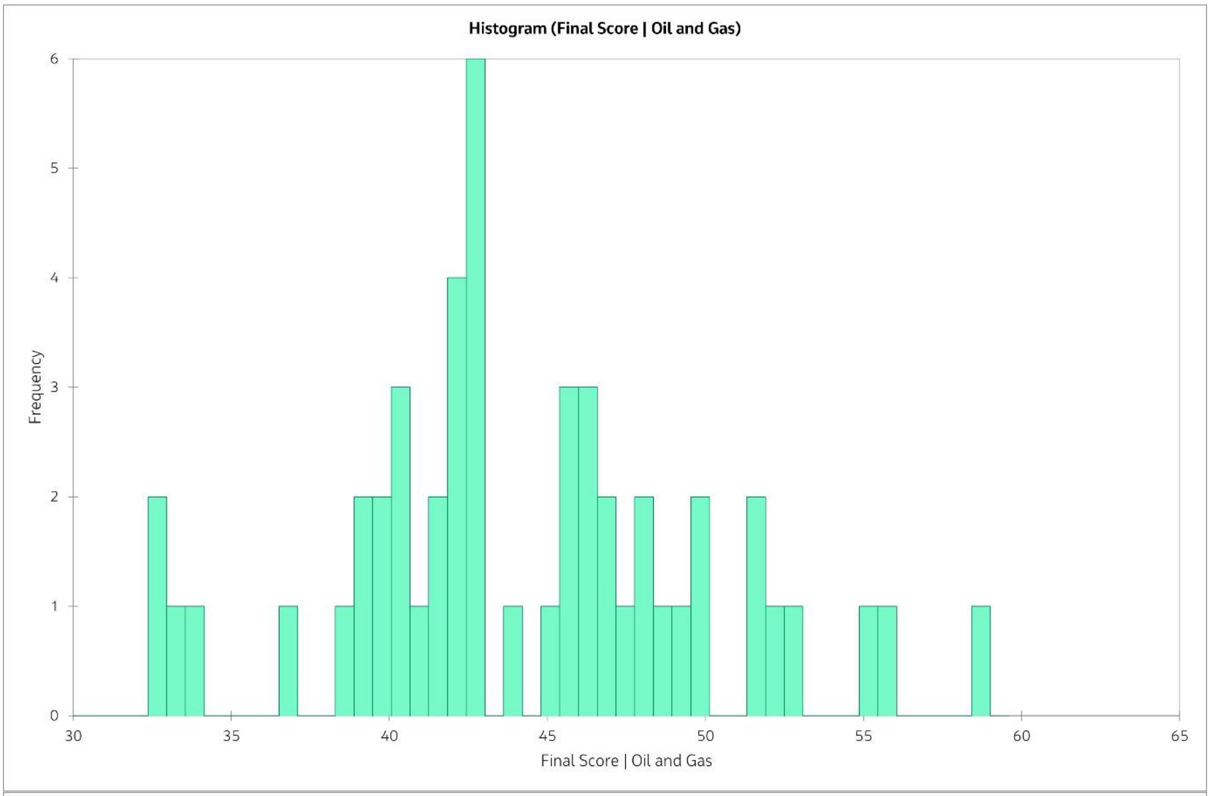

Histogram (Site Area | COMAH/Chemicals Sites/Refineries**)
Frequency
0
500
1,000
1,500
2,000
2,500
0
1,000,000
2,000,000
3,000,000
4,000,000
5,000,000
6,000,000
7,000,000
8,000,000
Site Area | COMAH/Chemicals Sites/Refineries**

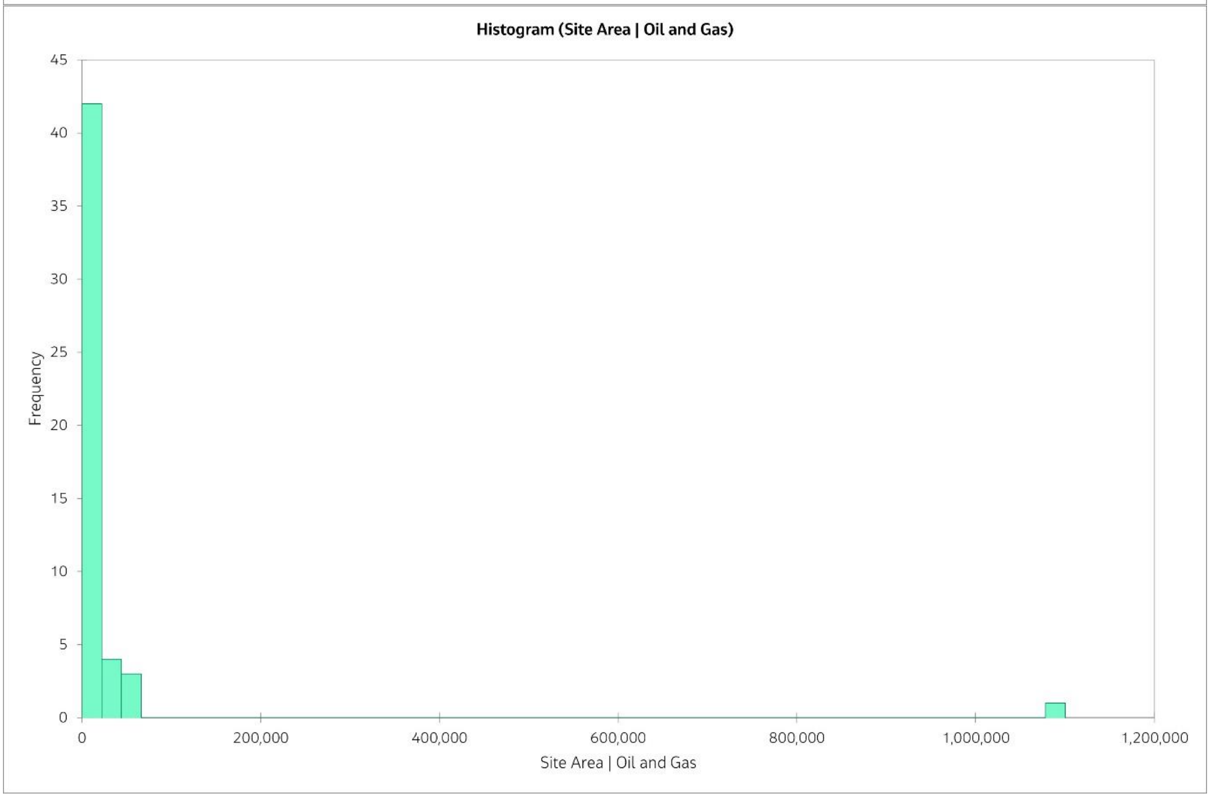

Histogram (Final Score | Nuclear Permitted Site)
Frequency
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
40
45
50
55
60
65
70
Final Score | Nuclear Permitted Site


Histogram (Site Area | Nuclear Permitted Site)
Frequency
7
6
5
4
3
2
1
0
0
500,000
1,000,000
1,500,000
2,000,000
2,500,000
3,000,000
Site Area | Nuclear Permitted Site


Histogram (Final Score | TULAC/Metals/Pulp and Paper***)
Frequency
0
5
10
15
20
25
20
30
40
50
60
70
80
Final Score | TULAC/Metals/Pulp and Paper***


Histogram (Site Area | TULAC/Metals/Pulp and Paper***)
Frequency
0
20
40
60
80
100
120
140
160
180
0
200,000
400,000
600,000
800,000
1,000,000
1,200,000
1,400,000
Site Area | TULAC/Metals/Pulp and Paper***


Histogram (Final Score | Oil and Gas)
Frequency
0
1
2
3
4
5
6
30
35
40
45
50
55
60
65
Final Score | Oil and Gas


Histogram (Site Area | Oil and Gas)
Frequency
0
5
10
15
20
25
30
35
40
45
0
200,000
400,000
600,000
800,000
1,000,000
1,200,000
Site Area | Oil and Gas

Appendix E. Factoring

	Proportion of sites in current use, vs historical		A Proportion of mapped site area likely to be impacted		B Proportion of sites likely to have PFAS impact		C Proportion of current English sites likely mapped in PFAS explorer		D Proportion of historical English sites likely mapped in PFAS explorer		E Proportion of missing historical sites likely to have PFAS impact		F Double Counting	
Air Transport Sites/Military	75%	Based on operational or 'out of service' status	0.3	Large sites mapped as polygons including runways etc; PFAS sources generally localised but maybe several locations.	0.8	PFAS use common at most air transport sites.	0.98	Generally good mapping	0.85	Generally good mapping but may have missed some WWII sites	0.25	Generally older sites that have been missed (less use of PFAS in older sites)	1	Little evidence for double counting of area
Fire Stations	62%	Based on attributes for active or otherwise	0.3	Mainly yards and drainage affected	1	PFAS use likely at all sites; varying volume of use captured in site scores	0.98	Generally good mapping.	0.9	Good mapping of historical sites	0.25	Generally older sites that have been missed	0.85	Some double counting e.g. fire stations in air sites and COMAH sites
Permitted Landfill	100 %	Note some of these are closed, but the definition of the dataset means all count as current	1	Polygons; source dispersed across whole site	0.8	Variable PFAS occurrence in Permitted Landfills	1	EA dataset	1	EA dataset	0	complete set	0.86	Permitted landfills on Historic Landfill sites
Historic Landfill	0%	By definition all historic	1	Polygons; source dispersed across whole site	0.4	Variable PFAS occurrence in historical landfills. Less PFAS use pre 1960.	1	Not applicable as historical landfills; EA dataset	0.85	EA dataset - but not exhaustive	0.25	Generally older sites that have been missed	0.88	Self overlaps and some overlap with Permitted Landfills
Wastewater Treatment Works	100 %	Dataset is defined on all current	0.3	Site area from mapping; assume only partially impacted	0.8	Widespread observations of PFAS in effluent	0.9	Environment Agency defined dataset	0.25	Not targeted in mapping; % based on possible number of sewage works that have closed.	0.25	Generally older sites that have been missed	0.95	Some overlaps
COMAH/Chemicals/Refineries	34%	Mixed current and historic COMAH sites, all Chemicals and Refineries are current	0.6	Impact possible throughout most of site	0.8	PFAS use in fire protection likely at most sites	0.8	Some smaller chemicals sites likely to be missing.	0.5	May be missing some COMAH type sites pre 2002, and chemicals	0.25	Generally older sites that have been missed	0.5	mixture of self overlaps of COMAH sites, but also refineries, and

	Proportion of sites in current use, vs historical		A Proportion of mapped site area likely to be impacted		B Proportion of sites likely to have PFAS impact		C Proportion of current English sites likely mapped in PFAS explorer		D Proportion of historical English sites likely mapped in PFAS explorer		E Proportion of missing historical sites likely to have PFAS impact		F Double Counting	
														chemicals sites which are in this group; also allow for exclusion of all nuclear sites and some metal sites from this group
Nuclear Permitted Site	100 %	Dataset is defined on all current / no historic	0.3	Large sites mapped as polygons; PFAS sources generally localised but maybe several locations.	1	PFAS use common in past at all sites.	1	Defined dataset	0	All still current	0	none	1	Assume all overlaps in this group not COMAH
TULAC/Metals/Pulp and Paper	100 %	Dataset is defined as all current, dataset size doesn't reflect historic count	0.5	PFAS sources may be localised within larger sites	0.2	Specialist PFAS uses only. Larger high risk sites captured under COMAH.	0.05	Limited dataset based on Regulated Industries and limited other sources; known to be many other potential sites e.g. point of interest datasets	0.05	Regulated industries dataset does not include sites no longer in use. Potential for large numbers of historic sites no longer in use.	0.2	average	0.8	Large metal sites shared with COMAH
Oil and Gas	100 %	Dataset is defined as all current, dataset size doesn't reflect historic count; historic sites less likely to have PFAS use	1	Small sites, assume all impacted	0.1	Specialist PFAS uses only; High risk sites also captured under COMAH.	1	Regulated Industries complete dataset	0.5	Regulated industries dataset does not include sites no longer in use.	0.1	Generally older sites that have been missed	1	negligible