SoBRA
The Society of Brownfield Risk Assessment

SOCIETY OF BROWNFIELD RISK ASSESSMENT

The Climate Emergency:
Practical Considerations in Brownfield Risk Assessment

Summer Workshop 2022 Report

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PUBLICATION

This report is published by the Society of Brownfield Risk Assessment (SoBRA). It presents the output of the summer workshop held in Birmingham on 22nd June 2022. The publication presents the conclusions and recommendations of the workshop presentations and workshop sessions on how to consider and account for the potential effects of climate change in land contamination risk assessment.

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There is currently significant research and development with respect to further understanding the impacts of future climate change on land contamination risk assessment. This publication therefore reflects a point in time in our understanding of climate change and how to assess it.

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1 INTRODUCTION

Brownfield regeneration can and should play an important part in climate change adaption and resilience. Regeneration should include preparation for, and response to, the challenge of climate change, and climate-related risks must be considered. Risk assessment is a fundamentally important component of a multi-disciplinary approach to successful brownfield regeneration and therefore the adoption and integration of climate change considerations in brownfield risk assessment is critical. We need to adjust our approach to brownfield risk assessment to account for actual or anticipated climate change and its effects on contaminant sources, pathways and receptors. This is why SoBRA tackled the practical application of climate change in risk assessment head on at its 2022 Summer Conference and Workshop.

The re-use of brownfield land provides two key benefits in relation to climate change:

- It can help preserve our natural resources by reducing development on greenfield land. This lack of greenfield development can then permit natural climate resilient activities, like infiltration, flood attenuation, and carbon sequestration, to occur on that undeveloped land that can help limit future climate impact.
- It can reduce the environmental impact of development. It can reduce the requirement for new transport infrastructure, improve the use of land in existing areas of development, can permit the re-use of existing buildings, and provides opportunities for centralised heat / power distribution.

Risk assessment is embedded in our regulatory approach to brownfield remediation and redevelopment in relation to soil and water contamination and potential risks to human health and the environment. The UK Government's wider approach to the management of the environment, and climate change, should be no exception, with risk assessment fundamental to ongoing adaptation to climate change.

The key pillars of risk assessment – robust evidence, identification of hazards, consequences and their probabilities, and dealing with uncertainties and limitations – should also apply to our approach to climate change during brownfield regeneration. We should not be leaving the challenges of climate change solely to future generations; uncertainty over future impacts means a precautionary principle should be adopted in our risk assessments and approach to remediation of contaminated land. We should not be designing remediation schemes and brownfield redevelopment schemes that will not endure future climate change events. Key requirements of remediation schemes are effectiveness and durability – will they work throughout the timeframe required? A key requirement of risk assessment is the provision of robust evidence to inform risk management decisions on what risks might exist now and in the future.

All of this is rooted in a robust conceptual model of ground and contaminant conditions and how that might change with time. We cannot prevent climate change, and adapting to future changes must be taken into consideration during our decision making.

We cannot adapt efficiently and effectively to climate change without robust risk assessment. One of the key challenges is the uncertainty in what climate change means in practice for a particular site – what might the impacts be and when might they be realised? We would argue that as an industry, we can evaluate, and manage, those uncertainties along with all the other uncertainties that we invariably must consider within conceptual models for brownfield sites. Existing approaches to assessing uncertainty can be used in many cases and expanding our sources of information and/or widening our collaboration with other disciplines such as flood risk will provide cross-industry knowledge transfer to enhance all our approaches.

Our industry is already developing ideas and approaches to how to tackle this additional consideration in brownfield risk assessment. Collaborative initiatives are already in play, and this is great to see. Climate change should be a consideration (even if it is ruled out early) in every investigation of a potentially contaminated site. The need to incorporate the effects of climate change into qualitative and quantitative risk assessments is set out within Managing and Reducing Land Contamination: Guiding Principles (GPLC2) FAQ 8 (Environment Agency, 2010), the National Planning Policy Framework (NPPF) in England[1] and Land Contamination Risk Management (LCRM)[2]. However, no accompanying technical guidance has been published by UK regulators on how to consider the effect of climate change on contaminated land, leaving land contamination practitioners uncertain of how this complex area should be assessed. As a result, it is often not considered at all.

The summer workshop enabled the SoBRA workshop groups to discuss the potential implications of climate change for their area of specialism, alongside the practical application and incorporation of climate change into existing risk assessment methodologies.

Since the summer workshop took place, in August 2022 SoBRA published freely available guidance from the SoBRA sub-group on climate change and controlled waters risk assessment (SoBRA 2022) – the first best practice technical guidance detailing how to actively consider future climate change effects within controlled waters risk assessments to ensure they remain sustainable, robust and resilient. The Environment Agency, in April 2023 updated its guidance on climate change risk and adaption under the Environmental Permitting Regime[3], and more climate-related datasets and guidance are becoming available that are applicable to brownfield risk assessment. These include NHBC (2023) that includes guidance on accounting for climate change in ground gas risk assessment, BGS's GeoClimate[4] datasets, which aims to increase the understanding of the combined impacts of climate change and natural geohazards on infrastructure in the UK and the CEH's Enhanced Future Flows and Groundwater (eFLaG) portal[5] with the recent inclusion of groundwater recharge data in the latter. Representatives from SoBRA's sub-group on climate change and controlled waters are currently in discussions with environmental database providers about developing a product to enable a simple 'one-stop-shop' for accessing relevant climate change projection data such as the BGS's and CEH's in a consistent manner.

With other organisations' initiatives on climate change and brownfield risk assessment due to be published later this year maybe as an industry we will have increased consensus and direction on a way forward for brownfield risk assessment.

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[1] https://www.gov.uk/government/publications/national-planning-policy-framework--2

[2] https://www.gov.uk/government/publications/land-contamination-risk-management-lcrm

[3] https://www.gov.uk/guidance/climate-change-risk-assessment-and-adaptation-planning-in-your-management-system

[4] https://www.bgs.ac.uk/geology-projects/hazard-and-resilience-modelling/climatic-hazards-and-natural-geological-events-change/

[5] https://eip.ceh.ac.uk/hydrology/eflag

2 MORNING SESSION PRESENTATIONS

The presentation slides from the morning session are available on the SoBRA website for members[6]. The presentations were:

The Climate Emergency (overview) - Danielle King (RSK Centre for Sustainability Excellence)

Climate change, what does that mean for Land Condition Assessment? – Jonathan Atkinson (Environment Agency)

Climate Change in Controlled Waters Risk Assessment – James Wilson (Atkins)

Carbon Accounting – Adrian Johnson (Stantec)

Flooding, drought and groundwater modelling: Lessons from other disciplines – Rachel Dewhurst (Stantec)

Climate Change Influences on Ground Gas Risk Assessment – Amy Juden (EPG)

Climate Change Influences on Vapour Intrusion Risk Assessment – John Andrews (EPG)

Natural Source Zone Depletion in a Climate Emergency – James Rayner (Geosyntec)

[6] https://sobra.org.uk/resources/presentations/2022-summer-conference/

3 AFTERNOON WORKSHOPS

Four afternoon workshops focused on brownfield risk assessment and climate change were convened:

- Ground Gas and Soil Vapour Risk Assessment
- Controlled Waters Risk Assessment (discussion around the future SoBRA publication)
- Non-Aqueous Phase Liquids and Natural Source Zone Depletion
- Carbon Accounting

Each workshop took a slightly different approach to discussing the impacts of climate change on the subject area, typically followed by a discussion focusing on key issues, data gaps and recommendations for data-gap filling and future actions. A summary of the topics discussed in each workshop is presented in the sections below.

4 AFTERNOON WORKSHOP SESSIONS – GROUND GAS AND SOIL VAPOUR

4.1 Introduction

The aim of the workshop was to evaluate at the potential impacts of climate change on ground gas and vapour risk assessment, and the sustainability of ground gas mitigation and design in the face of climate change.

4.2 Key Issues

The key issues identified by the workshop group are presented and discussed below:

1. How often are climate change factors going to lead to increased remediation requirements?

The group discussed the potential for climate change factors to result in increased remediation requirements in relation to ground gas and vapour intrusion. In particular, the feasibility of a ground gas/VOC-resistant membrane lasting many years and how such membranes could be affected by varying ground conditions changing as a result of more extreme weather was discussed. Gas protection systems should be designed with multiple lines of defence so that they are not overly reliant on only a single element providing complete protection. Gas protection systems should be designed to be appropriate for the design life of the building, and future changes in climate and weather patterns, therefore in some situations gas membranes may not be the most suitable form of long-term protection.

It was also noted that ground gas sources are typically assumed to be constant, and climate change could have the potential to increase or decrease the magnitude of ground gas sources and associated emissions. Landfill gas sources are however, generally decreasing in gas potential over time as the source is used up, so it is therefore less likely that climate change effects would be of significant enough magnitude and rate to increase landfill gas risk overall on most sites. This emphasises that the consideration and assessment of climate change should be site-specific.

The participants agreed that ground gas risk assessment is already highly conservative and theoretical climate change effects, which are identified in the early stages of a risk assessment as unlikely to occur, should not be a driving factor to increase remediation requirements.

Regarding vapour intrusion (VI) risks, participants discussed that there are likely to be too many conflicting variables to indicate either positive or negative trends in VI risks with increasing climatic changes (e.g. wind, rain events, temperature), even where the trend of these changes are predicted to be rapid. It was considered likely that the biggest potential increase of VI risks, including potential acute risk, are more likely to be influenced by extreme short-term weather events rather than by trends.

Participants discussed that changes to UK building stock, due to increasing sustainability requirements driven by climate change, may affect VI potential and therefore remediation requirements. For example, low carbon Passivehause designs maintain a tighter building envelope, often with a requirement for mechanical ventilation. There are also likely to be changes to the ground floor slab design of more conventional buildings to improve sustainability.

2. How to predict gas emissions as a result of potential variation in ground water levels and weather conditions?

Participants discussed the potential for the displacement of gas from soil pores as a result of heavy (extreme) rainfall events and as a driver for gas flux. Continuous gas monitoring data can be used to generate predictive models for this. The effects are likely to be very site specific and only relevant for certain ground gas conceptual models.

There is the potential for increased heavy rainfall events and flooding to trigger acute gas migration risks, if gas generation rates are high enough and/or there is a preferential pathway or permeable reservoir for gas allowing significant volumes to accumulate. However, on most low to moderate risk sites this is unlikely to be significant as the gas risk is limited by the generation rate of the source materials.

Groundwater level changes and increased range in seasonal water table fluctuations do have the potential to change the risk profile on sites affected by coal mine gas emissions, in particular where coal workings are close to groundwater level.

The impact of the shrink swell effect in clay-rich soils[7]on previously installed gas membranes was also raised as a potential effect of climate change post-remediation, however this was not considered to present a significant risk to the long-term viability of such remedial measures.

Participants discussed windspeed effects on void performance and whether 10 hours[8] with no wind was conservative under climate change. There is limited understanding around whether increased duration of settled periods with low/no wind will be a future impact of climate change in the UK, and therefore need to be considered in a ground gas risk assessment.

3. How to generate attenuation factors based on climate change which will project into the future?

Participants discussed the potential for climate change to impact attenuation of gas and vapour into properties, with regards to VI. For example, temperature differential (indoor/outdoor) and stack effects (pressure differential – indoor/sub-floor), as well as building tightness, have been shown in the USA to significantly affect VI potential. With predicted future changes to temperature and wind due to climate change, as well as changes to building tightness becoming increasingly prevalent in low carbon homes, it should therefore be possible to predict future changes to VI potential. Participants discussed the possibility of defining climate change ‘zones’ in the UK and developing respective attenuation factors in a region-specific approach. Whilst this was discussed in relation to research undertaken in the USA with more extremes of climate zones, it could still be useful in the UK.

Current UK guidance doesn’t differentiate between chlorinated solvents and petroleum hydrocarbons (unlike the USA) even though the VI risk profile of these two types of volatile organic compound (VOC) differ markedly. Participants discussed that it could be beneficial to distinguish the different approaches to assessing VI from chlorinated and petroleum hydrocarbons and to generate separate attenuation factors when considering climate change.

4. Climate change effects on landfill gas migration?

Participants discussed the extent to which climate change is considered when landfill assessments are undertaken and whether this will be, or should be, reassessed when an environmental permit is surrendered, varied or renewed at any time in the future.

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[7] GeoClimate UKCP09 and UKCP18 Shrink-swell national datasets

[8] In the UK it is generally accepted that the maximum period when the wind speed is effectively zero (i.e., no ventilation) is 10 hours, and the gas should not exceed the critical value in the void over this period (typically 5% is used for both methane and carbon dioxide) (NHBC, 2023).

Consideration was then given to the potential for flooding on landfill sites, due to increased frequency of heavy rainfall events / increased rainfall intensity, and how this might impact landfill gas extraction systems. The possibility of desiccation in clay caps occurring at surrendered sites was also raised as a discussion point, and whether this could this lead to a potentially significant increased risk of ground gas emissions and how will this could be monitored and/or included in a ground gas risk assessment for redevelopment. It was noted that if wet waste was to be saturated further, this could decrease the risk of gas emissions; however, if dry waste was to be flooded this could potentially increase the risk of gas emissions.

Another discussion point was raised on the potential for landfill modellers to predict climate change effects.

Participants agreed that climate change effects should be taken into account with respect to landfill gas risk, and the potential for increased flooding should be accounted for in the design of gas abatement systems.

5. How will VI risk assessments be undertaken in regard to climate change – qualitative vs quantitative

Participants discussed the approach to risk assessment in the face of a potentially rapidly changing climate and agreed there is considerable uncertainty to predict the risk assessment changes required for quantitative VI risk assessment. Participants agreed that taking account of predicted changes to differential temperature and pressure, and the move to lower carbon building stock, might be useful for predicting future changes to VI risk profiles. Certainly, the increasing potential for sort-term acute VI risk associated with extreme weather events should be taken into account on both a qualitative and quantitative basis if possible, and on a site-specific basis.

4.3 Conclusions

The main conclusions from the workshop discussions are presented below:

- Participants agreed upon the level of uncertainty and difficulty in predicting climate change effects in relation to ground gas and VI. Higher risks are associated with short-term extreme weather events, which are predicted to increase in both frequency and intensity going forward, highlighting the importance of considering such effects in risk assessment. The effect on risk assessment from more gradually changing trends (the rate of change is likely to increase however) in the climate are more difficult to estimate and predict due to a counter-balance of factors, for example increasing VI drivers (differential temperature and pressure) vs changes to building stock and decrease in fossil fuel use.
- Participants agreed that uncertainty in weather conditions can be accounted for using conservative models.
- Participants agreed that remediation requirements in relation to ground gas and VI is unlikely to be increased as a result of climate change if climate change factors are adequately considered in the risk assessment.

4.4 Recommendations

The recommendations from the workshop are presented below:

- Consider potential acute risks from VOC and ground gas and how these might be exacerbated by climate change, both generically and on a site-specific basis.
- Further research could be undertaken into how heavy rainfall events may act as a driver for gas flux.

- Further training on conceptual models for VI and ground gas model pathways should be conducted to raise awareness of potential future risks from climate change factors, including potential increase in acute risk events.
- Further research is needed within the UK to ascertain which ground gas and VI parameters are the most sensitive to climate change.
- Consideration should be given to developing a range of VI attenuation factors for different climate zones/regions in the UK, which also differentiate between chlorinated solvents and petroleum hydrocarbons.
- Consideration should be given to strengthened guidance in the need to account for climate change in ground gas and VI risk assessment.
- Further research is required into the impact of flooding on ground gas migration pathways in active and closed landfills.

Footnote:

Since the ground gas and soil vapour workshop, further guidance on the consideration and potential implications of climate change on ground gas risk has been published as part of the NHBC Foundation guidance (NHBC, 2023). Section 3.4.5 of this guidance deals with how to account for climate change in ground gas risk assessment. It concludes that an "*assessment of climate change effects should be site-specific and realistic. There is normally a significant degree of conservatism already built into ground gas risk assessments and consideration of future changes due to climate change should determine if the likely changes are significant when compared to assumptions already accounted for in the baseline risk assessment*". Such a site-specific assessment should include:

- "*a balanced consideration of credible and foreseeable events against hypothetical events that are not realistically likely to occur*
- *consideration of credible pathways considering what is known about the geology and hydrogeology, building construction and services layout, etc.*
- *site specific consideration of the impact of foreseeable events such as flooding, changes in groundwater level, extreme weather conditions and possible changes to the gas regime caused by future development*
- *where appropriate, quantitative assessment of any credible changes in gas regime and the impact this may have on the risk posed by hazardous ground gases*"

5 AFTERNOON SESSIONS – NAPL AND NATURAL SOURCE ZONE DEPLETION

5.1 Introduction

This workshop considered the key issues associated with the assessment of non-aqueous phase liquids (NAPLs) and explored what impact, if any, climate change might have on their behaviour and the processes involved in natural source zone depletion (NSZD; vaporisation, volatilisation, dissolution and biodegradation).

Four participants attended this workshop, representing consultancies, a remediation contractor and the Environment Agency.

5.2 Objective

To outline the main areas of concern when incorporating climate change risks for NAPL and NSZD site assessments.

To help reach these objectives, the following issues were considered for discussion:

- What key site information is needed to develop a NAPL/NSZD conceptual site model (CSM)?
- To what extent, if any, will climate change make a difference to NAPL sites and NSZD in the UK?
- Approaches to developing a NAPL and NSZD CSM;
- When is quantitative understanding needed versus qualitative; and,
- What guidance is available currently and where are the gaps? What is required to close the gaps?

5.3 Preamble and Key Site Information

Generally, NSZD concerns sites impacted with petroleum hydrocarbon sources of light NAPL (LNAPL) as this reflects the current body of scientific evidence. This summary is focussed on petroleum hydrocarbon LNAPL and does not consider dense NAPLs (DNAPL), e.g. chlorinated solvents.

To establish whether climate change is likely to impact upon LNAPL behaviour and NSZD, participants sought to identify the key elements of a LNAPL CSM that need to be understood before any additional effects created by a changing climate can be estimated. These key elements were identified as:

- Properties of LNAPL (density, viscosity, composition, interfacial tension, all of which can be analysed in UK laboratories);
- LNAPL partitioning behaviour and biodegradation (dissolution -> dissolved phase, vaporisation/volatilisation -> vapour phase, biodegradation -> bulk gases - carbon dioxide/methane);
- LNAPL mobility, which indicates the potential for migration where specific conditions are met (see below). NAPL mobility is a function of NAPL saturation, and other factors. NAPL saturation and these factors, indicating whether the NAPL is mobile or immobile, can be determined by specialist NAPL laboratories, including a few in the UK, and/or through monitoring, in situ testing and modelling. Residual saturation is the threshold below which LNAPL is immobile and is typically low. Mobile LNAPL typically has higher saturation; and,
- LNAPL migration potential and behaviour. LNAPL must not only be mobile, but other site conditions need also to be favourable to initiate and sustain migration at relevant scales

(e.g., excess volume of mobile LNAPL, critical thickness/pressure head, viscosity of LNAPL etc.).

Understanding these key factors will help to establish the NAPL CSM when climate change is actively being considered. The SoBRA NAPL sub-group[9] is in the process of publishing various documents to assist practitioners to do this. Evaluating how a changing climate may affect the key processes involved in NSZD (vaporisation, volatilisation, dissolution, biodegradation) will help identify whether NAPL presents more, or less risk, to receptors under different environmental conditions.

Participants commented that Regulators will expect that remediation (or mitigation) is undertaken in cases where there are unacceptable risks posed by dissolved-phase contaminants in groundwater, vapour risks, or where NAPL is mobile and also migrating (Environment Agency, 2017). Recent LNAPL releases are more likely to result in direct risks to nearby receptors from LNAPL migration than aged releases, where LNAPL bodies have typically ceased migrating, stabilised and been subjected to weathering/degradation processes. In these cases, it is typically indirect risks such as those associated with vapour intrusion and/or dissolved-phase plume migration that drive mitigation efforts. It was also noted that regulators often require remedial action to address NAPL, because, to date, there has been limited uptake of NAPL assessment and modelling tools compared with dissolved-phase or vapour-phase contaminants, and sometimes insufficient, specific site data is collected to predict mobility/migration behaviour. Therefore, in addition to delineating dissolved phase plumes and soil gas concentrations, investigative effort should be given to establishing whether LNAPL is likely to migrate and impact a receptor at a particular site. This may reduce the need for unnecessary remediation.

5.4 Key Issues

Subsequent discussions focussed on the following key issues, which are summarised here.

<u>Is climate change a concern for LNAPL migration potential and/or NSZD?</u>

NSZD is the term used to describe the collective, naturally occurring processes of dissolution, vaporisation, volatilisation and biodegradation that result in observable reductions in mass, saturation and mobility of LNAPL, most commonly oils and fuels, within the subsurface. Although NSZD rates can be significant (1,000s to 10,000s litres of LNAPL per hectare per year), these processes occur over periods of years to decades and climate change may therefore be a significant consideration for LNAPL sites. It is anticipated that under a changing climate, developing a NAPL CSM considering possible effects of future site conditions on LNAPL migration risk and NSZD will become a requirement.

For LNAPL and NSZD, the main changes to site conditions are temperature rise and a dynamic (fluctuating) water table. Further information regarding potential changes to site conditions can also be found in SoBRA's Controlled Water and Climate Change guidance (SoBRA 2022b).

Although subject to local variations, in general terms the predicted changes for the UK include a reduction of rainfall in summer, an increase in rainfall in winter, an increase in extreme weather events and a rise in air temperature (and thus soil temperature). To what extent these changes would be significant for LNAPL sites and NSZD was considered using two environmental variables likely to be affected by climate change, i.e., temperature rise and a more dynamic water table. The

[9] https://sobra.org.uk/about-us/sub-groups/

anticipated changes were considered for each of the key NSZD processes of biodegradation, volatilisation and dissolution.

General trends are given in Table 1 and Table 2, although it must be stressed that predicting the effect of climate change on LNAPL behaviour and NSZD is complex (Cavelan et al., 2022) and often limited to site-scale and particular climatic conditions. Well-designed site investigation and data analysis is needed to confirm the CSM in each case.

Temperature Rise

Soil temperature increases are generally anticipated to be of the order + 1.5 to + 5.4°C (up to + 9°C locally) by 2100. The key LNAPL characteristics relating to a temperature rise are presented in Table 1.

Table 1 Predicted scenarios under temperature rise (Cavelan et al., 2022)

Temperature Rise	
LNAPL partitioning (vaporisation, dissolution and plume volatilisation)	Expected to increase but not significantly at the predicted lower end of soil temperature increase (+ 1.5 to + 5.4°C). Changes could be more significant at + 9°C, if achieved locally
Biodegradation	Expected to increase but not significantly at the predicted lower end of soil temperature increase (+ 1.5 to + 5.4°C). Changes could be more significant at + 9°C, where achieved locally. Biodegradation also dependent on availability of electron-acceptors and other factors not influenced by temperature change.
LNAPL mobility	Expected to change as capillarity responds to temperature rise, but not significantly
LNAPL migration	Changes to LNAPL migration potential due to temperature rise alone are not expected to be significant.

Dynamic water table

Predicted changes include a reduction of rainfall in summer, an increase in rainfall in winter, and an increase in extreme weather events e.g., flooding. Resultant scenarios potentially include a low water table and a high water table, both gradual and sudden changes, as presented in Table 2.

Table 2 Predicted NSZD scenarios under a dynamic water table (Cavelan et al., 2022)

	High water table	Low water table
NAPL partitioning	Dissolution is expected to increase due to higher groundwater flow. Volatilisation is expected to decrease due to thinner unsaturated zone, although soil gas will have a shorter pathway to near-surface receptors.	Dissolution is expected to decrease due to lower groundwater flow. Volatilisation is expected to increase due to larger smear and unsaturated zone, but there will be a longer migration pathway for soil gas to near-surface receptors.
	Rapid water table fluctuations may temporarily promote advective vapour and gas transport.	
Biodegradation	On the whole is expected to decrease due to reduced availability of electron acceptors, specifically oxygen, in the saturated zone compared to vadose zone	Expected to increase due to greater availability of oxygen in the vadose zone. If vadose zone soils dry out, reduced availability of water required by bacteria may slow rate if water table remains low for extended periods.
NAPL mobility	Likely to decrease if LNAPL becomes mostly submerged and entrapped as capillary-held residual by rising groundwater.	Receding groundwater levels can cause LNAPL to redistribute, increasing saturation and mobility in the vadose zone.
NAPL migration potential	Uncertain Dynamic water table may cause temporarily high hydraulic gradients in the saturated zone, causing migration. Over time, dynamic water table conditions can smear LNAPL, reducing saturation and limiting migration potential.	

Of the two environmental variables, a more dynamic water table is expected to have a more significant impact upon LNAPL and NSZD than increased temperatures. Extreme events may temporally yield more risk of LNAPL migration than gradual changes, but the short-term nature of these events is such that migration enhancement should decrease with time.

Developing a LNAPL and NSZD conceptual site model (CSM). When is quantitative understanding needed versus qualitative?

Site-specific data will help provide a more data driven rather than judgment-based assessment. Data regarding NAPL saturation distribution and multiphase flow properties (viscosity, density, interfacial tension, residual saturation, etc), as well as site geology, hydrogeology and history are required to determine the potential for NAPL migration.

Screening lines of evidence for NSZD might include assessing the distribution and flux of bulk gases, vapours and/or temperature above the LNAPL, evaluating mass discharge and biogeochemical evolution of the dissolved phase plume and/or studying compositional changes in the LNAPL itself. Some of these data will be collected for detailed quantitative risk assessment (DQRA).

Development of a CSM will require an understanding of likely site conditions in terms of anticipated changes to temperature, rainfall, flooding, extreme events such as storms. The rate of change will also be significant, i.e., sudden events such as flooding or storms, compared with gradual changes, such as temperature increase. For more detail regarding the anticipated regional impacts of climate change, refer to SoBRA's Controlled Water and Climate Change guidance (SoBRA 2022a).

Investigations should be designed to establish whether these scenarios will increase or decrease risks from NAPL and to what extent what role NZSD may have at a site. Key questions include the LNAPL distribution in the subsurface, whether the LNAPL is mobile or not, and therefore have the potential to migrate? Will the risks from soil gas intrusion or (dissolved-phase) groundwater impact increase or decrease? Understanding the physical and chemical properties of LNAPL (density, viscosity, composition, interfacial tension, residual saturation etc) is the first step to estimating partition behaviour (SoBRA in prep. a) and mobility. Estimating NAPL mobility (as residual saturation) can be determined in specialist laboratories, alternatively there is guidance available to estimate this and migration potential (CL;AIRE, 2014; SoBRA, 2023). Field techniques such as baildown tests can be used to further estimate potential mobility and recoverability of mobile LNAPL. Once these aspects of the CSM are established then predicting changes under changing environmental conditions can commence.

NAPL must be mobile to migrate but not all mobile NAPL migrates. Multiple lines of evidence may be needed to distinguish between mobile and migrating LNAPL. LNAPL transmissivity, e.g. from baildown tests, provide better information regarding migration and recoverability in differing aquifer types (unconfined, confined, perched), than simple in-well NAPL thickness measurements. A discussion on NAPL monitoring options is the focus of forthcoming SoBRA guidance (SoBRA in prep. b). Other types of test such as skimming tests and total fluids recovery data are also available for estimating LNAPL transmissivity (ASTM, 2021).

Field testing methods are available to help with various elements of assessing NSZD potential, refer to guidance (ITRC, 2018).

A better understanding of likely NAPL behaviour at a site can reduce the need for mitigation/remediation. If indirect risks arising from dissolved-phase plumes and vapour intrusion are being addressed in site management and remediation activities, mitigation of NAPL risks (where needed) can transition to or deploy NSZD as a standalone longer-term management strategy.

<u>What guidance is available about the role of climate change and where are the gaps? What is required to close the gaps?</u>

Most of the scientific literature and guidance pertaining to LNAPL behaviour and NSZD originates from the USA and Australia. While this literature and guidance has relevance in the UK, there is a need for more UK-based data and case studies.

As previously stated, in August 2022 SoBRA published a guidance note for contaminated land practitioners on assessing risk to controlled waters under conditions of future climate change (SoBRA 2022a). This sets out the current regulatory and guidance context, identifies current sources of authoritative information on climate change impacts for the UK, and describes an approach for a qualitative appraisal of climate change impact at the preliminary risk assessment stage. The report identifies the limitations that existing standard DQRA modelling software (such as Remedial Targets

Methodology worksheet (RTM)[10] and ConSim[11]) have when looking to model the short-term, transient nature of many climate change impacts, and recommends a series of steps to mitigate this in DQRAs.

Land Contamination Risk Management[2] guidance suggests information pertaining weather and natural patterns, including climate change, may be required to establish site conditions for generic risk assessment. It also states that climate change should be a consideration "*to ensure site works and any long-term remediation is sustainably robust*", in particular with reference to the remediation option appraisal and remediation design phases of work.

CIRIA are currently developing guidance that deals specifically with how climate change will affect the CSM, risk assessment and remediation, which is yet to be published[12]).

5.5 Summary

Participants agreed that often it is indirect risks (vapours, dissolved-phase contaminants) arising from LNAPL in the sub-surface that are the focus of site investigative and remediation/mitigation efforts. There is more uncertainty in assessing direct risks from LNAPL, and as a result, remediation is often selected as a risk management strategy with little understanding of whether the LNAPL presents a direct risk and/or whether NSZD could play a significant role in managing risks.

Development of a NAPL/NSZD CSM considering climate change requires firstly an understanding of site NAPL characteristics and secondly an understanding of site NSZD processes namely biodegradation, vaporisation, volatilisation and dissolution. Alongside this are site conditions in terms of anticipated changes to temperature, rainfall, flooding, extreme events such as storms. The rate of change will also be significant.

Where receptors are not at imminent risk, monitoring NSZD may be a useful long-term risk management strategy. As such climate change and its potential effects upon LNAPL and NSZD should be considered as part of decision making. Climate change effects may change how NAPL behaves in the sub-surface, which could in turn also affect NSZD. An increase in temperature and a fluctuating water table were used to assess potential impacts on NSZD and subsequent risks from LNAPL. It was felt that an increase in temperature is expected to be less of a concern for NAPL migration and partitioning than a fluctuating water table.

Case study applications of scientific literature and guidance for NAPL and NSZD in the UK are required. Some examples of UK work include SoBRA's (in prep. a) guidance[7].

There is currently a significant gap between current practice and being able to quantitively predict the effects of climate change on NAPL behaviour and NSZD. However, site specific data that can be helpful to reduce these uncertainties include NAPL properties (composition, viscosity, density, interfacial tension, residual saturation), and NAPL behaviour (mobility, recoverability, constituent partitioning and biodegradation) all of which can be used to provide a more data driven rather than judgment-based assessment.

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[10] https://www.gov.uk/government/publications/remedial-targets-worksheet-v22a-user-manual

[11] http://www.consim.co.uk/

[12] https://www.ciria.org/Research/Project_proposals2/P3266_-_A_guide_for_managing_changing_climate_and_contaminated_land_projects.aspx.

5.6 Recommendations

It was recommended by the participants that a framework for developing LNAPL CSMs, that includes establishing the potential for NSZD, is needed. The framework could be designed to characterise risks from LNAPL, establishing indirect risks to receptors posed by vapours/dissolved phase contaminants, alongside direct risks presented by migrating LNAPL and potential for NSZD. Only then can any predicted effects of climate change be addressed consistently.

The framework could consider the following for any given LNAPL site:

- Evaluating evidence for LNAPL;
- Establishing site-specific characteristics of NAPL (density, viscosity, composition, interfacial tension, etc);
- Evaluation of direct risks posed by NAPL migration (e.g. migrating into controlled waters/water environment, deterioration of buildings/infrastructure);
- Evaluation of indirect risks from NAPL (e.g. vapour intrusion, risks to controlled waters/water environment);
- Evaluation of NSZD and the potential merits of monitoring NSZD as a risk management strategy following active remediation or as a standalone approach;
- Evaluation of likely impacts of climate change and over what period of time these will take place;
- Evaluation of changes to key NSZD processes biodegradation, vaporisation, volatilisation and dissolution;
- Evaluation of risks posed by NAPL given changes to NSZD processes; and,
- Development of risk management strategy for LNAPL.

6 AFTERNOON SESSIONS – CARBON ACCOUNTING

6.1 Introduction

The workshop on Carbon Accounting and reducing impact on Climate Change, focused on brownfield risk assessment but also evaluating other aspects of brownfield redevelopment such as remediation, discussed the opportunities to apply carbon account in contaminated land, data needs to support the inclusion, how to change or challenge current practice and guidance to support the inclusion of carbon accounting, and training needs.

While carbon accounting is increasingly applied in some areas of brownfield redevelopment, currently it is rarely explicitly considered in brownfield risk assessment nor documented in site investigation reports.

6.2 Discussion Summary

The summary below reflects participants opinions.

1. **Opportunities to apply carbon accounting/management:**
    a. There is the potential to consider climate change during the Preliminary Risk Assessment (PRA) stage, through site investigation, assessment, cost benefit analysis and remediation. It may be of benefit to allow initial site development and master development plans to incorporate sustainable land management practices to reduce the need for remediation. This could include consideration of leaving contaminated land areas to provide aspects such as biodiversity net gain, and climate change mitigation.
    b. The climate can be considered as a receptor in the CSM with a general aim to reduce the impact to the climate (carbon generated) of any development or remediation scheme. Biodiversity could also be considered a receptor in the CSM.
    c. A PRA could identify if:
        i. Certain areas of the site are better for development than others when considering the carbon footprint of the development. e.g., suggesting development away from areas that would require remediation so as to reduce carbon emissions during the development process.
        ii. Development could take place away from areas of greenfield soil, preserving the soil and carbon located within such a resource.
        iii. The suitablity of using local materials or any current buildings during the development process.
    d. Site investigations can be designed to obtain information to support the design of a development with a lower carbon impact. This would involve an understanding of any proposed outline designs from the developer.
    e. Risk assessors should move away from overly generic assessments and associated recommendations of precautionary remediation measures that are not necessarily needed and would not be supported if a more detailed and site-specific assessment was completed. Regulators should give consideration to the suitability of generic assessments and recommendations. This approach may remove some of the costs and carbon impact of unrequired remedial measures such as cover layers or vapour membranes. Generally, a more pragmatic and less overly conservative approach to risk assessment, reducing unneeded remediation that impacts the climate, should be considered as part of carbon accounting.

f. During any Cost Benefit Analysis the carbon impact of a remediation scheme from inception to completion of a scheme (where a consultant or contractor would complete their contract with the client) should be considered. This would involve doing an estimated carbon account for the proposed scheme(s).

2. Data needs

a. Carbon accounting for projects should be undertaken in line with the Green House Gas (GHG) Protocol[13] and Construction Leadership Council PAS 2080 guidance (Construction Leadership Council, 2019). However, these schemes leave much to interpretation and it would be beneficial if there was industry standard guidance on consistent and reliable metrics to use. As well as an expectation to include GHG Protocol Scope 1 and 2 emissions[14] in any carbon accounting there should be an industry standard on the minimum expected to be included within Scope 3 emissions[15]. This will ensure that the major carbon emissions of a project are always accounted for.

b. It would be beneficial to know the inherent CO_2 equivalent emissions associated with the production, installation, and operation of different remediation technologies. For example, what is the CO_2 equivalent emission of producing a vapour intrusion membrane and a groundwater remediation pump? It would be useful to collate the emissions associated with various remediation technologies.

c. To provide accurate risk assessment with reduced conservatism it would be suitable to have long term soil, gas, groundwater etc data from a site. Greater carbon cost upfront at the site investigation stage will likely reduce any carbon emissions involved in remediation.

3. How to change or challenge current practice and guidance

a. A greater emphasis on contaminated land risk assessment being used in development master planning, and early development site layout decision making, to make sure collectively carbon emissions are being reduced, is suggested. For example, if potential contamination is only expected in localised areas of a site, developments could be designed to avoid construction on such areas, potentially reducing the need for site investigation and remediation.

b. Consistency in use of Construction Leadership Council PAS 2080 and the GHG protocol guidance (see above) would be of benefit.

c. A requirement for the collection of baseline groundwater and soil monitoring data at the point of purchase would potentially reduce future conservatism in risk assessment and more accurate estimates for remediation.

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[13] https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf

[14] Scope 1 emissions are direct emissions from sources controlled or owned by a company. For example, company owned vans/ cars, gas heating where the company is control of the heating level or use of remediation plant owned by a company. Scope 2 emissions are indirect emission related to the production of energy that a company uses. For example, emissions produced in generating electricity used in an office. https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf

[15] Scope 3 emissions are all other emissions not included within Scope 1 or Scope 2. This can include and is definitely not limited to company air travel, commuting, subcontractor emissions and emissions generated during the product of company used equipment (e.g., computers). https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf

   d. A strong promotion of the reuse of materials where possible under End of Waste Protocol guidance could reduce the need for remediation, quarrying of virgin material, and landfill, all of which have a carbon impact, would reduce the carbon footprint of a development. Preference should be given to remedial solutions where materials can be reused or have less carbon impact.
   e. Greater emphasis on reducing conservatism, to reduce waste.

4. **Training needs**
   a. Carbon accounting should be undertaken by a competent person, preferably who understands the site investigation process for a brownfield site.
   b. Advice from an experienced Climatologist should be sought when selecting climate scenarios to use in brownfield development, and understanding uncertainties around different climate change tools available.
   c. Participants were unaware of any current UK certification of someone being deemed competent in carbon accounting. This would be of benefit.
   d. Participants recommended that internal company / employee training on the Construction Leadership Council PAS 2080 (Construction Leadership Council, 2019), carbon accounting tools and on how to consider climate change/ carbon emissions in PRAs would be of benefit to brownfield professionals. This will help drive a consistent approach and consideration of climate change throughout our work.
   e. Participants suggested that the ASoBRA[16] competencies required to achieve this level of accreditation could include questions on climate change and consideration of carbon accounting.

[16] https://sobra.org.uk/accreditation/

7 CONTROLLED WATERS AND CLIMATE CHANGE GUIDANCE

Whilst there was a workshop session on controlled waters[17], this has since been superseded by the SoBRA (2022a) publication Guidance on Assessing Risk to Controlled Waters from UK Land Contamination Under Conditions of Future Climate Change, published in August 2022. Below is an introduction to that guidance including the rationale for its development.

This Guidance is the first industry guidance document on climate change effects on land contamination risk assessment focused on risks to controlled waters, which was prepared by volunteers on behalf of SoBRA. Climate change is an important and developing area requiring consideration within the brownfield land sector, which is only going to increase in significance over time. SoBRA recognised the critical and urgent need for industry guidance, and tools, to be developed to provide land contamination professionals with a framework to enable the effects of future climate change on controlled waters risk assessment to be assessed. and to support sustainable site redevelopment, as mandated by LCRM[2] and the NPPF[1].

7.1 Background

Climate change is expected to alter the frequency and distribution of rainfall, increase atmospheric temperatures, and increase the frequency and severity of extreme weather events, leading to longer periods of drought, and more extreme rainfall events, with associated rising groundwater and surface water levels causing flooding and coastal inundation. The need to incorporate the effects of climate change into qualitative and quantitative risk assessments is set out within Managing and Reducing Land Contamination: Guiding Principles (GPLC2) FAQ 8 (Environment Agency, 2010), the NPPF[1] in England and LCRM[2]. However, no accompanying technical guidance has been published by UK regulators on how to consider the effect of climate change on contaminated land leaving land contamination practitioners uncertain of how this complex area should be assessed. As a result, it is often not considered at all. At SoBRA's AGM in December 2020, members voted in favour of creating a new SoBRA sub-group focusing on controlled waters and climate change. The sub-group was formed in May 2021 and comprised a total of 14 volunteers including consultants with a range of experience including SoBRA accredited risk assessors (ASoBRA). Regulators from the Scottish Environment Protection Agency (SEPA), Environment Agency (EA) and National Resource Wales (NRW) were also represented and provided invaluable direction, particularly in the absence of detailed policy being available.

The overall aim of the sub-group was to develop clear, practical guidance to support risk-based decision making about the potential effects of climate change within all stages of controlled waters land contamination risk assessments (CWRA). The sub-group also wanted to provide a pragmatic but robust framework on which to base climate change considerations within CWRA, with resources applied being proportionate to the level of risk. It is considered that effective use of this guidance by industry will ensure that CWRA completed by practitioners remain sustainable, robust and resilient and enable climate change to be incorporated in a consistent manner.

7.2 Approach

A literature review was completed which included reviewing existing UK and international approaches relating to land contamination and interactions with predicted climate change impacts. An understanding of key climate change consequences for the UK was developed based on a review

[17] The water environment in Scotland

of Met Office UK Climate Projections 18 (UKCP18) for meteorological effects (temperature and precipitation) and sea level rise; and the British Geological Survey (BGS) and Centre of Hydrology (CEH) eFLaG for projections of climate induced change to groundwater (recharge and groundwater level) and surface water (river flow).

Based on the findings of the literature review, future climate change was considered to have the potential to alter the CSM by affecting source zone dimensions, altering exposure pathways and/or changing receptor characteristics, all of which could change the calculated 'risk' posed to controlled waters. Several "what-if" scenarios were developed to enable users of the guidance to understand possible effects/considerations of climate change induced weather events in relation to source-pathway-receptor components of the CSM which were presented both in pictorial and tabular format within the guidance document. The guidance also provides a framework outlining how climate change considerations can be incorporated into all CWRA stages from the desk-based stages of PRA and then enabling an effective site investigation design to collect data to further refine the CSM. This then informs the generic quantitative risk assessment (GQRA), and ultimately identification of parameters that could influence the outcomes of numerical modelling completed as part of DQRA. Useful data sources and references are presented along with case study example sites, with different site-specific considerations, to demonstrate application of the guidance.

A key challenge associated with developing the guidance was the absence of detailed published policy outlining which climate change projection Representative Concentration Pathway (RCP) scenario should be selected within land contamination risk assessments. The guidance recommends an initial conservative approach be undertaken whereby 'worst-case' projections comprising RCP8.5 for the far future (2080s) is considered and, if required, consideration could also be given to looking at the near future (2050s) and contrasting RCP scenarios particularly where the outcome of the risk assessment is not clear and obvious. The inclusion of regulators on the sub-group was beneficial to help inform the recommended approach in the absence of policy. Due to the frequent publication of research and academia relating to climate change the sub-group restricted their literature review to references published up to and including 31 January 2022, which was recognised as a potential limitation within the guidance in this fast-moving field. It is planned that the links to references will be periodically updated. In the meantime, presentations given on the guidance at industry events have included reference to more recently published literature.

The SoBRA guidance recognises that standard commercially available environmental simulation models are unable to model temporal changes to parameter values, a key component of climate change. The guidance provides an approach for risk assessors to consider the impact of future climate change on the modelled result in the event it needs to be considered as part of a DQRA and identifies key parameters that should be considered as part of a sensitivity analysis.

The literature review and methodology, developed in relation to CSM considerations associated with climate change, is based on the latest relevant climate change projections. To our knowledge this is the first time that CSM considerations for climate change have been considered. These illustrative example CSMs developed by the sub- group within the guidance consider climate change effects associated with changes in precipitation and sea level rise. Ultimately SoBRA has provided the land contamination sector with much needed, freely available guidance on how predicted climate change impacts should be incorporated within controlled waters risk assessments to ensure they remain sustainable, robust and resilient.

7.3 Regulatory Context

LCRM[2], GPLC2 (Environment Agency, 2010) and NPPF[1] (and equivalents in the devolved administrations) outline the need to incorporate climate change into qualitative and quantitative land contamination risk assessments. In addition, BS EN 21365 (British Standards Institute, 2020) CSMs for Potentially Contaminated Sites states the need to consider and identify '*possible foreseeable events*' that could affect contaminant impacts or create new exposure pathways, e.g. flooding, rising groundwater or seawater levels and extreme weather, which are all consequences of climate change. However, none of the guidance documents detail how climate change should be practically considered, likely because regulators are still developing their own policy in relation to this area.

CL:AIRE (2007) published a SUB:RIM bulletin (SUB3) entitled "Climate change, pollutant linkage and brownfield regeneration" in March 2007, which outlined an adaptation strategy to address the impact of climate change within the UK regulatory framework. This document is now out of date and doesn't appear to have been widely applied within the industry. Several of the principles outlined within SUB3 have been further developed within the SoBRA guidance. In line with industry standards (e.g. LCRM[2]), the SoBRA guidance recognises that any change to a CSM (due to future climate change effects) must be determined by a suitably competent and experienced professional, using evidence-based reasoning, and that the risk assessment process should only progress to higher tiers (i.e. generic quantitative and detailed quantitative) if the risk cannot be determined 'acceptable' at the preliminary stage. The SoBRA guidance supports practitioners in doing this by setting out "What-if" scenarios for source, pathway, receptor CSM components that could be affected by climate change, in order to guide evidence-based reasoning. This is in line with the approach detailed in BS EN 21365 (British Standards Institute, 2020).

7.4 Methodology

The methodology developed by SoBRA is designed to be replicable for other areas of risk assessment, identifying key overarching considerations such as:

- Climate projections vary on a seasonal and regional basis and so climate change considerations influencing the CSM need to be considered at a site-specific level, a uniform UK-wide approach to climate change considerations is not considered suitable.
- The magnitude of climate change projections vary widely depending on which RCP greenhouse gas emission scenario is selected.
- Medium to long term climate change effects can be assessed quantitatively by considering climate change projections whereas extreme weather events can only be assessed qualitatively via the use of "What if" scenarios.
- Climate change considerations are an important part of risk-based decision making and need to be considered at the outset from PRA stage. It was identified that in some instances the influence of the impact of future climate change could effectively be screened out at this stage.

8 REFERENCES

ASTM, 2021. E2856-13R21 Standard Guide for Estimation of LNAPL Transmissivity. Available at https://www.astm.org/e2856-13r21.html

British Standards Institute (2020). Guidance on Assessing Risk to Controlled Waters from UK Land Contamination Under Conditions of Future Climate Change.

Cavelan et al., (2022). A Critical review of the influence of groundwater level fluctuations and temperature on LNAPL contaminants in the context of climate change. Volume 806, Part 1, 2022. Available at DOI: 10.1016/j.scitotenv.2021.150412

CL:AIRE. (2007). Climate Change, Pollutant Linkage and Brownfield Regeneration. Sustainable Urban Brownfield Regeneration: Integrated Management (subr:im) Bulletin SUB 3. Available at http://www.claire.co.uk/pdf_usr/SUB3_final_amended_figs.pdf

CL:AIRE, 2014. *An Illustrated Handbook of LNAPL Transport and Fate in the subsurface.* Document includes equations for estimating the critical head of LNAPL in boreholes for lateral mobility and the penetration depth of LNAPL for a given head of LNAPL in formation above the water table. Available at www.claire.co.uk/

Construction Leadership Council (2019). Guidance Document for PAS 2080. Available at https://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2019/06/Guidance-Document-for-PAS2080_vFinal.pdf

Environment Agency (2017). Land contamination groundwater compliance points: quantitative risk assessments. https://www.gov.uk/guidance/land-contamination-groundwater-compliance-points-quantitative-risk-assessments.Last updated 14 March 2017.

Environment Agency (2010). GPLC2 – FAQs, technical information, detailed advice and references. March 2010. Available at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/297454/geho1109brgz-e-e.pdf

ITRC (2018). Light Non-Aqueous Phase Liquid (LNAPL) Site Management: LCSM Evolution, Decision Process, and Remedial Technologies. LNAPL-3. Appendix B – Natural Source Zone Depletion (NSZD) Appendix. Washington, D.C. Available at https://lnapl-3.itrcweb.org.

NHBC (2023). Hazardous ground gas - an essential guide for housebuilders. NF94. April 2023. Available at https://www.nhbc.co.uk/foundation/hazardous-ground-gas

SoBRA (in prep. a). Non-Aqueous Phase Liquid – Guidance Notes for their Assessment in Contaminated Land Scenarios in the UK. 2. Effective solubility tool. Guidance tool to help estimate effective solubility of multi component NAPLs.

SoBRA (in prep. b). Non-Aqueous Phase Liquid – Guidance Notes for their Assessment in Contaminated Land Scenarios in the UK. 4. NAPL monitoring options and their merits.

SoBRA (2022a). Guidance on Assessing Risk to Controlled Waters from UK Land Contamination Under Conditions of Future Climate Change. Version 1.0. Available at https://sobra.org.uk/category/climate-change/

SoBRA (2022b). Guidance on Assessing Risk to Controlled Waters from UK Land Contamination Under Conditions of Future Climate Change. Version 1.0, August 2022. Available at https://sobra.org.uk/resources/reports/

SoBRA, 2022c. Non-Aqueous Phase Liquids – Guidance Notes for their Assessment in Contaminated Land Scenarios in the UK. 5. Baildown test guidance for light non-aqueous phase liquids. Available at www.sobra.org.uk/resources/reports/

SoBRA, 2023. Light Non-Aqueous Phase Liquid – Guidance Notes for their Assessment in Contaminated Land Scenarios in the UK. 3. LNAPL Mobility Screening Tool.