Summary

Although there is considerable uncertainty in predicting future impacts of climate change, there is
global and national evidence that suggests that the UK will be subjected to warmer and wetter winters,
hotter and drier summers, rising air temperatures, increased storminess and heavier rainfall. The
potential impact of these factors on the risk assessment, design of future remediation systems and
management of current and future contaminated sites is likely to be significant. The work presented in
this paper forms part of multi-institutional multi-disciplinary UK-based research consortium with the
aim of producing integrated and sustainable solutions for the development of brownfield land in urban
areas in order to promote better quality of life and economic growth in the UK. It concentrates on the
impact of climate change on contaminated land and pollutant linkages and examines technical
evidence of the impact of climate change, using both experimental investigations and numerical
modelling, and addresses technical adaptation issues and stakeholder perspectives and adaptation.

Keywords
Climate change, contaminated land, experimental validation, modelling, technical adaptation,
stakeholder responses

1. Introduction

Proper management of contaminated land requires an understanding of the magnitude of current and
future pollutant linkages. There is a risk that changes in environmental conditions and processes will
affect the standards of remediation required to ensure receptors are not significantly impacted in the
future. Remediation choices being made now should be influenced by future land use, climatic
conditions and societal demographics. There is a need for tools to assist the remediation industry in developing and adapting techniques so that they will be sustainable despite changes in processes affecting pollutant linkage which arise from climate change. This paper presents work carried out as part the SUBR:IM (Sustainable Urban Brownfield Regeneration: Integrated Management) multi-institutional multi-disciplinary UK-based research consortium funded by the UK Engineering and Physical Sciences Research Council (EPSRC). Its aim is to produce integrated and sustainable solutions for the development of brownfield land in urban areas in order to promote better quality of life and economic growth for all UK citizens. It is divided into a number of work packages that address a range of technical and social science aspects of the problem. One such work package which integrates technical and social science research approaches is entitled ‘Impact of climate change on pollutant linkage’ aims to provide technical evidence of potential impacts of climate change on contaminated land and remediation systems and examined potential technical adaptation strategies and current stakeholder perspectives and strategies. Its objectives are:

- To quantify the short and long-term impacts of climate change predictions.
- To evaluate effects of climate change on contamination linkages
- To develop appropriate adaptation design strategies to account for climate change.
- To examine the adaptive response of key brownfield stakeholders to climate change.

This paper summarises the output from this work package.

2. Experimental evidence of potential impacts

There is currently very little published work providing experimental evidence of potential direct impacts of climate change on contaminated land and remediation systems. The closest work is that which investigates and compares the impacts of different climatic regions on biological and chemical properties of contaminated soils and contaminant behaviour. Those studies show that climate changes towards warmer conditions would favour biologically driven degradation of compounds amenable to degradation while drier conditions would have the opposite effect. On the other hand heavy metal soil contaminants, which are more related to issues of leachability, would feature less risk in higher temperature and drier climate due to increased soil cation exchange capacity and pH. However, this may be counteracted by increased redox potentials associated with the drier conditions leading to increased solubility. It has also been shown that hot regions are not able to retain as high a level of soil organic carbon as cold regions although it has also been reported that this depletion will be compensated for by the greater organic matter supply from vegetation and crops growing more vigorously in hotter regions. In addition, seasonal changes are seen to have a more pronounced impact than annual changes. Engineered cover systems and stabilised/solidified soils are two of the most studied remediation technique in terms of the impact of climate-related impacts. Both systems have been shown to become extensively damaged under severe wet-dry and freeze-thaw cycles significantly reducing their mechanical properties and hence effectiveness. Figure 1 shows a typical cover system damaged by desiccation (Benson, 1999).

An extensive laboratory programme was conducted to provide some relevant direct evidence of the impacts of climate-related effects on a range of contaminated land systems. The systems investigated included the following: (i) stabilised/solidified contaminated and uncontaminated soils, (ii) aged stabilised/solidified contaminated and uncontaminated soils, (iii) compacted clay and sand-bentonite cover systems (iv) contaminated soil amended with compost, (v) contaminated soil amended with compost and bioaugmented and (vi) bioremediation site soil. Extreme seasonal temperatures as predicted by UKCIP02 ((Hulme et al., 2002) were applied to those soil systems together with a range of precipitation scenarios representing dry summers, summers with intermittent rainfall, summers with frequent rainfall, flooded winters and dry winters. Two years in real time were investigated and a
range of physical, chemical and biological properties were tested at different time intervals. Figure 2 shows the typical and different type of damage of physical damage that was observed in some of the stabilised/solidified soil samples tested. Figure 3 shows the effect of different 2080 climate scenarios on the biological activity of a bioremediated soil (System 1) and an amended and bioaugmented soil (System 2), compared to baseline conditions. The two 2080 conditions differ in that the 2080a scenario includes dry summers with no rainfall while the 2080b scenario includes intermittent summer rainfall (wet-dry conditions).

Fig. 1 Damaged compacted clay cover system in southern Wisconsin caused by desiccation (Benson, 1999).

Fig. 2 Damage on stabilised/solidified soil samples following different imposed climate scenarios.

Fig. 3 Effect of two different 2080 climate scenarios on the biological activity a bioremediated soil (System 1) and an amended and bioaugmented soil (System 2), compared to baseline conditions.

The experimental work showed that certain climate change scenarios or combinations of scenarios do give rise to potentially significant impacts on the different soil systems investigated. For the
stabilised/solidified soil systems, wet-dry conditions were found the most damaging, the damage was most severe in the first season of severe climate conditions and ageing of the system was found to be an advantage. In the compacted clay cover system, more damage was observed after the winters than the summers with an increase in permeability of one order of magnitude. Combining the results with model predictions (using the model HELP: Hydrologic Evaluation of Landfill Performance (Schroeder et al, 1994; Berger, 2000)) enabled the assessment of the longer-term impact of exposure to severe climate conditions. For the amended or bioremediated contaminated site soils, the results show that the changes were more severe between seasons and between different soil systems compared to between climate change scenarios and that the overall changes are a combination of both sets of changes together with long-term natural changes in soil conditions.

Such observations will have an impact on the management of contaminated land and existing remediation systems as well as the management and design of future systems. For example a permeability value of $10^{-9}$ m/s is usually required for both engineered cover and stabilised/solidified systems. Hence the design of future systems might require much lower initial permeabilities to be achieved to allow for orders of magnitude of potential increases over time due to climate change conditions. Containment systems with improved technical performance and which are more durable and sustainable, and hence likely to offer an improved resistance to climate change conditions, are currently being investigated and developed.

3. Numerical modelling of potential impacts

Modelling tools have perhaps the greatest potential for examining the effects of predicted climate changes on contaminant availability and transport without the timescales and costs associated with laboratory simulations, especially as the latter are often not practically achievable. Modelling tools can be used in two ways: 1) for studying how climate change may affect pollutant linkage on contaminated sites, and 2) for simulating remediation options prior to conducting remediation at the field scale. Understanding the environmental parameters and processes that control pollutant linkages is a first step in modelling them and a prerequisite for defining appropriate remedial responses. Examples of such links are shown schematically in Figure 4. For example, when redeveloping a landfill site into a community woodland, engineers may want to model the likelihood of interactions between the future vegetation and the landfill cap to forecast potential risks to ground water (and therefore human health) through contaminant leaching.

To explore the value of a modelling approach the RUSLE2 model (Foster, 2004) was used together with the UKCIP02 climate change predictions (Hulme et al., 2002) to forecast the effects of climate change on contaminant sediment movement via soil erosion processes by water. Erosion estimates were modelled with RUSLE2 for a spoil tip on a disused tin mining site located in the southern part of the Tamar Valley in south-west England. The contaminant source was a highly erosive coarse (1-2 mm) sandy spoil with significantly elevated levels of arsenic, lead and cadmium. The spoil tip was steep sided (54 %) and completely devoid of vegetation. The effects of climatic changes under the two scenarios tested (low and high emissions) showed a significant and gradual increase in erosion rates with time (Figure 5). Predicted changes for a contrasting climate (East Sussex) were used to model the impacts had the site been situated in south-east England (Figure 5).

Erosion rates for the site (SW) were up to twice those that a similar site would have generated in the SE, demonstrating how contrasting regional variation in predicted changes in climate could significantly influence soil erosion processes. This highlights the need for modelling at a localised
scale. Taking the average across the low and high emission scenarios, our results suggested that soil erosion rates could increase by almost 22% by the 2080s.

Fig. 4 Flow chart of some key environmental parameters and processes susceptible to climate change in the context of pollutant linkage. LAI (Leaf Area Index), ETP (Potential EvapoTranspiration), SOM (Soil Organic Matter), T (Temperature).

Using contaminant concentrations in the spoil, the mass of contaminants which would be generated via sediment production was calculated. The worst case climate scenario (high emissions) for the 2080s showed a 31% increase in arsenic mobilisation from 3.6 to 4.8 t.ha⁻¹.yr⁻¹ (Figure 6, SW Bare spoil). Simulated vegetation establishment on the spoil showed that a well established vegetation cover on the site would cause a dramatic reduction (by two orders of magnitude) in the amount of metals mobilised as sediments, reducing the mobilisation well below existing levels (Figure 6, SW Grass).

This case study showed that vegetation establishment may represent a cost-effective remedial action to lessen or overcome the adverse effects of climate change on pollutant linkage through soil erosion. Modelling also demonstrated that erosion rates took several years to stabilise during the establishment phase of revegetation until the maximum grass cover was stable at 83% ground cover. Establishment of perennial grasses for which winter die-back is minimal, as well as adoption of best practice for timing of site operations (tillage, addition of soil-forming materials, sowing, installation of irrigation systems, etc.) will maximise the rate of vegetation coverage over the bare soil. However, it is clear that choice of vegetation must, itself, consider likely effects of climate change on species suitability. As a remedial option for sites without organic matter rich soil materials, species should be chosen which are most suited to low spoil fertility and water holding capacity (Moffat and McNeill 1994). Modelling the impact of vegetation establishment for a specific site requires that the vegetation type is
consistent with the location’s climate, irrigation, soil type and fertility, pest control, and other management conditions.

![Fig.5 Bare spoil absolute and relative erosion rates for a contaminated site located in the Tamar Valley (SW, left) and for a similar site which would have been located in East Sussex (SE, right). Results are presented for the periods 1961 to 1990 (Baseline), 2011 to 2040 (2020s), 2041 to 2070 (2050s), 2071 to 2100 (2080s).](image)

![Fig.6 Metal mobilisation in the sediments before (SW Bare Spoil, left) and after vegetation establishment (SW Grass, right) for the high emissions scenario. Results are presented for the periods 1961 to 1990 (Baseline), 2011 to 2040 (2020s), 2041 to 2070 (2050s), 2071 to 2100 (2080s).](image)

**4. Technical adaptation and risk management strategies**

The current approach to risk assessment and management for brownfield sites is based upon the source – pathway – receptor model of pollutant linkages (CLR 11, 2004). The adaptation strategy defined
adapts the site-specific approach for contaminated land in addressing climate change. The key items are as follows:

- The impact of climate change should be based upon site specific situations.
- The adaptation strategy for each site will take as its starting point the current situation based upon CLR 11.
- The impact of climate change should be addressed through the conceptual model of pollutant linkages at each stage.
- The impact of climate change should then use the UKCIP scenarios and focus on the actual location of the site and its climate factors.

The adaptation strategy requires a detailed adaptation methodology.

The methodology for adaptation to climate change for brownfield sites is set in four stages, see boxes below. It is important that the methodology works sequentially through from Stage 1 to Stage 4, although some degree of iteration may be required.

**Stage 1 – risk assessment based on current situation: key requirements**

The following steps need to be completed at this stage:

- Carry out a risk assessment, use CLR 11, using specific models or guidance to determine risks to humans (e.g. CLEA models), plants, water and property (e.g. BRE Special Digest 1 (BRE and The Concrete Centre, 2005)).
- Develop a conceptual model of pollutant linkages as part of risk assessment, including determining all sources, pathways and receptors.
- Determine and report the risks of historic contamination on the site, including the conceptual model of pollutant linkages.

This stage is based upon the current approach to risk assessment; experienced and fully qualified practitioners will need to be involved at this stage.

**Stage 2 – risk assessment based on climate change**

The following steps need to be completed at this stage:

- Determine UKCIP climate change data, using all four scenarios for a particular location and considering the periods for 2020, 2050 and 2080 using the scenario data.
- Make a qualitative assessment of the impact on sources, pathways and receptors; and determine potential impacts on the pollutant linkages in the conceptual model.
- Redefine the conceptual model of pollutant linkages based upon the period 2020, 2050 and 2080. Redefine soil levels on the site based on the climate change risk factors from UKCIP and adjust site trigger levels as appropriate. Compare revised values with soil guideline values for human health, water, buildings and other receptors.
- Report the results and the revised conceptual model of pollutant linkages.

**Stage 3 – Risk management current position**

The current risk management needs to be based on a thorough risk assessment (stage1). The following steps need to be completed at this stage:

- Use a technology-based approach, either excavation and removal, containment or treatment for the source and pathways. For property, address the materials used to ensure receptors are resistant to the contamination.
Non-technical measures for managing sites may be used, or on-going monitoring or maintenance may be required.

Follow best practice in risk management and determine verification requirements for the remedial work.

Stage 4 – Risk management based on climate change

The starting point is risk management using the current approach presented in stage 3 and all other information gathered during stages 1 and 2. The following steps will then need to be considered at this stage:

- If stage 2 has demonstrated a potential increase in the risk, then reassess the risk management options in stage 3. If no greater risk is perceived, then no action is required.
- If the risk is determined as being greater, then undertake further assessment of the remediation options. Use modelling if possible of the additional risk from climate change over 2020, 2050 and 2080. Alternatively use qualitative judgement to address the requirements of remediation options.
- Any remediation technology that removes, destroys or permanently changes the contamination, without a time dependent factor, will remove the climate change risk. The use of such technology will not therefore be subject to the impact of climate change.
- Containment and some treatment technologies will need to be addressed as to the impact of climate change. Over time, changes to the materials used in cover systems (as shown in section 9.2), slurry walls and geomembranes from temperature and moisture changes are likely to be significant. Design changes to the technologies or a change of technology may be required. For example, excavation and removal may be required in place of the use of containment in some situations.

5. Stakeholder Perspectives and Strategies

Two stakeholder groups given prominence in government reports on adaptation to climate change are local authorities and the development industry. These two sets of organisations are crucial to the production and management of the built environment and to the take-up and implementation of climate change mitigation and adaptation measures. This is especially true in relation to strategies and measures that might be applied to the remediation of contaminated land. As such they were the focus of the survey work in this area.

When the responses of the ‘developers’ group (some 43 responses) towards climate change are examined it suggests that the potential impact of climate change on site remediation is considered not to be as substantive an issue as in the master plan/site layout; building design, construction and choice of materials phases of the building lifecycle (Figure 7). However, there were some group differences with residential developers placing more importance on remediation impacts than choice of materials or the construction process. Similarly most developers believed that subsidence, flooding and storms were more important than either higher temperatures or the increased risk of remediation schemes failing (Figure 8). Finally in relation to remediation options, developers suggested that there was still some concern over the issue of future climate change. They would therefore be more likely to either reject a particular option and use an alternative, or switch, if there were no additional costs. This suggests that developers are currently cost-driven in this respect.

To follow up the survey work, six interviews were also conducted with three practitioners and three developers. Generally, and unsurprisingly, the level of knowledge regarding the impact of climate change on remediation was greater amongst the first group than the latter. As one consultant put it:
“My own personal view is that there are still a lot of question marks about the use of cover systems and the retention of contaminated materials on site and I suspect that in a number of cases not adequate consideration is given to the real cost of ensuring long term durability of those systems”.

Several developers were aware of potential future problems, but tended to treat the issue as connected to wider concerns over flooding. As one developer suggested:

“No, we would certainly be concerned because the impact of climate change would, if it’s going to have an impact on the methodology for carrying out remediation, it is probably going to have a more direct impact on the development itself anyway. So you know so we
would be planning for whatever the impact of it was: it has a secondary impact on the methodology for remediating the site - well therefore you know the methodology’s got to be changed as well.”

As the same developer continued:

“...for instance you know most of the issues to do with climate change are obviously to do with flood risk and flood risk assessments, so therefore our site that you know you’d be looking at all of the problems you have and then it would be an holistic approach to the design solution.”

The survey of local authorities revealed that just over half of local authorities have a dedicated climate change officer and a similar proportion consider themselves adequately informed of climate change impacts. Significantly fewer (42%) are confident about their knowledge of climate change adaptation practices. There is an encouraging sign that local politicians are becoming more aware of climate change issues with 65% of respondents acknowledging that local authority members were giving it more priority, albeit from a low and variable base-level. Despite this increase in interest, only 36% of the respondents’ authorities had signed the Nottingham Declaration on Climate Change and 23% had an adopted climate change strategy. In terms of the provision of information on climate change, that originating from government agencies (including UKCIP) and regional networks are perceived as most reliable and widely used. This has implications for the effective dissemination of information on contaminated land remediation processes and appropriate adaptation measures.

As Figure 9 illustrates, land remediation is seen as a relatively important issue in relation to climate change impacts, even though it is given a lower priority than some, more obvious, issues such as flooding and flood plain development. Notwithstanding this, taking that concern through into action has been less notable, with only about 10% of local authorities undertaking an appraisal of the robustness of contaminated land remediation measures and just 15% adopting measures to improve the robustness of past remediation works. In a more positive light, about a third of our respondents said that they were considering introducing measures to improve the robustness of past remediation. In a similar vein, many local authorities are considering changing specific mechanisms to assist in climate change adaptation and these are illustrated in Figure 10. They clearly show the potential role of the planning system in making improvements to the land remediation process through the imposition of more stringent conditions on planning permissions, the use of legal agreements with developers or strengthening the requirements in environmental assessment. This opportunity for local authorities to (re)shape land remediation processes is in keeping with the government’s vision of integrated ‘spatial’ planning.

The review of policy and practice within the development sector and local authorities suggests that there is a growing awareness of the generalities and specific implications of climate change for land remediation policy and procedure. However, that awareness and action has risen from a very low base and many developers and local authorities are still largely ignorant of the issues and inactive on developing strategies and mitigation/adaptation measures to deal with climate change. Although land remediation is given some priority in the list of relevant issues, most developers and local authorities are currently operating according to a ‘business as usual’ scenario. Overall the survey findings support the view that there is still much to be done by planning and property professionals to address the impact of climate change on brownfield remediation strategies, procedures and techniques.

The body is the primary message of the paper and should break down into a number of Sections and Subsections as appropriate.
Fig. 9 Priority given to climate change impacts.

Fig. 10 Number of local authorities who have considered changing mechanisms in relation to contaminated land remediation.
6. Conclusion

From the evidence available in the literature and collected as part of the study presented here it is clear that certain climate change scenarios are expected to have significant impacts on current and future contaminated land and remediation systems. Examples include severe physical damage to soil cover systems and stabilised/solidified soils and extensive soil water erosion and associated contaminant transport. These impacts will have major effects on the future management of contaminated and remediated sites and are expected to influence the way risk is managed on those sites and the design of future remediation strategies. A conceptual adaptation strategy has been developed highlighting four stages to be considered when addressing the impact of climate change in the current risk-based contaminated land management regulatory framework in the UK. The results of the surveys carried out on a range of stakeholders, namely the development industry and local authorities, clearly demonstrate that these stakeholders are still largely unaware of the issues surrounding climate change and its impact on contaminated land management and redevelopment and are hence not yet considering potential impacts of climate change and related evidence in their decision-making process and this has inherent dangers associated with it.

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