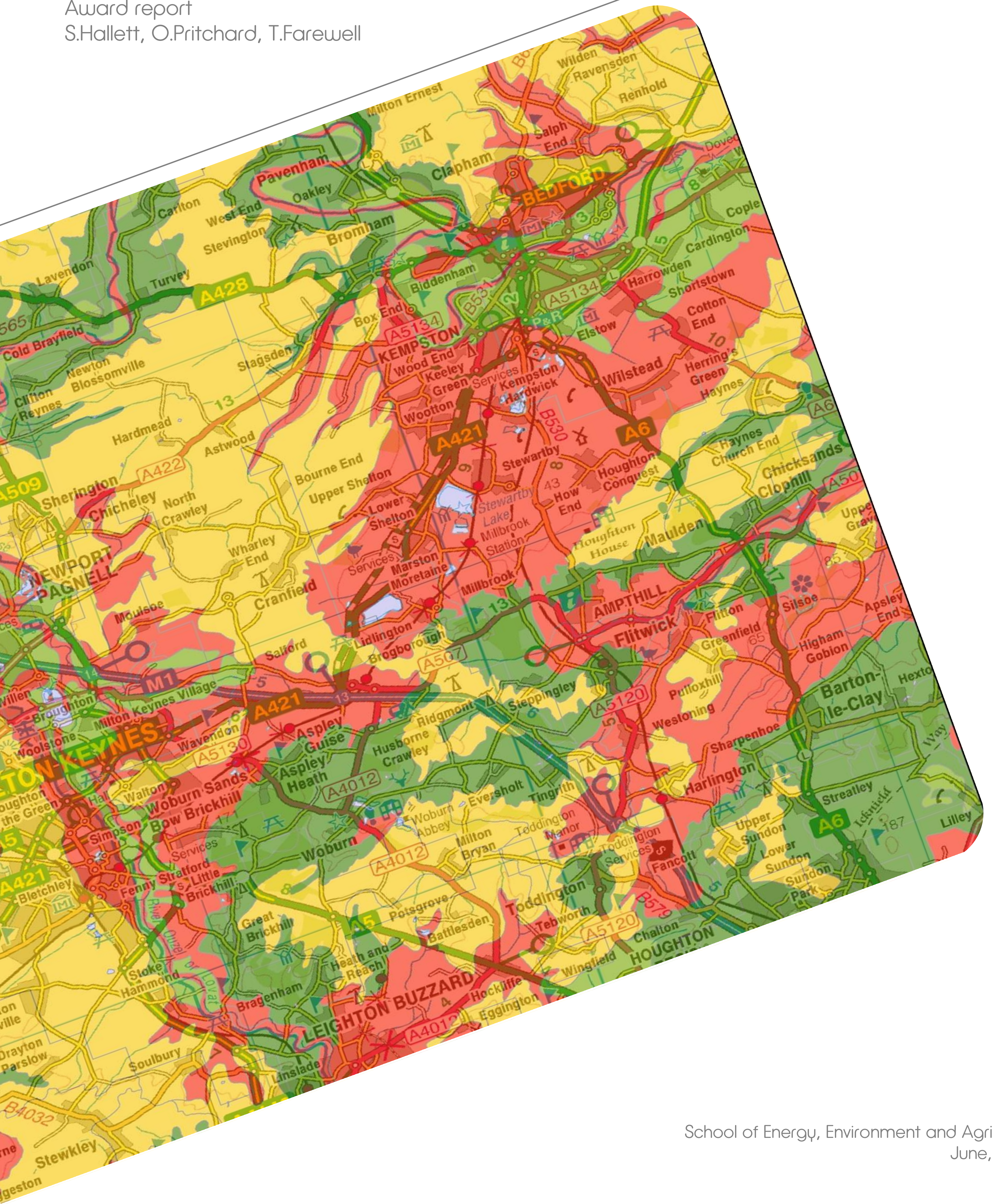
# Forward-looking climatic scenarios of UK clay-related subsidence risk

EPSRC Impact Acceleration Account (IAA) – Award report

S.Hallett, O.Pritchard, T.Farewell



School of Energy, Environment and Agrifood
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## Executive summary

An award drawing upon the Cranfield University EPSRC-funded Impact Acceleration Account (IAA) was awarded to staff in the University's School of Energy, Environment and Agrifood (SEEA) (Hallett, Farewell, Pritchard), to undertake processing of UKCP09 climate projections for the United Kingdom (UK) in support of assessments of future geohazards and societal impact. This report identifies the technical outcomes from this work and presents the resultant climate change cartography and related data.

Spatially coherent national data ensembles are generated for the UKCP09 'Baseline' period, for '2030' and '2050'. Maps of Potential Soil Moisture Deficit (PSMD) are produced for each to exemplify its application. The findings suggest that the extremes in PSMD observed at the current time in the UK are likely to become the norm by 2030 and 2050.

The data produced has a range of potential applications, from geohazard assessments to the built environment and infrastructure, to agri-informatic modelling of agricultural crops, as well as modelling for 'future-proofing' of buildings against predicted climate change by example.

It is anticipated that the datasets presented from this IAA will be of benefit to a range of end-user stakeholders. One example is in the insurance, reinsurance and water utility sectors, where modelling of future impacts of climate change are conducted.

Recent research has suggested this data will likely prove of use for County Councils and municipal authorities, for example in the allocation of targeted road maintenance funding, particularly on local-authority owned highways.

Rail network operators, having faced a number of embankment failures, and track undulations as a result of shrink/swell activity are also likely to benefit from this research. The soil moisture deficit scenarios produced could help such organisations better manage geotechnical assets and vegetation management of susceptible slopes and soils.

Cranfield's School of Energy, Environment and Agrifood (SEEA) manage and operate the Natural Perils Directory (NPD). The NPD is a widely used geohazard thematic dataset portraying vulnerabilities arising from soil-climate responses to long-term climate change. NPD will incorporate directly the datasets produced and described here.

## Glossary

CSAFI – Cranfield Soil and Agrifood Institute
CSV – Comma Separated Value data files
Defra – Department of environment, food and rural affairs
EPSRC – Engineering and Physical Sciences Research Council
GIS – Geographical Information System
IPCC – Intergovernmental Panel on Climate Change
ISO – International Standards Organisation
NPD – Natural Perils Directory
PET – Potential evapotranspiration
SMD – Soil Moisture Deficit
UFS – Underground Foundation Stability
UK – United Kingdom
UKCP – United Kingdom Climate Projections (UKCP09 from 2009)

*Keywords*
Soils, Climate Change, Geohazards, UKCP09

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Report cover shows a selective geospatial output from the 2050 UKCP09 climate projections, processed in the course of the IAA here reported.

The research herein presented is funded through the Cranfield University EPSRC-funded Impact Acceleration Account (EP/K503927/1) (http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/K503927/1).

## 1. Introduction

Clay-related subsidence costs the UK economy some £300-400 million per annum and accounts for over 70% of valid insurance claims; making it the most damaging soil-related geohazard in the UK (Plante, 1998; Pugh, 2002). Geohazards are environmental phenomena capable of causing harm to both life and the built environment (Forster and Culshaw, 2004). Cranfield University are the custodians of the unique national soils map and database for England and Wales. Held in the national Land Information System 'LandIS', (Keay *et al*., 2009), this data has been used to develop property geohazard assessments for soil-related impacts including subsidence and ground movement. These models have a climatic component, drawing on assessment of 'Potential Soil Moisture Deficit' (PSMD) calculations. Undertaking future impacts assessments for these geohazard assessments has necessitated the comprehensive processing of future climatic projection data for the UK.

A range of potential user applications of these data exist. For example, to date, no national soil-related geohazard dataset has existed that incorporates projected changes in climate from the United Kingdom Climate Projections 09 (UKCP09) future climate scenario projections. However, advancements in the understanding of potential future geohazard distribution offer the potential to bring highly visible and substantial benefit to a range of organisations and stakeholders. These include organisations such as finance and insurance/reinsurance, infrastructure operators, local authorities, house buyers/owners, planners, and land and property developers.

The soils of England and Wales are highly variable, with over 700 series recorded in LandIS. These soils are represented in the National Soil Map (NATMAP) shown in Figure 1. Soil types may contain quantities of clay minerals prone to seasonal shrinking and swelling in response to soil moisture flux. The magnitude and frequency of clay-related subsidence is predominantly controlled by the soil's moisture content, which in turn is controlled by the climate, and changes in the climate in future decades. UKCP09 projections reveal that that the UK is likely to experience hotter, drier summers and warmer, wetter winters in future. These climate change projections mean that the spatial and temporal occurrence of clay-related subsidence is likely to change in the future. There is thus the potential for areas currently lacking adaptation measures to be at higher risk in future if appropriate design action is not taken (Corti *et al*. 2011).

It is therefore important to understand if the magnitude and frequency, as well as the uncertainty, of such phenomenon are likely to become more prevalent for a range of future climatic scenarios. The ability to anticipate future trends in geohazard potential have the potential to benefit many organisations and policy-makers, including; an insurers resource planning (Pugh, 2002) as well as the asset maintenance of UK infrastructure (Pritchard *et al*. 2014a; Pritchard *et al*. 2014b).

## 2. IAA and Preceding research

The research presented in this report is funded by Cranfield University's EPSRC (Engineering and Physical Sciences Research Council) Impact Acceleration Account

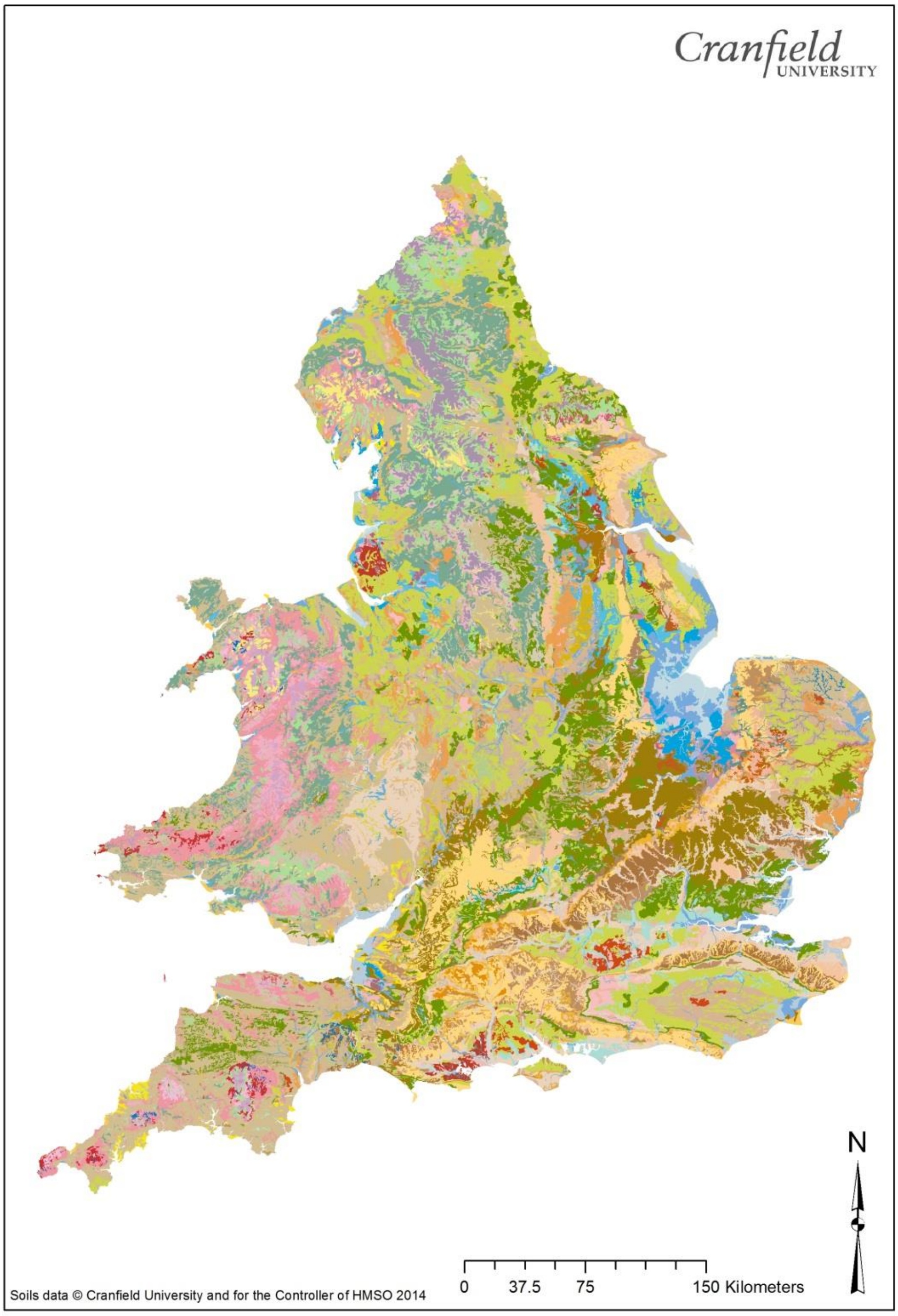
(IAA). A key aim of the fund is to enhance the exploitation of the outputs of EPSRC-funded research. Cranfield University has elected to use part of this fund to support the early stages of commercialisation of methods and technologies, to encourage their uptake and to make the ideas more attractive for commercial investment. The main grants supporting the foundation development of this work to date are:

1. EPSRC-funded project 'CREW' – or 'Community Resilience to Extreme Weather' *(with multiple projects within programme)*
Cranfield staff Hallett was project coordinator
http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/F036795/1
http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/F036442/1
http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/F037716/1
http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/F035861/1
http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/F037422/1
http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/F036817/1
2. EPSRC-funded project 'ITRC' – or 'UK Infrastructure Transitions Research Consortium (ITRC): PROGRAMME GRANT: Long term dynamics of interdependent infrastructure systems', PI Professor J.Hall, ECI Oxford University.
Cranfield staff Hallett and Farewell are working within 'Work Stream 2: The future risks of infrastructure failure'. PhD student Pritchard's research on soil geohazards.
http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/I01344X/2
3. Defra funded project 'LandIS Reference Site', Contract SP1621
Hallett and Farewell are developing a soil-related national data infrastructure
http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=17331

## 3. Scope

This report documents the data processing and subsequent GIS-based (Geographic Information System) framework used for incorporating climatic projections within a range of applications, such as Cranfield's existing Natural Perils Directory (NPD) thematic soil geohazard model. A version of the UKCP09 spatial weather generator has been used to provide the project a set of forward-looking scenarios (Baseline, 2030 and 2050) of potential soil moisture deficit.

Subsequent results of the climatic modelling are presented and finally the discussion focuses upon the potential uses and applications resulting from this study. Avenues of further work are also considered and outlined.



Soils data © Cranfield University and for the Controller of HMSO 2014

Figure 1: The National Soil Map (NATMAP) of England and Wales (1:250,000 scale)

## 4. Potential Soil Moisture Deficit (PSMD)

Potential Soil Moisture Deficit (PSMD) is a climatological parameter revealing potential fluxes in the soil hydrology through a season. PSMD represents the relationship between incoming rainfall and outgoing evaporation and plant transpiration (evapotranspiration). PSMD can be computed as a cumulative index of ‘water stress’ in the soil. PSMD values are used in a range of applications from modelling and predicting agricultural productivity, to soil-related geohazard assessments.

## 5. Soil-related Geohazard modelling and PSMD

The Cranfield Soil and Agrifood Institutes’ (CSAFI) Natural Perils Directory™ (NPD) Geohazard thematic dataset (see http://www.landis.org.uk/npd) comprises a detailed and comprehensive assessment of the environmental vulnerabilities to building structures posed by soil-related subsidence, flood extent and wind exposure. The dataset is expressed in GIS (Geographical Information System) data format on a vector polygon basis across England and Wales, being in widespread use across a number of sectors. This unique data represents the most detailed available information for any kind of soil-related vulnerability assessment in the environmental sector. The subsidence peril includes a range of soil-related models together with associated climatic scenarios.

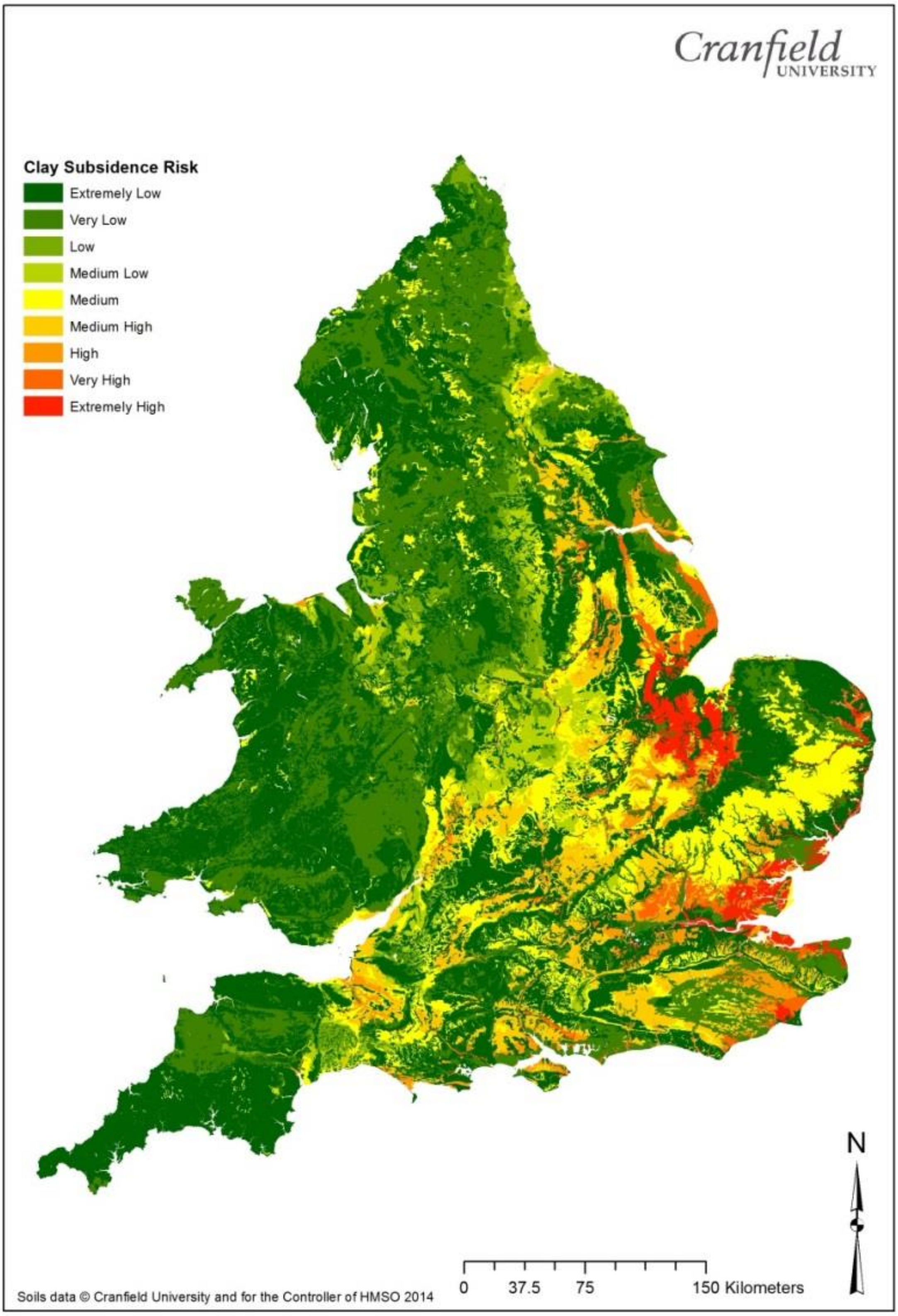
The Underground Foundation Stability (UFS) model, forming the core of the NPD, uses data derived from the Soil Survey of England and Wales (SSEW) together with expert knowledge, climatic and laboratory data. Laboratory data includes the representative testing of soil types for their shrink-swell characteristics at depths of 1.0m below ground level. However, it is the climate and relative moisture fluctuations within the soil that govern whether clay-susceptible soils will ultimately shrink or swell.

Before the adoption of the newly modelled PSMD data, the UFS model has used mean maximum PSMD (Potential Soil Moisture Deficit) calculated from the baseline (1961-75) empirical met office dataset to represent the climatic input. The mean maximum PSMD value is considered as representing the then current *average* conditions. Equation 1 below shows how PSMD is calculated within the NPD model and for the probabilistic projections discussed in this report:

$$PSMD = \sum (rain - [potential]\ evapotransipration)$$

**Equation 1: Calculation of Potential Soil Moisture Deficit (PSMD)**

Extremes in PSMD are considered in the current NPD model through the addition of standard deviations around the mean PSMD value, drawn from the temporal run of observed data. Thus, for a ‘1 in 45 year event’ the addition of 2.0 Standard Deviations to the mean is applied. Weaknesses of this approach include both the now historical time series of data, and the fact that no effective, probabilistic element is employed in the modelling, allowing for management of uncertainty. Before the work reported here, no models existed which were able to apply national UKCP09 climate projections to provide estimations of likely clay-related subsidence potential across England and Wales. Therefore, the research presented is entirely novel and innovative in its approach.



Soils data © Cranfield University and for the Controller of HMSO 2014

**Figure 2: Natural Perils Directory Clay subsidence risk model, based upon annual mean potential soil moisture deficit (1961-75 baseline).**

## 5.1 Soil shrink-swell (SSWELL)

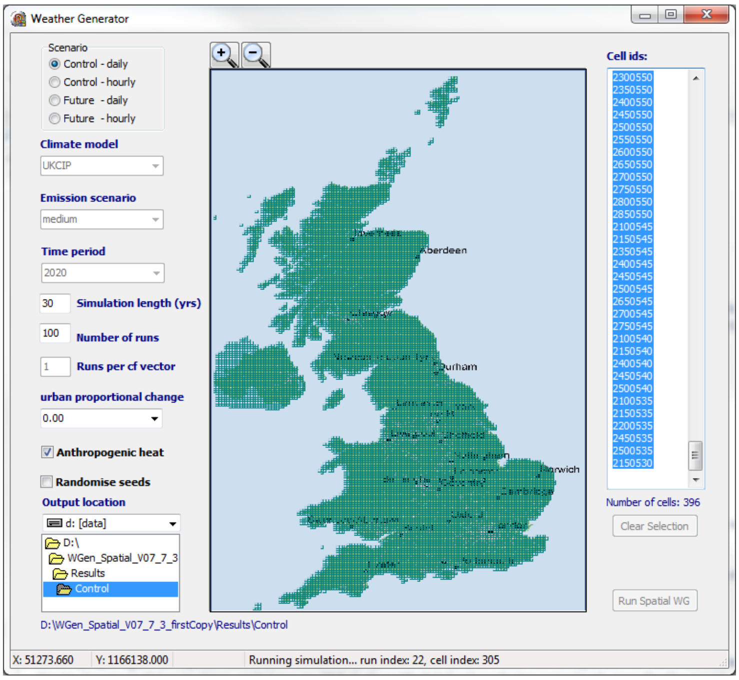
The ability of a soil to shrink or swell is predominantly characterised by its relative mineralogy. Specific clay minerals (i.e. Smectite and Montmorillonite) have to be present within the soil, often in abundance, for it to have the ability to shrink-swell. It is the subsequent response of these clay minerals to the external climatic, seasonal moisture fluxes that ultimately promotes the physical action of shrinkage and swelling.

Physical testing was previously undertaken on samples obtained from the Soil Survey of England and Wales (SSEW), providing a measurement of volumetric shrinkage for each of the soil series represented on the 1:250,000 scale soil map of England and Wales. Volumetric shrinkage testing at suctions of between 0.05 and 15 Bar, representative of field capacity and wilting point, respectively, were undertaken providing an indication of the soils shrinkage range. This assessment is representative of soils at 1m depth, chosen as it is the depth of many building foundations and buried infrastructure within the UK. Six classes of shrink-swell (SSWELL) are recognised in the UK. These range from *very low* (<3% volumetric shrinkage) to *very high* (>15% volumetric shrinkage). These soil measurements of shrink-swell constitute the most comprehensive dataset of shrinkage potential that has ever been assembled for the study of subsidence in the UK.

# 6. Methodology

## 6.1 UKCP09 Weather Generator

The UKCP web portal provides tools that allow users to extract gridded data for selected areas of interest drawing on the various downscaled global climate models, for example ‘2050 Business as Usual’. However, the interactive ‘cell-by-cell’ nature of these tools would frustrate attempts to extract national and regional sets of data from these scenarios. Therefore, this project employed a modified version of the UKCP09 spatial weather generator, able to provide spatially coherent daily values for a range of weather variables at a $5km^2$ gridded resolution. This tool was provided by Newcastle University (V. Glenis, *Pers. Comm*.). The tool provides a simple ‘Graphical User Interface’ (GUI) (Figure 3) for selecting result sets for selections of gridded 5kmx5km cells. UKCP09, released in 2009, provides the UK with its first probabilistic assessment of climate change for the 21st century, replacing earlier, simpler modelling approaches. Moreover, it allows the user to understand the spread of possible climatic changes, and therefore interpret inherent uncertainty in projection outputs, and importantly provides results not dissimilar to specific climate models (Burton *et al*. 2010).


Weather Generator

Scenario
● Control - daily
○ Control - hourly
○ Future - daily
○ Future - hourly

Climate model: UKCIP

Emission scenario: medium

Time period: 2020

Simulation length (yrs): 30

Number of runs: 100

Runs per cf vector: 1

urban proportional change: 0.00

☑ Anthropogenic heat

☐ Randomise seeds

Output location: d: [data]
D:\
WGen_Spatial_V07_7_3
Results
Control

D:\WGen_Spatial_V07_7_3_firstCopy\Results\Control

Cell ids:
2300550
2350550
2400550
2450550
2500550
2550550
2600550
2650550
2700550
2750550
2800550
2850550
2100545
2150545
2350545
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2650545
2700545
2750545
2100540
2150540
2400540
2450540
2500540
2100535
2150535
2200535
2450535
2500535
2150530

Number of cells: 396

X: 51273.660 Y: 1166138.000 Running simulation... run index: 22, cell index: 305

Figure 3: The Newcastle University UKCP09 spatial weather generator graphical user interface

UKCP09 provides probabilistic estimates of key meteorological phenomena (Table 1). However, unlike its predecessors (UKCIP98 and UKCIP02) UKCP09 does not provide projections of (likely) soil moisture, representing the balance between rainfall and evapotranspiration. The spatial weather generator does provide daily values of rainfall and potential evapotranspiration however, which using Equation 1 can be used to calculate estimates of soil moisture deficit and/or surplus.

| Variable | Field | Unit |
|---|---|---|
| Year (nominal) | Year | Year (3000..) |
| Month | Month | Month |
| Day | Day | Day |
| Hour | Hour | Hour |
| Minute | Minute | Minute |
| Daily Precipitation Total | precip_dtotal | mm/day |
| Daily Minimum Temperature | temp_dmin | degC |
| Daily Maximum Temperature | temp_dmax | degC |
| Daily mean Vapour Pressure | vapourpressure_dmean | hPa |
| Daily mean Relative Humidity | relhum_dmean | % |
| Daily mean Wind Speed | wind | m/s |
| Daily Total Sunshine | sunshine_dtotal | Hours |
| Diffuse daily Radiation | diffradt_dtotal | $kWh/m^2$ |
| Direct daily Radiation | dirradt_dtotal | $kWh/m^2$ |
| Daily mean Potential Evapotranspiration | pet_dmean | mm/day |

Table 1: Meteorological parameters provided by the UKCP09 spatial weather generator

## 6.2 Climate data processing

The UKCP09 spatial weather generator was used to produce a set of daily values (Table 1) of climate data over a 30 year stationary sequence for ‘baseline’ (1961-1990), ‘2030’ (2020-2059) and ‘2050’ (2040-2069) scenarios (Figure 4). The following section discusses the methodology used to process the resultant data into the format applicable for subsequent geohazard modelling.

All of the future projections were run at a medium emissions scenario, equivalent to the IPCC’s (Intergovernmental Panel on Climate Change) ‘SRES A1B’ scenario. Each scenario was also run with urban land use unapplied (0.0), the same as UKCP09.

**Figure 4: The UKCP09 climatic probabilistic scenarios considered within this research (*modified from: http://ukclimateprojections.metoffice.gov.uk*)**

### 6.2.1 Baseline

UKCP09 baseline (1961-1990) data were extracted to provide both a baseline for the future projection datasets, and also a means to tie the data to previous empirical observations used in earlier versions of the NPD assessments. Baseline data can aid the understanding as to what extent the weather generator can model the existing climate (Eames *et al.* 2012). Due to the lower uncertainty arising from the baseline data, the 30 year series were run 100 times each based on a different randomly sampled vector of change factors, providing a probabilistic analysis. In effect the resultant file has 30 x 100 = 3,000 'January 1st' values and so on.

### 6.2.2 Future projections

The weather generator was then also run for the future scenarios of 2030 and 2050. However, unlike the baseline these were run 1,000 times based on a differently randomly sampled vector of change factors, providing the probabilistic analysis. Thus these resultant files have 30 x 1000 = 30,000 'January 1st' values and so on. The spread of values allows a probabilistic spread of the 'ensemble' of climatic determinants assessed.

## 6.3 Data processing

The data produced by the weather generator provided *daily* outputs of variables detailed in Table 1. Appendix 1 shows examples of the data formats provided and created in this process. For the purposes of this study, only rainfall and potential evapotranspiration were required. Although the data output was daily, due to the relatively chronic 'long-term' nature of soil moisture accumulation and loss, a temporal resolution of monthly and annual data was deemed suitable. The future scenarios which were representative of 1,000 daily records over a 30 year series provided 30,000 realisations of daily climate. Therefore, each of the 10,398 5km$^2$ cells representing the land mass of England, Wales and Scotland represented over 10,000,000 rows of data in its raw form for the Control, 2030 and 2050 data runs (Figure 5).

The amount of data produced from the UKCP09 Weather generator was substantial, approaching some 50 Terabytes in its entirety. Custom tools were required to process and manipulate these raw data in order to produce the summary data products required by NPD. Accordingly, a series of programmes were prepared in order to automate the

Figure 5: The UKCP09 data cells available for modelling

calculation of SMD values.

The sequence of processing the datasets is outlined in Figure 6. Three key scripts were used, thus:

***Perl script: 'IAA.pl'***

This Perl script was used to process the raw text 'txt' files output by the weather generator, creating the 'Comma Separated Value' CSV files for each determinant (e.g. Accumulated SMD).

Thus source file '5200125_cntr.txt' is processed to create files

*5200125_cntr_pet_output.csv*
*5200125_cntr_accsms_output.csv*
*5200125_cntr_accsmd_output.csv*
*5200125_cntr_sms_output.csv*
*5200125_cntr_smd_output.csv*
*5200125_cntr_rain_output.csv*

***Perl script: 'IAA_Statistics.pl'***

This Perl script takes these cell by cell outputs and creates a single statistics file

Thus files are created:

*5200125_cntr_accsmd_output.csv*
*5200150_cntr_accsmd_output.csv etc...*

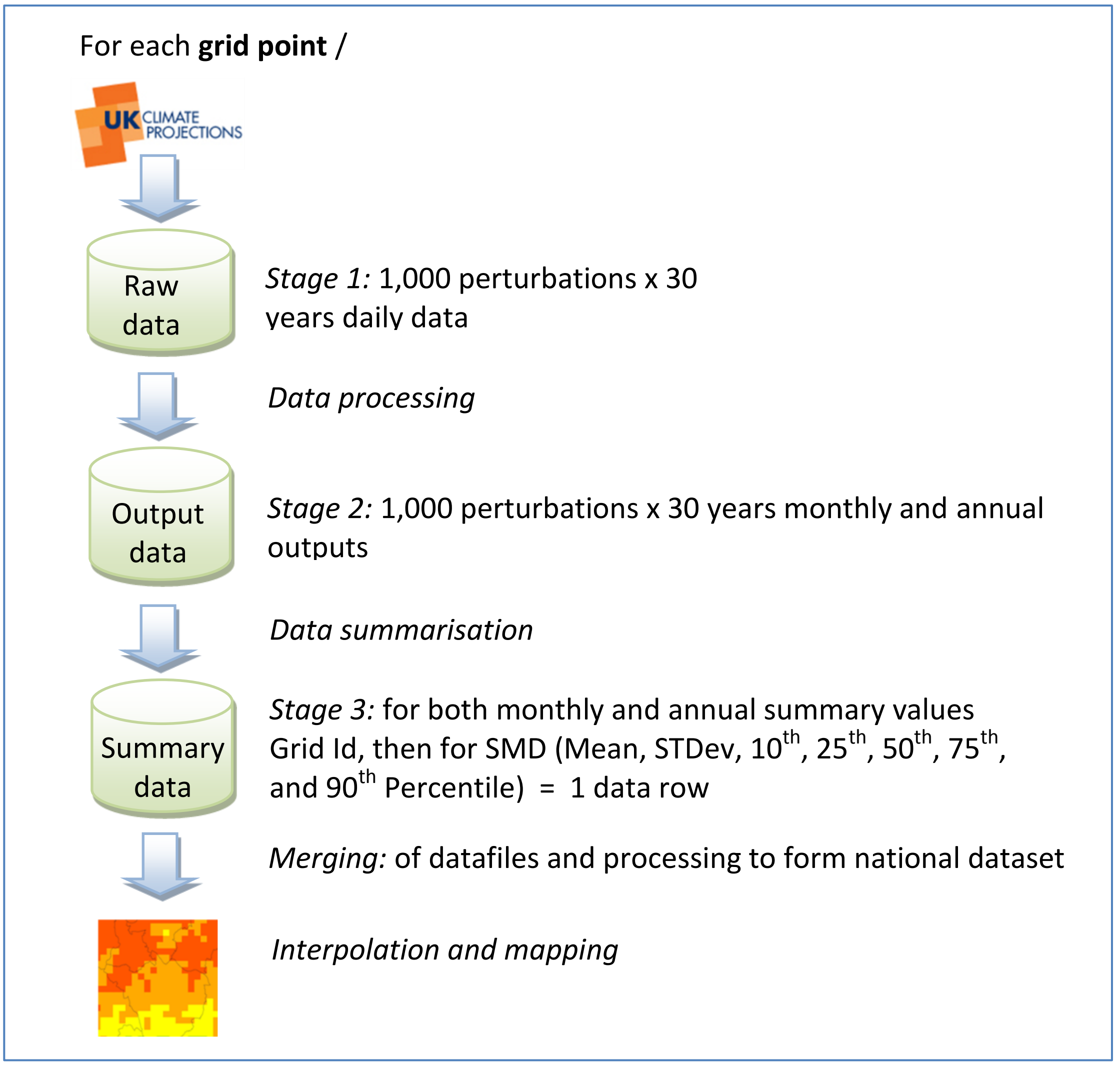
**Batch file: 'BatchRun_IAA_Statistics.bat'**

This is a MS Windows 'Batch' file that can be used to help automate the process of running the Perl scripts above.

**Batch file: 'merge_statistics.bat'**

The number of grids are too numerous to run in one go, so country was split into a series of sub-regional runs. Once all the separate run statistic files are created, then as long as source data files are in the prescribed folder structure below, the batch file can be used to merge the results into one file suitable for subsequent use in GIS etc.

```
|
\ Results_Run1  (each results folder contains the set of grid cells exported
                  in form: 'Run6_Export_Output.csv')
          |
          \ Control  (each end folder contains the source txt files, all processed csv
                  file and final statistics file)
          \ 2030  (statistics file name follows form: 'Run6_Statistics_accsmd_2050.csv')
          \ 2050
\ Results_Run2
          | etc...
```



*Stage 1:* 1,000 perturbations x 30 years daily data

*Data processing*

*Stage 2:* 1,000 perturbations x 30 years monthly and annual outputs

*Data summarisation*

*Stage 3:* for both monthly and annual summary values Grid Id, then for SMD (Mean, STDev, 10th, 25th, 50th, 75th, and 90th Percentile) = 1 data row

*Merging:* of datafiles and processing to form national dataset

*Interpolation and mapping*

Figure 6: The data processing workflow used for manipulating the UKCP09 data files

## 6.4 Statistics

At the point of processing the raw data tables, a range of statistics were further computed for the processed monthly and annual rainfall and PET data. These included producing the mean, standard deviation and a range of percentiles (10th, 25th, 50th, 75th and 90th). To provide similarity to the UKCP09 outputs, the 10th, 50th and 90th percentiles were then selected to best represent the range of uncertainties inherent in the data. The '90th Percentile' is typically taken as being '*Unlikely to be more than*', and the '10th Percentile' being '*Unlikely to be less than*' – these accompanying the '50th Percentile' representing the central tendency in the data.

This standardised approach in clarifying uncertainty provides potential users, who are likely to be familiar with the UK climate projections, to use these models alongside other climate modelling and adaptation schemes.

## 7. Forward-looking projections of potential soil moisture deficit

The following section presents both the baseline and forward-looking (2030 and 2050) potential soil moisture deficit (PSMD) scenario maps (for each of the percentiles calculated).These maps have been constructed through the steps undertaken in Section 5. Monthly and annual accumulated values are presented.

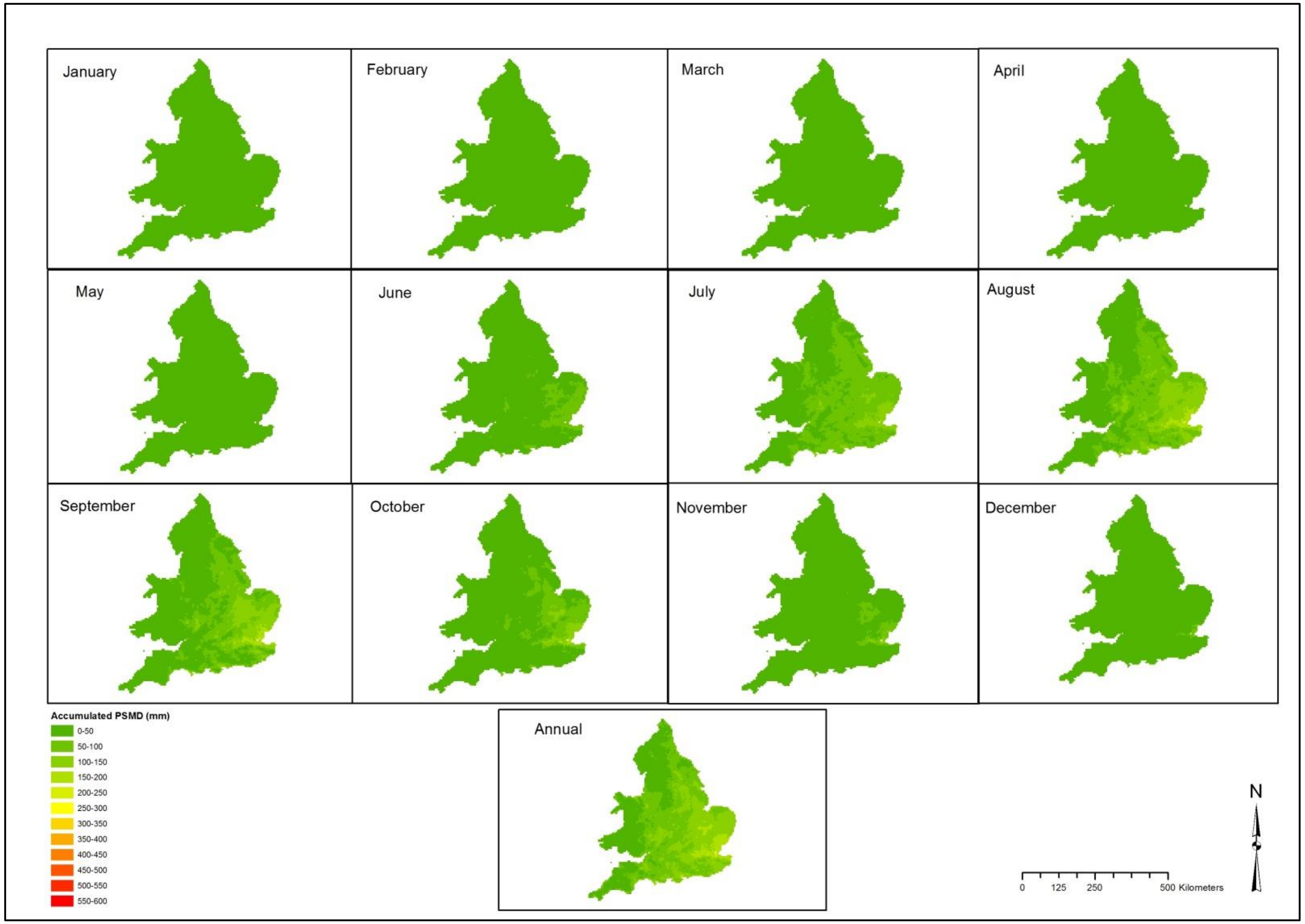


Figure 7: An 'unlikely to be less than' (10th percentile) monthly and annual UKCP09 baseline (1961-1990) Accumulated Potential Soil Moisture Deficit (PSMD)

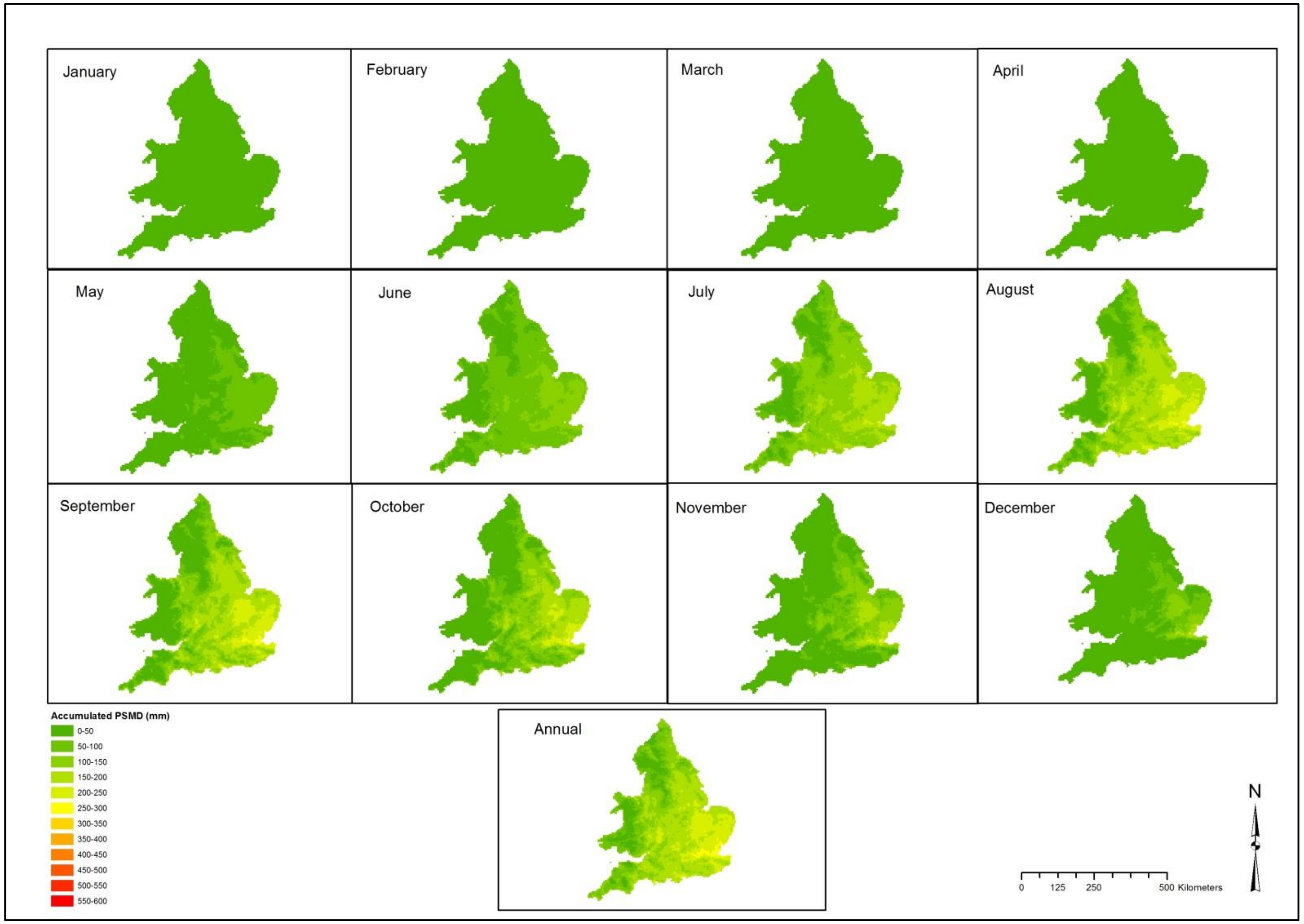


Figure 8: A ‘central estimate’ (50th percentile) monthly and annual UKCP09 baseline (1961-1990) Accumulated Potential Soil Moisture Deficit (PSMD)

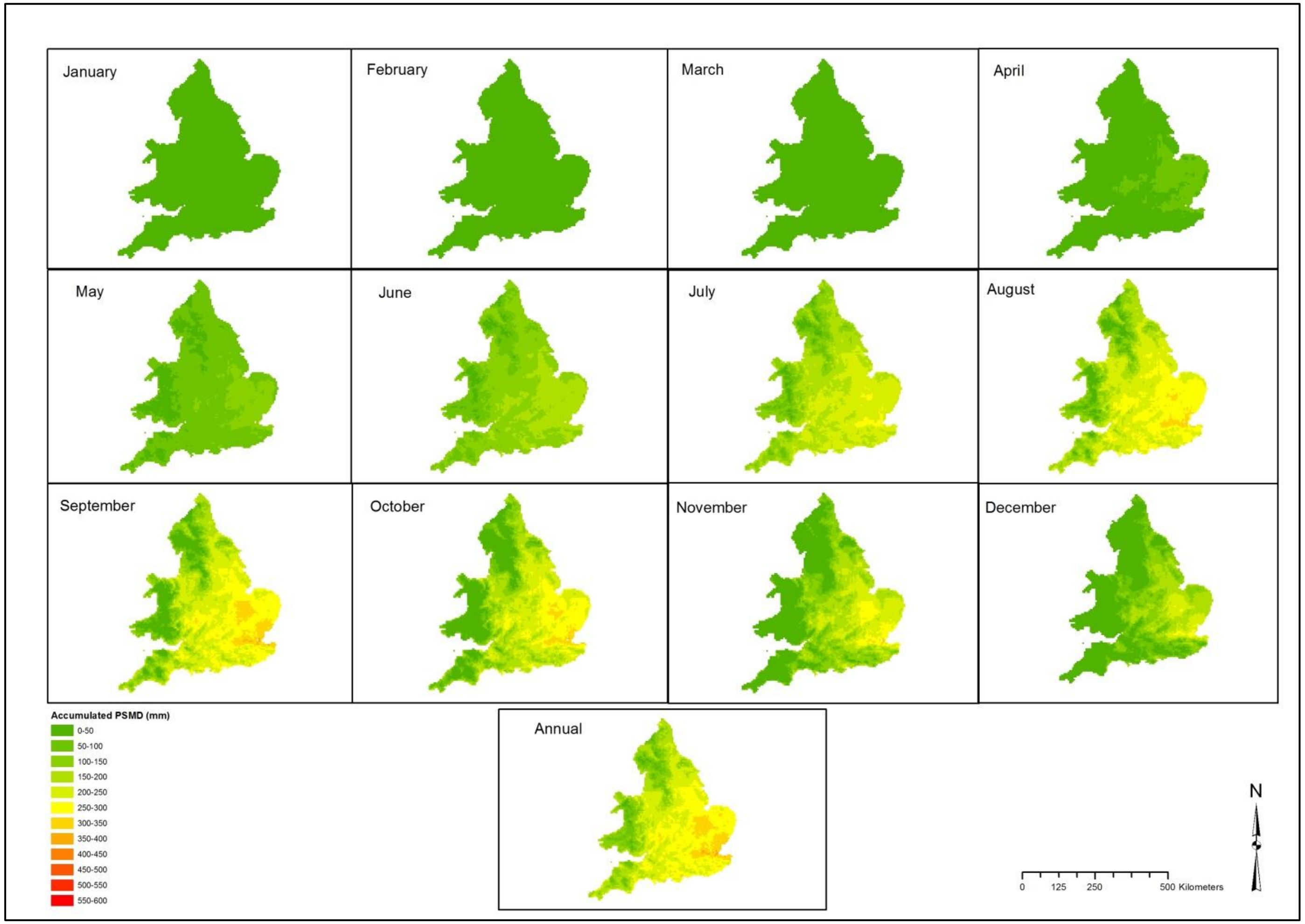


Figure 9: An ‘unlikely to be more than’ (90th percentile) monthly and annual UKCP09 baseline (1961-1990) Accumulated Potential Soil Moisture Deficit (PSMD)

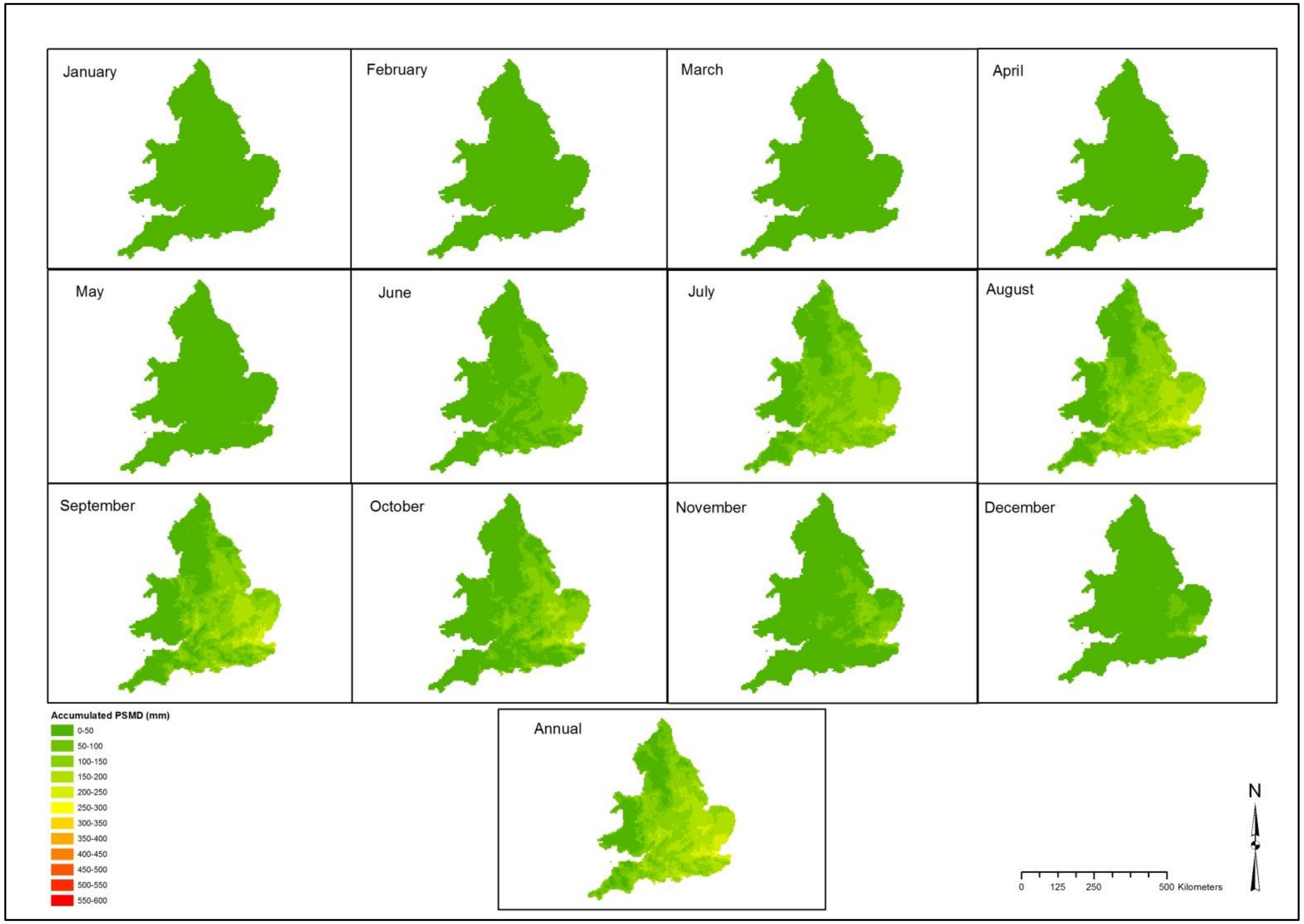


Figure 10: An 'unlikely to be less than' (10th percentile) monthly and annual UKCP09 2030 (2020-2049) Accumulated Potential Soil Moisture Deficit (PSMD)

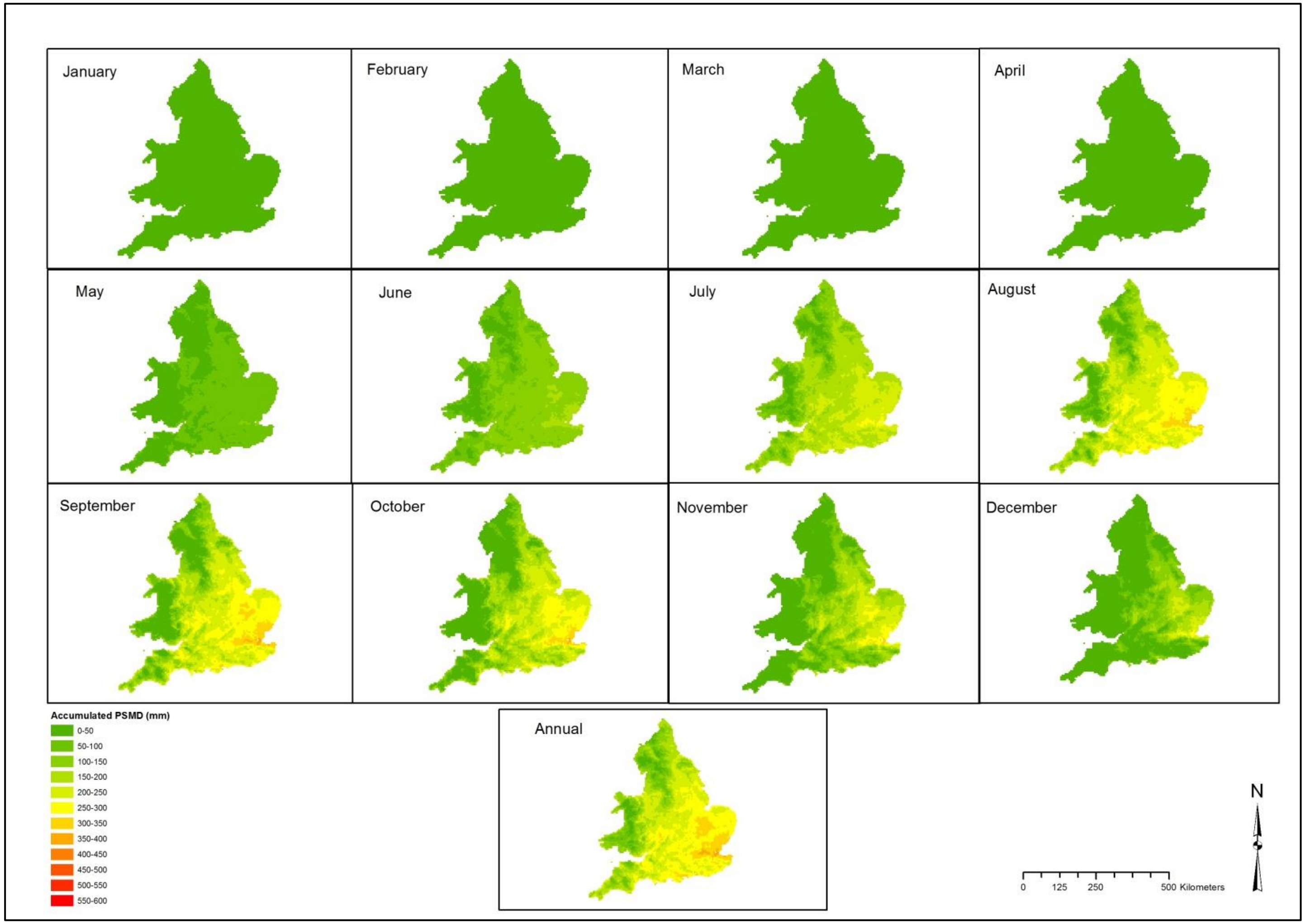


Figure 11: A 'central estimate' (50th percentile) monthly and annual UKCP09 2030 (2020-2049) Accumulated Potential Soil Moisture Deficit (PSMD)

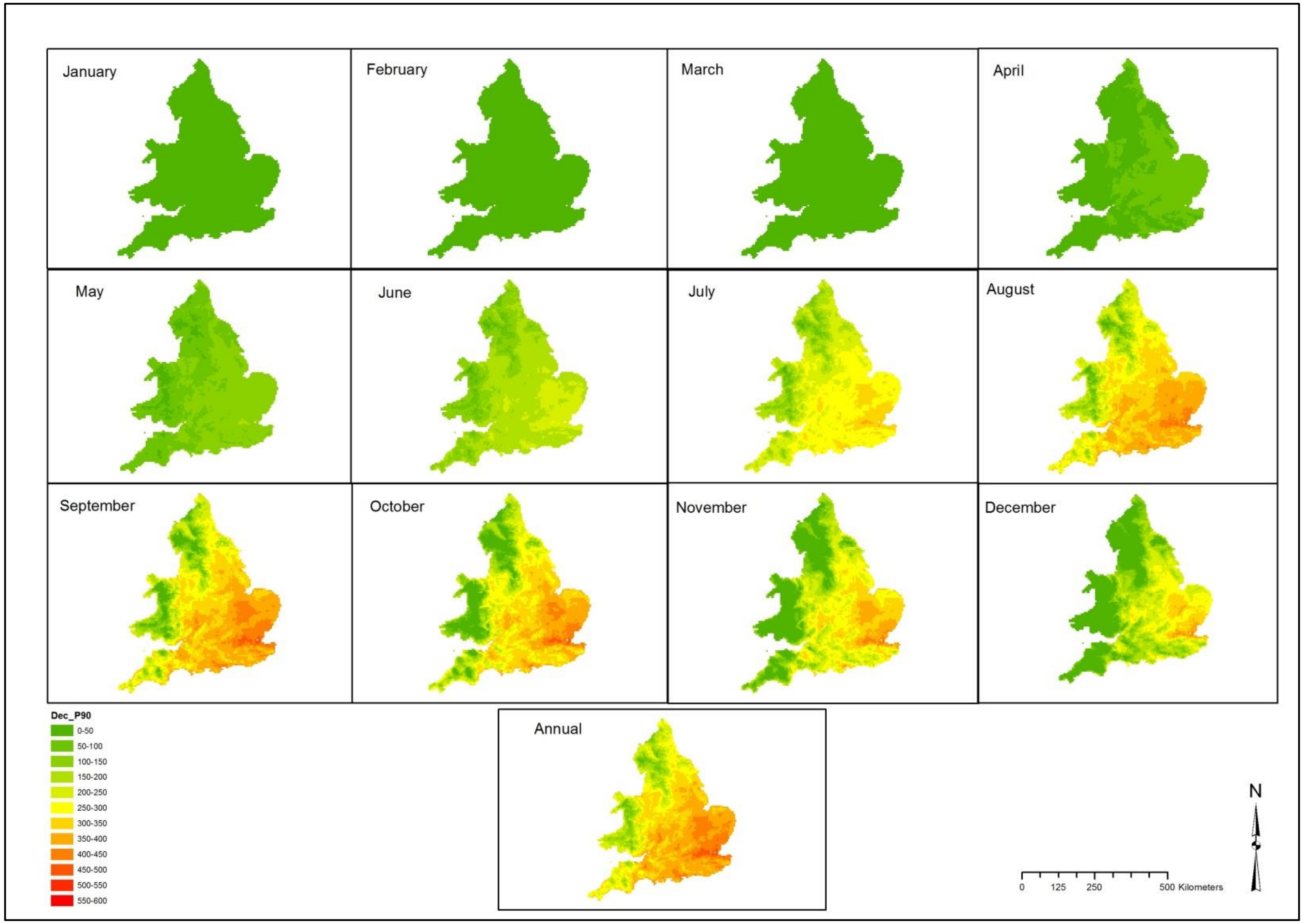


Figure 12: An 'unlikely to be more than' (90th percentile) monthly and annual UKCP09 2030 (2020-2049) Accumulated Potential Soil Moisture Deficit (PSMD)

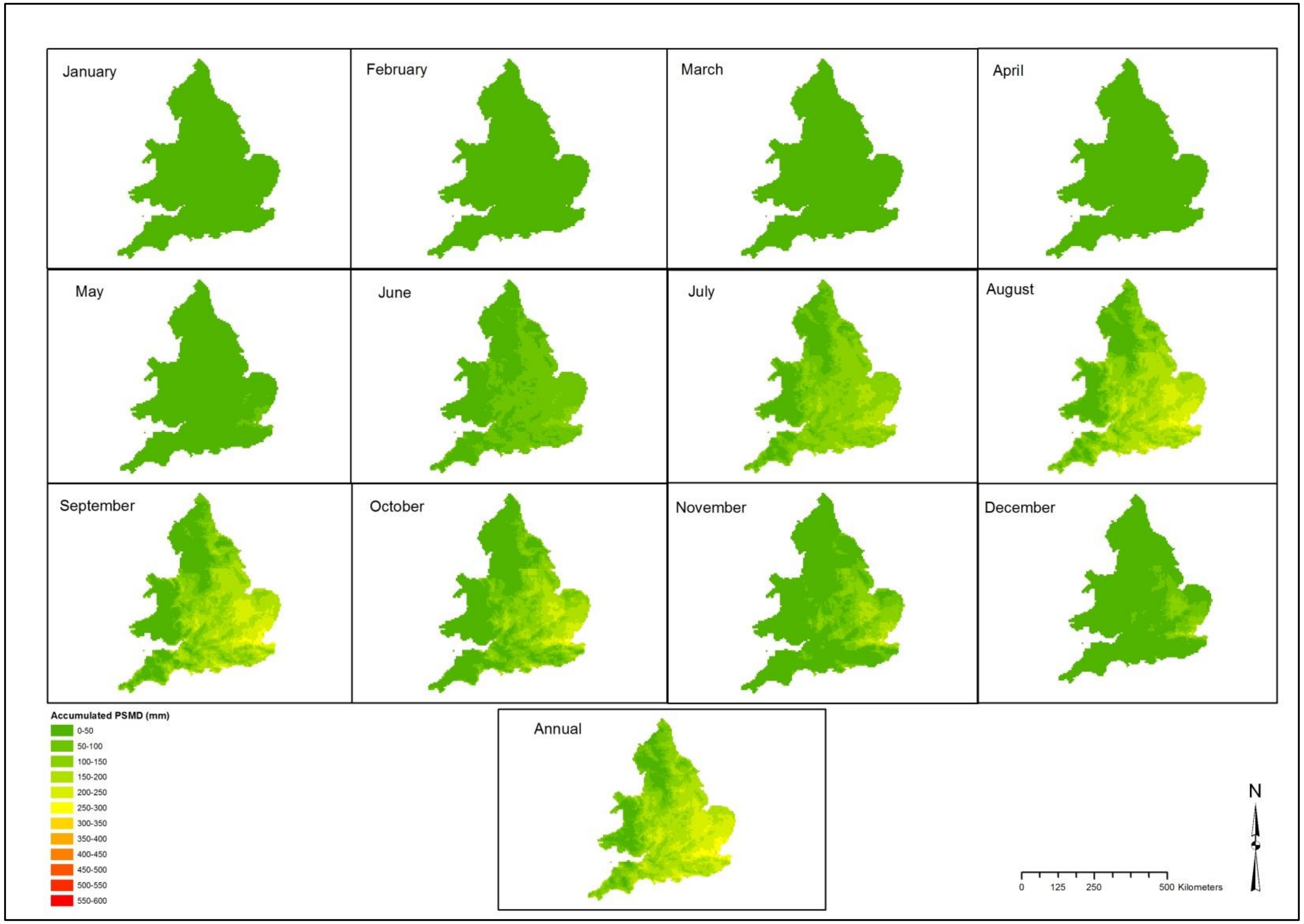


Figure 13: An 'unlikely to be less than' (10th percentile) monthly and annual UKCP09 2050 (2040-2069) Accumulated Potential Soil Moisture Deficit (PSMD)

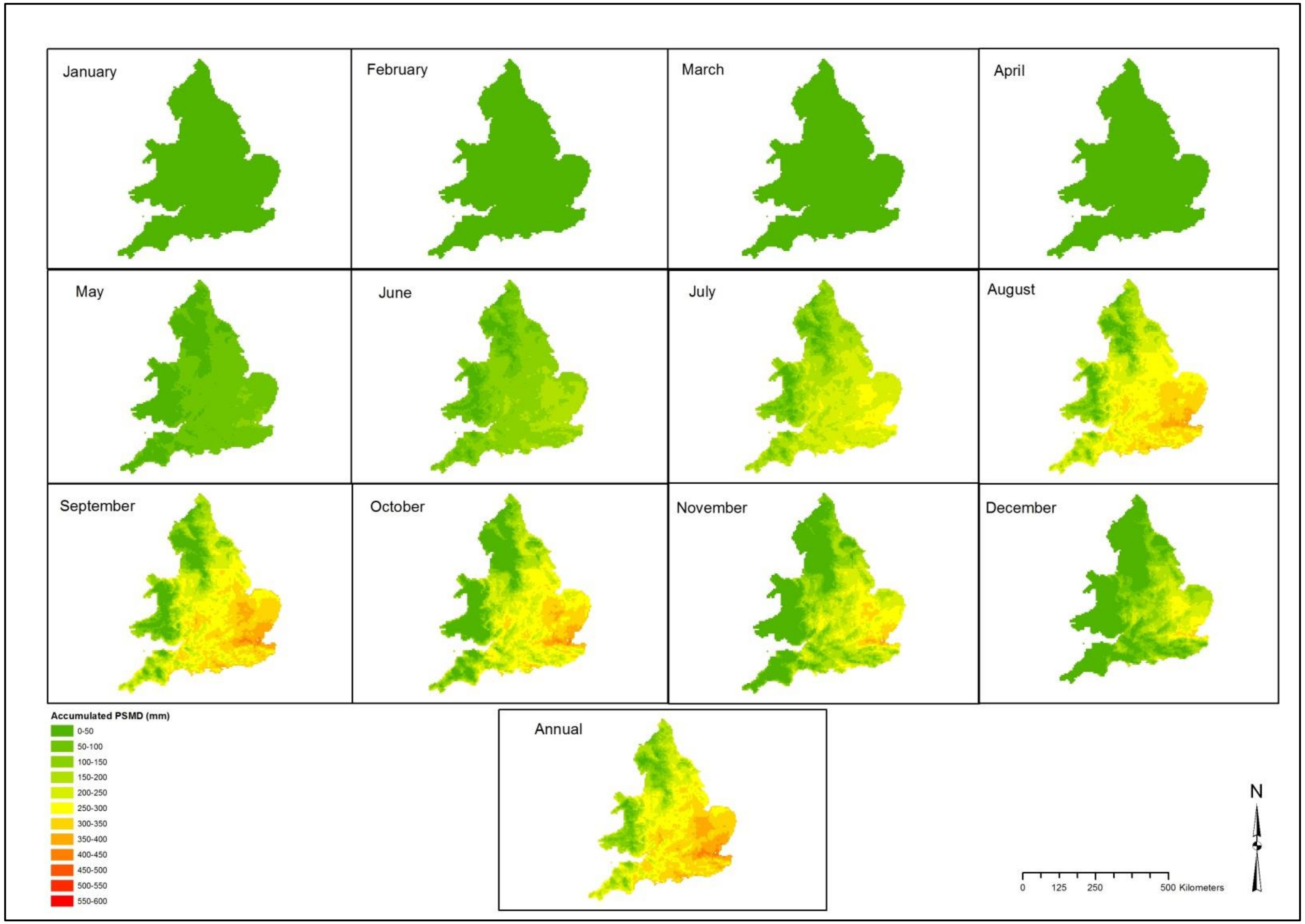


Figure 14: A 'central estimate' (50th percentile) monthly and annual UKCP09 2050 (2040-2069) Accumulated Potential Soil Moisture Deficit (PSMD)

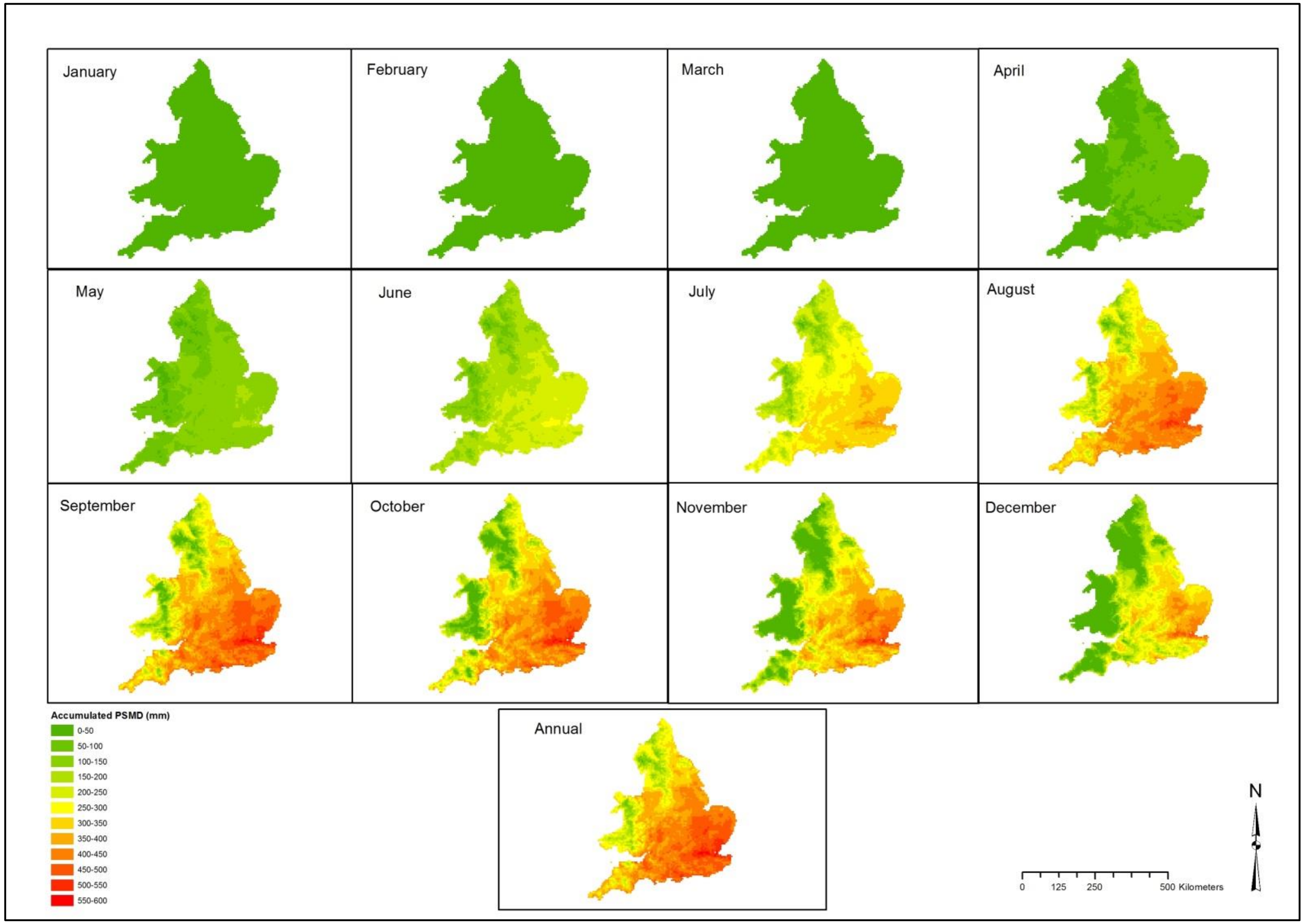


Figure 15: An 'unlikely to be more than' (90th percentile) monthly and annual UKCP09 2050 (2040-2069) Accumulated Potential Soil Moisture Deficit (PSMD

## 8. Potential applications of the research

Raw soils data is in itself of limited utility. More useful are the many thematic interpretations of soil, derived when ‘fused’ together with other data such as meteorological data. This is the case where the national soil map has been popularised through its development in the Natural Perils Directory and related ‘Leakage Assessment from Corrosivity and Shrinkage’ (Leacs) assessments (see http://www.landis.org.uk/services/). These interpretative maps have proven themselves to offer an important environmental data source for the insurance, reinsurance, water and the highways sectors.

The aging infrastructure of England and wales, up to 150 years in some instances, is regarded as being at risk from climate change and soil-related geohazards (Pritchard *et al.* 2014b). Much literature exists on the historic and current threats to the built environment. However, there is less work to date offering a consideration as to a forward-looking approach to managing the hazard.

The increasing adoption of asset management schemes and the recognised international standard (ISO 55000:2014), and reducing budgets, many asset managers are acutely aware of the need to better maintain their assets in light of climate change.

# 9. Future work

Any advancement in the understanding of potential future geohazard distribution has the potential to bring highly visible and substantial benefits to a number of organisations and stakeholders. These include national government, as well as organisations such as finance and insurance/reinsurance, infrastructure operators, local authorities, house buyers/owners, planners, and developers and other private enterprises.

The work has resulted in a new national data framework of soil-related future climatic projection parameters suitable for a range of application. Initial work will focus on its application and interaction with the Cranfield national soil map. A following phase of this work will permit staff to produce a market opportunity assessment for deploying this data resource to three key user-groups, namely: 1) conveyancers and home-buyers; 2) small to medium insurance companies, and; 3) local planning and transport officers at local councils. Infrastructure providers will also have a key interest in these assessments. A further report arising from this work will assess the market opportunities for the use of these data and provide some themed case studies.

## 9.1 Data legacy

This project has produced a large amount of UKCP09 spatial weather generator data files which could be applied over many sectors and applications. Therefore, consideration is now underway as to how best to make this data available to other research groups and authorities.

A range of possible avenues are under consideration:

- A Cranfield hosted web-data service, with a data portal providing access – an example of such a service is the EPSRC-funded project: ‘PROMETHEUS’ (http://emps.exeter.ac.uk/research/energy-environment/cee/projects/prometheus/downloads/)
- Data would be deposited in an external EPSRC data centre for openly available access.
- Data would be included as a part of the UK Climate Impacts Programme (UKCIP) data offerings.
- Similarly, data could be provided as a part of the British Atmospheric Data Centre’s (BADC) data offerings.

## 10. Conclusion

This work has reported on the creation of a novel data resource for modelling the impact of future climates. The application of these data has been exemplified through its incorporation and portrayal in the Natural Perils Directory, providing a national assessment of soil-related geohazards. A series of research themes and operational end users of these data have been highlighted and the importance of application areas drawing on these assessments noted. The work progresses the ‘Natural Perils Directory’ (NPD) assessments from the current form, now including future climatic impacts and opening the way for a new generation of thematic applications of these data.

## 11. References

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## Appendix 1. Data Formats

This Appendix provides examples of the various data files provided and created in the modelling activities described in the main report.

Table 2 shows the raw data format output by the weather generator. These files were substantial in size. For the 1,000 runs of 30 year data for the climate future scenarios, the files were c. 1.2Gb in size, for the Control files of 100 runs of 30 year data the files were 120Mb in size. Combining output data for each of the 10,398 5km$^2$ cells representing the land mass of England, Wales and Scotland, the total file size approximated 12.5 Tb.

```
3001  01  01    1   1     0.00     0.43     5.05     6.69     0.90     0.74     4.95     0.52     0.52     0.00
3001  01  02    2   5     0.00     2.00     7.01     8.41     1.00     5.14     0.32     0.46     0.04     0.04
3001  01  03    3   3     4.40     0.81    11.06     7.92     0.85     5.06     0.75     0.49     0.06     0.69
3001  01  04    4   2     3.20     3.84     7.67     9.18     1.00     8.84     0.90     0.51     0.07     0.08
3001  01  05    5   2     1.20     0.44     8.35     8.35     1.00    10.15     0.60     0.49     0.05     0.24
3001  01  06    6   2     5.10     0.85    10.35     9.08     1.00    11.56     2.49     0.57     0.21     0.20
3001  01  07    7   2     5.80     3.78     8.51     8.68     0.92    10.99     0.74     0.51     0.06     0.50
…
```

Table 2: Raw data table output by the weather generator

Scripts were written in the Perl programming language to process these substantive files for each of the parameters required, calculating monthly sum values as well as an annual value. Processed control files were c.300Kb each, processed scenario files c. 3Mb each, Table 3.

```
Perturbation, Year, Jan_AccSMD,  Feb_AccSMD,  Mar_AccSMD,  Apr_AccSMD,  May_AccSMD,  Jun_AccSMD,  Jul_AccSMD,
Aug_AccSMD,  Sep_AccSMD,  Oct_AccSMD,  Nov_AccSMD,  Dec_AccSMD, Year_AccSMD
1, 3001, 0.00, 0.00, 0.00, 0.00, 27.22, 87.53, 148.01, 115.58, 59.49, 0.00, 0.00, 0.00, 148.01
1, 3002, 0.00, 0.00, 0.00, 0.00, 47.72, 70.40, 24.60, 0.00, 0.00, 0.00, 0.00, 0.00, 70.40
1, 3003, 0.00, 0.00, 0.00, 0.00, 11.58, 29.43, 0.00, 9.14, 0.00, 0.00, 0.00, 0.00, 29.43
1, 3004, 0.00, 0.00, 0.00, 8.65, 0.00, 0.00, 1.30, 0.00, 0.00, 0.00, 0.00, 0.00, 8.65
```

Table 3: Processed data

A further script was then written, also in Perl to process these specific determinant files into an aggregate summary file suitable for inclusion in a modelling application. Each processed output file was c.90Kb, Table 4.

```
Grid, Source, Jan_Mean, Jan_StDev, Jan_P10, Jan_P25, Jan_P50, Jan_P75, Jan_P90, Feb_Mean, Feb_StDev, Feb_P10,
Feb_P25, Feb_P50, Feb_P75, Feb_P90, Mar_Mean, Mar_StDev, Mar_P10, Mar_P25, Mar_P50, Mar_P75, Mar_P90, Apr_Mean,
Apr_StDev, Apr_P10, Apr_P25, Apr_P50, Apr_P75, Apr_P90, May_Mean, May_StDev, May_P10, May_P25, May_P50, May_P75,
May_P90, Jun_Mean, Jun_StDev, Jun_P10, Jun_P25, Jun_P50, Jun_P75, Jun_P90, Jul_Mean, Jul_StDev, Jul_P10, Jul_P25,
Jul_P50, Jul_P75, Jul_P90, Aug_Mean, Aug_StDev, Aug_P10, Aug_P25, Aug_P50, Aug_P75, Aug_P90, Sep_Mean, Sep_StDev,
Sep_P10, Sep_P25, Sep_P50, Sep_P75, Sep_P90, Oct_Mean, Oct_StDev, Oct_P10, Oct_P25, Oct_P50, Oct_P75, Oct_P90,
Nov_Mean, Nov_StDev, Nov_P10, Nov_P25, Nov_P50, Nov_P75, Nov_P90, Dec_Mean, Dec_StDev, Dec_P10, Dec_P25, Dec_P50,
Dec_P75, Dec_P90, Annual_Mean, Annual_StDev, Annual_P10, Annual_P25, Annual_P50, Annual_P75, Annual_P90
2950230, 2950230_50s_scen_rain_output, 210.92, 87.06, 108.40, 150.10, 201.40, 260.40, 324.60, 149.21, 67.25, 69.30,
101.70, 142.10, 188.90, 238.30, 126.58, 56.30, 59.40, 86.20, 120.90, 160.30, 201.20, 100.33, 47.53, 43.40, 66.30,
95.60, 129.20, 163.00, 85.53, 41.00, 37.50, 56.80, 80.80, 109.00, 139.10, 68.95, 42.35, 21.10, 38.80, 62.40, 91.50,
124.00, 64.14, 43.91, 16.80, 32.40, 55.80, 85.90, 120.80, 73.49, 48.70, 21.60, 38.80, 64.00, 97.80, 137.20, 122.00,
64.60, 47.60, 75.50, 114.30, 158.80, 206.40, 166.84, 78.15, 75.00, 111.10, 157.50, 212.30, 271.20, 192.29, 74.13,
105.40, 139.90, 183.90, 235.00, 290.30, 228.73, 94.09, 115.60, 162.20, 219.40, 284.50, 353.70, 1589.01, 227.83,
1304.10, 1431.50, 1580.50, 1735.50, 1886.00
2950235, 2950235_50s_scen_rain_output, 172.42, 71.22, 88.60, 122.40, 164.40, 213.30, 265.40, 124.22, 56.00, 57.60,
84.70, 118.40, 157.20, 198.00, 106.06, 47.11, 49.80, 72.20, 101.30, 134.40, 168.30, 87.21, 41.35, 37.60, 57.70,
83.10, 112.10, 141.60, 71.92, 34.54, 31.60, 47.50, 67.90, 91.90, 116.90, 60.61, 37.24, 18.50, 34.20, 54.90, 80.50,
108.80, 58.34, 39.94, 15.20, 29.50, 50.80, 78.10, 110.10, 64.36, 42.71, 18.80, 33.90, 56.10, 85.80, 119.80, 104.90,
55.56, 41.20, 65.20, 97.90, 136.30, 177.60, 142.61, 66.86, 64.30, 95.00, 134.30, 181.60, 231.90, 164.12, 63.33,
90.10, 119.50, 157.10, 200.40, 247.50, 193.29, 79.34, 98.00, 136.90, 185.50, 240.80, 298.70, 1350.05, 193.54,
1107.80, 1217.40, 1342.10, 1475.30, 1602.20
```

**Table 4: Final data summary file**

This file contained percentiles (10, 25, 50, 75, 90) for each month, as well as a mean and Standard Deviation value. The same was also provided as an annual calculation.

# Forward-looking climatic scenarios of UK clay-related subsidence risk

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