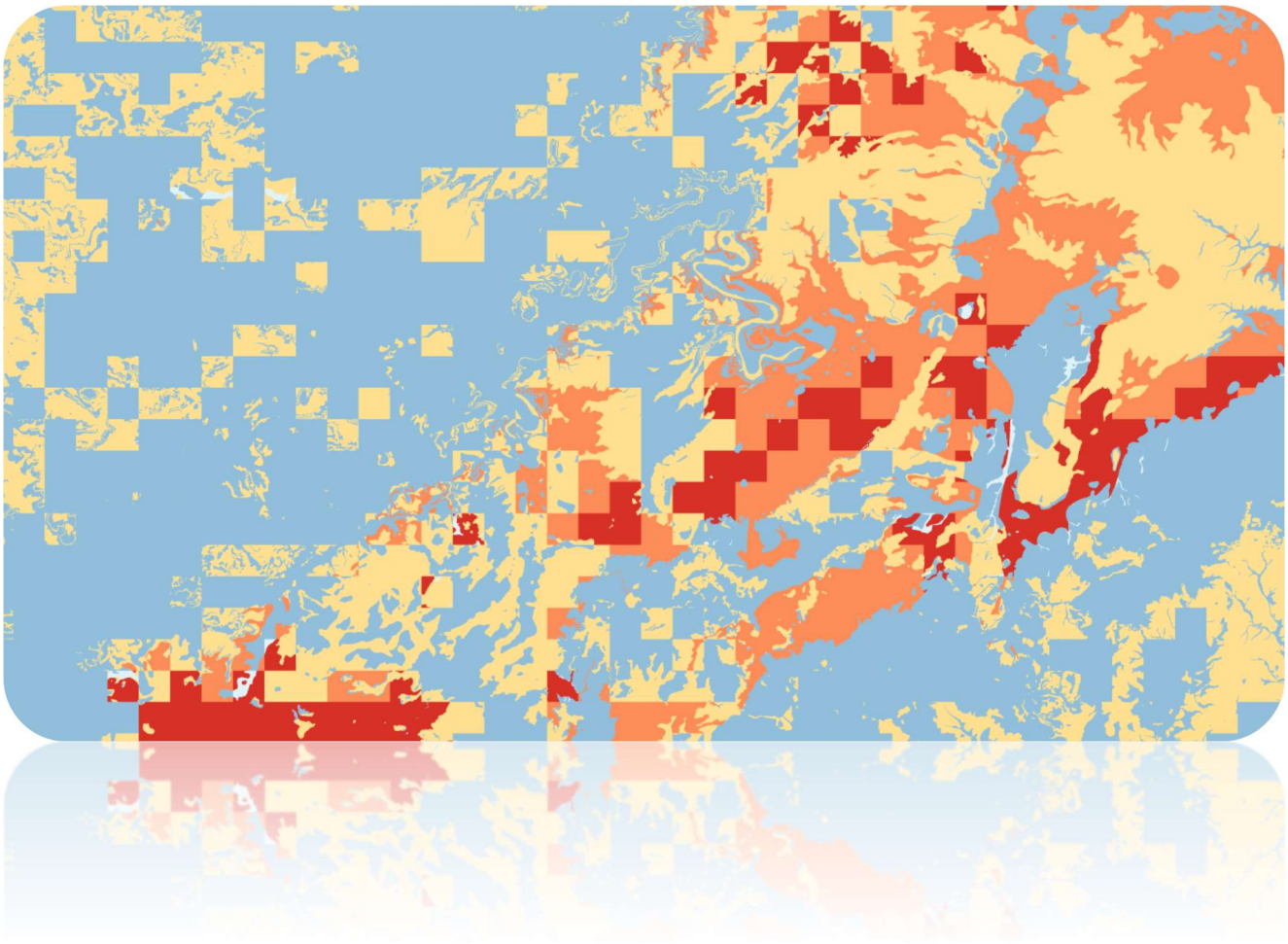


BGS INFORMATICS

User Guide: BGS GeoClimate Shrink-Swell

Open report OR/25/076

British Geological Survey

User Guide: BGS GeoClimate Shrink-Swell

A.M. Harrison., A. Hulbert., J. Richardson., K Lee.

Keywords

Climate Change, CHESS-SCAPE, UKCP18, clay shrink-swell, subsidence, GeoClimate.

Front cover

1:50 000 scale GeoClimate extract.

Bibliographical reference

BRITISH GEOLOGICAL SURVEY 2025. User Guide: BGS GeoClimate Shrink-Swell. *British Geological Survey Open Report*, OR/25/076. 31pp.

DOI: https://doi.org/10.5285/13142a27-f2b1-44e5-8ea4-252850d96b65

Keyworth, Nottingham British Geological Survey 2026

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of UK Research and Innovation.

British Geological Survey offices

Nicker Hill, Keyworth,
Nottingham NG12 5GG
Tel 0115 936 3100

BGS Central Enquiries Desk
Tel 0115 936 3143
email enquiries@bgs.ac.uk

BGS Sales
Tel 0115 936 3241
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South,
Edinburgh EH14 4AP
Tel 0131 667 1000
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road,
London SW7 5BD
Tel 020 7589 4090
Tel 020 7942 5344/45
email bgslondon@bgs.ac.uk

Cardiff University, Main Building, Park Place,
Cardiff CF10 3AT
Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford,
Wallingford OX10 8BB
Tel 01491 838800

Geological Survey of Northern Ireland, Department of Enterprise, Trade & Investment, Dundonald House, Upper Newtownards Road, Ballymiscaw,
Belfast, BT4 3SB
Tel 01232 666595
www.bgs.ac.uk/gsni/

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

UK Research and Innovation, Polaris House,
Swindon SN2 1FL
Tel 01793 444000
www.ukri.org

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Foreword

The British Geological Survey (BGS) is a world-leading geological survey, focusing on public-good science for Government and research to understand earth and environmental processes.

We are the UK's premier provider of objective and authoritative geoscientific data, information and knowledge to help society to:

- use its natural resources responsibly
- manage environmental change
- be resilient to environmental hazards

We provide expert services and impartial advice in all areas of geoscience. As a public sector organisation, we are responsible for advising the UK Government on all aspects of geoscience as well as providing impartial geological advice to industry, academia and the public. Our client base is drawn from the public and private sectors both in the UK and internationally.

The BGS is a component body of the Natural Environment Research Council (NERC), part of UK Research and Innovation (UKRI).

DATA PRODUCTS

BGS produces a wide range of data products that align to Government policy and stakeholder needs. These include baseline geological data, engineering properties and geohazards datasets. These products are developed using in-house scientific and digital expertise and are based on the outputs of our research programmes and substantial national data holdings.

Our products are supported by stakeholder focus groups, identification of gaps in current knowledge and policy assessments. They help to improve understanding and communication of the impact of geo-environmental properties and hazards in Great Britain, thereby improving society's resilience and enabling people, businesses, and the government to make better-informed decisions.

Acknowledgments

This user guide was written by Anna Harrison, Jen Richardson and Andy Hulbert with editorial input from Katy Lee. Many individuals within BGS have contributed to the dataset. This assistance has been received at all stages of the study. Jim White, Lee Jones, Majdi Mansour, Jon Mackay, Sophie Dorwood, Andrew Hughes and Claire Dashwood, and all members of the GeoClimate project team and have contributed to the details of the methodology throughout its development.

Contents

FIGURES

TABLES

Summary

Developed by the British Geological Survey (BGS), GeoClimate data are available in a Premium version in grid and vector polygon formats. Data coverage is Great Britian (not including Shetland and parts of the Orkneys). This GeoClimate shrink-swell dataset have been developed using the same methodology as GeoClimate UKCP18. It provides outputs for RCP2.6 and RCP4.5, whereas GeoClimate UKCP18 only provided RCP8.5. It also provides projections from a larger number of time periods: 11-year windows centred on 2030, 2050 and 2070. GeoClimate UKCP18 is now superseded by GeoClimate shrink-swell.

GeoClimate shrink-swell utilises climate projection data from the UKCEH CHESS-SCAPE future climate dataset, which is derived and extended from the climate model output provided by the UK Climate Projections 2018 (UKCP18).

The data are useful for a range of users, particularly longer-term resilience planning, infrastructure owners, lenders and insurers.

This user guide provides the information required to enable the reader to understand and use this BGS data product.

1 Introduction

The purpose of GeoClimate shrink-swell is to provide information on the projected future change in susceptibility of clay shrink–swell across Great Britain due to climate change. It considers the changing climate and the associated changes in near-surface groundwater content, as well as the static variables of geology and geotechnical values. In this guide, GeoClimate shrink-swell is hereafter referred to as GeoClimate.

The GeoClimate datasets, and accompanying documentation, provide information for users on the natural characteristics and properties of shrink-swell prone geological units for the assessment of climate change impacts in Great Britain. GeoClimate looks specifically at the geological factors that influence shrink-swell subsidence and the climatic effects/interactions. It does not consider any human or artificial factors.

GeoClimate is useful to those concerned with the effects of climate change on their assets and infrastructure. Key examples are banks, building societies and insurance companies who must carry out mandatory Bank of England climate stress testing to provide an indication of the risk and resilience to the consequences of climate change. It is also of relevance to those adhering to regulatory and legislative standards and reporting, such as the Bank of England stress testing and Solvency UK regulations and requirements, to build an understanding of their climate-related risks.

GeoClimate shrink-swell is available as a Premium licensed dataset (Figure 1).

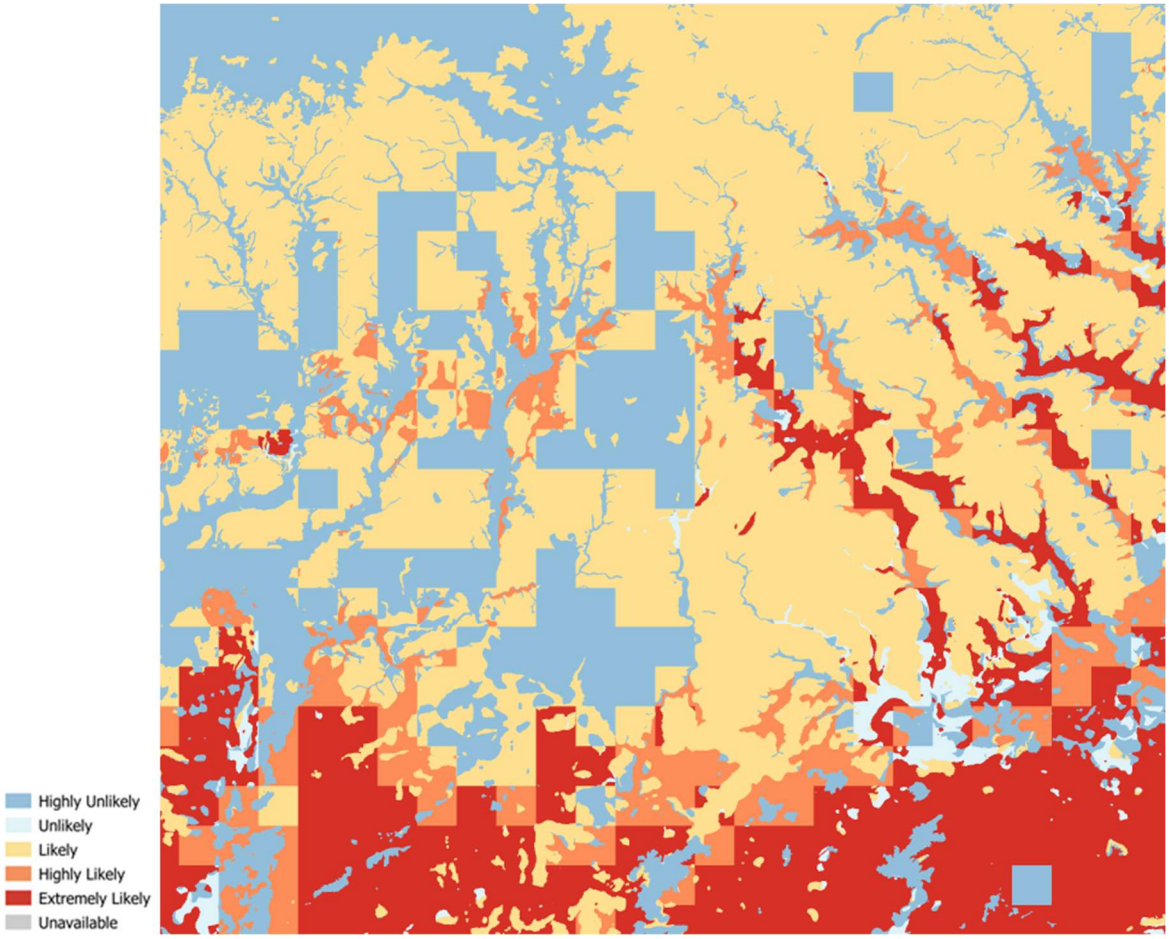


Figure 1: Example of the GeoClimate shrink-swell data for a 50 km^2 area of southeast England BGS © UKRI

1.1 BACKGROUND TO THE DATASET

Shrink-swell is recognised as the costliest geohazard across Great Britain, with the increasing occurrence of warmer drier summers driving up claims. For example, due to the hot dry summer of 2018, more than 10,000 households made claims worth a total of £64 million to deal with the impact of subsidence, according to the Association of British Insurers (ABI) (Insurance Times, 2018). More recently, in 2022, the summer heatwave caused a surge in subsidence insurance claims (23,000 claims) totalling approximately £219M (Insurance Times, 2023).

The BGS GeoSure Shrink-swell dataset considers the physical properties of the geology to provide a susceptibility rating for potential ground movement. It does not, however, account for changes in climate, and parameters that will affect soil water content.

GeoClimate shrink-swell has been developed to enable the climate variables to be considered, alongside the geotechnical properties of the ground immediately below and around building foundations, and provide a longer term, modelled analysis for resilience or adaptation assessments. It is essentially a national hazard susceptibility map, showing change in susceptibility with time, due to changes in climate.

The methodology was developed, initially using United Kingdom Climate Projections (UKCP) climate data, by engineering geologists, hydrogeologists, geophysicists and information developers at the British Geological Survey, following stakeholder engagement, and is presented as a series of GIS data layers. This new GeoClimate release uses the same methodology with new, derived climate model inputs.

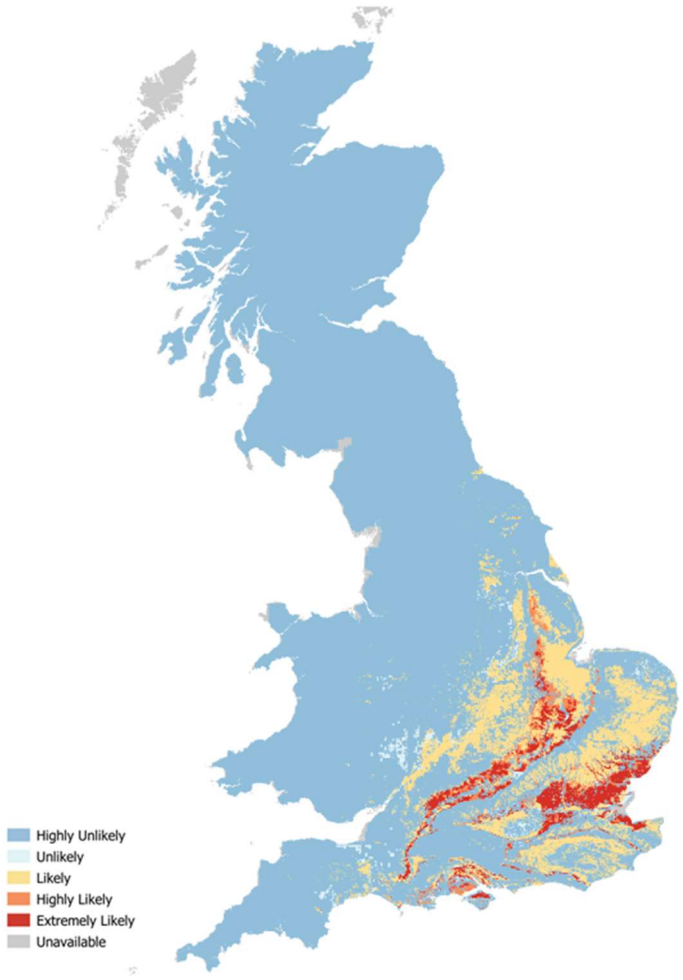


Figure 2: Example of the data and coverage (showing GeoClimate shrink-swell). BGS © UKRI. Contains OS data © Crown copyright and database right (2026)

1.2 WHAT THE DATASET INCLUDES

GeoClimate provides projections at the highest resolution possible, taking into consideration the methodology and input datasets. It is based on the best and most appropriate resolution datasets available at national scale and coverage; the 1:50 000 BGS geological data and 1 km grid CHESS-SCAPE climate projection data. The 2 km pixels seen in GeoClimate, which contrast with the finer resolution provided by the BGS geological linework, originate from the climate projections and the output grid generated by the ZOODRM groundwater model.

GeoClimate is provided as area polygons, for 3 time period envelopes, centred on 2030, 2050 and 2070, and based on the 3 Representative Concentration Pathways (RCP) emissions scenarios (2.6, 4.5, 8.5), with the 10th 50th and 90th percentile (wetter, average and drier) statistics provided. An example of the variation shown between the average, wetter and drier scenarios, is provided in Figure 3.

GeoClimate is provided for three 11-year windows:

- Centred on 2030 (11 year window 2025 to 2035)
- Centred on 2050 (11 year window 2045 to 2055)
- Centred on 2070 (11 year window 2065 to 2075)

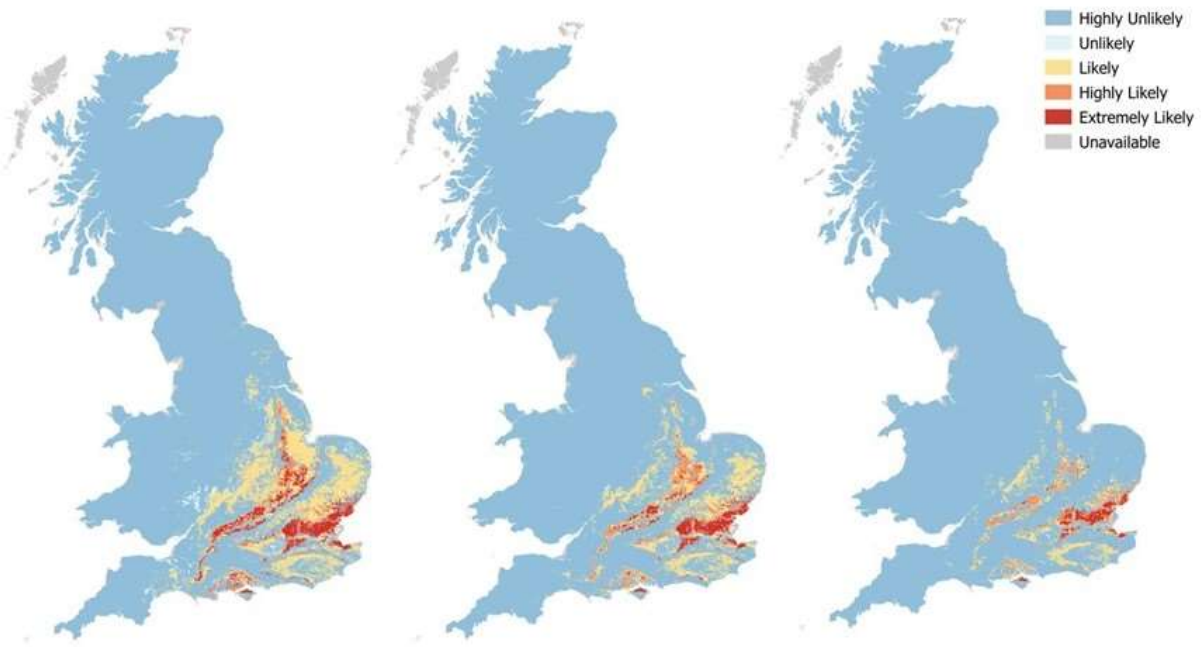


Figure 3: Drier, average and wetter scenarios for GeoClimate RCP8.5, centred on the 2070s. BGS © UKRI. Contains OS data © Crown copyright and database right (2026)

Historic baseline dataset

In addition, we provide a modelled baseline dataset, centred on 1996 (11-year window 1991 to 2001, referred to as the 1990s). This allows provision of a difference map to show the differences between a modelled baseline and the modelled forecasts. Differences in classification from the baseline are calculated for each time period to provide a value for a difference-in-classification map.

The 1990s was identified as the baseline time period for 2 reasons. Firstly, the availability of historic modelled data. CHESS-SCAPE provides historic climate projections from 1980, and the groundwater model utilised in the methodology requires 10 years of input values, to provide

robust soil moisture deficit values. Therefore, the earliest robust soil moisture deficit values generated are for 1991. The methodology utilises 11-year windows for which it provides a GeoClimate projection, thus the historic baseline for CHESS-SCAPE is the 1990s, centred around 1996. Secondly, the RCP trajectories describe different climate change scenarios, all of which were considered possible depending on the amount of greenhouse gases (GHG) emitted in the years to come. As time progresses into the 21st Century in the climate projections, temperature and rainfall projections are just that, projections, which were not reality. Therefore, selecting a later time period as a baseline, would be misleading, as the baseline was reflecting changes in climate that had not occurred.

The table below shows the RCPs, time periods and the data packages available for GeoClimate shrink-swell.

Table 1: data available in GeoClimate shrink-swell

RCP	Time periods	Data
RCP 2.6 lower emission pathway	2030, 2050, 2070	10th, 50th and 90th percentile (wetter, average and drier)
RCP 4.5 medium emissions pathway	2030, 2050, 2070	10th, 50th and 90th percentile (wetter, average and drier)
RCP 8.5 high emissions pathway	2030, 2050, 2070	10th, 50th and 90th percentile (wetter, average and drier)
Difference map (compared to the 1990s)	2030, 2050, 2070	10th, 50th and 90th percentile (wetter, average and drier)

1.3 WHY THE DATASET IS USEFUL

Natural ground stability hazards, such as clay shrink-swell may lead to financial loss for anyone involved in the ownership or management of property. These hazards could increase in likelihood and propensity when considering the impacts of a changing climate. These impacts could relate to increased insurance premiums, depressed house prices and, in some cases, engineering works to stabilise land or property.

The identification of areas of potential increased risk of clay shrink–swell susceptibility from climate change will be of use to all those required to plan for longer-term resilience into the 21st Century. This includes planners, developers, construction companies, and utility companies, consulting engineers, builders, loss adjusters, the insurance industry, architects and surveyors. These hazards may also impact on anyone involved in infrastructure networks (road or rail) or utility companies.

GeoClimate has been created in response to feedback from our customers and the need of the financial services sector to assess and manage their portfolios in line with the Bank of England Stress Testing requirements.

A benefit of GeoClimate is that it provides a ‘hot spot’ map of susceptible areas, which can inform mitigation strategies (and therefore save time associated with fewer manual site visits), prioritise works and aid risk reduction. The product might be used to inform future requirements for changes in the design of foundations, so buildings are not affected by the increased hazard. The cost of such prevention may be very low and could be many times lower than the repair bill following ground movement. Where GeoClimate can be integrated within the workflows of our intended user base it can support prioritisation of remedial action, or help define buildings at most risk, thereby reducing subsidence events and potentially saving the costs of rebuild and disruption.

2 Case study: Clay subsidence in London

This chapter provides a specific case study example to describe a set of issues and challenges relevant to stakeholders and explain how the datasets could potentially be used in such a situation. In this section we focus on clay shrink swell subsidence in the London area.

2.1 THE PROBLEM

The changing climate, hotter drier summers, and warmer wetter winters projected for the coming century, will put increasing numbers of buildings at risk of subsidence. In areas where the ground is susceptible to movement due to the clay content, a decreasing soil moisture will lead to shrinkage, and consequently, could cause structural damage to buildings. Many of the more shrink-swell vulnerable geological deposits are found in the southeast of England (Figure 4), with key areas being London, Essex and Kent.

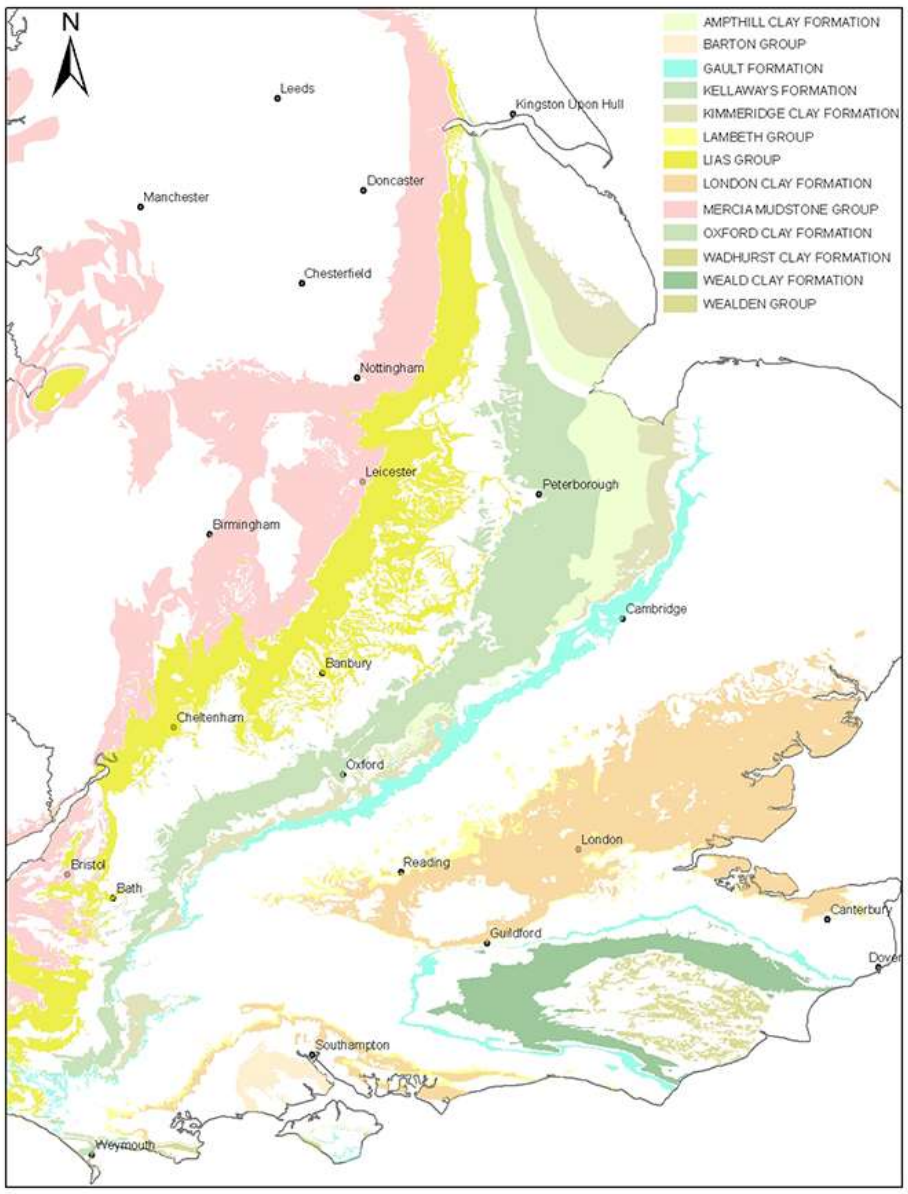


Figure 4: The rock formations most susceptible to shrink–swell behaviour is found mainly in the south-east of Britain. BGS © UKRI. Contains OS data © Crown copyright and database right (2026)

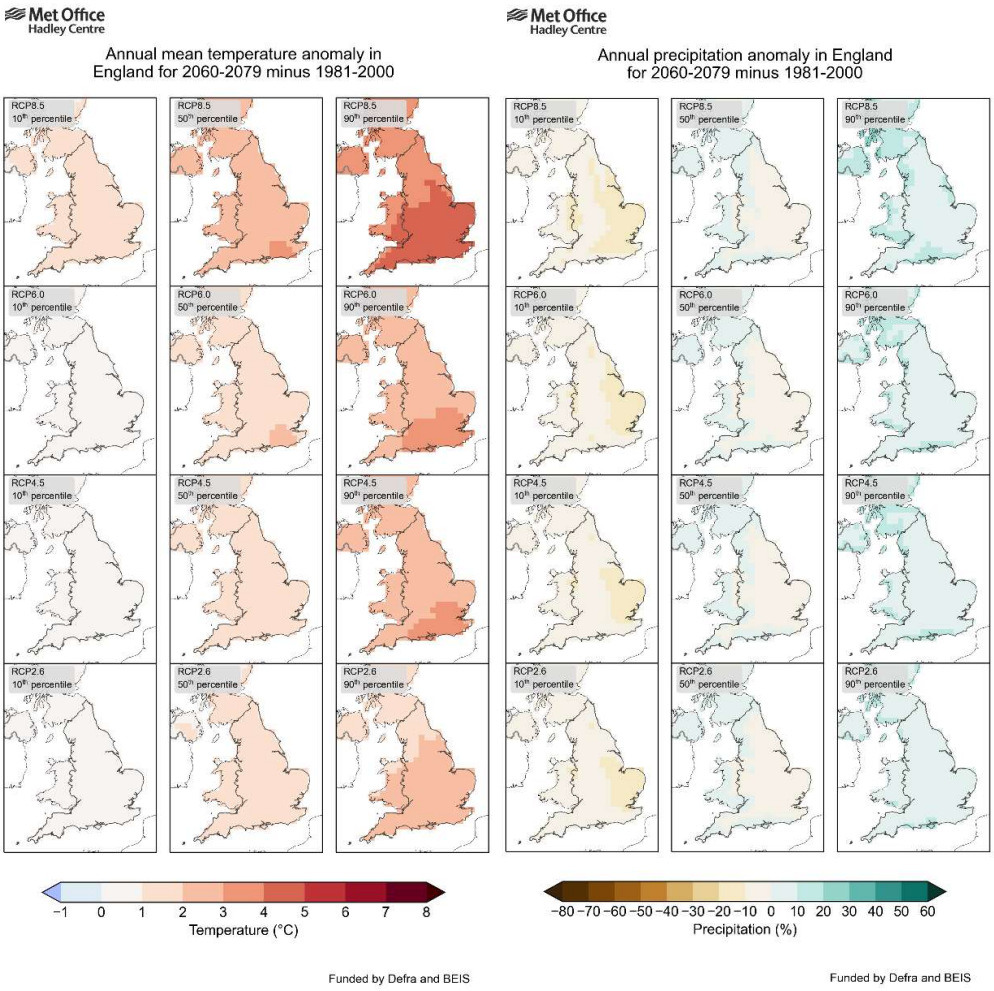


Figure 5: Annual mean temperature and precipitation change for 2060-2070 compared to 1981-2000 (Climate change projections over land - Met Office).

The southeast of England is also an area projected to see the larger increases in temperature, and decreases in precipitation, in the coming century (Figure 5). This leads to many buildings in the London area becoming increasingly vulnerable to clay shrink-swell subsidence (Figure 6 based on GeoClimate UKCP18 higher emissions projections).

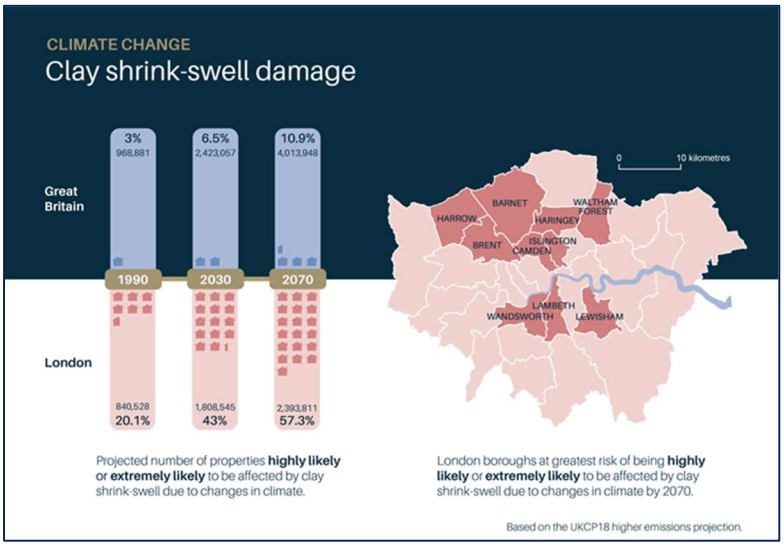


Figure 6: The number of homes projected to be affected by clay shrink swell subsidence in the coming century (based on UKCP18 RCP8.5 projections). BGS © UKRI

2.2 THE CHALLENGE

The number of subsidence insurance claims has been increasing over the last decade. Shrink-swell subsidence currently costs the UK economy over £400 million a year, with dry hot summers linked to increased exposure. In the second half of 2022, there was a claim made on average every 15 minutes linked to subsidence, with insurers expected to have paid out over £219million in 2022 alone (ABI). The ABI recently published figures showing that home insurance payouts for subsidence claims have risen to the highest quarterly payout figure on record at £60 million for Q2 2024, compared with damage from storms, heavy rain and frozen pipes which cost £144million in the same quarter (ABI). The costs of subsidence to insurance could increase to £1.9bn by 2030 according to PWC. Both homeowners and Insurers need data to enable informed decision-making (e.g. for insurance: risk screening, portfolio management, regulatory requirements; and for homeowners: building adaptation measures).

2.3 HOW CAN GEOCLIMATE BE USED?

GeoClimate data highlights areas with increased (and the level of change in) future susceptibility and enables targeted mitigation and adaptation responses. GeoClimate provides detailed, accurate and precise information, in areas identified as potentially vulnerable to ground movement, at a quasi- 1:50,000 scale.

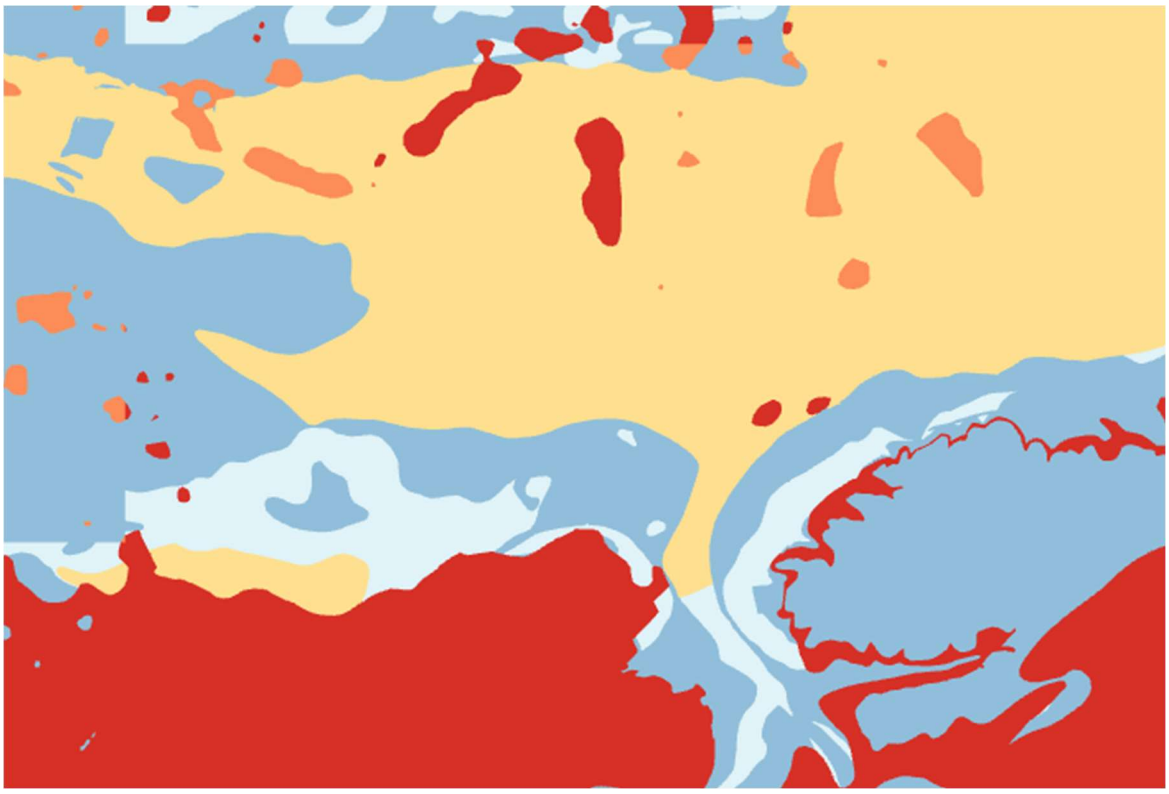
Geological context:

The London Clay Formation is one example of clay-rich deposits that is highly susceptible to shrink-swell subsidence issues. It occurs in the London Basin, East Anglia and the Hampshire Basin, and mainly comprises a stiff, bluish grey mudstone (Kemp & Wagner, 2006), with a thickness of up to 200m in the eastern extent of the London Basin. London Clay contains smectite and is therefore likely to undergo shrink-swell volume changes during wetting and drying and provide problems in terms of it's engineering behaviour.

Overlying the bedrock formations, are variable Quaternary deposits including Alluvium, interglacial lacustrine deposits and the Langley Silt Member. These deposits have varying thickness and propensity to shrink and swell, all of which are considered within the GeoClimate data classifications.

Homeowners or Insurers need to assess their buildings' risk. Utilising GeoClimate a user might want to assess their 'worst-case' scenario and therefore use the RCP8.5 projection (**Figure 7**). Houses within this area are built upon a wide range of geological deposits, and therefore when considering the GeoClimate data (which takes into account geology, hydrogeology, soil moisture and climate change), demonstrates the variability of a changing climate on projected clay shrink swell in 2070. Buildings along one street for example, could have quite differing risk levels.

a)



b)

Figure 7: GeoClimate projection for an area of London Clay Formation, overlain by quaternary deposits (a) 2030s and b) 2070s). BGS © UKRI

The GeoClimate dataset provides projections for 3 time periods up until 1970, as well as worse (drier) and best case (wetter) scenarios for each, allowing short-term and longer-term planning, and for the largest potential impact.

The GeoClimate dataset includes Difference layers for each projection, which provides a magnitude of change from 1991-2001 (1996) projections (number of classifications the GeoClimate classification has increased by). This allows stakeholders to consider historic data regarding impact and not only identify areas with increase vulnerability but also understand what the baseline was.

3 Methodology

3.1 OVERVIEW

GeoClimate combines current GB clay shrink-swell hazard susceptibility, GB groundwater modelling, and climate change projections to project future clay shrink-swell hazard susceptibility. The methodology considers multiple climate realisations, which results in multiple daily soil moisture projections. These are sorted from wettest to driest at every location (on a 2 km grid), and the 10th and 90th percentile calculations of these provide the wetter and drier projections. These 'extreme' projections convey the variation and uncertainty within the scenario modelling and allow the user to consider the best- and worst-case scenario for shrink-swell susceptibility according to their needs.

3.2 SOURCE DATASETS

The BGS GeoClimate Data Product consists of 36 data layers (see Table 1), which identify areas of potential geological hazard in Great Britain. The datasets and other components used to create and validate these layers are:

1. **BGS GeoSure Shrink-swell** dataset. The potential for shrink–swell to be a hazard, assessed using 1:50,000 scale digital maps of superficial and bedrock deposits. https://www.bgs.ac.uk/products/geosure/shrink_swell.html (Lee & Diaz Doce, 2018)

2. **CEH Hydrology of Soil Types** (HOST) (Boorman et al., 1995). A soil class value sampled at daily intervals at 1 km. https://www.ceh.ac.uk/services/hydrology-soil-types-1km-grid

3. **CHESS-SCAPE: Future projections of meteorological variables at 1 km resolution for the United Kingdom 1980-2080 derived from UK Climate Projections 2018 (UKCP18)** Representative Concentration Pathways (RCP) 2.6, 4.5 and 8.5. https://catalogue.ceda.ac.uk/uuid/8194b416cbee482b89e0dfbe17c5786c/

4. **BGS Hydrogeology 1: 625,000** GIS polygon data. https://www.bgs.ac.uk/products/hydrogeology/maps.html To determine run-off coefficient values.

5. **NEXTMap®** Britain elevation data. Digital Terrain Model licensed from INTERMAP® Built using Interferometric Synthetic Radar (InSAR) data. 5 m resolution.

3.3 METHODOLOGY

There are 3 main stages to the methodology (see figure 8): 1. Inputting source data and calculating soil moisture deficit per grid cell per time series across Great Britain; 2. Analysis of the time series modelled outputs and trigger thresholds; and 3. Combining the time series

outputs and thresholds with the geological data to establish areas of future susceptibility to shrink-well subsidence.

The hydrological model uses the BGS Groundwater Zooming Object Oriented Distributed Recharge (ZOODRM) distributed recharge model (Mansour et al., 2018). This model generates gridded daily soil moisture deficit (SMD) values for GB, based on inputted climate variables and ground data.

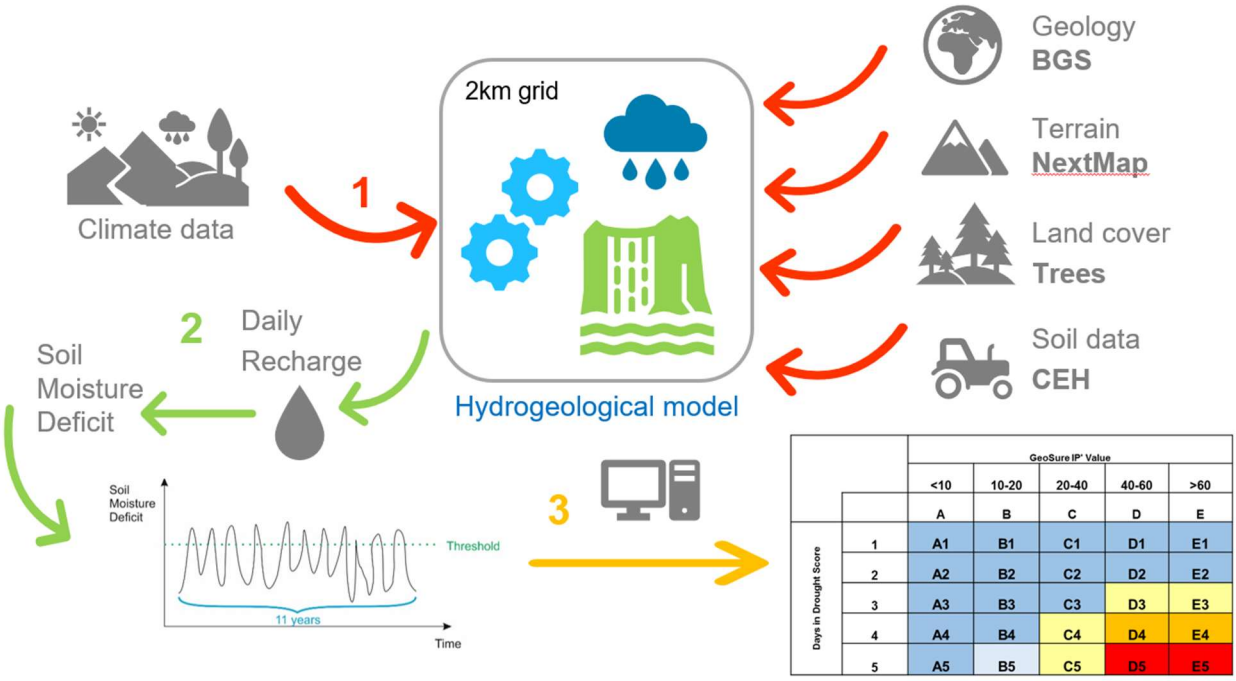


Figure 8: Diagrammatic overview of the methodology steps to generate GeoClimate. BGS © UKRI

This data is then output as a series of daily time series for each 2 km grid cell across GB. The time series is analysed over an 11-year window (to avoid any one year being 'unusual' and therefore biasing results). High power computing is then used to analyse the soil moisture deficit and identify days above threshold of days in drought. This is then combined with the geological properties (clay-rich deposits) to identify the areas of potential susceptibility change.

These are sorted from wettest to driest at every location (2 km grid cell), and the 10th and 90th percentile calculations of these provide the wetter and drier projections. These 'extreme' projections convey the variation and uncertainty within the scenario modelling and allow the user to consider the best- and worst-case scenario for shrink-swell susceptibility according to their needs.

Outputs are provided for the 3 RCP scenarios for the specified time periods. Other time periods and frequencies can be processed on request (at additional cost), if required.

3.4 CHESS-SCAPE CLIMATE PROJECTION DATA

There are several primary sources of climate projection data that cover the UK including the Met Office's UKCP data. The most recent is UKCP18 data, but these only cover RCP8.5 at the required resolutions detailed above. There is also the Coupled Model Intercomparison Project (CMIP) which is now in its sixth phase (CMIP6). These use Global Circulation Models to generate global climate projections over a range of RCPs including RCP6.0. However, the spatial resolution available is only 100 km. This is too coarse to produce a robust clay-shrink-swell map for Great Britian.

CHESS-SCAPE is a new climate projections dataset produced by UK Centre for Ecology & Hydrology (UK CEH), as part of the UK-SCAPE project (Robinson *et al*., 2023), which meets the need for enhanced, consistent, extended and accessible high resolution climate projections to drive impact models. It contains the relevant meteorological variables, at high spatial and temporal resolution, from 1980 to 2080, allowing for integration into the GeoClimate methodology. It is derived from the regional climate projections in the UKCP18 regional climate model (RCM) 12 km ensemble. It is based on four ensemble members, selected from the original 12 in UKCP18 to represent the range of temperature and precipitation change, thus representing the ensemble climate model uncertainty. The data was downscaled to a 1 km grid to account for local topography, bias corrected using historical data, time shifted using substitution of years with similar climate, and pattern scaled to the 3 other RCPs. The outputs compare well with the moderate to high end UKCP18 probabilistic projections, and GeoClimate shrink-swell projections for RCP8.5 are very comparable to GeoClimate UKCP18 projections for RCP8.5, demonstrating the reliability of the dataset.

4 Technical Information

This section provides more detailed information on the Data Product, its content, and advice on best use as well as highlighting some important considerations.

4.1 SCALE

The GeoClimate datasets have been developed at a quasi- 1:50,000 scale and must not be used at coarser scales. GeoClimate provides projections at the highest resolution possible, considering the methodology and input datasets. It is based on the best and most appropriate resolution datasets available at national scale and coverage. The initial scale of climate projections should be considered when carrying out detailed local-scale assessments.

Temporal scale

The data layers are provided for the following 11-year time periods:

- 2030 (2025 to 2035)
- 2050 (2045 to 2055)
- 2070 (2065 to 2075)

4.2 COVERAGE

All the GeoClimate datasets have coverage for Great Britain, not including Shetland and parts of the Orkneys (see Figure 2).

4.3 ATTRIBUTE DESCRIPTION

The tables below show the attributes of the BGS GeoClimate datasets.

Table 2: Attributes of the GeoClimate dataset.

Field name	Field description
CLASS	Classification of hazard using values: - Highly Unlikely, Unlikely, Likely, Highly Likely, Extremely Likely, Unavailable
LEGEND	Description of the potential for the hazard susceptibility
VERSION	Dataset name and version number

Table 3: Attributes of the GeoClimate difference map

Field name	Field description
BASE_CLASS	Classification of the baseline value: - Highly Unlikely, Unlikely, Likely, Highly Likely, Extremely Likely, Unavailable in the baseline dataset
LEGEND	Description of the changes (see Table 7)
CLASS_20**	Classification of the projected value
DIFFERENCE	Number of classification changes (-1 to +4)
VERSION	Dataset name and version number

4.4 DATA FORMAT

The BGS GeoClimate Datasets are available as vector GIS datasets with attribute values relating to shrink-swell hazard susceptibility under a range of climate scenarios. The dataset comprises both polygon and grid data.

4.5 DATASET HISTORY

Below is an outline of the data history of BGS GeoClimate:

- GeoClimate UKCP09 (released 2018): Derived from BGS GeoSure Shrink-swell V8, UKCP09 2 km gridded climate ensemble, NEXTMap® Britain elevation data, OS Open Map – Local (coastline), CEH Hydrology of Soil Types (HOST), BGS Hydrogeology 1: 625,000.

- GeoClimate UKCP18 (released 2020): Derived from BGS GeoSure Shrink-swell V8, UKCP18 2.2 km gridded CPM climate ensemble, NEXTMap® Britain elevation data, OS Open Map – Local (coastline), CEH Hydrology of Soil Types (HOST), BGS Hydrogeology 1: 625,000.

- GeoClimate shrink-swell (released 2026): Derived from BGS GeoSure Shrink-swell V8, UKCEH CHESS-SCAPE 1 km resolution dataset, NEXTMap® Britain elevation data, OS Open Map – Local (coastline), CEH Hydrology of Soil Types (HOST), BGS Hydrogeology 1: 625,000

4.6 DISPLAYING THE DATA

The GeoClimate datasets are provided with .lyrx files for use in ESRI format or the colour RGB values are provided in the tables below for users of non-ESRI software.

The GeoClimate shrink-swell susceptibility class descriptions include the following 5 categories, plus an ‘unavailable’ category (Table 6).

Table 4: GeoClimate shrink-swell colours, classes and susceptibility text

Colour	Class	Description of susceptibility
Blue	Highly unlikely	It is highly unlikely that foundations will be affected by increased clay shrink-swell due to climate change.
Light Blue	Unlikely	It is unlikely that foundations will be affected by increased clay shrink-swell due to climate change.
Yellow	Likely	It is likely that foundations will be affected by increased clay shrink-swell due to climate change.
Orange	Highly likely	It is highly likely that foundations will be affected by increased clay shrink-swell due to climate change.
Red	Extremely likely	It is extremely likely that foundations will be affected by increased clay shrink-swell due to climate change.
Grey	Unavailable	Input datasets unavailable.

Table 5 describes the classification of the GeoClimate shrink-swell Difference maps.

Table 5: GeoClimate shrink-swell difference map, colours, values and text

Difference in classification	Difference from 1991-2001 susceptibility text	Colour identifier (RGB)
-4	Decrease of 4 classifications	69,117,180
-3	Decrease of 3 classifications	116,173,209
-2	Decrease of 2 classifications	171,217,233
-1	Decrease of 1 classification	224,243,248
0	No change in classification	255,255,191
1	Increase of 1 classification	254,224,144
2	Increase of 2 classifications	253,174,97
3	Increase of 3 classifications	244,109,67
4	Increase of 4 classifications	215,48,39
-999	Unavailable	204,204,204

Note 'Unavailable' classification: It is not possible to generate output grids for islands **remote** to mainland Great Britian, due to groundwater modelling limitations. Therefore, GeoClimate values for the Scottish Islands (including Orkney and Shetland Isles) are categorised as 'Input datasets unavailable'.
Similarly, some areas of the coastal zone are not classified due to the incomplete extent of the input datasets.

5 Licencing the data

5.1 BGS LICENCE TERMS

The British Geological Survey does not sell its digital mapping data to external parties. Instead, BGS grants external parties a licence to use this data, subject to certain standard terms and

conditions. In general, a licence fee will be payable based on the type and geographical extent of data, the number of users, and the duration (years) of a licence.

All recipients of a licence (potential licensees) are required to return a signed digital data licence document before authorisation for release of BGS digital data is given.

- GeoClimate shrink-swell is provided under the BGS DEL (Data Exploration Licence) terms. Please contact BGS digitialdata@bgs.ac.uk if commercial use is required.

Please use the following acknowledgement when using BGS GeoClimate shrink-swell:

- 'Derived from BGS Digital Data under Licence (cite your licence number) British Geological Survey © UKRI. All rights reserved.'

Further details about licensing BGS data can be found on our web page https://www.bgs.ac.uk/information-hub/licensing/.

For more information on the availability of data or to obtain a quote for licensing the data, please email digitaldata@bgs.ac.uk. For any questions related to the licence agreement or to discuss your proposed usage of the data, please email iprdigital@bgs.ac.uk.

5.2 CONTACT INFORMATION

For all data and licensing enquiries please contact:
BGS Data Services
British Geological Survey
Environmental Science Centre
Keyworth
Nottingham
NG12 5GG
Direct Tel: +44(0)115 936 3143
Email: digitaldata@bgs.ac.uk

6 Limitations

6.1 DATA CONTENT

Geology: GeoClimate is concerned with potential ground stability related to ***natural*** shrink–swell geological conditions only. Factors including building foundations, tree size and proximity, and surface sealing should also be considered for a full assessment of the potential risk to a property.

- GeoClimate is based on, and limited to, an interpretation of the records in the possession of The British Geological Survey at the time the dataset was created.
- An indication of natural ground movement due to shrink–swell does not necessarily mean that a location will be affected by ground movement or subsidence. Such an assessment can only be made by inspection of the area by a qualified professional.

GeoClimate does not identify the cost of a hazard being realised and, therefore, does not consider risk. GeoClimate examines the conditions that leave an area exposed to a hazard and the change in potential for this hazard to worsen due to climatic change.

A high hazard does not necessarily translate to a high risk. For example, if a particular location has a relatively high ground stability hazard, but the properties are designed to withstand the hazard, with foundations that take the effects of climate change into consideration, they will not be at risk due to this geohazard.

The level of potential hazard does not mean that damaging ground movement is going to happen but is an indication of causative factors that may occur and how severe they are thought to be.

The text provided in the GeoClimate shrink-swell dataset are designed to provide a general indication of the meaning of the various GeoClimate shrink-swell dataset levels. If the data are to be used for advising specific sectors of end users in detail, e.g. home-buying, property insurance, site development and construction, then the BGS can provide additional end user guidance and attribution details for the data. To find more about this, please contact our Business Solutions department through the Central Enquiries Desk using the contact details above.

GeoClimate is concerned with potential ground stability related to ***natural*** shrink–swell geological conditions only.

6.2 SCALE

The GeoClimate dataset has been developed at a quasi-1:50,000 scale and must not be used at coarser scales. GeoClimate provides projections at the highest resolution possible, considering the methodology and input datasets. It is based on the best and most appropriate resolution datasets available at national scale and coverage. The initial scale of climate projections should be considered when carrying out detailed local-scale assessments.

6.3 ACCURACY AND UNCERTAINTY

BGS Geological data: The mapping accuracy associated with the BGS GeoSure natural ground stability dataset is based on that of the BGS Geology50 dataset. This is nominally 1 mm which equates to 50 m on the ground at 1:50 000 map scale. This is only a measure of how faithfully the lines are captured. Consequently, this dataset must not be used at scales finer than 1:50 000.

CHESS-SCAPE climate data:

The UK Centre for Ecology & Hydrology worked with the UK Meteorological Office in the SPEED (Spatially explicit Projections of EnvironmEntal Drivers) project. One of their key outputs was the CHESS-SCAPE future climate dataset. This is derived directly from climate model output provided by UK Climate Projections 2018 (UKCP18) but extending it by: downscaling to 1 km resolution based on physical and empirical relationships; bias-correcting to the CHESS-met observation-based data set and lastly, developing alternative RCP scenarios, derived from the original RCP8.5 scenario provided by UKCP18.

CHESS-SCAPE provides several physical climate variables over the UK for the period 1980-2080. GeoClimate CHESS-SCAPE utilises the 1 km spatial resolution daily averages for temperature and rainfall. It is derived from four members of the UKCP18 12 km Regional Climate Model (RCM) ensemble, chosen to represent the values and variation of the original ensemble, and cover four scenarios: RCP2.6, 4.5, 6.0 and 8.5, of which GeoClimate CHESS-SCAPE uses 3. By averaging the outputs of the different models, this will to some extent reduce any variability associated with individual members specific performance.

6.4 ARTEFACTS

The BGS Geology 50k dataset represents data from different times and origins. This can result in disagreements between older and more recently gathered observations (such as boreholes). Consequently, adjacent geological sheets/tiles (of different survey dates) may not seamlessly fit together spatially, or in terms of lithological description. This can result in some map-sheet 'edges' that exhibit contrasting colours/attribution.

GeoClimate can appear to be pixelated, even though it is derived from the 1:50,000 geology polygons. This is due to the gridded nature of areas of GeoClimate, due to the resolution of the soil moisture deficit data generated using the BGS groundwater model (ZOODRM). This provides an output grid with a resolution of 2 km. Therefore, when combined with the geological 1:50,000 polygon dataset, in areas where the soil moisture deficits values lead to a varying

GeoClimate classification, across areas of consistent volume change potential, the grid is clearly visible.

6.5 DISCLAIMER

The use of any information provided by the British Geological Survey ('BGS') is at your own risk. Neither BGS nor the Natural Environment Research Council (NERC) or UK Research and Innovation (UKRI) gives any warranty, condition or representation as to the quality, accuracy or completeness of the information or its suitability for any use or purpose. All implied conditions relating to the quality or suitability of the information, and all liabilities arising from the supply of the information (including any liability arising in negligence) are excluded to the fullest extent permitted by law. No advice or information given by BGS, NERC, UKRI or their respective employees or authorised agents shall create a warranty, condition or representation as to the quality, accuracy or completeness of the information or its suitability for any use or purpose.

Our range of GeoClimate Products are developed using climate scenario data obtained from 3rd parties, so, although BGS strives to make it as accurate as possible, we can offer no warranty as regards fitness for purpose or accuracy. Furthermore, the Products information provided is the result of modelled outputs and provided as best available, scientifically modelled data only.

BGS strives to maintain its information products to the highest standards. Information products released are quality checked for both their scientific and technical completeness and merit. Any feedback from users should be notified to BGS via digitaldata@bgs.ac.uk. All feedback will be logged, assessed and prioritised, feeding into the product development process for action as appropriate.

Appendix 1

FREQUENTLY ASKED QUESTIONS

These questions and answers have been provided to address any potential issues relating to how the product can be used or how it can be interpreted. If you have any additional questions, please contact digitaldata@bgs.ac.uk

Q: What does the BGS GeoClimate shrink-swell data show?
A: This dataset provides information on the projected future change in susceptibility of clay shrink–swell across Great Britain due to climate change. It considers the changing climate and the associated changes in near-surface groundwater content, as well as the static variables of geology and geotechnical values.

Q: **What areas does the BGS GeoClimate shrink-swell cover?**
A: All the GeoClimate datasets have coverage for Great Britain (see Figure 2).

Q: In what data formats can the BGS GeoClimate shrink-swell dataset be provided?
A: The BGS GeoClimate datasets are available as vector GIS datasets with attribute values relating to shrink-swell hazard susceptibility under a range of climate scenarios. The dataset comprises both polygon and grid data. Please email digitaldata@bgs.ac.uk to request further information.

Q: What is the relationship between GeoSure and GeoClimate?
A: The GeoSure Shrink–Swell is a hazard susceptibility rating that does not change for a geological deposit. However, the projected changes in climate vary across Great Britain, and therefore the GeoSure shrink-swell rating is combined with climate projections, to provide a GeoClimate rating.

Whereas GeoSure shrink-swell considers only the physical properties of the geology, GeoClimate considers how these physical properties may be affected in the future as a consequence of projected changes in climate. Where users are interested in the level of modelled 'change' from "current climatic conditions", we provide a 1996 baseline dataset (based on the time period 1991-2001) which should be referred to.

Q: How does GeoClimate shrink-swell compare to GeoClimate UKCP18?

A: GeoClimate UKCP18 was only available for RCP8.5. The UKCEH CHESS-SCAPE RCP8.5 average climate projection is slightly drier than UKCP18, providing projections with slightly higher increases in subsidence susceptibility. Overall, the difference in outputs in very comparable, showing the robustness of the CHESS-SCAPE subset of 4 ensemble members to represent UKCP18 (Figure 9).

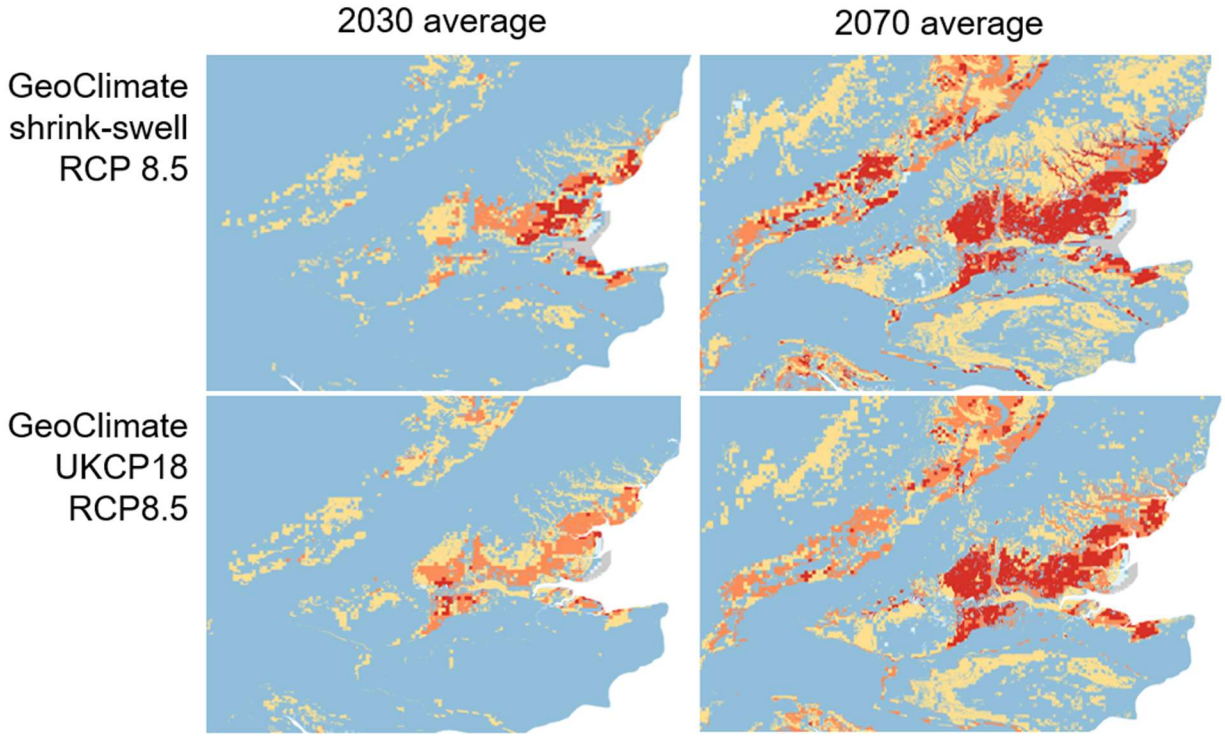


Figure 9: GeoClimate shrink-swell RCP8.5 and GeoClimate UKCP18 RCP8.5 projections for 2030 and 2070. BGS © UKRI. Contains OS data © Crown copyright and database right (2026)

Q: Why does the susceptibility change over time?

A: Changes in susceptibility are driven by both the mineralogical and lithological characteristics of the geology, combined with the climate. Some areas of the country will never experience clay shrink-swell due to the underlying geology, and these areas remain 'improbable' in every time period. In other areas, the underlying geology contains clay minerals that can shrink and swell due to the varying water content but are not yet experiencing fluctuations large enough to trigger visible volume change and ground movement. As climate conditions change and become more extreme, these areas could see increased hazard and impacts.

Q: Why doesn't GeoClimate shrink-swell simply show a worsening over time, with drier conditions the higher the Representative Concentration Pathway (RCP)?

A: There is a general relationship that RCP8.5 is drier than RCP4.5, which is drier than RCP2.6, and the further into the future, the larger the increase in clay shrink-swell susceptibility. However, this is greatly simplified and there are deviations from this, due to complexities such as;

- reductions in aerosols accompanying the reduction in greenhouse gas (GHG) emissions. Aerosols have a cooling effect, and a much shorter lifetime in the atmosphere, leading to non-linear responses and potentially an increase in temperature following rapid mitigation strategies, followed by cooling in the longer term.
- lag times of decades in the GHG emissions reductions and impact on global temperatures, due to long lifetime of carbon dioxide in the atmosphere.
- variation in rainfall infiltration rates due to increasing summer temperatures causing drying of the ground surface and leading to increased runoff.

Q: How are the GeoClimate shrink-swell average, wetter and drier scenarios calculated?

A: CHESS-SCAPE has four ensemble members, which were chosen to span the range of temperature and precipitation change in the UKCP18 ensemble, representing the ensemble climate model uncertainty. The GeoClimate shrink-swell methodology therefore provides four soil moisture deficit values for each grid square; The values from each of the climate realisations are sorted from wettest to driest and the 10th, 50th and 90th percentile of the model distribution were calculated. The 10th percentile has been utilised to represent the wetter conditions, the 50th percentile represents median average conditions and the 90th percentile represents drier conditions.

Q: What does the data unavailable category represent?

A: The reason for the 'unavailable' category arises from 2 different sources. Firstly, all the input datasets required are not available for the Scottish Islands (including Orkney and the Shetland Isles). Therefore, results for these areas are categorised as 'Input datasets unavailable'.

Secondly, during the data processing, various points along the coastline produced extremely high outlying values of soil moisture deficit. Those events originate with the climate scenario data. To account for this, any grid point with extremely high soil moisture deficit values was removed and replaced with a null value. It is therefore not possible to provide a GeoClimate score and the cell is recorded as 'unavailable'.

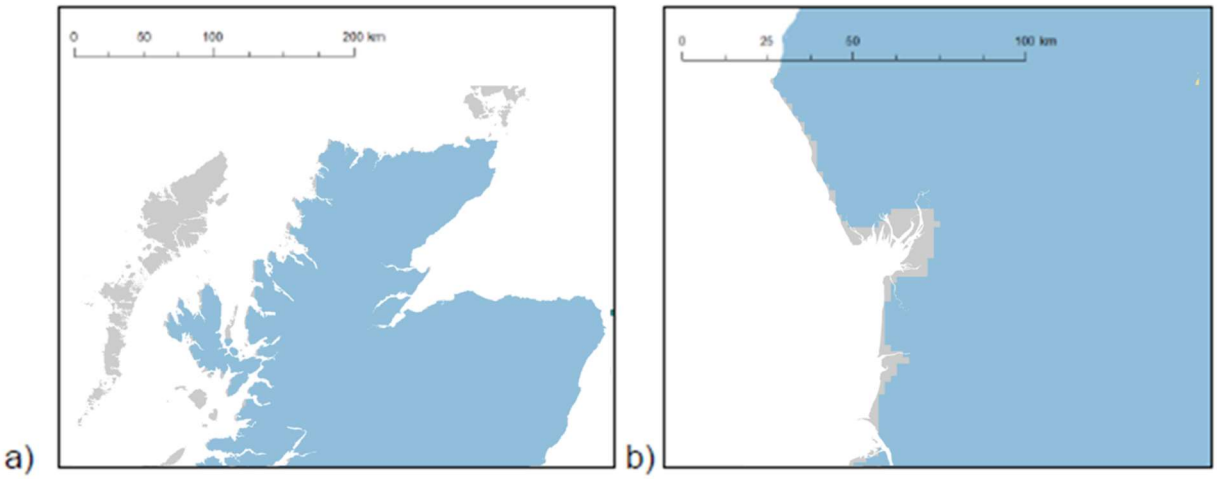


Figure 10: GeoClimate shrink-swell of a) the Outer Hebrides and b) Morecambe Bay, demonstrating the two origins of data unavailable areas (grey). BGS © UKRI. Contains OS data © Crown copyright and database right (2026)

Q: Why does GeoClimate appear to be pixelated, when it is derived from the 1:50,000 geology polygons?

A: The gridded nature of areas of GeoClimate is due to the resolution of the soil moisture deficit data generated using the BGS groundwater model (ZOODRM). This provides an output grid with a resolution of 2 km. Therefore, when combined with the geological 1:50,000 polygon dataset, in areas where the soil moisture deficits values lead to a varying GeoClimate classification, across areas of consistent volume change potential, the grid is clearly visible.

Q: What BGS geological map scale is utilised in the BGS GeoClimate dataset?
A: GeoClimate shrink-swell utilises 1:50 000 scale geological data and is therefore quasi-1:50 000 scale and is intended for use at this scale. All spatial searches of the maps should be undertaken using a minimum 50 m buffer. This is because the smallest detectable feature at this scale is 50 m. Consequently, digital data should therefore be used at about the same scale as the original compilation; for example, 1:50 000-scale data should not normally be used at 1:10 000 scale.

Most geological maps were originally fitted to a particular topographic base and care must be taken in interpretation, for example when the geological data is draped over a more recent topography.

Q: How often will the BGS GeoClimate shrink-swell dataset be updated?
A: This dataset is not routinely updated. The dataset is revised on an ad hoc basis, as and when there are significant changes in its source data, and/ or it is prioritised for update.

Q: Can I use the BGS GeoClimate shrink-swell dataset as part of a commercial application?

A: This dataset is licenced from BGS, please refer to the terms of your licence or contact iprdigital@bgs.ac.uk for further information.

Q: For RCP2.6, why is the 2050 projection the driest, drier than 2070?

A: Despite the aggressive mitigation described in RCP2.6, warming continues and peaks mid-century and then gradually declines and stabilizes. Even with immediate, sustained, and very rapid reductions in greenhouse gas emissions globally, UKCP18 suggest the country will experience an additional warming of around 0.6°C between now and 2050 (Reference: CCC). By 2070, RCP2.6 projects long term stabilisation occurs with recovery towards wetter conditions.

Q: Why don’t the near-term projections for 2030 show a simple relationship of increasing susceptibility with the higher emissions scenarios?

A: Due to there being relatively modest differences between the emissions for the different RCPs at the start of the century, and the atmospheric lags experienced, there is no simple clear relationship between the RCPs for the 2030 projections. Due to the lag between carbon dioxide emission reductions and climate response (decades), these only starts to have a clearer impact after 2050s.

Q: In 2030, why is the RCP4.5 projection suggesting a larger increase in clay shrink-swell, than RCP2.6 and RCP8.5?

A: Coal and fossil fuel burning releases GHGs and sulphate aerosols. Sulphate aerosols have a cooling effect on the climate, by reflecting sunlight and promoting cloud formation, leading to less sunlight reaching the ground surface, partially masking the warming effect of GHGs. Sulphates have a relatively short lifetime in the atmosphere, of days to weeks, in comparison to carbon dioxide, of which around 50% is absorbed within 30 years.

A very rapid decrease in coal use is projected for RCP2.6 by 2020, leading to a swift reduction in GHG and sulphate emissions. Hence, the RCP2.6 projection is dominated by the success of the reduction in GHG emissions, and there is little additional impact from the reduction in sulphate aerosols. In comparison, with the intermediate mitigation pathway RCP4.5, the reduction in aerosols contributes to the warming projected for 2030, and the related increase in shrink-swell susceptibility. This is because when production falls, due to the shorter atmospheric lifetime of the sulphates, levels decrease quicker than those for carbon dioxide and GHGs.

Just as RCP2.6 is dominated by the impact of rapidly decreasing GHG emissions, RCP8.5 is driven by the gradually increasing GHG emissions over the coming century, with the sulphates again playing a minor role. The near-term projections (2030) for GeoClimate shrink-swell for RCP4.5 and RCP8.5 are therefore no that dis-similar.

Q: Why does RCP4.5 suggest increasing susceptibility to clay shrink-swell in the south-east in the coming century?

A: RCP4.5 assumes GHG emissions peak around 2040 and then start to decline. Due to lags in atmospheric GHG concentrations the trends of increasing summer temperatures, decreasing summer rainfall and increasing summer rainfall intensity persist until the end of century.

Q: Why is the GeoClimate data gridded at 2km when the climate data is gridded to 1km and the geological data is 1:50000?

The GeoClimate methodology involves a hydrogeological model, which provides soil moisture deficit values at a 2 km grid resolution. Therefore, though the projected rainfall and temperature values are daily 1 km grid datasets, the output is a 2km grid, which is then combined with the 1:50000 geological data.

Q: Why have BGS not produced an Open version of GeoClimate shrink-swell?

As there is the potential of low-resolution data being used inappropriately for site-specific or high-stakes decisions, when used outside its intended scale and limits and without a clear understanding of the methodology and input datasets, a corporate decision was made to withdraw future Open GeoClimate datasets.

Q: Are previous versions of GeoClimate (UKCP18 and UKCP09) still available to licence?

BGS GeoClimate UKCP09 and BGS GeoClimate UKCP18 have now been withdrawn and superseded as BGS data products. As such the datasets are not actively maintained, although they are still scientifically correct and valid at the time that they were originally published. This BGS GeoClimate shrink-swell (CHESS-SCAPE) data product is being actively supported within the BGS portfolio of data products and utilises our most up to date climate projections, so we would encourage the use of this dataset.

Glossary

Jargon	Explanation
ArcGIS	Geographic information system (GIS) software for working with maps and geographic information maintained by the Environmental Systems Research Institute (ESRI).
Attribute	Named property of an entity. Descriptive information about features or elements of a database. For a database feature like census tract, attributes might include many demographic facts including total population, average income, and age. In statistical parlance, an attribute is a variable, whereas the database feature represents an observation of the variable.

Bedrock	The main mass of rocks forming the earth, laid down prior to 2.588 million years ago. Present everywhere, whether exposed at the surface in rocky outcrops or concealed beneath superficial deposits, artificial ground or water. Formerly called solid.
CHESS-SCAPE	Climate hydrology and ecology research support system - Status, Change and Projections of the Environment. Future projections of meteorological variables at 1 km resolution for the United Kingdom 1980-2080 derived from UK Climate Projections 2018. Produced by the SPEED project (Spatially explicit Projections of EnvironmEntal Drivers) by UK Centre for Ecology & Hydrology and the UK Meteorological Office.
ESRI	Environmental Systems Research Institute (ESRI) is an international supplier of geographic information system (GIS) software, web GIS and geodatabase management applications.
Geographical Information System	Geographic Information Systems (GIS) provides accurate information, assistance, support, and maintains and creates information to aid in the development of maps and data analysis.
Geohazard	Geological and environmental conditions, involving long and short-term processes which may lead to widespread damage. There are many different types of geohazard with different natural and artificial processes causing them to occur. All have the potential to create problems for development of the human environment and threats to the safety and well-being of people. Geohazards can develop quickly (seconds or minutes) in response to the processes that drive them, or take tens, hundreds, or thousands of years to develop to a point where they pose a danger. They are found in most parts of the world, including marine and fluvial environments.
Geology	The study or science of the earth, its history, and its life as recorded in the rocks; includes the study of geologic features of an area, such as the geometry of rock formations, weathering and erosion, and sedimentation.
Geotechnical	The application of technology to engineering problems caused by geological factors.
Ground resolution	The detail with which the location and shape of geographic features is depicted. The larger the map scale, the higher the possible resolution. As scale decreases, resolution diminishes and feature boundaries must be smoothed, simplified, or not shown at all; for example, small areas may have to be represented as points.
Hazard rating	Scale or classification used to indicate low to high degree of identified threat.
Hazard susceptibility	Likelihood of a vulnerability occurring at a given location.
Lithology	Rocks maybe defined in terms of their general characteristics of appearance: colour, texture and composition. Some lithologies may require a microscope or chemical analysis for the latter to be fully determined.
Modelled	Constructing a set of parameters to form a framework, populating with data and programmatically interpolating a surface by extrapolating across areas with no usable data.
Polygon	Polygons are a representation of areas. A polygon is defined as a closed line or perimeter completely enclosing a contiguous space and is made up of one or more links.

RCP	Representative Concentration Pathways (RCP) are climate change scenarios to project future greenhouse gas concentrations. These pathways (or trajectories) describe future greenhouse gas concentrations and have been formally adopted by Intergovernmental Panel on Climate Change (IPCC).
Resolution	Resolution expresses the size of the smallest object in a spatial data set that can be described. It refers to the amount of detail that can be discerned. It is also known as granularity.
Scale	The relation between the dimensions of features on a map and the geographic objects they represent on the earth, commonly expressed as a fraction or a ratio. A map scale of 1/100,000 or 1:100,000 means that one unit of measure on the map equals 100,000 on the earth.
Shapefile	The shapefile format is a geospatial vector data format for geographic information system software. It is developed and regulated by Esri as a mostly open specification for data interoperability among Esri and other GIS software products.
Subsidence	Subsidence is a lowering or collapse of the ground. It can be triggered by a change in drainage patterns, heavy rain, by water abstraction or man-made disturbance. Subsidence has the potential to cause engineering problems such as damage to foundations, buildings and infrastructure.
UKCP18	UKCP18 uses cutting-edge climate science to provide updated observations and climate change projections out to 2100 in the UK and globally. The project builds upon UKCP09 to provide the most up-to-date assessment of how the climate of the UK may change over the 21st century.
Vector	A representation of the spatial extent of geographic features using geometric elements (such as point, curve, and surface) in a coordinate space.
ZOODRM	Zooming Object Oriented Distributed Recharge model.

References

The British Geological Survey holds most of the references listed below and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at https://envirolib.apps.nerc.ac.uk/olibcgi.

BOORMAN, D B, HOLLIST, J M, AND LILLY A. 1995. Hydrology of soil types: a hydrologically-based classification of the soils of the United Kingdom. Institute of Hydrology Reports, No. 126. Wallingford, UK.

CRILLY, M. 2001. Analysis of a database of subsidence damage. Structural Survey, 19, 7-15.

GUARDIAN, 2018. Cracking summer: UK insurers expect rise in subsidence claims. Heatwave has caused damage to walls of homes, with south-east particularly susceptible. Available from https://www.theguardian.com/business/2018/aug/17/cracking-summer-uk-insurers-expect-rise-subsidence-claims-heatwave)

HARRISON, A, White J, Mansour M, Wang L, Mackay J.D, Hulbert A, Hughes, A.G. 2018. User Guide for the British Geological Survey GeoClimateUKCP18: Clay Shrink-Swell dataset. British Geological Survey Open Report, OR/20/13 19.pp.

HARRISON, A M, PLIM, J F M, HARRISON, M, JONES, L D, AND CULSHAW, M G. 2012. The relationship between shrink–swell occurrence and climate in south-east England. Proceedings of the Geologists' Association, 123, 556–575.

HUGHES, A G, AND MANSOUR, M, 2018. Application of the recharge model code ZOODRM to the British Mainland under conditions of climate change: scoping sources of uncertainty. Nottingham, UK, British Geological Survey, 29pp. British Geological Survey Open Reports, OR/18/021. (Unpublished)

INSURANCE TIMES, 2018. Industry fears realised as subsidence claims quadruple. Available from: https://www.insurancetimes.co.uk/news/industry-fears-realised-as-subsidence-claims-quadruple/1428969.article

INSURANCE TIMES, 2023. Summer 2022 heatwave saw surge in subsidence payouts – ABI. Available from: https://www.insurancetimes.co.uk/news/summer-2022-heatwave-saw-surge-in-subsidence-payouts-abi/1444127.article

JONES, L D. 2002. Shrinking and swelling soils in the UK: assessing clays for the planning process. Earthwise, Issue 18. British Geological Survey, 22–23.

JONES, L D. 2004. Cracking Open the Property Market, Autumn edition. Planet Earth, 30–31.

KEMP, S.J. AND WAGNER, D.. 2006. The mineralogy, geochemistry and surface area of mudrocks from the London Clay Formation of southern England. British Geological Survey Internal Report, IR/06/060. 81pp.

LEE K A, DIAZ DOCE, D. 2018. User Guide for the British Geological Survey GeoSure dataset: Version 8. British Geological Survey Open Report, OR/17/050. 18pp

MANSOUR, M M, WANG, L, WHITEMAN, M, AND HUGHES, A G. 2018 Estimation of spatially distributed groundwater potential recharge for the United Kingdom. *Quarterly Journal of Engineering Geology and Hydrogeology*, 51 (2), 247-263. https://doi.org/10.1144/qjegh2017-051

MET OFFICE HADLEY CENTRE. 2019. UKCP Local Projections at 2.2km Resolution for 1980-2080. Date of citation: December 2019. Available from http://catalogue.ceda.ac.uk/uuid/d5822183143c4011a2bb304ee7c0baf7.

MURPHY, J. M., SEXTON, D. M. H., JENKINS, G. J., BOOTH, B. B. B., BROWN, C. C., CLARK, R. T., COLLINS, M., HARRIS, G. R., KENDON, E. J., BETTS, R. A., BROWN, S. J., HUMPHREY, K. A., MCCARTHY, M. P., MCDONALD, R. E., STEPHENS, A., WALLACE, C., WARREN, R., WILBY, R., WOOD, R. A. 2009. UK Climate Projections Science Report: Climate change projections. Met Office Hadley Centre, Exeter, UK. 192pp.

MURPHY, J M, HARRIS, G R, SEXTON, D M H, KENDON, E J, BETT, P E, CLARK, R T, EAGLE, K E, FOSSER, G, FUNG, F, LOWE, J A, MCDONALD, R E, MCINNES, R N, MCSWEENEY, C F, MITCHELL, J F B, ROSTRON, J W, THORNTON, H E, TUCKER, S, AND YAMAZAKI, K. 2018. UKCP18 Land Projections: Science Report. UK Met Office. https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Overview-report.pdf

ROBINSON, E.L., HUNTINGFORD, C., SHAMSUDHEEN SEMEENA, V., AND BULLOCK, J.M. 2023, CHESS-SCAPE: high-resolution future projections of multiple climate scenarios for the United Kingdom derived from downscaled United Kingdom Climate Projections 2018 regional climate model output. *Earth Syst. Sci. Data, 15, 5371-5401*

ROBINSON, E.L.; HUNTINGFORD, C.; SEMEENA, V.S.; BULLOCK, J.M. (2022): CHESS-SCAPE: Future projections of meteorological variables at 1 km resolution for the United Kingdom 1980-2080 derived from UK Climate Projections 2018. NERC EDS Centre for Environmental Data Analysis, 01 April 2022. https://dx.doi.org/10.5285/8194b416cbee482b89e0dfbe17c5786c

VAN VUUREN, D, EDMONDS, J, KAINUMA, M, RIAHI, K, THOMSON, A, HIBBARD, K, HURTT, G, KRAM, T, KREY, V, LAMARQUE, J-F, MASUI, T, MEINSHAUSEN, M, NAKICENOVIC, N, SMITH, S, AND ROSE, S. 2011. The representative concentration pathways: an overview. *Climatic Change,* 109, 5-31.

WHICH, 2018. Subsidence claims hit record high: will your home insurance costs rise? Accessed March 2020. https://www.which.co.uk/news/2019/01/subsidence-claims-hit-record-high-will-your-home-insurance-costs-rise/

WHITE, J C, HARRISON, A M, ENTWISLE, D C, HULBERT, A G, JONES, L D, MANSOUR, M AND WANG, L. 2020. Forecasting future susceptibility to clay shrink-swell as a consequence on climate change. *Climatic Change*. Submitted 2019