Assessing future flood risk at BGS and NERC observatory sites: summary report

British Geological Survey

ENVIRONMENTAL CHANGE , ADAPTATION & RESILIENCE

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Glossary of terms

Coastal flooding	Flooding that results from a combination of high tides and stormy conditions, or from sea level rise.
Critical storm	a design storm which provides the highest peak flood discharges/water surface elevations for the flooding source.
Critical storm duration	the duration of the design storm, for a given return period, which provides the highest flood discharges/water surface elevations for the flooding source. This depends on the response time of the catchment and its general wetness.
Design storm	A hypothetical discrete rainstorm with a return period (or frequency), a specific duration, and temporal distribution of rainfall intensity values.
Digital terrain model (DTM)	A digital representation of the elevation of the land surface, mostly commonly on a regular grid.
Fluvial flooding	Flooding caused by the water level in a river, lake or stream rising and overflowing onto the surrounding banks, shores and neighbouring land.
Groundwater flooding	The emergence of groundwater at the ground surface away from perennial river channels or the rising of groundwater into man-made ground, under conditions where the 'normal' ranges of groundwater level and groundwater flow are exceeded.
HEC-RAS	A computer program that models the hydraulics of water flow through open channels and rivers accounting for the effects of bridges, culverts, weirs, and structures.
Hydrograph	Graphical representation of the rate of flow (discharge) over time.
Hyetograph	Graphical representation of the distribution of rainfall intensity over time.
LIDAR	Light Detection and Ranging (LIDAR), is a remote sensing method that uses light in the form of a pulsed laser to measure distances. It is widely used to measure land surface elevations e.g. from aircraft of drones.
Pluvial flooding	Flooding that results from rainfall runoff flowing or ponding over the ground before it enters a natural (e.g. watercourse) or artificial (e.g. sewer) drainage system or when it cannot enter a drainage system (e.g. because the system is already full to capacity, or the drainage inlets have a limited capacity).
RCP	Representative Concentration Pathway (see opposite).

RCP8.5	In RCP8.5 greenhouse gas emissions continue to rise throughout the 21st century. This has been thought to be very unlikely, but still possible as feedbacks are not well understood. RCP8.5 is generally taken as the basis for worst-case climate change scenarios.
Representative Concentration Pathway (RCP)	A greenhouse gas concentration trajectory adopted by the Intergovernmental Panel on Climate Change
Return period	Defines how often an event occurs. A 100-year storm refers to the storm (of a given duration and rainfall total) that occurs on average once every hundred years.
Surcharge	When the rate of flow of water entering a feature, such as a culvert constructed of a pipe, exceeds its capacity to convey it downstream. In this case, water may back up behind the feature and may flow over it or divert around it.
SWMM	Storm Water Management Model — a computer program that simulates the flow of rainfall-runoff through an urban drainage system including pipes, channels, storage units, pumps, and regulators.
UKCP18 climate projections	A set of climate model projections (temperature, precipitation, wind, sea level rise and storm surge, snow and weather types) for the UK produced by the UK Meteorological Office (Met Office) and partners.
Unit hydrograph	A direct runoff hydrograph resulting from one unit (e.g. one cm) of constant intensity uniform rainfall occurring over the entire watershed.

Summary

UK Research and Innovation (UKRI) recognises the problems posed by climate change, its impact on society, and the need for positive action to address the environmental sustainability challenges we now face. By 2040, UKRI aspires to be 'net-zero' for its entire research undertaking, which includes reducing and mitigating all carbon emissions from UKRI owned operations (UKRI, 2020). Surface water flooding can cause disruption to people's daily activities, businesses, and societal functioning, consequently increasing the pressure on natural resources. UKRI aims to understand the risk of flooding to its properties to act where possible to enhance climate resilience.

This Summary Report describes work undertaken by the British Geological Survey (BGS) in partnership with the Natural Environment Research Council (NERC) to investigate the risk of flooding to the BGS Keyworth and BGS Edinburgh sites, and to four NERC observatory sites (at Capel Dewi, Eskdalemuir, Hartland, and Herstmonceux). Flood risk was assessed under both 'current' and 'future' climate conditions. After reviewing existing assessments of the risk of flooding at these locations, additional flood analyses and modelling were undertaken for the sites that have been mapped as being at risk of fluvial or pluvial flooding. These sites are BGS Keyworth, BGS Edinburgh, and the National Centre for Atmospheric Science (NCAS) Capel Dewi Atmospheric Observatory (CDAO). This report summarises the findings from the analyses and hydraulic modelling studies of the three sites. It is accompanied by a second report, which provides more detailed technical information (Nagheli et al., 2022).

Flooding due to direct heavy rainfall (pluvial flooding) or due to overflowing surface water features (fluvial flooding) could cause water to inundate areas of the sites investigated, potentially resulting in business disruption and damage to infrastructure. The risk of this is assessed by evaluating whether a feature would be affected by surface water or not, and if so, how often it would be expected.

The UKCEH Flood Estimation Handbook (Institute of Hydrology, 1999) methodology was used to obtain profiles of rainfall over time for *design storms* (see Glossary). The ReFH2 software (the Revitalised Flood Hydrograph rainfall-runoff method version 2; Kjeldsen, 2006) was used to estimate the corresponding surface runoff hydrographs for catchments above points of interest.

The HEC-RAS flood modelling software (US Army Corps of Engineers, 2022) was used to simulate fluvial flooding. The SWMM modelling software (Storm Water Management Model; US EPA. 2022) was used to simulate pluvial flooding and to assess the capacity of drainage infrastructure (for BGS Keyworth only).

The assessment of how flood risk will change in the future makes use of climate change 'uplift' factors. These factors have been used to shift historical design storms. Uplift factors have been estimated using the latest UK Met Office Hadley Centre climate projections — the UKCP18 projections — by the UKRI-funded FUTURE-DRAINAGE project (Chan et al., 2021). Factors are only available for a 'worst case' atmospheric greenhouse gas concentration trajectory (referred to as a Representative Concentration Pathway or RCP) — the RCP8.5 pathway.

Based on these uplift factors, Table 1 summarises how flood risk at each of the sites is predicted by the modelling to change between the historical period (1961–1990) and the two future time horizons considered: the 2050s (2041–2060) and the 2070s (2061–2080).

The following findings and recommendations (see also Appendix 2) are presented for the three sites considered:

BGS Keyworth

- The site is not at risk of flooding from rainfall-runoff causing the water level within the channels running along the north-west and

Table 1 Summary of changing flood risk. (See section 3.2 for definition of risk categories).

	BGS Keyworth		BGS Edinburgh	NCAS Capel Dewi
	Fluvial	Pluvial	Fluvial	Fluvial
Historical	–	High	Medium	High
2050s	–	High	High	High
2070s	–	High	High	High

north-east of the site to rise and inundate parts of the site.

- The *critical storm duration* (see Glossary for definition) for BGS Keyworth was calculated to be seven hours.
- There are three culverts in the channel along the north-west of the site. If we adjust the historical 7-hour duration, 100-year return period summer storm to account for climate change, then the modelling indicates that the culverts in the drainage channel along the north-west of the site will surcharge but not result in inundation of any parts of the site. (Summer and winter storms are treated separately statistically by flood hydrologists because summer storms are more intense).
- Considering the same storm as described in the previous bullet, then if it is assumed that the bottom half of the culverts become blocked, the modelling predicts that the Platt Lane entrance to the site will be inundated by approximately 20 cm of water. No other part of the site would be affected.
- Again, considering a 7-hour storm with a return period of 100 years (calculated using data for the period 1981–2020), analysis of the UKCP18 climate projections for RCP8.5 suggests that the frequency of this event will change to:
    - 1 in 20 years over the period 2021–2040
    - 1 in 10 years over the period 2061–2080
- BGS facilities team should inspect the culverts at least annually and arrange for any debris to be cleared by the appropriate authority, if necessary.
- BGS should make Nottinghamshire County Council, the Lead Local Flood Authority (LLFA) for Keyworth, aware of this work, given the potential vulnerability to flooding of the new homes recently built on the northern side of Platt Lane, and of Severn Trent Water's sewage pumping station at the corner of Platt Lane and Nicker Hill.
- There has not been sufficient information about the site's drainage network to assess the risk of water appearing on the ground surface when the drainage network becomes surcharged. Furthermore, the development of a model to do this would be a complex task. Consequently, we have modelled the capacity of the subsurface drainage pipes and used this as a proxy to indicate which parts of the system are more likely to cause water to pond on the surface. Those pipe sections that have been simulated to surcharge, or exceed 90% of their capacity, during a 30-minute storm, need further investigation. The model simulates that 6% of the network's pipes exceed 90% of their capacity during a 30-minute, 10-year return period storm, which increases to 9% during a 30-minute, 75-year return period storm. First, the slopes and lengths of the problematic network sections should be measured accurately, and the modelling exercise repeated to confirm the findings of this study. Updating and rerunning of the model would be relatively quick. After confirming the fidelity of the model, several potential solutions could then be reviewed, and their costs and benefits evaluated against the level of risk that NERC BGS are willing to accept. Solutions could include replacing small diameter pipes with larger pipes, increasing the slopes of the pipes, optimising the size of catchment areas generating runoff by altering the direction of surface flow paths/directions. It is important to maintain the drainage infrastructure to avoid surcharging of the network and flooding.

BGS Edinburgh

- The levee and flood gates constructed along the Murray Burn in 2020 have enhanced the protection of the Lyell Centre. However, our modelling predicts that the Lyell Centre would still be affected by flood water under a 20-year return period storm. We conclude that the levee is not sufficiently high at its downstream end and, based on our new drone-based LIDAR survey of land surface elevations, flood water overtopping the levee here flows towards the Lyell Centre. If it is considered that the degree of flood protection is currently insufficient, we recommend that NERC and Heriot Watt University discuss what the options are for increasing the level of protection to the Lyell Centre. For example, this could include extending the levee downstream and increasing its height, or potentially increasing the cross-sectional area of the channel.

- The critical storm duration for BGS Edinburgh was calculated to be seven hours. Considering a 7-hour storm with a return period of 100 years (calculated using data for the period 1981-2020), analysis of the UKCP18 climate projections for RCP8.5 suggests that the frequency of this event will change to:
    - 1 in 20 years over the period 2021–2040
    - 1 in 7.1 years over the period 2061–2080
- Our modelling has shown the potential for flooding of other buildings on the Heriot Watt campus, e.g. the Energy Academy and the buildings north-east of the Lyell Centre on the opposite side of the Murray Burn and Research Avenue South. This report should be shared with the Heriot-Watt estate management department to make them aware of the risks to the occupiers of these buildings, and to allow them to consider any necessary actions.

NCAS Capel Dewi Atmospheric Observatory (CDAO)

- The south-east corner of the site was flooded on 21 January 2018. Measurements of rainfall every 10 minutes during this day have been made available by the CDAO's Project Scientist. Comparison against long-term historical observations of rainfall has indicated that the design storm that most closely matches the peak rainfall intensity and total rainfall of the observed storm has a 7-hour duration and 30-year return period.
- Land surface elevation data for the site are only available on a relatively coarse, 5 m grid. Because of this, there is significant uncertainty about the cross-sectional shape, and slope, of the Afon Peithyll, which flows east to west along the south of the site. The results of the modelling must, therefore, be considered as 'indicative'.
- For a 7-hour, 30-year return period design storm the current model simulates flooding that was more extensive than that observed in January 2018. However, it does indicate the area of the facility that is at higher risk — the south-east and east of the site, which is consistent with the observations.
- Simulation of the influence of the culvert (approximately 300 m downstream of the site) and whether it is partially blocked or not, suggests that it has little impact on the flood risk of the site.
- The critical storm duration for the site was calculated to be four hours. The modelling suggests that a 4-hour storm with a return period of seven years will *initiate* out of bank flooding at the south-east corner of the site.
- Considering a 4-hour storm with a return period of 100 years (calculated using data for the period 1981–2020), analysis of the UKCP18 climate projections for RCP8.5 suggests that the frequency of this event will change to:
    - 1 in 20 years over the period 2021–2040
    - 1 in 10 years over the period 2061–2080
- A survey of the Afon Peithyll and its floodplain is needed to define the dimensions and slope of the channel accurately and improve confidence in the model.
- A number of engineering options are listed that could be considered to protect the site from flooding; their viability would depend on the characteristics of the site, cost, and possible environmental impacts.
- Consideration could be given to the feasibility, and costs and benefits of moving infrastructure located in the south-east of the site, where flood risk is higher, to another part of the site.

1. Background

UKRI's Sustainability Strategy outlines the organisation's commitment to protect and enhance the quality of the physical environment (including water, air and land quality) while ensuring UKRI is resilient in the face of environmental change (UKRI, 2020). As part of this, UKRI has required all of its councils, including NERC, to adopt Climate Change Adaptation Plans.

The process of climate change adaptation depends on the regular reassessment of the risks and potential impacts of climate change, and subsequent adjustment of adaptation strategies and adaptive actions. Flooding is one hazard that will have to be adapted to as the risk of extreme rainfall increases as the climate changes.

The purpose of this work has been to assess of the risk of flooding to the BGS sites and to four NERC observatory sites, thereby supporting NERC and the BGS to manage this risk to their estate. Flood risk is assessed under both historical and future climate conditions. The project aims to contribute to the development of flood mitigation options and adaptation strategies, if deemed necessary based on the findings of the work.

The scope of the work was based on a prior review of existing assessments of flood risk undertaken by each of the environmental regulators for England, Scotland, Wales, and Northern Ireland. These previous assessments, which are based on the analysis and modelling of historical rainfall data and observations of flooding, are summarised in Appendix 1. Those sites where an area of the site has been mapped as being at risk of pluvial or fluvial flooding (based on historical climate) have been subject to further analysis as part of this study — these are BGS Keyworth, BGS Edinburgh, and the NCAS Capel Dewi sites. Investigation of flood risk at the UKCEH/BGS Wallingford and British Antarctic Survey, Cambridge sites was out of scope (see Appendix 1 for further information).

2. Project Objectives

The purpose of this study was to estimate by how much climate change could alter flood risk at BGS Keyworth, BGS Edinburgh, and the following four NERC observatory sites:

- BGS Eskdalemuir Magnetic Observatory, Dumfries and Galloway.
- BGS Hartland Magnetic Observatory, Devon.
- NCAS Capel Dewi Atmospheric Observatory (CDAO), Ceredigion.
- NERC Space Geodesy Facility, Herstmonceux, East Sussex.

Flood *risk* is a combination of the probability of the *hazard* occurring, and *vulnerability*, which defines the extent of harm that can be expected under certain conditions of exposure. Harm could include, for example, damage to buildings and infrastructure inundated with floodwater, business disruption, and impacts on the health and safety of people.

Risk is assessed in this study by calculating whether a feature of interest is expected to be affected by flooding produced by *design storms* of different *return periods*. These design storms are derived from analysis of historical rainfall. Historical design storms are 'shifted' using information from simulations of future global climate to generate design storms that account for climate change.

The sites considered in this study could be affected by either *fluvial* or *pluvial* flooding, or both. None of the sites are at risk of *coastal* or *groundwater* flooding. Fluvial flooding occurs when the water level in a river, lake or stream rises and overflows onto the surrounding banks, shores and neighbouring land. Pluvial flooding is caused by an extreme rainfall event that generates rates of runoff that exceed the capacity of the land or drainage network to transport the water away, causing it to pond or surcharge drains.

3. Methodology

3.1 Modelling approach

3.1.1 Describing rainfall events using design storms

The Flood Estimation Handbook (FEH) web service (UKCEH, 2022) provides estimates of *design rainfall* for different storm durations and return periods for any location in the UK. The FEH rainfall frequency analysis, based on rainfall observations for the period 1961–1990, uses the annual maximum depths of rainfall for calendar years aggregated over various durations from one hour to eight days. This leads to a statistical model that links the rainfall depth to duration and frequency.

The tools provided through the FEH web service were used to produce storm *profiles* or *hyetographs* for different storm durations and return periods; these profiles describe the variation of rainfall over time for the selected duration and return period. The profile is symmetric, single-peaked and bell shaped and provided for winter and summer events. The summer profile is more peaked than the winter profile because of the prevalence of intense convective storms in the summer. The return period defines the average time between events. Higher return period storms (of a given duration) are less frequent and generate higher amounts of rainfall.

The flooding generated by different storm profiles is assessed to identify the *critical storm duration* for a selected return period. This is the duration of the design storm that generates the highest flood discharge rates or water elevations for the source of flooding. It depends on the response time of the catchment and its general wetness and is found by testing a number of storm durations.

Figure 1 shows example storm profiles (hyetographs) for a 7-hour duration storm for return periods of 100, 200 and 300 years and summer and winter seasons for BGS Keyworth.

3.1.2 Converting a design storm into a runoff time-series for a catchment

Given a design storm profile, the runoff hydrograph for any catchment above a user-defined location within the UK can be estimated using the ReFH2 software (Revitalised Flood Hydrograph rainfall-runoff method version 2; Wallingford HydroSolutions, 2022). The ReFH2 model uses the Flood Estimation Handbook (Institute of Hydrology, 1999) catchment descriptors (for climate, drainage characteristics, and soils) to estimate the runoff hydrograph. It divides the catchment into two compartments, a rural compartment and an urban compartment, and applies hydrological models that suit the characteristics of these compartments to derive the runoff time-series.

Figure 2 shows an example of the catchment areas produced by the FEH method at BGS Keyworth and the runoff hydrographs produced by the ReFH2 method at two points G2 and G3 located upstream of the Keyworth site.

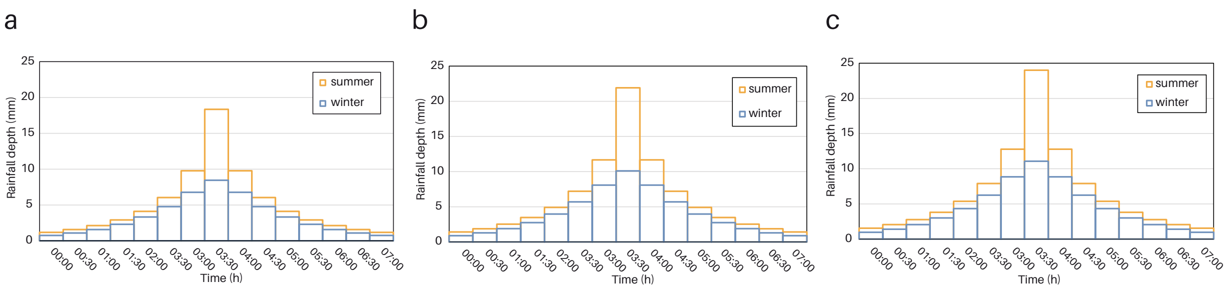

Figure 1 Design rainfall with 7-hour duration for a) 100, b) 200 and c) 300-year return periods for BGS Keyworth.

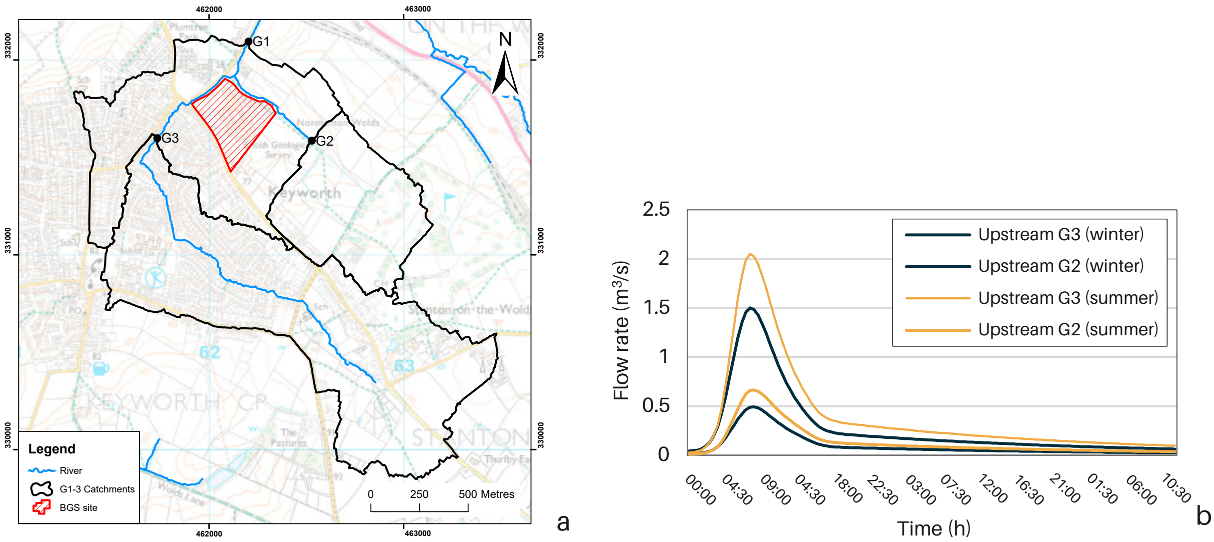

Figure 2 a) Catchment areas generating runoff at BGS Keyworth, b) flood hydrographs at Points G2 and G3 generated by ReFH2. [© Crown copyright and database rights [2022] OS].

3.1.3 Adjusting historical design storms to account for future climate change

Changes in the intensity and frequency of extreme rainfall events in the UK due to climate change are typically modelled via an 'uplift' to existing FEH design rainfall, where the rainfall intensities at each time-step are multiplied by a climate change factor. Uplift factors have been estimated using the latest UK Met Office Hadley Centre climate projections — the UKCP18 projections -by the UKRI-funded FUTURE-DRAINAGE project (Chan et al., 2021). Factors are provided for a 'worst case' atmospheric greenhouse gas concentration trajectory (referred to as a Representative Concentration Pathway or RCP) — the RCP8.5 pathway.

The uplift values are provided for 2050 and 2070, compared to the baseline of 1990, for precipitation durations of 1, 3, 6, 12 and 24 hours, and return periods of 2, 30 and 100 years. Two estimates of future changes are provided by estimating percentiles from the distribution of outputs from the ensemble of 12 climate model runs used to simulate future climate - a central (50%) and high (95%) estimate. The uplift factors were used in conjunction with ReFH2 to generate the projected future storm hydrographs for 2050 and 2070.

3.1.4 Further use of UKCP18 climate projections

To further explore changes in the occurrence of rainfall events between historical and future periods we have used the UKCP18 climate change projections (Murphy et al., 2018). Specifically, the following UKCP18 dataset has been used:

- Local projections of hourly rainfall on a 2.2 km grid across the UK for the three time periods: 1981–2000, 2021–2040, and 2061–2080 (Met Office Hadley Centre, 2019).

For each 20-year window, time-series of hourly rainfall are provided from 12 climate model simulations. The simulations are based on models with different initial conditions and parameters, which were run to provide an ensemble of time-series outputs that enable an assessment of the uncertainty contained in the modelling process.

We analyse these data by identifying the number of times the amount of rainfall for an individual storm of a given duration is exceeded within the three time-horizons. For example, we may select the rainfall amount for a 7-hour duration storm that has a return period of 100 years based on either the historical observations or the 1981–2000 simulated period. Return periods from time-series of hourly rainfall have been estimated using a statistical method: extreme value analysis using the Gumbel Type I distribution function (Linsley, 1979). Because of the uncertainty associated with producing return periods from only 20 years of data, these 100-year return period rainfall totals should only be considered to be indicative. Though this approach contains uncertainty it does allow us to make some statements about the projected increase in frequency of storms over the coming century due to climate change, which can guide decision-making about future adaptation to climate change.

3.1.5 Modelling fluvial flooding

Fluvial flooding was modelled using the freely available and widely applied HEC-RAS software (US Army Corps of Engineers, 2022). Surface water flows and levels can be modelled in HEC-RAS: (i) along river channels by defining cross-sections (1D); (ii) across a floodplain surface described by a gridded elevation map (2D), or (iii) using a combination of both in which water spills out of the channels and onto the floodplain (1D+2D).

River channel cross-sections and floodplain elevations were derived from LIDAR surveys. LIDAR is an airborne mapping technique that accurately measures the height of the terrain and surface objects on the ground, through the use of a scanning laser that measures the distance between the aircraft (or drone) and the ground. Gridded LIDAR data, available from the Environment Agency (EA) in England and the Scottish Environmental Protection Agency (SEPA) in Scotland (at 1 m horizontal resolution), were supplemented by LIDAR surveys of BGS Keyworth and BGS Edinburgh sites (at 0.086 m horizontal resolution) undertaken by BGS Remote Sensing scientists using a drone.

The variation of flood water levels was predominantly simulated using the 1D functionality in HEC-RAS (i.e. flow along channels defined by multiple cross-sections). However, additional 2D and 1D+2D simulations were undertaken to validate the 1D simulations, and to check the accuracy of the simulated flood extent on the floodplain.

3.1.6 Modelling pluvial flooding

Modelling of pluvial flooding (undertaken for the BGS Keyworth site only) was performed using the US EPA's Storm Water Management Model (SWMM) software (US EPA, 2022). This open-source software is widely applied to simulate stormwater runoff, combined and sanitary sewers, and other drainage systems. The modelling software calculates rainfall-runoff from a number of sub-catchment areas and transports it through a system of pipes to a defined outlet feature. The model requires the definition of the catchment areas for drainage/sewer inlets and the specification of the structure of the different drainage/sewer networks. Catchment areas for input into the model were calculated from the high-resolution LIDAR survey undertaken by BGS staff. The software simulates the water depth in the drains/sewers, the capacity of which can be exceeded by the runoff entering the network, resulting in ponding and/or surcharging of the network.

3.2 Categorisation of risk

The Environment Agency define the long-term flood risk for an area in England according to the following categorisation:

- **High**: each year the area has a chance of flooding of greater than 3.3% (i.e. more often than once in 30 years).
- **Medium**: each year the area has a chance of flooding of between 1% and 3.3% (i.e. between once in every 100 and once in every 30 years).
- **Low**: each year the area has a chance of flooding of between 0.1% and 1% (i.e. between once in every 1000 and once in every 100 years).
- **Very Low**: each year the area has a chance of flooding of less than 0.1% (i.e. less frequent than 1 in 1000 years).

When describing the results of our modelling with the terms 'very low', 'low', 'medium', and 'high, the same categorisation is used.

3.3 Modelled sites

A table summarising the current assessment of risk for NERC sites made by the environment agencies is provided in Table 12 in Appendix 1. These assessments guided the selection of sites investigated as part of this study.

Of the BGS office sites, only BGS Keyworth and BGS Edinburgh were modelled as part of this study. The assessment of changing flood risk at the UKCEH/BGS Wallingford site, arising from the River Thames, was out of scope. The assessment of flood risk at BGS Cardiff and the Geological Survey of Northern Ireland (GSNI) office in Belfast was also out of scope. However, the Main Building of the University of Cardiff, within which the BGS

Cardiff office is located, is outside of the mapped ‘low risk’ zones for all forms of flooding. The GSNI office is mapped to be outside of the 1 in 1000-year flood risk zone for both fluvial and pluvial flooding.

Of the four NERC observatory sites considered, only the NCAS Capel Dewi Atmospheric Observatory is within a current flood risk zone (see Appendix 1 and accompanying Technical Report for further details). Consequently, only the Capel Dewi site was subject to further assessment and additional modelling within this study.

4. BGS Keyworth

4.1 Site description

The BGS Keyworth site is located at the north-east side of the village of Keyworth, Nottinghamshire. It covers an area of approximately 9.6 ha and constitutes office and laboratory buildings, and a large building hosting the national repository of geological cores (Figure 3 and Figure 4). There are two stream channels, which carry runoff from the Keyworth village and from surrounding land upstream of the site. These channels, illustrated by the blue lines in Figure 3, run adjacent to the site.

The site has two entrances. The main entrance is from the Nicker Hill road, which borders the south-west side of the site. The second entrance is on Platt Lane, which borders the north-west side of the site. Nicker Hill road slopes gently up towards the south and surface water will not pond next to the main entrance. Platt Lane slopes gently downward from south to north. The land to the south of the site slopes downwards towards the site. Along the south-east site boundary, a drainage channel (brown line in Figure 3), which collects surface water from the south, feeds into a pipe.

The natural drainage characteristics of the site are disrupted by buildings and the alteration of ground surface by roads and car parks etc. A network of drainage pipes has been constructed to remove

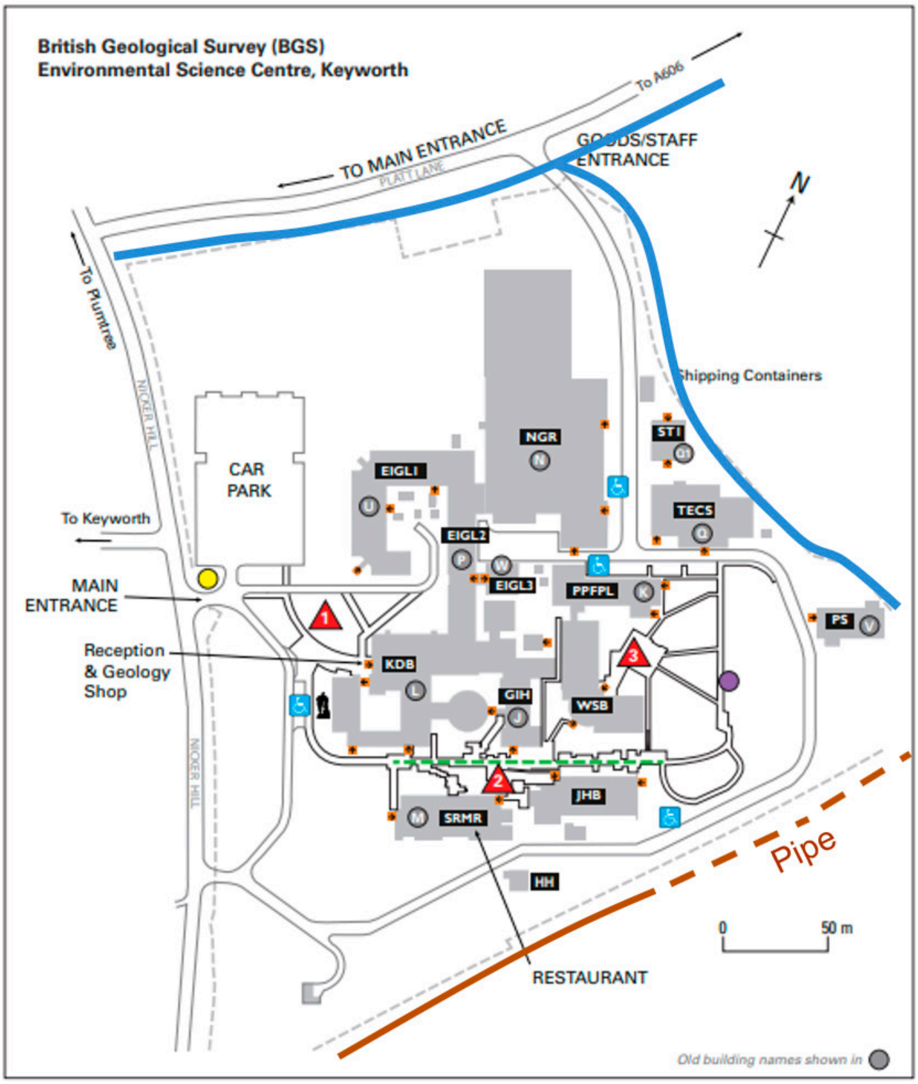

Figure 3 Details of the Keyworth BGS site.

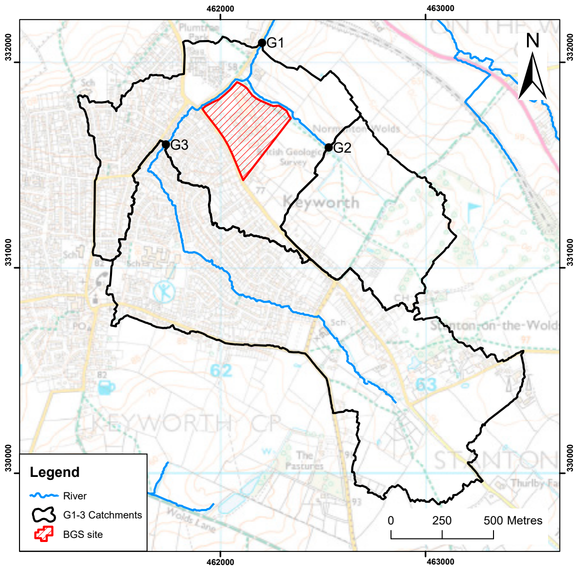

Figure 4 Sub-catchment areas contributing runoff to points G1, G2, and G3 along the stream channels. [© Crown copyright and database rights [2022] OS].

the surface water that cannot reach the natural channels. The layout of the network of pipes constituting the drainage infrastructure is complex; its performance has been investigated.

4.1.1 Previous assessment of flood risk

The assessment of the risk of flooding to BGS Keyworth from surface water made by the Environment Agency is shown in Appendix 1. Parts of the site have been characterised as being at medium risk. However, this assessment does not consider all the manmade changes to the topography and the drainage infrastructure constructed to discharge the surface water that may accumulate on the ground surface.

4.2 Flood risk from open channels

4.2.1 Model setup

A one-dimensional HEC-RAS model was developed to simulate flow in the channels along

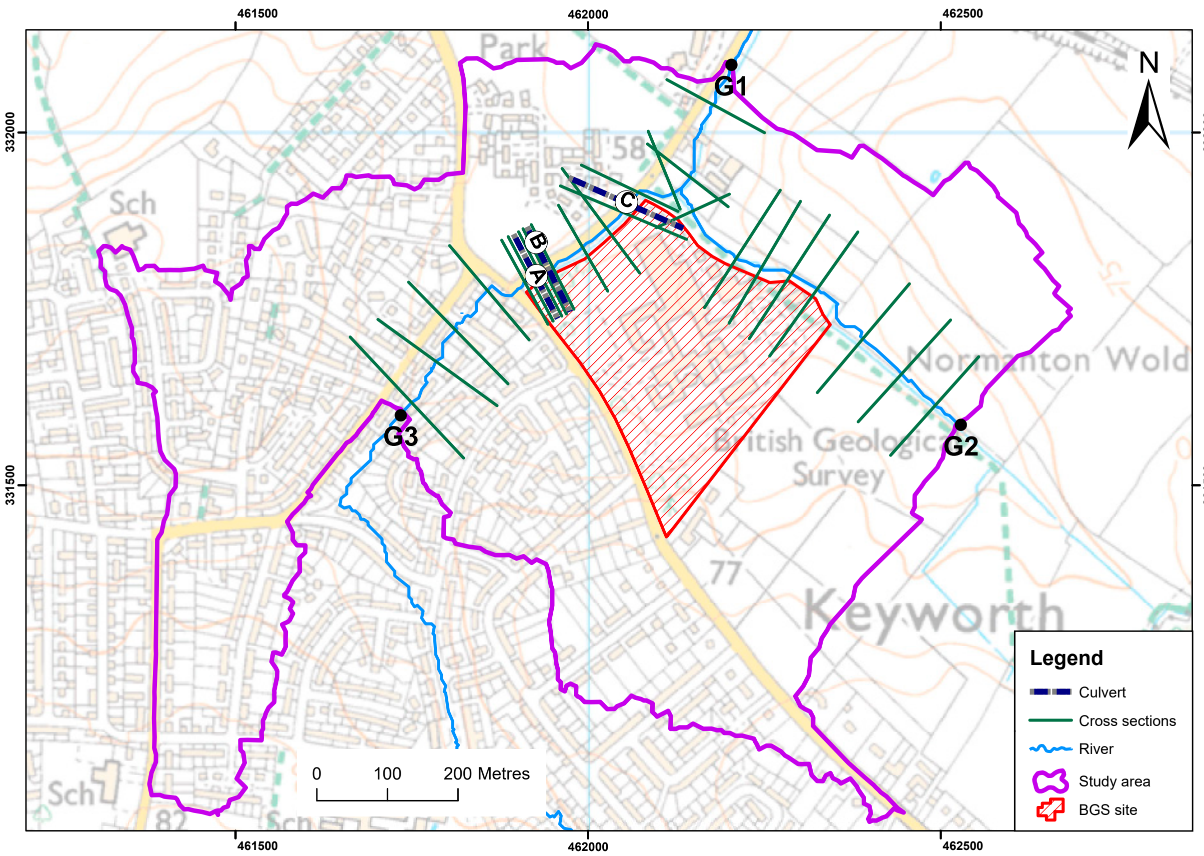

Figure 5 HEC-RAS model setup at Keyworth site. Location and extent of cross sections. [© Crown copyright and database rights [2022] OS].

the site boundaries and potential flooding from these. The EA and BGS LIDAR groundwater elevation data were used to define the pathways, gradients, and cross-sectional shapes of the channels (Figure 5 and Figure 6). The numbered dashed lines in Figure 5 represent the cross sections where within-channel structures have been constructed to enable crossing. These structures increase the level of the risk of flooding as they can restrict the passage of high flows along the channel. Their dimensions were measured and incorporated into the HEC-RAS model.

The Manning coefficient, which is used to calculate the loss of energy of flowing water due to friction, was set to a value of 0.04 as recommended in the literature for minor streams with overgrown vegetation and a rough surface (Coon, 1998). This value was used for all the parts of a cross section such as the left and right overbanks and the main channel. For culverts and bridge decks, the values for both the entrance and exit loss coefficients were set to 0.5, the Manning coefficient value used to calculate the friction losses within the culvert was set to 0.012, and the weir coefficient value was set to 1.4.

Design storm profiles for return periods of 100, 200 and 300 years and for summer and winter seasons were produced using the FEH web service. The use of FEH to generate design storms of various durations and ReFH2 to convert these into runoff hydrographs indicated that peak flows into the channels at points G1 and G2 (Figure 5) would be generated by storms of a 7-hour duration. Table 2 shows the peak flow rates calculated at these two points for the winter and summer season 7-hour storm duration and for 100, 200, and 300-year return periods. Rainfall-runoff generated in the catchment above G1 and below G2 and G3 (the purple catchment in Figure 5) was also routed to the channel.

Table 3 shows the values of the 100-year return period 7-hour storm event peak rainfall intensities and runoff flow rates calculated after the application of the UKCP18 climate projection uplift factors for the 2050 and 2070 time horizons. This table shows that the peak flow rates predicted for the 2070s with the 95% estimate of change at G2 and G3 are the highest and exceed the flow rates calculated using the historical 300-year return period storm event.

4.2.2 Findings

Figure 7 shows the spatial extent of the flooding simulated by HEC-RAS using the 100-year return period summer season storm event hydrographs for the 2070s and 95% interval, i.e. the results for the largest of the historical and future events considered. The model shows that water backs up behind the culverts at points B and C (Figure 5 and Figure 6), and predicts that parts of Platt Lane and Nicker Hill would be inundated, but the flooding would not reach any part of the BGS site, i.e. the front car park, the Platt Lane site entrance, and the National Geological Repository building are not affected.

In Figure 8, data derived from the UKCP18 time-series of hourly rainfall (described in section 3.1.4) are plotted. For each of the time-series of hourly rainfall produced by the 12 simulations of the Met Office Hadley Centre climate model for each of the three time periods (1981–2000, 2021–2040, and 2061–2080) the 7-hour duration rainfall with a return period of 100 years was estimated. The distribution of these 12 values is plotted as a box-and-whisker plot in Figure 8. The figure shows that the 7-hour, 100-year return period rainfall increases from the earlier to later time periods, but the spread of the simulated values also increases; the larger spread indicates that there is more uncertainty in the later climate simulations. The averages of the ensemble of 12 values (as depicted by the crosses in Figure 8) are: 50.9 mm (1981–2000); 60.1 mm (2021–2040); 68.2 mm (2061–2080). Assuming that the 7-hour, 100-year return period rainfall estimated from the i^{th} ensemble member (i = 1, 2, . . . ,12) for the 1981–2000 time-period is *R* mm (which, on average, would occur 0.2 times in the 20-year window), then the number of times that *R* occurs in the corresponding i^{th} ensemble member of the two future time period can be counted. On average *R* is simulated to occur once time during 2021–2040, and twice during 2061–2080. Therefore, imagining the year is 1990 then the chance of *R* is 0.01 (1/100). Within the 2021–2040 window the chance of *R* occurring in any year is estimated to be 0.05 (1/20), and in the 2061–2080 window this chance is estimated to be 0.1 (2/20).

To assess how the uncertainty in setting the roughness of the channels in the model could affect the results we increased the Manning's roughness coefficient to 0.08. This value represents an unmaintained channel with overgrown dense weeds and uncut brush. This simulation (based on the 100-year return period

Cross-section A

Cross-section B

Cross-section C

Figure 6 Structures built across the Murray Burn at cross-sections A-C in Figure 5.

Table 2 Maximum rainfall intensity values of a historical 7-hour storm duration and the corresponding peak flood volumes at points G2 and G3 in Figure 5.

Return period (Years)	Peak rainfall (mm) (hyetograph with 30 minutes time intervals)		Point G2 peak flow (m3/sec)		Point G3 peak flow (m3/sec)	
	Winter	Summer	Winter	Summer	Winter	Summer
100	8.46	18.35	0.49	0.66	1.49	2.05
200	10.09	21.9	0.6	0.83	1.82	2.54
300	11.06	24.0	0.67	0.93	2.02	2.85

Table 3 Rainfall peak intensity values and the corresponding peak flows at points G2 and G3 in Figure 5 for the design storms calculated by shifting the historical 100-year return period 7-hour duration design storm to account for climate change.

Time horizon	Estimate of change (%)	Uplift factor (%)	Peak rainfall (mm) (hyetograph with 30 minutes time intervals)		Point G2 peak flow (m^3/sec)		Point G3 peak flow (m^3/sec)	
			Winter	Summer	Winter	Summer	Winter	Summer
2050	50	20	10.15	22.02	0.60	0.83	1.84	2.56
	95	35	11.42	24.78	0.69	0.97	2.10	2.96
2070	50	25	10.57	22.94	0.63	0.88	1.92	2.69
	95	45	12.26	26.61	0.75	1.06	2.28	3.24

without the climate change uplift being applied) did not produce a flood extent that is larger than that shown in Figure 7, and again indicated the site infrastructure was not affected by flood waters.

The model was also used to assess if blockage of the culverts could generate flooding that affects the site. The culverts were modified in the model so that their bottom half was considered

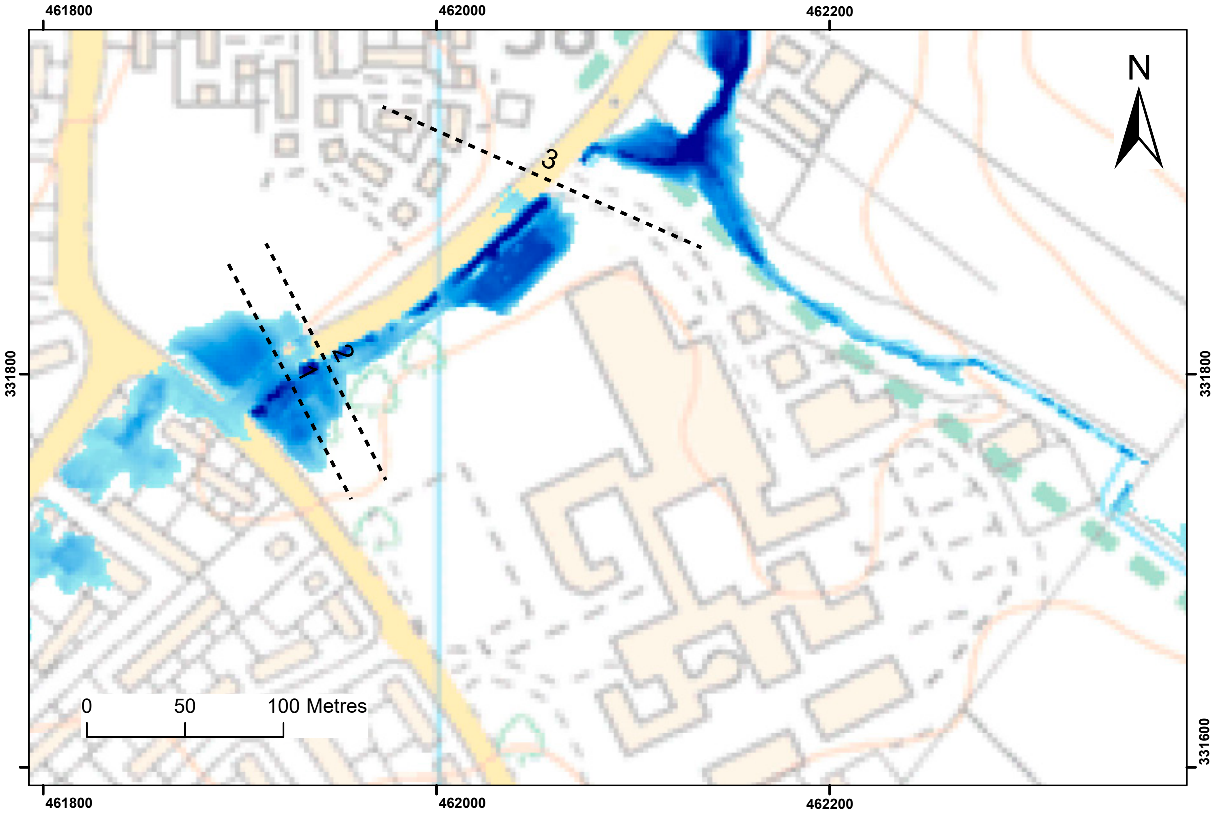

Figure 7 Simulated flood extent for Keyworth for the 2070s based on the design storm calculated by shifting the historical 100-year return period 7-hour summer season storm to account for climate change. [© Crown copyright and database rights [2022] OS].

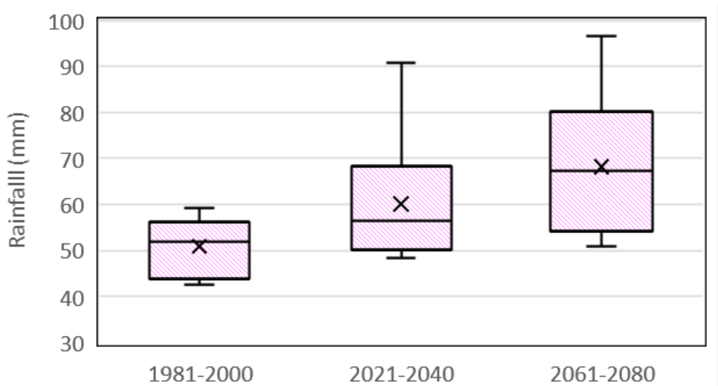

Figure 8 Box plots of 7-hour 100-year return period rainfall for BGS Keyworth calculated from the ensemble of 12 UKCP18 simulations for the three time periods: 1981–2000, 2021–2040, and 2061–2080.

to be clogged. A number of 7-hour duration design storms with different return periods were run though the model. It was found that the simulation using the historical 100-year return period summer 7-hour duration storm event results in the Platt Lane site entrance being inundated by approximately 20 cm of water. The extent of the flooding in this case is shown in Figure 9. Whilst the risk to the site is small, it is recommended that the condition of the culverts is checked at least annually, with debris being cleared if necessary.

4.3 Risk of flooding of subsurface drainage network

The sizes and slopes of pipes within a subsurface drainage network are designed so that they can contain the maximum flow without surcharging. In

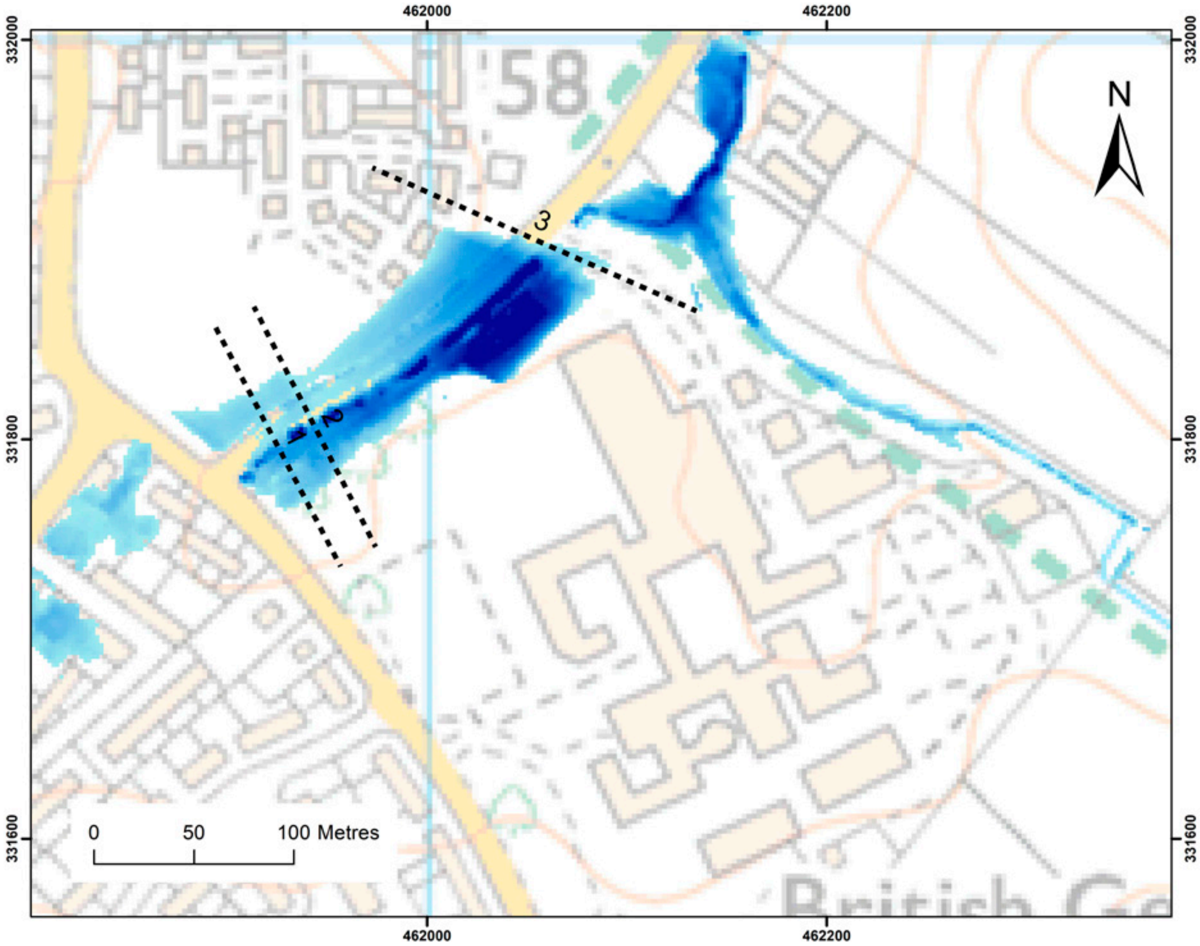

Figure 9 Simulated flood extent for the historical 100-year return period summer season storm with partially blocked culverts. [© Crown copyright and database rights [2022] OS].

addition, the velocity of the water inside the pipe must be high to prevent deposition of sediments or solids but not too high to avoid pipe wear. Stormwater pipe design can be based on full flow, which is usually achieved when the water depth inside the pipe is approximately 90% of the pipe diameter. At the design stage, the pipe diameter is chosen so that the above criteria are satisfied to ensure a cost-effective subsurface drainage network that can drain the storm water generated from a defined storm event over an urban catchment.

The peak flows of a selected design storm event may be exceeded under extreme weather events, which may lead the stormwater drainage pipes to become full. Under these conditions, the capacity of the pipes reduces and with further increases in inflows, the water backs up in the inspection boxes (manholes) and in the lateral pipes that connect the gullies (boxes with grates that are flush with road pavement) to the drainage network. Runoff water will stagnate on the surface when all these features become full as the pipe network fails to discharge the peak flows even with the additional rise of the water level. Surface flooding will then occur. In the current study, there has not been sufficient information about the sizes of the manholes, lateral pipes, and gullies to assess the risk of water appearing on the ground surface when the drainage network becomes surcharged. However, if this information was available, the development of a model to simulate surface water ponding accurately would be a complex task. Rather, the risk of pluvial flooding at BGS Keyworth site has been considered by assessing the capacity of the pipes within the stormwater drainage network. If the capacity of a pipe is reached, it is likely that water will appear on the ground surface. In this section we describe the application of a model to simulate the capacity of the drainage network under design storms.

4.3.1 Model setup

Figure 10 shows a map of the stormwater pipes (blue lines) and the foul sewer pipes (red lines) for the site. The stormwater pipes are connected to the building roofs through spouts and take land surface runoff through gullies. The collected water is discharged outside of the site at four outlets: one at the downstream end of the front car park (point A in Figure 10) and three to the back of the site (points B, C and D in Figure 10). Some stormwater is also discharged to two subsurface tanks one located underneath the car park at the back of the site and the second located at the south of the site (points T1 and T2 in Figure 10).

The EPA Storm Water Management Model (SWMM) software was used to simulate the depth of water in the stormwater network. The spatial characteristics of the different features required by the model (junctions, pipes, catchment areas) were produced using a Graphical Information System (GIS). The catchment areas from where direct runoff is generated were delineated using the digital terrain model (DTM) created from the LIDAR survey carried out as part of this project. The SWMM model takes a design storm profile and generates the corresponding surface flows based on the catchment characteristics as entered by the user.

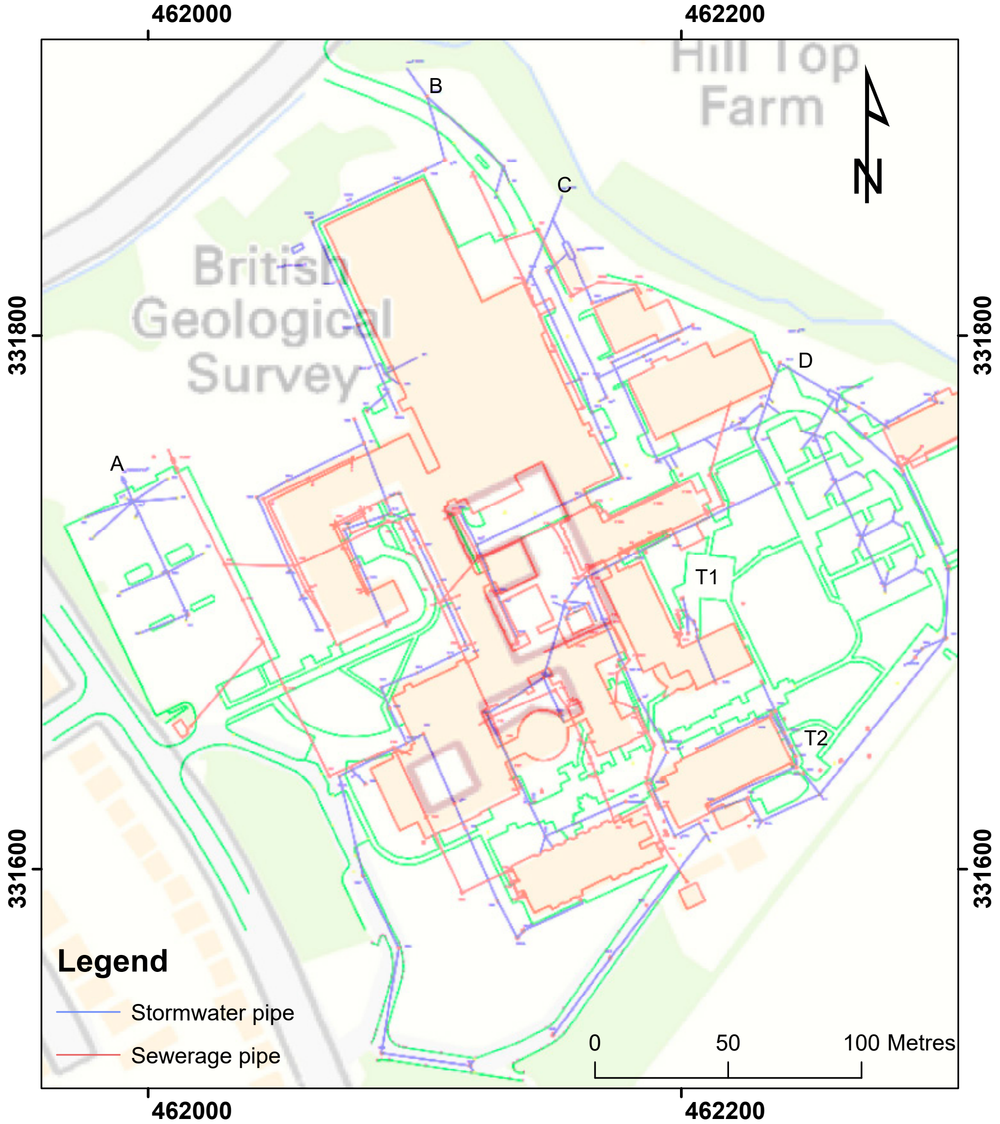

Figure 10 BGS Keyworth stormwater and sewerage network. [© Crown copyright and database rights [2022] OS].

Storm events with 100, 200, and 300-year return periods were used to assess the risk of network surcharge. The FEH method was used to produce design storm profiles with a duration of 30 minutes, the smallest duration the FEH method allows. For pluvial flooding of site-scale drainage features it is the shorter duration events that produce higher peak rainfall and determine if the pipe networks surcharge. Table 4 shows a comparison between the peak rainfall values of storms of 30-minute duration (described using 10-minute intervals) and storms with 7-hour duration (described using 30-minute intervals) used for fluvial flooding. This table shows that the peak rainfall values are 19 to 27 % greater when the storm duration is reduced from seven hours to 30 minutes across the different return periods.

Table 5 shows the peak rainfall for a 30-minute summer season storm with a 100-year return period calculated for the 2050s and 2070s and for the 50th and 95th percentile estimate of change. Peak rainfall values increase by approximately 8% between 2050 and 2070 in the RCP8.5 climate pathway considered.

4.3.2 Findings

Figure 11 shows where the capacity of the stormwater pipes is exceeded at the time of peak runoff (30 minutes) with surface water inflows to the network produced using rainfall intensity values corresponding to a historical 100-year return period storm event. Peak flows within the pipes shown in orange exceed 90% of their capacity, while those shown in red surcharge as the calculated water depths at their upstream or downstream ends are higher than the top of the pipes. The pipes in the drainage network perform well except for 9% (14 out of 155 pipes) for which either 90% of their capacity is exceeded or they surcharge.

Table 6 also shows the number of sewers that have 90% of their capacity exceeded by the peak flows calculated from design storms with different return periods. The orange storm pipe labelled 1 in Figure 11 is the pipe that has its 90% capacity exceeded by the peak flow of a storm with a return period of five years. The three orange pipes (2–4) can carry peak flows of a storm with 50-year return period but have their 90% capacity exceeded by peak flows of storms with 75- or 100-year return periods.

The simulation undertaken with extreme rainfall intensity values associated with a summer storm in the 2070s shows that peak flows will exceed 90% of pipe capacity in an additional five pipe sections (Figure 12) compared to the previous run. 12% (19 out of 155) of the pipes will have either 90% of their capacity exceeded or surcharge, while

Table 4 Comparison between the peak rainfall values of 30-minute and 7-hour duration storms with 100, 200, and 300-year return periods.

Return period (years)	Peak rainfall of 30-minute storm (mm) (hyetograph with 10 minutes time intervals)	Peak rainfall 7-hour storm (mm) (hyetograph with 30 minutes time intervals)
100	22.02	18.51
200	26.96	21.94
300	30.3	23.83

Table 5 Climate change uplift factors and corresponding rainfall values for a 30-minute summer season storm with a 100-year return period.

Time horizon	Estimate of change (%)	Uplift factor (%)	Peak rainfall (mm) (hyetograph with 10 minutes time intervals)
2050	50	20	26.38
	95	35	29.7
2070	50	25	28.71
	95	45	32.06

Table 6 Number of storm pipes with 90% capacity exceeded using different design storms.

Design storm return period (years)	Peak rainfall (mm) (hyetograph with 10 minutes time intervals)	Number of pipes with 90% capacity exceeded
5	9.62	1
10	11.81	9
20	14.37	11
50	18.19	11
75	20.35	14
100	22.78	14
200	26.96	16
300	30.3	18

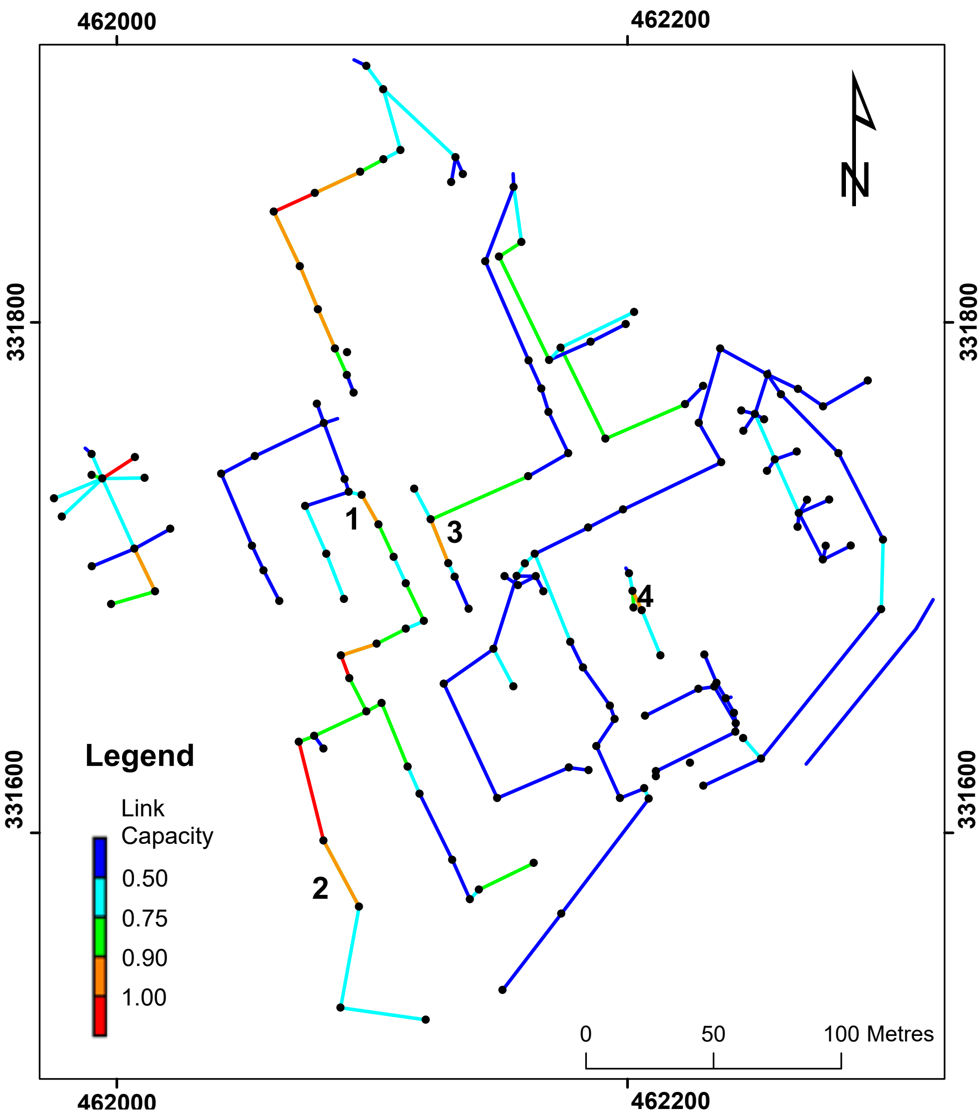

Figure 11 Plan view of the stormwater pipe network showing the exceedance of the pipes' capacities at the peak time (30 minutes) and under a storm event with a 100-year return period.

the remaining pipes keep performing well. Those pipes shown in orange or red are plotted on the BGS site plan in Figure 13.

4.4 Summary of changing flood risk

BGS Keyworth is not predicted to be at risk of fluvial flooding. Pluvial flooding has been modelled to be high under the historical climate because the capacity of sections of the network is exceeded under a 10-year return period storm. Consequently, with increasingly more extreme rainfall projected for the future, the risk is also categorised as high in the 2050s and 2070s (Table 7).

4.5 Recommendations

Recommendation KW1: Whilst the risk of flooding to the BGS Keyworth site from water flowing in the open channels along the site boundaries is very low, the risk increases if the culverts are not maintained. BGS facilities team should inspect the culverts at least annually and arrange for any debris to be cleared by the appropriate authority, if necessary.

Recommendation KW2: BGS should make Nottinghamshire County Council, the Lead Local Flood Authority (LLFA) for Keyworth, aware of this work. New homes have recently been constructed

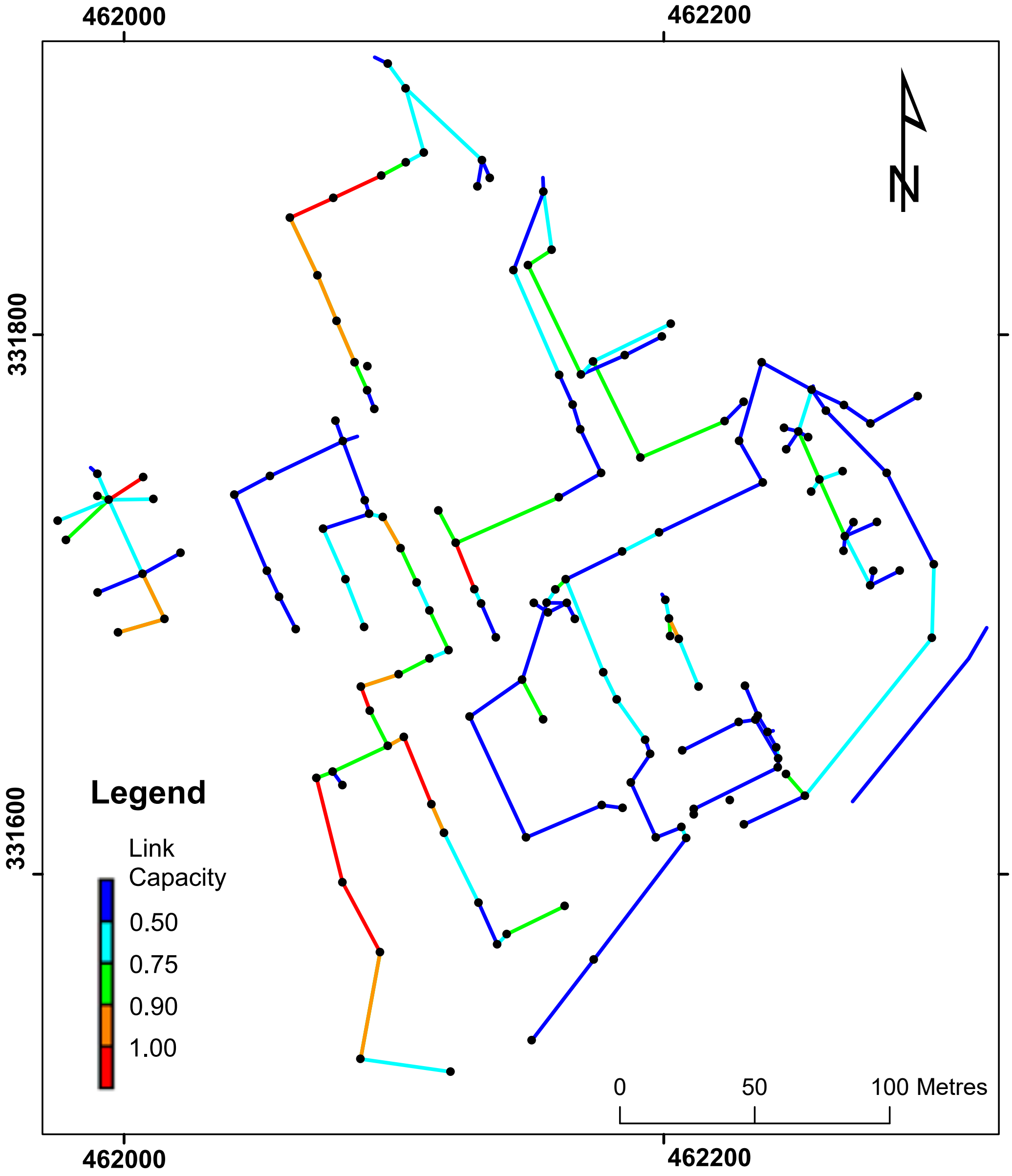

Figure 12 Plan view of the stormwater pipe network showing the exceedance of the pipes' capacities at the peak time (30 minutes) and under a 2070 summer storm event with a 100-year return period.

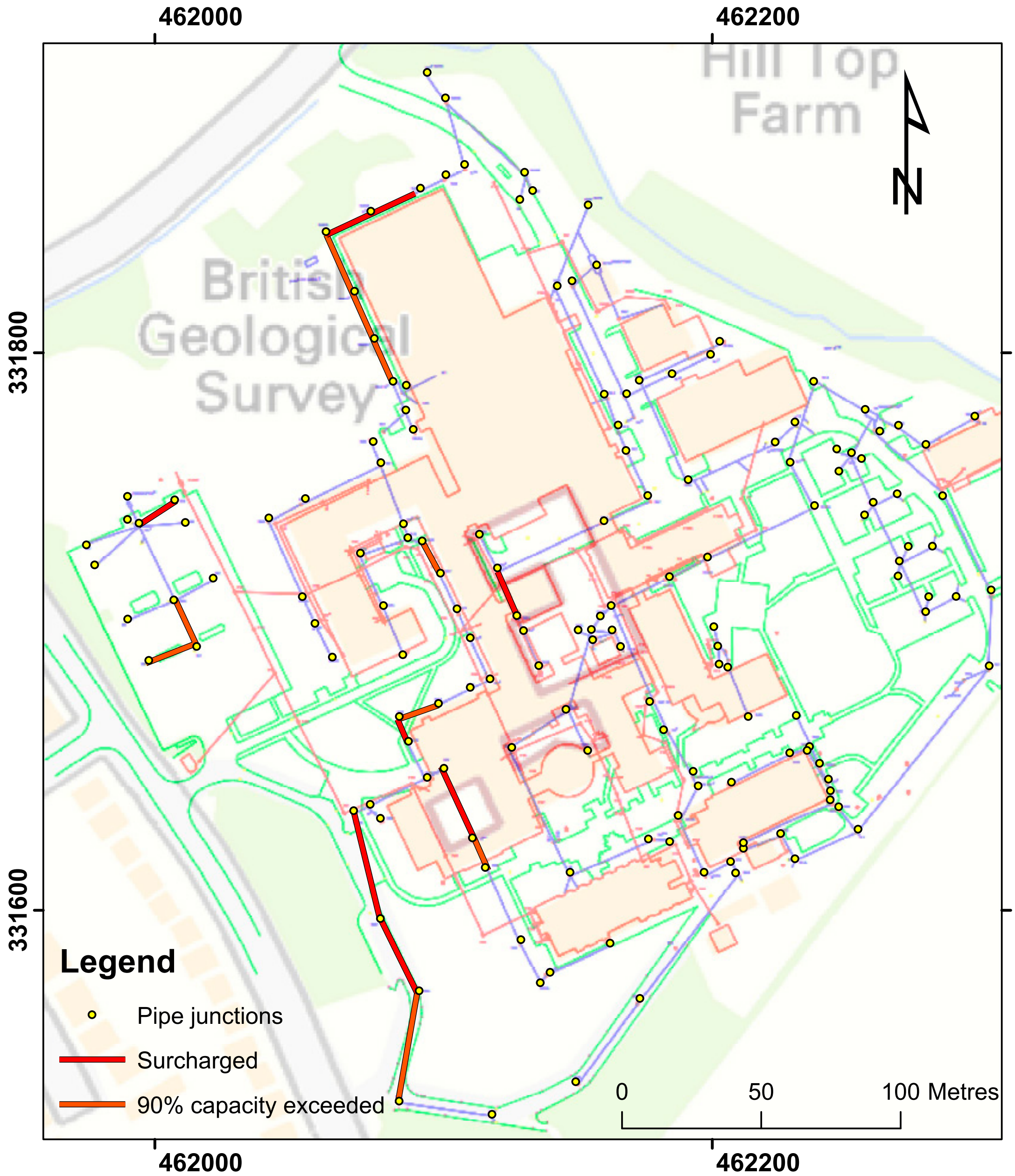

Figure 13 Drainage network pipes mapped onto BGS Keyworth site plan modelled to exceed 90% of their capacity or surcharge. [© Crown copyright and database rights [2022] OS].

along Platt Lane opposite the BGS site, which potentially could be flooded after intense rainfall. If it would be impacted by being inundated, the risk of flooding to Severn Trent Water's sewage pumping station at the corner of Platt Lane and Nicker Hill increases if the culverts are not kept clear.

Recommendation KW3: As stated previously, there has not been sufficient information about the drainage network to assess the risk of water

Table 7 Summary of categorised fluvial and pluvial flood risk for BGS Keyworth over the historical, 2050s and 2070s time horizons.

	BGS Keyworth	
	Fluvial	Pluvial
Historical	–	High
2050s	–	High
2070s	–	High

appearing on the ground surface when the drainage network becomes surcharged, and the development of a model to do this would be a complex task. Consequently, we have modelled the capacity of the subsurface drainage pipes and used this as a proxy to indicate which parts of the system are more likely to cause water to pond on the surface. Those pipe sections that have been simulated to surcharge, or exceed 90% of their capacity, during a 30-minute storm, need further investigation. The model simulates that 6% of the network's pipes exceed 90% of their capacity during a 30-minute, 10-year return period storm, which increases to 9% during a 30-minute, 75-year return period storm. First, the slopes and lengths of the problematic network sections should be measured accurately, and the modelling exercise repeated to confirm the findings of this study. Updating and rerunning of the model would be relatively quick. After confirming the fidelity of the model, several potential solutions could then be reviewed, and their costs and benefits evaluated against the level of risk that NERC BGS are willing to accept. Solutions could include replacing small diameter pipes with larger pipes, increasing the slopes of the pipes, and optimising the size of catchment areas generating runoff by altering the direction of surface flow paths/directions. It should be noted that the maintenance of the drainage infrastructure is of paramount importance to avoid surcharging of the network and flooding.

5. BGS Edinburgh

5.1 Site description

The BGS Edinburgh site is located within the Heriot Watt University campus and consists of the Lyell Centre and George Bruce buildings (Figure 14). Between them is a car park. The Murray Burn flows adjacent to these buildings and within approximately 10 m of the northern corner of the Lyell Centre.

The Murray Burn has flooded the grounds and water has entered the Lyell Centre building on two occasions in June 2016 and June 2019. In

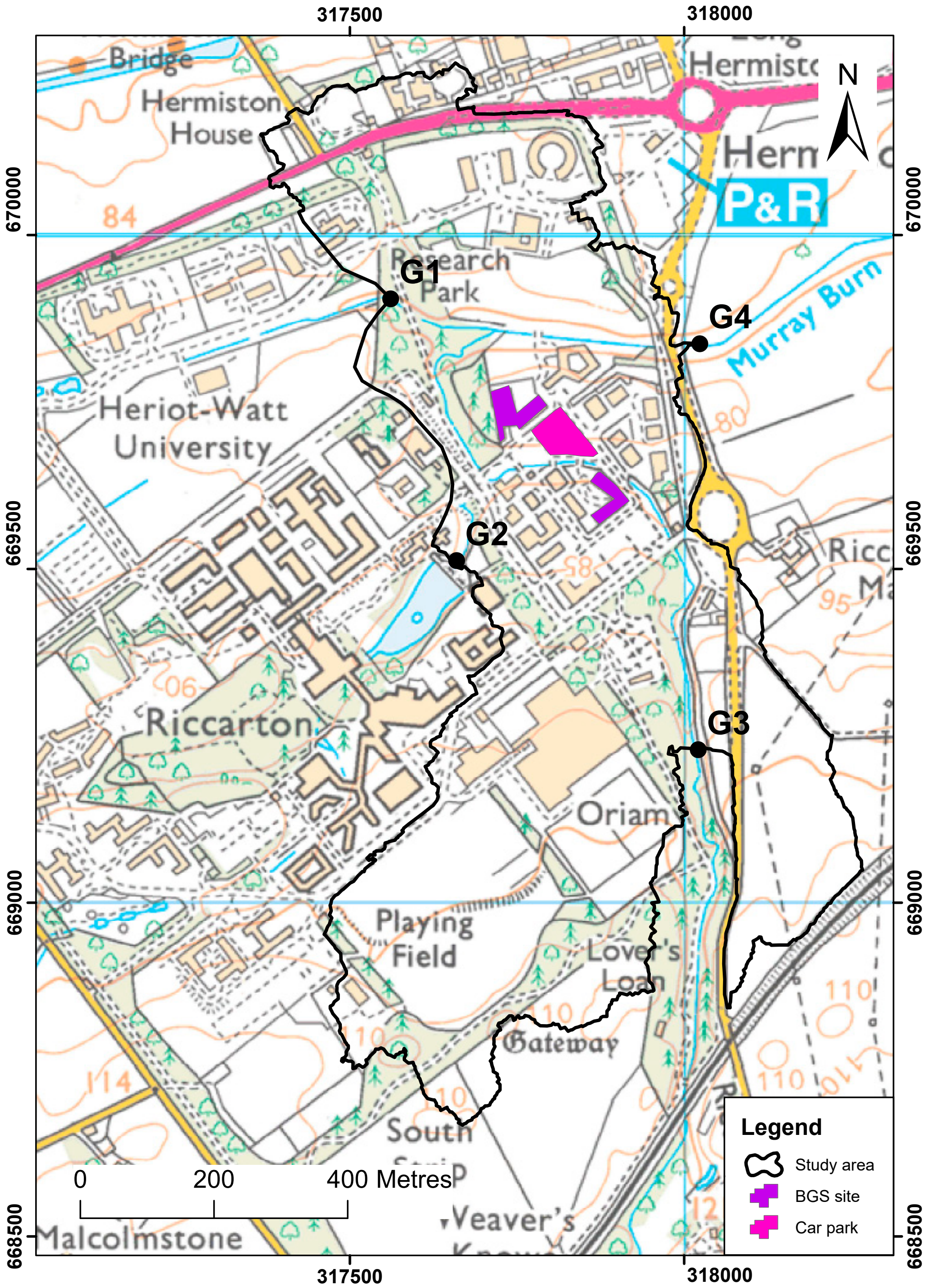

Figure 14 Location of the BGS Edinburgh site. [© Crown copyright and database rights [2022] OS].

a

b

Figure 15 Photos of (a) embankment and (b) flood gate constructed on Murray Burn to reduce risk of flooding to Lyell Centre.

response to this, in 2020 the university installed a flood gate on the bridge over the burn and created a new embankment (Figure 15). These flood defences prevented flooding on two occasions since installation. The focus of the modelling of flood risk at BGS Edinburgh has been on fluvial flood risk from the Murray Burn.

Figure 14 shows the catchment area included in the modelling of the risk of flooding from the Murray Burn. The burn flows from south to north and through or under a number of culverts and bridge decks. As the burn bends northward around the George Bruce building a tributary joins it. Approximately 300 m farther downstream, a second tributary flows into the channel from the west.

5.1.1 Previous assessment of flood risk

The risk of flooding along the Murray Burn, as published by the Scottish Environment Protection Agency (SEPA), is shown in the Appendix 1. The mapped zone defining the chance of flooding to be 10% each year touches the north-eastern side of the Lyell Centre. This assessment does not take account of the recent additional defences installed to protect the Lyell Centre. The George Bruce building is outside of the flood risk zones mapped by SEPA.

5.2 Fluvial flood risk modelling

5.2.1 Model setup

The pathways of the river channels, their cross-sectional shapes, and gradients were defined using the 0.086 m DTM generated by a LIDAR drone survey carried out by BGS staff on 6 December 2021. Figure 16 shows the locations and the extents of the cross sections used to construct the HEC-RAS model and simulate flooding at the BGS Edinburgh site. The dashed lines (A-H) in Figure 16 represent the cross sections where structures that allow channel crossing have been constructed (Figure 17). These structures increase the level of the risk of flooding as they can restrict the flow of water along the channel. The structures were added to the model as culverts or bridge decks. Their dimensions were estimated from measurements carried out by the BGS staff during the site visit to carry out the topographical survey. The vertical positionings and lengths of these structures were inferred from these measurements and from the ground elevations obtained from the DTM. The new levee constructed alongside the Lyell Centre and flood gate were included in the model.

The Manning coefficient representing frictional losses and used to calculate the water depth in the cross sections was set to a value of 0.04 as recommended in the literature for minor streams with overgrown vegetation and rough surface (Coon, 1998). This value was used for all the parts of a cross section such as the left and right overbanks and the main channel. For culverts and bridge decks, the values for both the entrance and exit loss coefficients were set to 0.5, the Manning coefficient value used to calculate the frictional losses within the culvert was set to 0.012, and the weir coefficient value was set to 1.4.

Design storm profiles for return periods of 20, 100, 200 and 300 years and for summer and

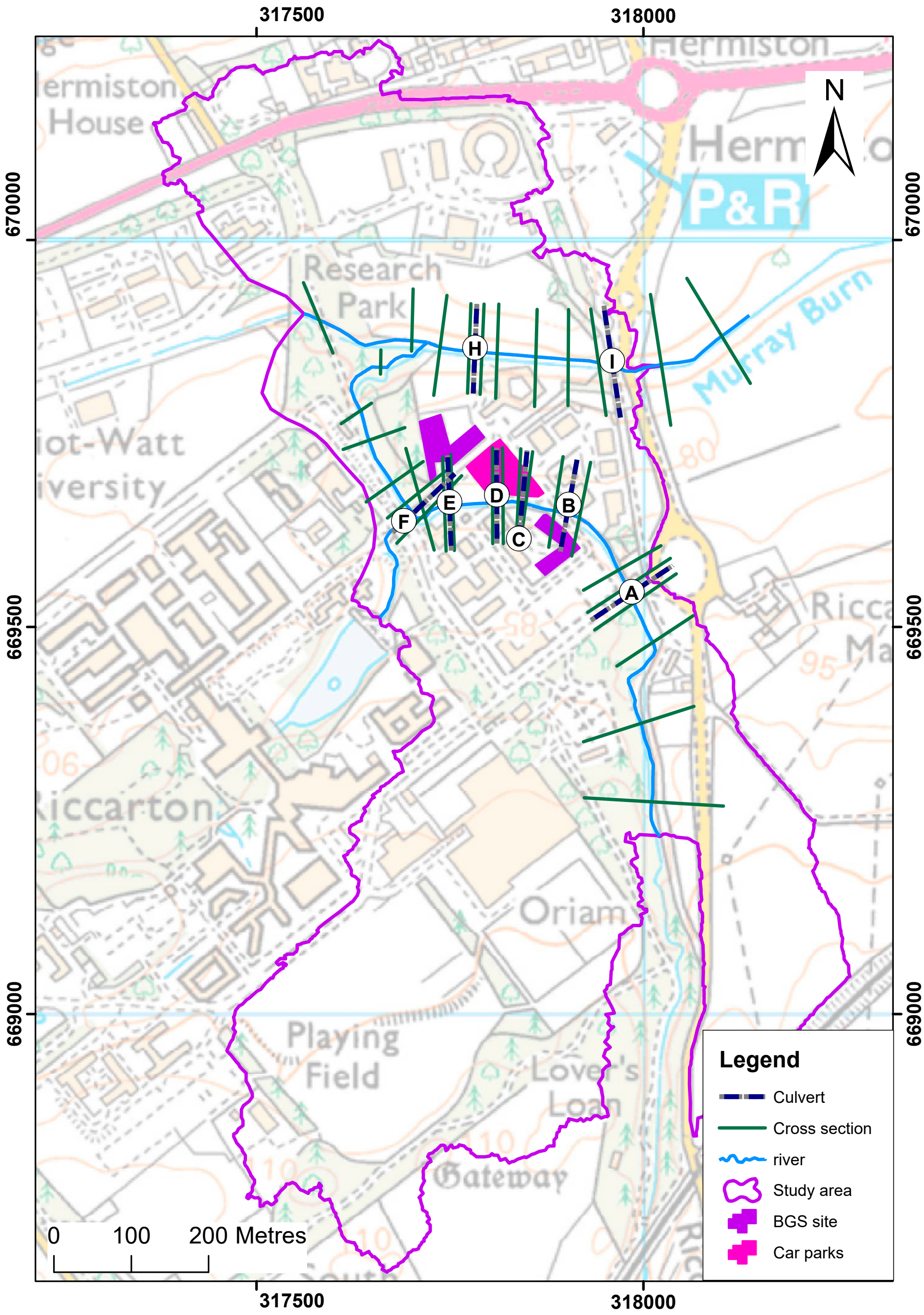

Figure 16 Locations and extents of cross-sections in HEC-RAS model of Edinburgh site. [© Crown copyright and database rights [2022] OS].

winter seasons were produced using the FEH web service. The use of FEH to generate design storms of various durations and ReFH2 to convert these into runoff hydrographs indicated that peak flows into the channels at points G1, G2 and G3 (Figure 18) would be generated by storms of a 7-hour duration. Table 8 shows the peak flow rates calculated at these three points for the winter and summer season 7-hour storm duration and for 100, 200, and 300-year return periods.

Table 9 shows the values of the 100-year return period 7-hour storm event peak rainfall intensities and runoff flow rates calculated after the application of the UKCP18 climate projection uplift factors for the 2050 and 2070 time horizons. This table shows that the peak flow rates predicted for the 2070s with the 95% estimate of change at G1, G2 and G3 are the highest and exceed the flow rates calculated using the historical 300-year return period storm event.

Cross-section B

Cross-section C

Cross-section D

Cross-section E

Figure 17 Structures built across the Murray Burn at cross-sections B-E in Figure 16.

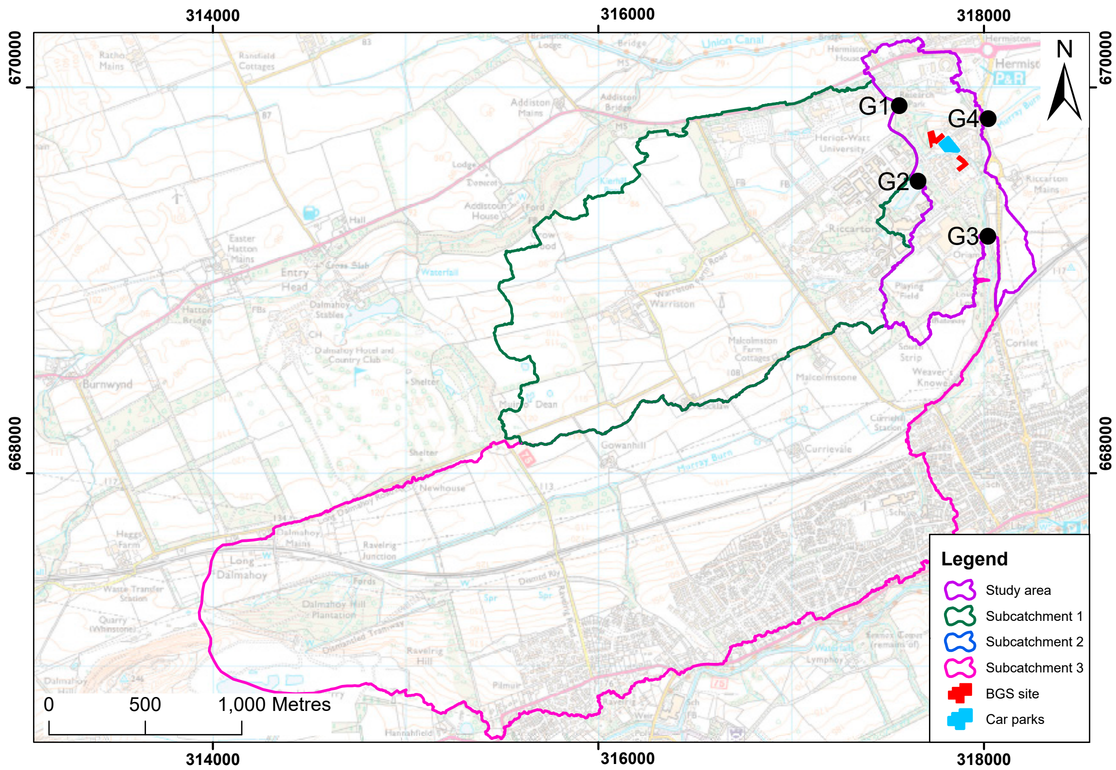

Figure 18 Sub-catchment areas contributing overland flow to points G1-4 along the stream channels. [© Crown copyright and database rights [2022] OS].

Table 8 Maximum rainfall intensity values of a 7-hour storm duration and the corresponding peak flow rates at Points G1, G2 and G3 in Figure 18, and winter (W) and summer (S).

Return period (years)	Peak rainfall (mm) (hyetograph with 30 minutes time intervals)		Point G1 peak flow (m^3/sec)		Point G2 peak flow (m^3/sec)		Point G3 peak flow (m^3/sec)	
	W	S	W	S	W	S	W	S
20	5.48	10.87	0.83	1.0	0.03	0.04	3.59	4.49
100	7.88	15.64	1.246	1.55	0.04	0.06	5.34	6.84
200	9.15	18.17	1.482	1.87	0.05	0.07	6.32	8.18
300	9.93	19.72	1.631	2.08	0.05	0.08	6.93	9.04

Table 9 Uplift factors, rainfall peak intensity values and the corresponding peak flows at Points G1, G2 and G3 for the 100-year return period design storm, and winter (W) and summer (S).

Time horizon	Estimate of change (%)	Uplift factor (%)	Peak rainfall (mm) (hyetograph with 30 minutes time intervals)		Point G1 peak flow (m3/sec)		Point G2 peak flow (m3/sec)		Point G3 peak flow (m^3/sec)	
			W	S	W	S	W	S	W	S
2050	50	25	9.85	19.55	1.61	2.06	0.05	0.07	6.86	8.94
	95	40	11.03	21.89	1.85	2.38	0.06	0.09	7.82	10.29
2070	50	35	10.64	21.11	1.77	2.27	0.06	0.08	7.50	9.83
	95	55	12.21	24.24	2.09	2.73	0.07	0.10	8.81	11.69

5.2.2 Findings

Figure 19 shows the spatial extent of the flooding simulated by HEC-RAS using the 100-year return period summer season storm event hydrograph for the 2070s and 95% interval, i.e. the results for the largest of the historical and future events considered. This simulation generates flooding at the rear of the Lyell Centre and over approximately half of the car park area. The George Bruce building, however, is not affected by flood water.

The levee constructed along the south side of the Murray Burn between Section B and Section D (Figure 19) reduces the risk of flood water overtopping the riverbank along this section. However, our HEC-RAS modelling based on our high-resolution LIDAR-survey indicates that floodwater overtopping the levee at Section D backs up towards the rear of the Lyell Centre. This occurs when the flood flows are greater than those produced by the historical 20-year return period summer season storm event (Table 8). The Lyell Centre remains vulnerable because there is a downhill pathway from Section D to the Lyell Centre. If the levee had not been constructed the model predicts that the Lyell Centre would suffer from flooding generated by a 20-year return winter season storm event. However, we have found that the levee along the bank above Section D is not high enough to protect the Lyell Centre from a 20-year return period summer season storm event.

The flood water adjacent to the Lyell Centre building in Figure 19 (the example of the 100-year period event in the 2070s) is caused by both water backing up from Section D and water overtopping the structure at Section B. Water remains in the channel at Section B under the historical 200-year return period flood, but not the 300-year return-period historical flood. Flood water also reaches the two buildings to the west of the Lyell Centre and south of the Murray Burn. The extent of the flooding under this scenario is also predicted

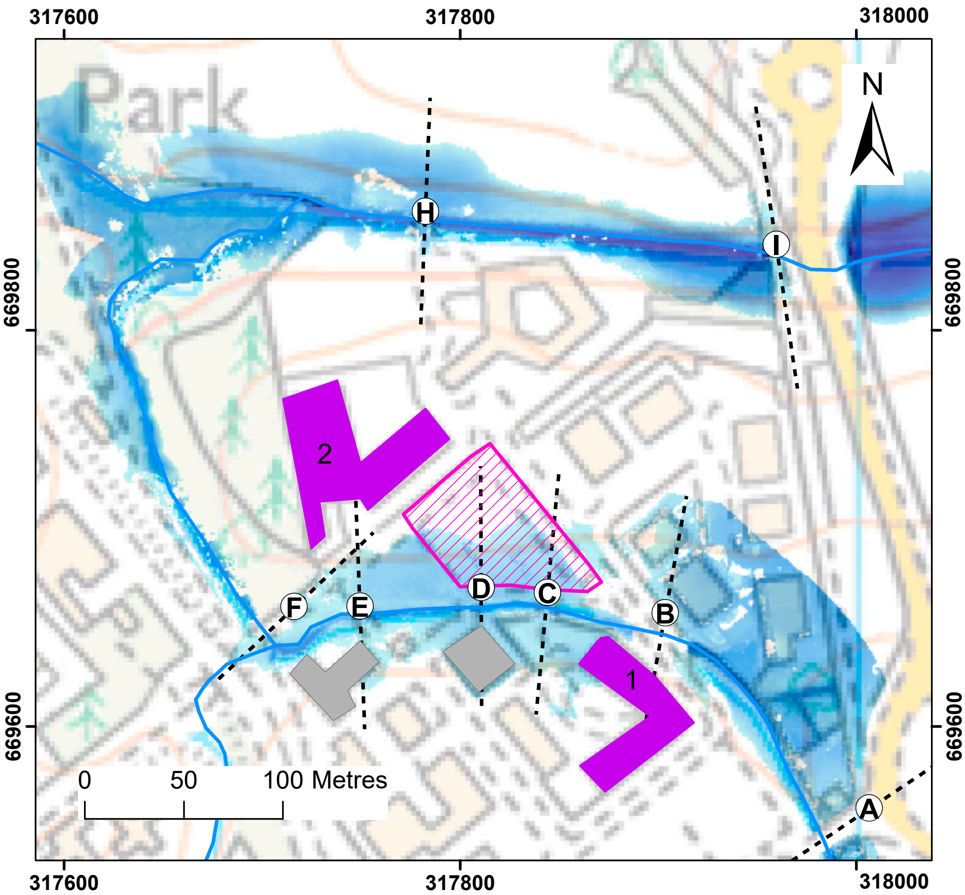

Figure 19 Simulated flood extent around the Lyell Centre for the 2070s based on the design storm calculated by shifting the historical 100-year return period 7-hour summer season storm to account for climate change. [© Crown copyright and database rights [2022] OS].

to affect the buildings to the north-east of the Lyell Centre on the opposite side of the Murray Burn. More detailed information about the flood extent for various return periods is provided in the accompanying Technical Report (Nagheli et al., 2022), but flooding in parts of this area is modelled to occur under a 20-year summer storm event.

Data derived from the UKCP18 time-series of hourly rainfall are plotted in Figure 20. For each of the time-series of hourly rainfall produced by the 12 simulations of the Met Office Hadley Centre climate model for each of the three time periods (1981–2000, 2021–2040, and 2061–2080) the 7-hour duration rainfall with a return period of 100 years was estimated. The distribution of these 12 values is plotted as a box-and-whisker plot in Figure 20. The averages of the ensemble of 12 values (as depicted by the crosses in Figure 20) are: 53.5 mm (1981–2000); 58.5 mm (2021–2040); 77.4 mm (2061–2080). The chance of the 100-year return period 7-hour duration rainfall (calculated from the 1981–2000 simulated time-series) occurring in any year during 2021–2040 is predicted to be 0.04, i.e. four times more likely. During 2061–2080 this chance increases to 0.14, i.e. 14 times more likely.

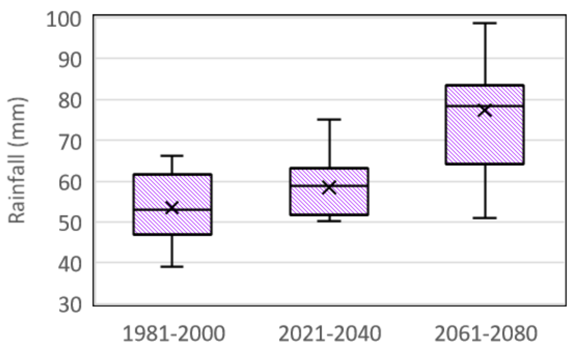

Figure 20 Box plots of 7-hour 100-year return period rainfall for BGS Edinburgh calculated from the ensemble of 12 UKCP18 simulations for the three time periods: 1981–2000, 2021–2040, and 2061–2080.

5.3 Summary of changing flood risk

Using data for the historical period (1961–1990) the modelling has shown that the Lyell Centre would be affected by flood water during a 20-year return period, 7-hour storm, where 7 hours is the critical storm duration. This level of risk is described as *medium* based on the categories defined in section 3.2. The peak rainfall intensity during this storm, as calculated by the FEH web service on a 30-minute time interval, is 10.87 mm. Assessment of the climate change uplift factors shows that the peak rainfall intensity for a one in 10-year historical storm, that is adjusted to account for climate change, is higher than 10.87 mm. Consequently, the categorisation of the risk of fluvial flooding to the Lyell Centre is designated as *high* in both the 2050s and 2070s.

5.4 Recommendations

Recommendation ED1: The levee and flood gates constructed along the Murray Burn in 2020 have enhanced the protection of the Lyell Centre. However, our modelling predicts that the Lyell Centre would still be affected by flood water under a 20-year return period storm. We conclude that the levee is not sufficiently high at its downstream end (at Section D in Figure 16) and, based on the use of the new drone-based LIDAR survey of land surface elevations, flood water overtopping the levee here flows towards the Lyell Centre. If it is considered that the level of flood protection is currently insufficient, we recommend that NERC and Heriot Watt University discuss what the options are for increasing the level of protection to the Lyell Centre. For example, this could include extending the levee downstream and increasing its height, or potentially increasing the cross-sectional area of the channel.

Recommendation ED2: Our modelling has shown the potential for flooding of other buildings on the Heriot Watt campus, e.g. the Energy Academy and the buildings north-east of the Lyell Centre on the opposite side of the Murray Burn and Research Avenue South. This report should be shared with the Heriot-Watt estate management department to make them aware of the risks to the occupiers of these buildings, and to allow them to consider any necessary actions.

Table 10 Summary of categorised fluvial flood risk for BGS Edinburgh over the historical, 2050s, and 2070s time horizons.

	Fluvial flood risk
Historical	Medium
2050s	High
2070s	High

6. NCAS Capel Dewi Atmospheric Observatory

The NCAS Capel Dewi Atmospheric Observatory (CDAO) is located near Capel Dewi, Aberystwyth. Its wind profiling instrument, which covers an area of approximately 1 ha (Figure 21), supports weather forecasting by several agencies. The site also operates a number of auxiliary instruments for measuring surface wind, temperature, pressure, humidity, and rainfall. The road running along the north of the site slopes gently from east to west. To the south of the site the Afon Peithyll flows from east to west. Approximately 300 m to the west of the site, the river flows through a culvert beneath a track joining the road. The LIDAR elevation data indicates that the river channel elevation next to the site is higher than the lowest ground elevation within the site (Figure 22). A part of the site was flooded on 21 January 2018, when flood water inundated the large shed at point A in Figure 21. It has been thought that it was possible that the flooding was exacerbated by debris clogging the culvert, which caused water to back up in the channel (Hooper, D., pers. comm. 2022).

6.1.1 Previous assessment of flood risk

The risk of flooding from the Afon Peithyll, as published by Natural Resources Wales, is shown in the Appendix 1. The mapped zone of high risk, which represents a chance of flooding that is greater than a 3.3% in any year, covers most of the site.

6.2 Fluvial flood risk modelling

6.2.1 Model setup

HEC-RAS was again used to simulate fluvial flooding at the site resulting from the rising level of

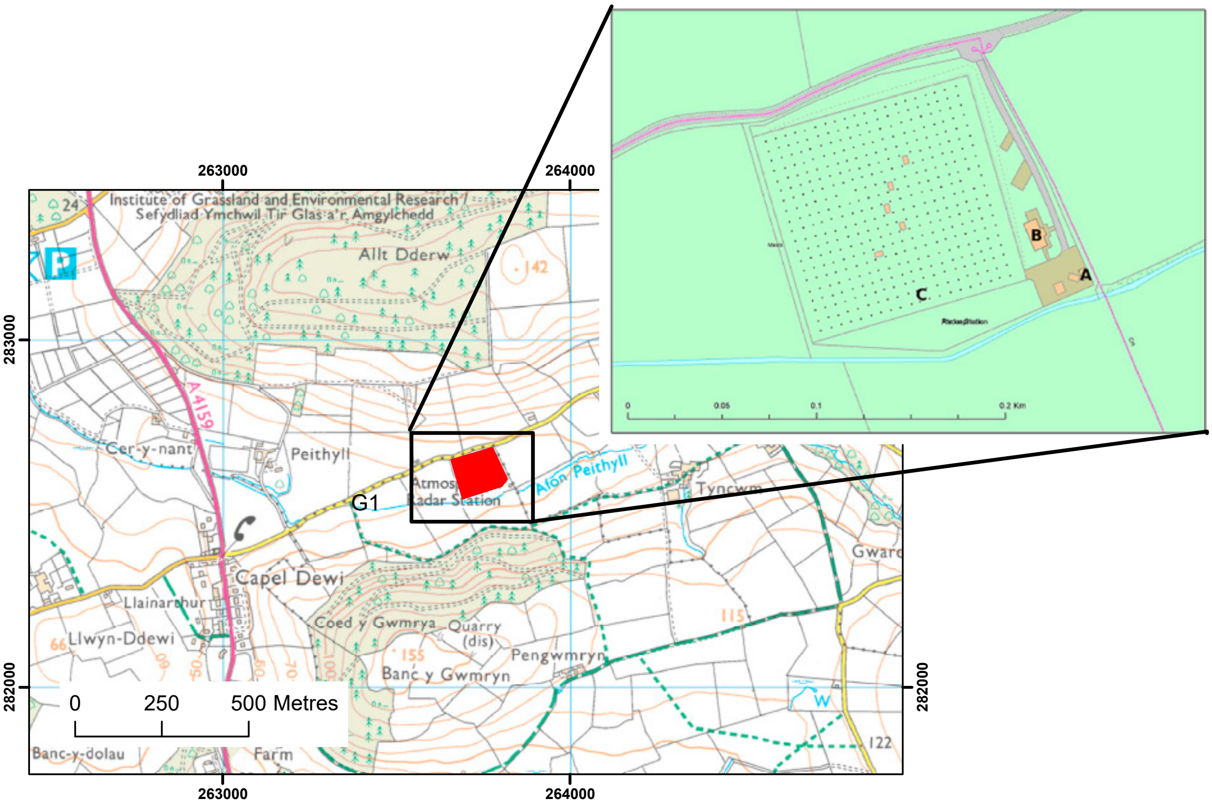

Figure 21 The Capel Dewi NERC site. [© Crown copyright and database rights [2022] OS].

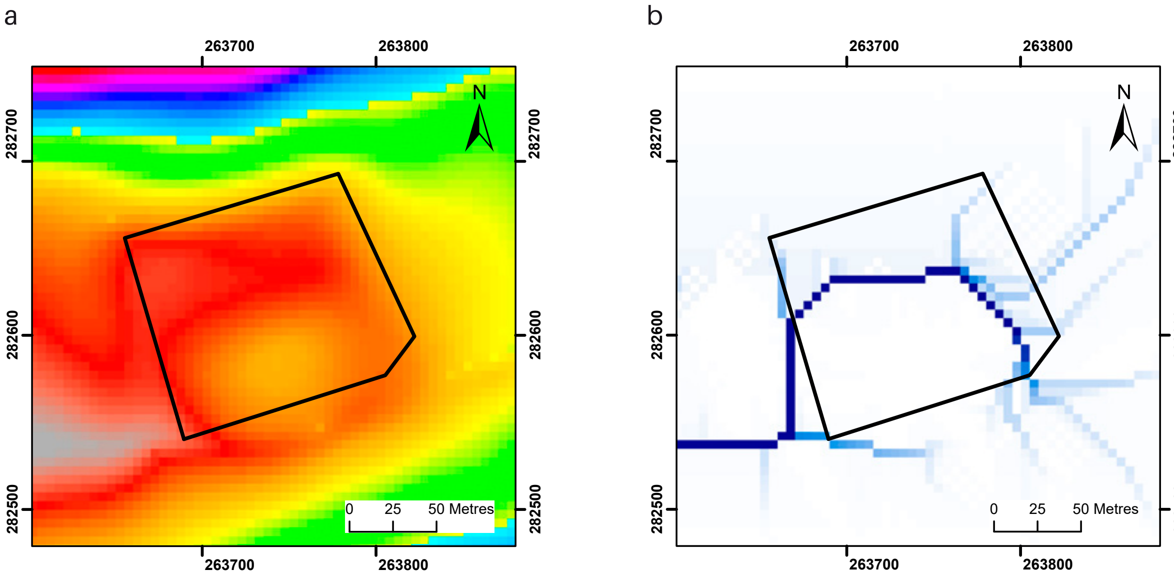

Figure 22 (a) LIDAR DTM of Capel Dewi site and (b) flow paths derived from DEM analysis. [© Crown copyright and database rights [2022] OS].

the Afon Peithyll. The LiDAR-based DTM available from Natural Resources Wales (Natural Resources Wales, 2022) was used to define the model cross sections and the slope of the channel. However, unlike the fine resolution DTMs generated from the drone surveys of Keyworth and Edinburgh, this DTM has a horizontal resolution of 5 m, which meant that it was not possible to define the elevation profiles of cross-sections across the river accurately. Google maps imagery was used to provide an approximate estimation of the dimensions of the channel and the culvert located approximately 300 m downstream of the site. The following assumptions and simplifications were used to construct the model:

- The 5 m resolution LIDAR-based DTM was used to define the cross sections across the flood plain. The main channel was assumed to be square, and 1.5 m wide and deep.
- The slope of the channel was derived from the DTM and varies between 0.7% and 4.11%.
- The culvert was represented as pipe, estimated to be 1 m in diameter.
- The Manning's roughness coefficients for the channel and culvert were set to 0.04 and 0.012, respectively. The entrance and exit loss coefficients to the culvert were set to 0.5.
- A broad-crested weir was used to represent water spilling over the track when the culvert surcharges; the related weir coefficient was set to 1.4.

The model was used to simulate a design storm similar in magnitude to that of the 21 January 2018. Observations of rainfall on 10-minute intervals for the 21 January 2018 were provided by the CDAO Project Scientist. The FEH web service was used to identify the design storm that most closely matched the peak rainfall intensity and total rainfall of the observed storm. This was found to be a design storm with a 7-hour duration and 30-year return period.

The flow hydrograph generated using this design storm for the catchment above point P2 (Figure 23) was input to the channel at this point — the upstream end of the modelled river. The runoff generated over the catchment between points G1 and P2 was applied to the channel just downstream of the site.

6.2.2 Findings

Given the approximations used in the model, the results should be considered to be indicative. A detailed survey of the Afon Peithyll channel and culvert is required to reduce uncertainty and improve the level of confidence in the model.

The simulated extent of the flooding for the 7-hour duration design storm with a return period of 30 years is shown in Figure 24. The extent of the flood inundation is greater than that observed in January 2018, which is not unexpected given the approximations contained in the model. However, it does indicate the areas of the site that are at higher risk; the model result is consistent with the observed flooding of the shed at point A (Figure 21). The DTM suggests that the slope of the channel is shallower along the south-east side of the site, which may mean that flow depths are greater and there is a higher risk of out of channel flows along this section; this is what the model predicts.

The culvert surcharges in the simulation of a 7-hour, 30-year return period design storm and water flows over the track and road. Water also flows out-of-bank between the culvert and the south-west corner of the site.

Two additional simulations based on the same design storm were performed. In the first, the culvert was removed and replaced by an open channel. In the second, the bottom half of the culvert was assumed to be blocked. Neither of these generated flooding that was significantly different from the original model containing an unblocked culvert.

The first additional simulation indicated that the capacity of the modelled channel is not enough to carry the peak flow of the hydrograph regardless of the presence or the absence of the culvert. The second additional simulation indicated that once the culvert surcharges, and water overtops the track, then only a small increase in water depth is needed to convey additional water that cannot go through the culvert. From this, we conclude that the culvert is likely to have no direct impact on flooding of the site.

The use of FEH to generate design storms of various durations and ReFH2 to convert these into runoff hydrographs indicated that peak flows into the channel at point P2 (Figure 23) would be generated by storms of a 4-hour duration. A series of simulations was run to identify the return-period of a 4-hour storm that would just cause the channel to overbank at different points along it. Considering a 4-hour storm, the modelling suggests that:

- a 4-year return period event caused the culvert to surcharge and initiate flooding of the track;
- a 5-year return period event initiated out of bank flooding at the south-west corner of the site;

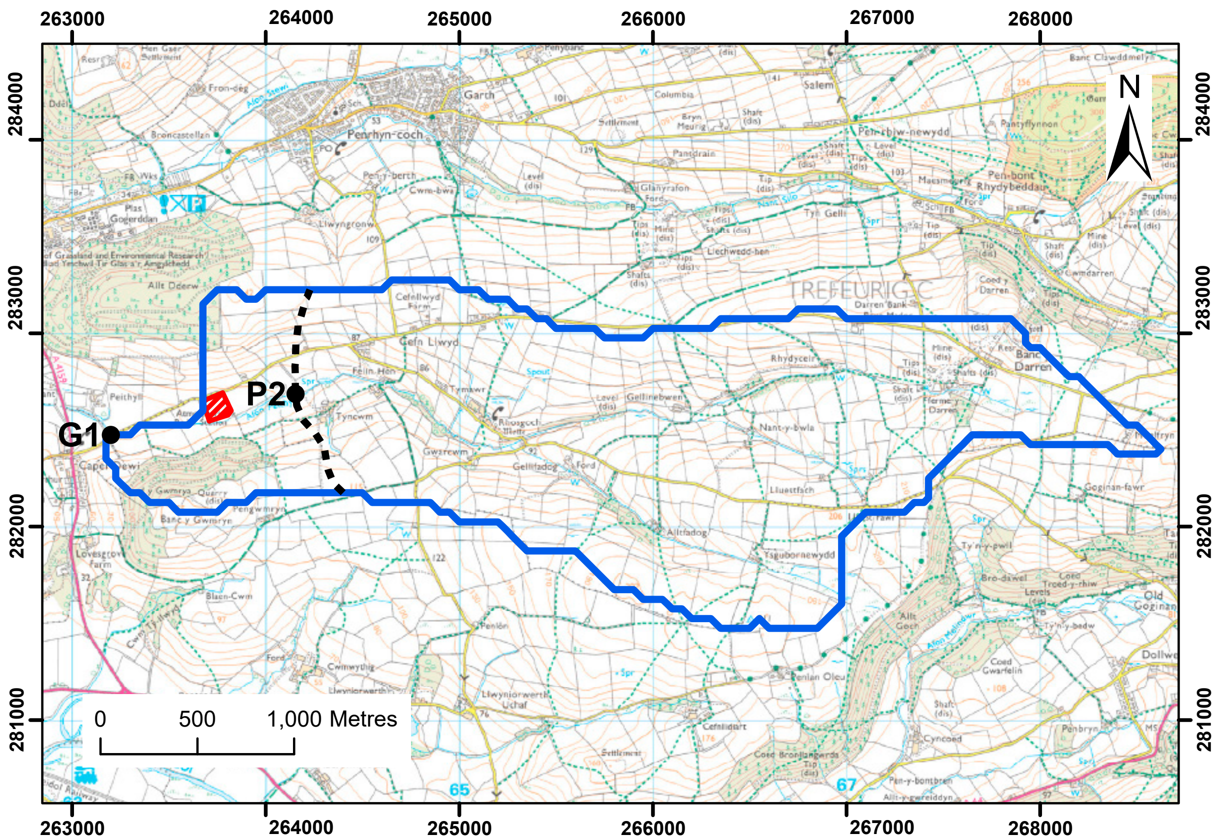

Figure 23 Catchment area contributing to flood hydrograph estimated at the stream location Point G1. [© Crown copyright and database rights [2022] OS].

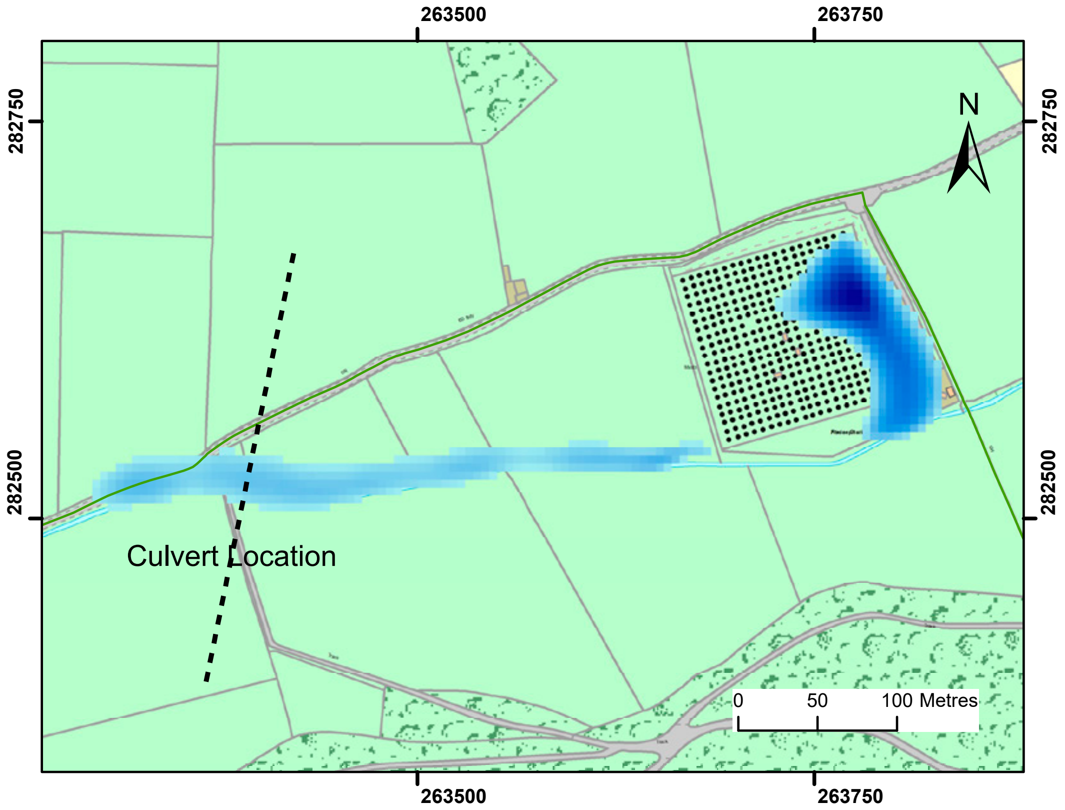

Figure 24 Simulated flood extent for 7-hour duration, 30-year return period winter storm. [© Crown copyright and database rights [2022] OS].

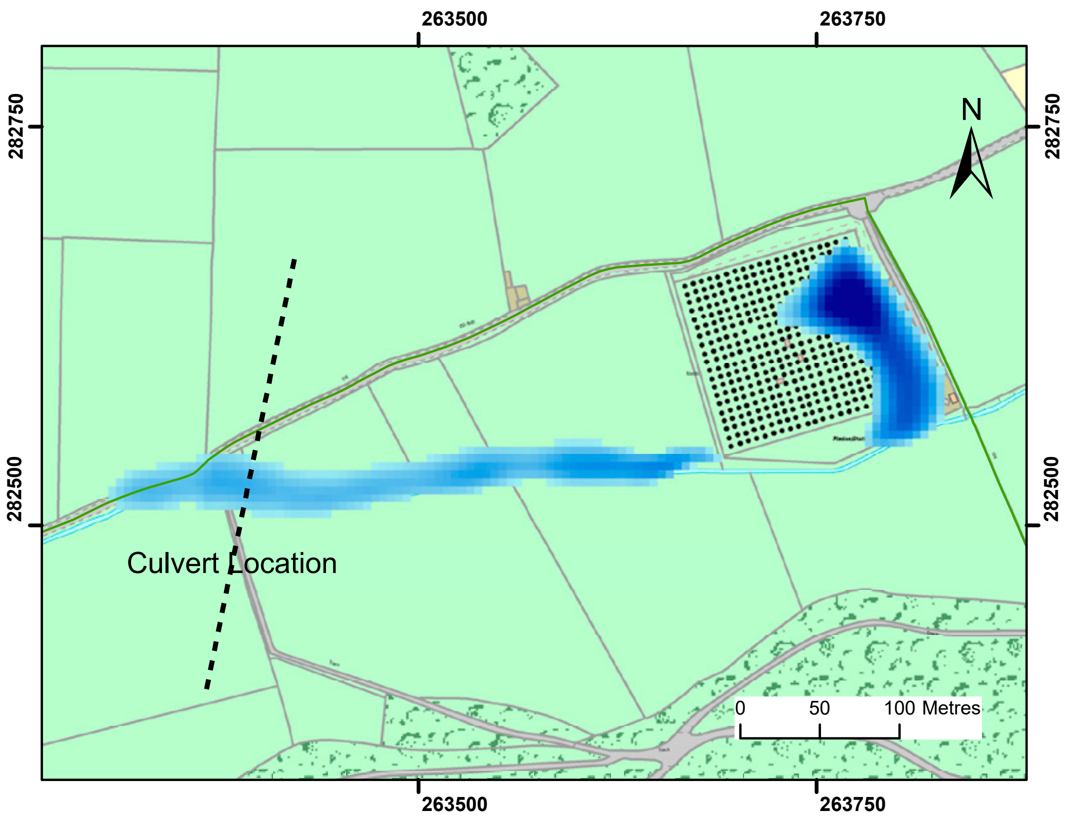

Figure 25 Simulated flood extent for 4-hour critical duration, 7-year return period summer storm. [© Crown copyright and database rights [2022] OS].

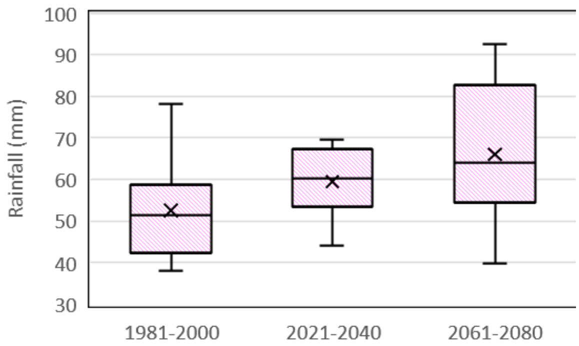

Figure 26 Box plots of 4-hour 100-year return period rainfall for Capel Dewi calculated from the ensemble of 12 UKCP18 simulations for the three time periods: 1981–2000, 2021–2040, and 2061–2080.

- a 7-year return period event causes flooding across the east of the site (Figure 25).

Data derived from the UKCP18 time-series of hourly rainfall are plotted in Figure 26. For each of the time-series of hourly rainfall produced by the 12 simulations of the Met Office Hadley Centre climate model for each of the three time periods (1981–2000, 2021–2040, and 2061–2080) the 4-hour duration rainfall with a return period of 100 years was estimated. The distribution of these 12 values is plotted as a box-and-whisker plot in Figure 26. The averages of the ensemble of 12 values (as depicted by the crosses in Figure 26) are: 52.5 mm (1981–2000); 59.5 mm (2021–2040); 66.1 mm (2061–2080).

The chance of the 100-year return period 4-hour duration rainfall (calculated from the 1981–2000 simulated time-series) occurring in any year during 2021–2040 is predicted to be 0.05, i.e. five times more likely. During 2061–2080 this chance increases to 0.1, i.e. 10 times more likely.

6.3 Summary of changing flood risk

Fluvial flood risk has been modelled to be *high* under the historical climate because a 4-hour (the critical storm duration), 7-year return period event is modelled to cause flooding of the east of the site. Consequently, with increasingly more extreme rainfall projected for the future, the risk is also categorised as high in the 2050s and 2070s (Table 11).

Table 11 Summary of categorised fluvial flood risk for NCAS Capel Dewi over the historical, 2050s, and 2070s time horizons.

	Fluvial flood risk
Historical	High
2050s	High
2070s	High

6.4 Recommendations

Recommendation CD1: A survey of the Afon Peithyll is required to define the dimensions and slope of the channel and improve the accuracy of the model. A higher resolution drone-based LIDAR survey of the area of the site could be undertaken within one day. Incorporating these measurements into the model will improve confidence in the simulations.

Recommendation CD2: The following engineering options could potentially be implemented to reduce flood risk at the site, but their viability would depend on the characteristics of the site, cost, and possible environmental impacts:

- The height of the northern bank, or both banks, along the channel could be raised. Raising just the northern bank would increase flood risk to the agricultural land to the south of the river.
- The size of the channel could be increased so that it can accommodate higher peak flows.
- If a survey confirms that the slope of the bed of the channel varies similarly to our assessment based on the LIDAR DTM (between 0.8 and 4%), then this could be modified. Implementing a more uniform slope as the river flows past the site would reduce the risk of flooding.
- Although the modelling has indicated that the culvert does not significantly increase the risk of flooding to the site, increasing the capacity of the culvert would minimise the potential for water to back up behind the river crossing.

Recommendation CD3: Both the observations from the January 2018 flood event and the modelling show that the south-east of the site is at the highest risk of flooding. Consideration could be given as to whether infrastructure in this area of the site could be relocated.

The result of implementing these changes could be assessed by the model after it has been updated with measurements from surveys of the channel and neighbouring floodplain. The model could be used to inform a cost-benefit analysis of each option considering different return-periods for the critical duration storm. The information would enable a decision to be made about what level of risk is acceptable.

Appendix 1 Flood risk mapping by UK environmental agencies

Mapping of historical flood risk published by the relevant environmental agencies can be found on the following web sites:

- England
- https://check-long-term-flood-risk.service.gov.uk/map
- Northern Ireland
- https://www.infrastructure-ni.gov.uk/topics/rivers-and-flooding/flood-maps-ni
- Scotland
- https://map.sepa.org.uk/floodmaps
- Wales
- https://naturalresources.wales/flooding/check-your-flood-risk-by-postcode/?lang=en

Table 12 summarises the risk of flooding, as assessed by the relevant agency, for the BGS sites and selected other NERC sites.

The Main Building of the University of Cardiff, within which the BGS Cardiff office is located, is outside of the mapped 'low risk' zones for all forms of flooding. The GSNI office in Belfast is mapped to

Table 12 Summary of historical flood risk for selected BGS and NERC sites as estimated by UK environmental agencies.

Site	Fluvial	Pluvial
BGS Keyworth	Outside of mapped flood risk zones	High risk (~2% of site area) Medium risk (~10% of site area)
BGS Cardiff	Outside of mapped flood risk zones	Outside of mapped flood risk zones
BGS Edinburgh	High risk (10% of site area)	Low risk (~1% of site area)
BGS Eskdalemuir	Outside of mapped flood risk zones	Outside of mapped flood risk zones
BGS Hartland	Outside of mapped flood risk zones	Outside of mapped flood risk zones
GSNI Belfast	Outside of mapped flood risk zones	Outside of mapped flood risk zones
BAS Cambridge	Outside of mapped flood risk zones	High risk (~2% of site area) Low risk (~25% of site area)
NCAS Capel Dewi	High risk (100% of site area)	High risk (~2% of site area)
NERC Herstmonceux	Outside of mapped flood risk zones	Outside of mapped flood risk zones
UKCEH/BGS Wallingford	Very low risk (~5% of site area) Distance to high risk zone: ~100 m.	Outside of mapped flood risk zones

be outside of the 1 in 1000-year flood risk zone for both fluvial and pluvial flooding.

The British Antarctic Survey's Cambridge site is mapped by the Environment Agency to be outside of all fluvial flood risk zones, but parts of the site are in the high risk zone for pluvial flooding. Accurate simulation of the flood risk at the BAS Cambridge site would require a detailed assessment of the flow and potential for accumulation of rainfall-runoff based on an accurate high-resolution map of land surface elevations (e.g. derived from a LIDAR scan), and modelling of the urban drainage system.

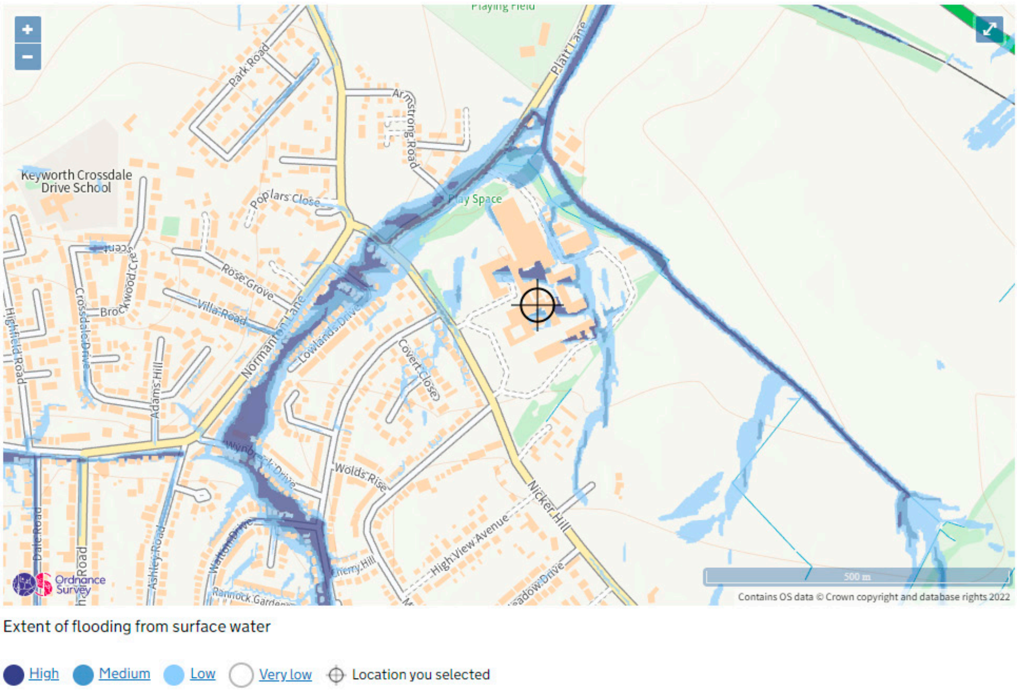

Figure 27 Current risk of flooding from surface water at BGS Keyworth as assessed by E. (https://check-long-term-flood-risk.service.gov.uk/map?easting=461925.84&northing=331930.02&map=RiversOrSea).

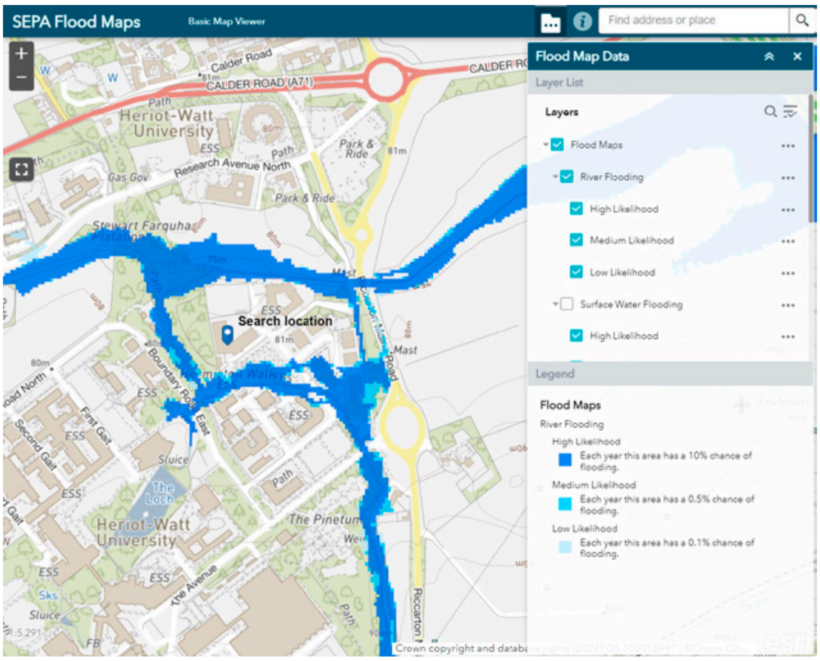

Figure 28 Current risk of fluvial flooding at BGS Edinburgh as assessed by SEPA. (https://scottishepa.maps.arcgis.com/apps/webappviewer/index.efa44e3b8a72a07cf5767663&showLayers=FloodMapsBasic_5265;FloodMapsBasic_5265_0&marker=317743.25;669727.69;27700;;;Search%20location&scale=16000).

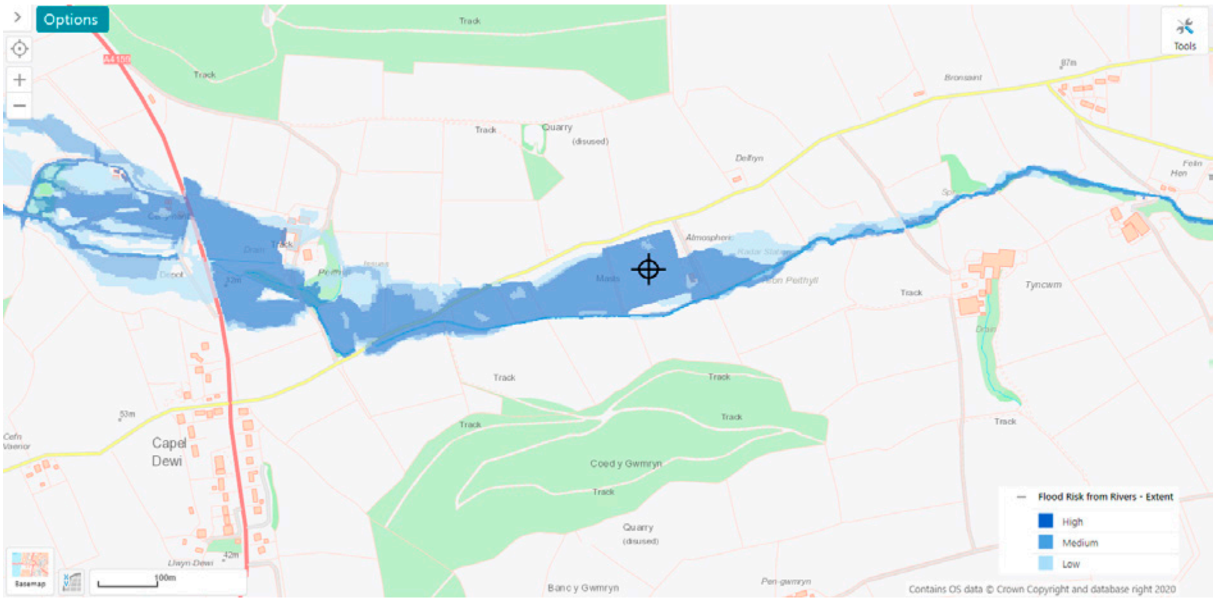

Figure 29 Current risk of fluvial flooding at the NCAS CDAO, Capel Dewi as assessed by NRW. (https://maps.cyfoethnaturiolcymru.gov.uk/Html5Viewer/Index.html?configBase=https://maps.cyfoethnaturiolcymru.gov.uk/Geocortex/Essentials/REST/sites/Flood_Risk/viewers/Flood_Risk/virtualdirectory/Resources/Config/Default&runworkflow=CYFR_Search&X=264501&Y=282934).

Appendix 2 Summary of recommended actions

The following table summarises the recommended actions for each site.

BGS Keyworth	
1	The BGS Estate & Facilities team should inspect the culverts in the channel running along the north-west of the site at least annually and arrange for any debris to be cleared by the appropriate authority, if necessary.
2	The BGS Estate & Facilities team should make Nottinghamshire County Council, the Lead Local Flood Authority (LLFA) for Keyworth, aware of this work. They should provide them with a copy of the report and highlight to them the potential risk of flooding to the newly constructed houses to the north of Platt Lane, and to the Severn Trent Water's sewage pumping station at the corner of Platt Lane and Nicker Hill.
3	The BGS Estate & Facilities team should review the results of the site drainage modelling with the report authors. The slopes and lengths of the problematic network sections should be measured accurately, and, given funding is available, the modelling exercise repeated to confirm the findings of this study. Updating and rerunning of the model would be relatively quick. After confirming the fidelity of the model, several potential solutions could then be reviewed, and their costs and benefits evaluated against the level of risk that NERC BGS are willing to accept. Solutions could include replacing small diameter pipes with larger pipes, increasing the slopes of the pipes, and optimising the size of catchment areas generating runoff by altering the direction of surface flow paths/ directions.
BGS Edinburgh	
4.	NERC, BGS and Heriot Watt University should consider the level of protection provided to the Lyell Centre, considering the findings of this study e.g. that a 20-year return period event will result in flood water reaching the Lyell Centre. If it is considered that the level of flood protection is currently insufficient, NERC and Heriot Watt University should discuss what the options are for increasing the level of protection to the Lyell Centre.
5	The study has shown the potential for flooding of other buildings on the Heriot Watt campus, e.g. the Energy Academy and the buildings north-east of the Lyell Centre on the opposite side of the Murray Burn and Research Avenue South. This report should be shared with the Heriot-Watt estate management department to make them aware of the risks to the occupiers of these buildings, and to allow them to consider any necessary actions.
NCAS Capel Dewi	
6	A survey of the Afon Peithyll should be undertaken to define the dimensions and slope of the channel. A drone-based LIDAR survey of the area of the site should also be undertaken to obtain a more accurate land surface elevation dataset. These measurements should be included in the HEC-RAS model of the site and the simulations rerun to improve confidence in the results.
7	After incorporating more accurate measurements of the channel shape and land surface elevations into the model, the updated model results should be reviewed by NERC and NCAS to consider what an acceptable level of risk is for the site. NERC should then seek advice from an engineering consultancy on the viability and cost-benefit of various engineering options that could be implemented to protect the site. The amount by which an engineering option could reduce flood risk to the site could be evaluated with the updated model.

8	NCAS staff should consider whether any infrastructure located in the south-east of the site, where the risk of flooding is higher, could be relocated to a higher part of the site.
Sites not considered in this study	
9	UKCEH/BGS WALLINGFORD: NERC should consider whether an assessment of changing flood risk to the UKCEH/BGS Wallingford site should be commissioned. Analysis of flood risk at this site under future climate would require simulation of overbanking of the River Thames taking into account the response of the large catchment upstream. This would be a significant piece of work and was beyond the scope of this project; it would be best undertaken by UKCEH hydrologists.
10	BAS CAMBRIDGE: Parts of the site have been mapped by the Environment Agency to be in the high risk zone for pluvial flooding. NERC should consider if a similar study should be commissioned to assess the changing risk of pluvial flooding. Accurate simulation of the flood risk at the site would require a detailed assessment of the flow and potential for accumulation of rainfall-runoff based on an accurate high-resolution map of land surface elevations and modelling of the urban drainage system.

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