

Exacerbation of levee failure with climate change: Insights from ERT monitoring

Authors: Adrian White^{*1}, Paul Wilkinson¹, James Wookey², John Michael Kendall³, Ross Stirling⁴, James Boyd¹, Arnaud Watlet⁵, Anthony Blake⁶, Joel Smethurst⁷, Jonathan Chambers¹

1. British Geological Survey, Nottingham, United Kingdom

2. University of Bristol, Bristol, United Kingdom

3. University of Oxford, Oxford, United Kingdom

4. Newcastle University, Newcastle, United Kingdom

5. Luxembourg Institute of Science and Technology, Luxembourg

6. Atlantic Technological University, Ireland

7. University of Southampton, Southampton, United Kingdom

* Corresponding author

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Abstract

Climate change in Western Europe is bringing hotter, drier summers and warmer, wetter winters. This will place greater stress on ageing levees by intensifying soil moisture fluctuations and increasing hydraulic loading. Conventional inspections cannot see inside these structures, so detecting and monitoring subsurface deterioration remains a critical challenge. We monitored a clay levee constructed from glacial till in northern England for four years using electrical resistivity tomography (ERT) at 48-hour intervals, alongside environmental conditions and river level. Time-lapse ERT shows resistivity variability concentrated in two zones: 1) The near-surface active layer (upper ~1–1.5 m), which undergoes progressive summer drying followed by autumnal rewetting. 2) The foundation strata, where resistivity decreases with rising river levels, consistent with water movement beneath the levee. In the active layer, resistivity-derived drying depth correlates strongly with weather-derived soil moisture deficit ($r = -0.95$), quantitatively linking climatic forcing to seasonal drying. Applying this relationship to bias-corrected UKCP18 projections (RCP8.5) suggests average maximum drying depths could increase from ~0.6 m to >1.0 m by the late 21st century. These findings demonstrate that future levee design and risk-informed asset management must account for the combined impacts of increasing drought and flooding to ensure long-term structural resilience.

Introduction

Levees (also known as flood embankments or dykes) are linear earthworks built along rivers and coasts to protect land, property, and infrastructure from floods up to a designed height or recurrence interval. When levees fail, particularly due to breaches, the resulting floods can cause significant damage, disrupt essential infrastructure, and lead to loss of life (Pistrika and Jonkman 2010; Orlandini *et al.* 2015; Hui *et al.* 2016). Over time, levees deteriorate due to the prevailing environmental conditions such as the local climate, river and groundwater levels, wave height and burrowing animals (Simm *et al.* 2012; Borgatti *et al.* 2026) (Fig. 1). The effects of this environmental loading are influenced by the levee's material properties (e.g. cohesive vs granular fill), which control its ability to resist water ingress and maintain structural integrity during flood events (Monteiro-Alves *et al.* 2025).

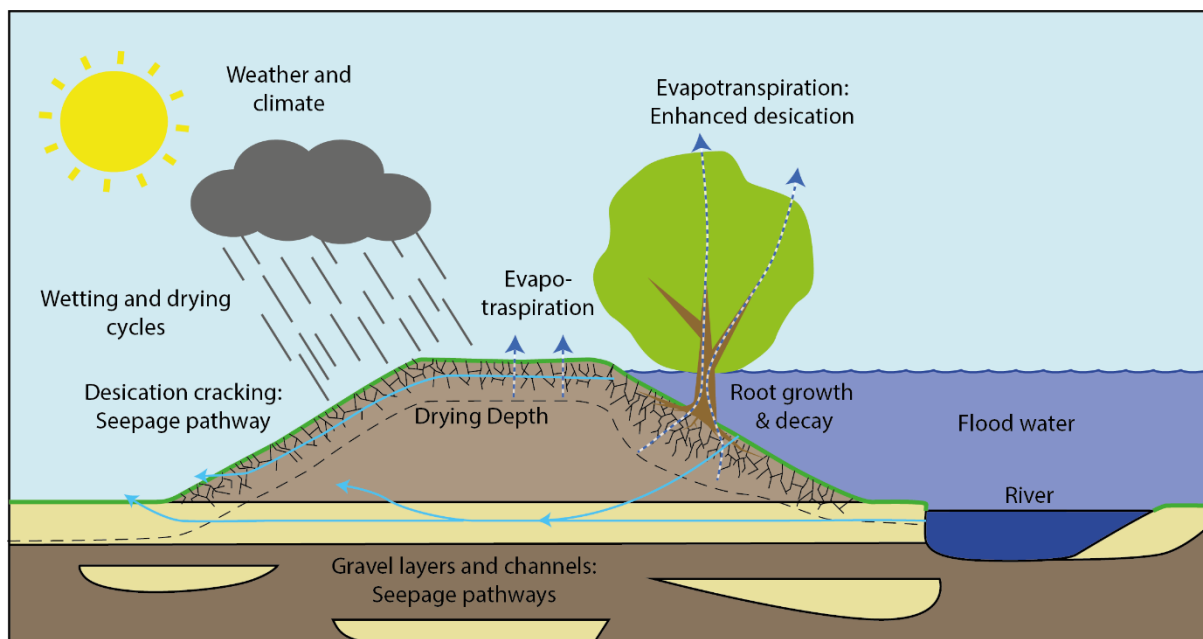


Fig. 1. Schematic diagram showing the effects of environmental loading on a levee, which can drive deterioration processes. These processes can lead to greater hydraulic conductivity, which may facilitate water ingress during flood events. Climate change is altering weather and climate patterns, which may exacerbate these processes. © University of Bristol & British Geological Survey © UKRI

New levees are designed to withstand these environmental loads by satisfying key ultimate limit states (Pickles and Sandham 2014), including overall stability (e.g. slope failure), uplift (buoyancy), hydraulic heave, and internal erosion (Zheng *et al.* 2024, 2025; Monteiro-Alves *et al.* 2025). Overtopping and external erosion are not considered in the geotechnical design criteria, as external erosion resistance is often provided by other features (e.g. turf, or geotextiles) (CIRIA *et al.* 2013). While no material specifications are prescribed, cohesive 'Class 2' soils compacted to at least 95% of maximum dry density are favoured for both new construction and repairs because they most effectively meet these performance requirements (National Highways, 2025). For existing levees, serviceability limit states are particularly important including, settlement, desiccation cracking, animal burrowing and seepage rates, as these can affect the ultimate limit states over time (Pickles and Sandham 2014). For example, poorly compacted, compressible, or organic soils can experience long-term settlement, increasing the risk of

64 localised overtopping and external erosion (Tarrant *et al.* 2017). Granular soils are particularly
65 susceptible to seepage, internal and external erosion. In such materials, backward erosion can
66 develop into concentrated leak erosion and ultimately piping failure. This process may be
67 exacerbated by suffusion, whereby the loss of fine particles increases hydraulic conductivity,
68 reinforcing seepage through a positive feedback mechanism (Johnston *et al.* 2021). Meanwhile,
69 soils susceptible to shrink-swell can develop regions of elevated hydraulic conductivity in the
70 near surface layer through repeated moisture cycling (Dixon *et al.* 2019; Stirling *et al.* 2021),
71 opening cracks (Yu *et al.* 2021) and degrading the soil structure (Dyer *et al.* 2009; Apriyono *et al.*
72 2025). High hydraulic conductivities are a major factor in non-overtopping levee failures during
73 flood events (Bettess and Reeve 1995; Zhang *et al.* 2016).

74 In addition to the direct impact of more frequent, larger floods (IPCC 2023), climate change is
75 altering the environmental loads on levees, which particularly affects the soil moisture dynamics
76 (Samaniego *et al.* 2018; Janga *et al.* 2024). The UK, for example, will face hotter, drier summers
77 and warmer, wetter winters, exacerbating seasonal moisture cycles (Lowe *et al.* 2018). These
78 shifts, especially prolonged droughts, will lead to more pronounced wetting and drying cycles in
79 levee soils, promoting desiccation crack formation and increasing hydraulic conductivity
80 (Stirling *et al.* 2021; Apriyono *et al.* 2025). Over time, these processes have the potential to
81 accelerate levee deterioration and heighten the risk of failure (Robinson and Vahedifard 2016;
82 Rouainia *et al.* 2020). Direct measurement of in situ hydraulic conductivity and its seasonal
83 variability due to opening and closing of cracks, is challenging to directly measure, and shows
84 large spatial variabilities that may mask temporal change (Dixon *et al.* 2019). By monitoring
85 moisture dynamics in the unsaturated zone, areas that respond rapidly to environmental loading
86 (e.g. rainfall, or river levels) may be separated from areas with little response. This qualitatively
87 highlights areas at risk of potential deterioration and failure pathways that may be exacerbated
88 by climate change.

89 Electrical Resistivity Tomography (ERT) can be used to monitor the internal moisture dynamics
90 of levees and embankments (Tresoldi *et al.* 2019; Amabile *et al.* 2020; Ali *et al.* 2025). ERT images
91 bulk resistivity values of the soil, which is sensitive to lithology, porosity, pore fluid conductivity,
92 moisture content and temperature (Waxman and Smits 1968). By comparing repeat
93 measurements, applying a correction for the effects of temperature variation, and assuming
94 constant pore fluid conductivity, the resistivity changes can be interpreted as moisture content
95 changes, providing insight into the levee's internal moisture dynamics (Chambers *et al.* 2014;
96 Jodry *et al.* 2019).

97 In this paper, we present the findings from a 4-year monitoring study of a clay levee in northern
98 England. Combining ERT monitoring with environmental sensor data, we assess the levee's
99 moisture dynamics and explore whether potential failure mechanisms can be inferred. We then
100 quantify the relationship between resistivity-derived drying depth and climatic forcing and apply
101 this relationship to future climate projections to assess the implications for long-term levee
102 deterioration and strategies to mitigate it. To our knowledge, this is the first study to combine
103 multi-year ERT-derived desiccation monitoring with climate projections to quantify future
104 changes in levee drying susceptibility.

Field site

The levee selected for this study is located on the River South Tyne at Warden, 3 km northwest of Hexham, UK (Fig. 2). The river reach at Warden is a local narrowing in the floodplain, increasing the flood risk (Fig. 2b). The 600 m long ~2.5 m high levee protects 33 houses and the train line from Newcastle to Carlisle from flooding (Environment Agency 2016).

This levee was selected due to its long history of flood events (Table 1), its recent (2007) reconstruction to modern standards and its material composition, which is a low to intermediate plasticity clay likely sourced from local glacial till. Glacial till is widespread across much of the UK, so this levee is likely representative of a significant proportion of UK levees, with the caveat that many levees have unknown compositions.

The first levee at Warden was built around 1950 from silt and sands following a snowmelt flood in 1947 (Archer *et al.* 2007b) (Table 1). In 2005, the levee breached, and although the failure mechanism is unknown (Table 1, Fig. 2c) over-steepened slopes (p.c. landowner), rabbit burrows (Mott Macdonald 2019), and overtopping (Archer *et al.* 2007b) followed by external erosion, have all been suggested. A temporary repair was made in 2005 (Fig. 2c) before the whole levee was re-constructed in 2007 using 18,000 tonnes of imported 'clay' (Evening Chronicle 2007), and was designed to protect against 1 in 100 year floods (Environment Agency 2020).

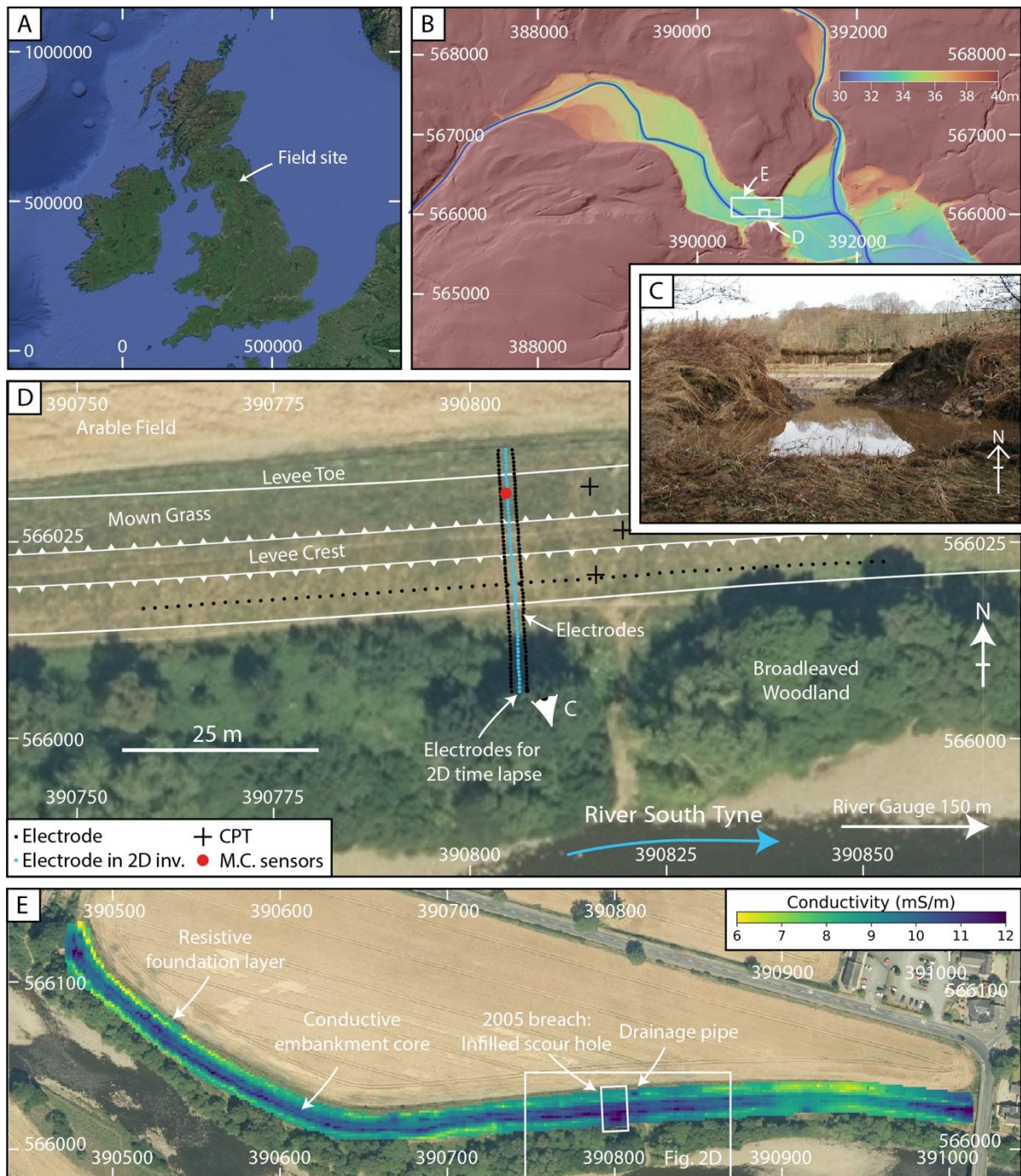


Fig. 2. Overview of the field site at Warden, Northumberland. **a)** Location of the field site in the UK. **b)** Digital Terrain Model (DTM) of the river valley, showing the levee located at a narrowing within the valley. **c)** Photograph of the 2005 breach looking North (Part D for location) from the riverside through the levee; image from the International Levee Performance Database (Özer *et al.* 2019). **d)** Map of the monitoring section, showing installed instrumentation. All electrodes in the monitoring array are shown (blue and black). The blue subset were chosen for 2D timelapse inversion. CPT = Cone Penetration Test, M.C. = Moisture content, and electrodes are for ERT monitoring. **e)** Electromagnetic (EM) conductivity survey results, for a depth of investigation of 1.2 m White *et al.* (2023). Copyright attribution: Part A) satellite imagery Google Maps © 2022 Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Landsat / Copernicus, Imagery©2022 Terra Metrics, Map data ©2022 Google, GeoBasis-DE/BKG. Coordinate system: British National Grid. Part B) Lidar base map © Environment Agency copyright and/or database right 2022. All rights reserved. UKRI. Part D & E) Aerial photography © UKP/Getmapping Licence No. UKP2006/01. Fig. © University of Bristol & British Geological Survey ©

Date	Event	Details
1947	Flood	Snowmelt
c. 1950	Levee constructed	First levee constructed at the site
1955	Flood	Peak River level 40.91 m - 8 properties flooded, mechanism unknown
8 January 2005	Flood, levee breach repaired	Peak River level 40.82 m Levee breached (Fig. 2c) - 23 properties flooded
2007	Levee replaced	Levee replaced and raised
23 June 2012	Flood	Peak River level 39.5 m – Flood water reaches levee toe
18 May 2013	Flood	Peak River level 39.95 m – Flood water retained by levee
05 December 2015	Flood	Peak River level 41.01 m - Water against levee, flood walls adjacent to the levee overtopped, 14 properties flooded

Table 1. Flood and levee history of the River South Tyne at Warden. Peak river level is defined as the water level above sea level recorded at the river gauge, plus a 0.5 m adjustment to represent the higher elevation at the levee monitoring location (Archer *et al.* 2007a, b; Environment Agency 2016; Northumberland County Council 2016).

The levee has been characterised along its length using geotechnical methods, including cone penetration testing and trial pits, and geophysical methods, including electro-magnetic imaging (EMI), ERT and multi-channel analysis of surface waves (White *et al.* 2023). These surveys, illustrated by the EMI (Fig. 2e), show that the levee properties are similar along its entire length. The EMI also shows a conductive anomaly, ~15 m wide, interpreted as the infilled scour hole produced during the 2005 breach.

Overall, the levee comprises a relatively homogenous compacted core covered by a plastic geogrid to prevent animal burrowing and topped with ~30 cm of topsoil. The core is glacial till (10% gravel, 34% sand, 30% silt, 26% clay, and the occasional cobble) with a liquid limit of 35%, a plastic limit of 20%, and a plasticity index of 15, making it a low to intermediate plasticity clay. The levee is grass-covered and mown a few times a year to maintain erosion protection (Smith *et al.* 2009; Simm *et al.* 2017); between the river and the levee are trees and shrubs. The levee foundations are superficial alluvial and river terrace deposits (Burns and Miller 1883), comprising sands and gravels. Detailed mapping upstream of the site found seven different river terrace levels, the oldest thought to have formed during late Pliocene deglaciation (Passmore and Macklin 2000). The riverbank shows a stratigraphy of silts, sands and gravels with large cobbles and boulders, typical of river channel and floodplain deposits. The bedrock geology is the Stainmore Formation, comprising limestones, mudstones and sandstone (British Geological Survey 1975), and is likely too deep to affect the levee performance.

Methodology

The characterisation survey identified a ~100 m section of the levee where it crosses a palaeochannel, is at its tallest point, and contains the location of the 2005 breach (Fig. 2d). All these factors can increase the risk of a breach developing, so this section was selected for monitoring. It was instrumented in the autumn of 2021 with an ERT monitoring system and geotechnical sensors (Fig. 2d) (Blake *et al.* 2022). Full data collection started in November 2021.

Environmental sensors

This site was instrumented with an array of environmental sensors (Blake *et al.* 2022), including two volumetric moisture content (VMC) and temperature sensors (Meter Group Terros 12) installed in the landward slope 0.1 m and 0.3 m below the surface, along with a 1D temperature array comprising four sensors (Meter Group RT-1) extending to 4 m below the surface (Fig. 2d, Fig. 5b). The temperature sensors were installed in a hand augered hole and backfilled with bentonite to prevent water movement. The VMC sensors were installed in the side of the hole. A pre-existing river gauge is located 150 m downstream of the site on the river bridge maintained by the UK Environment Agency (DEFRA 2025). All sensor data was collected at 15-minute intervals. Weather data are extracted from the 1 km HadUK database, which provides daily temperature and rainfall observations for the UK (Met Office *et al.* 2018). The HadUK data was chosen over a local weather station as it is a daily data set spanning over six decades, allowing for integration with the UKCPI8 climate data (Met Office *et al.* 2018).

Evapotranspiration and Soil Moisture Deficit

To assess the hydrological forcing on the levee, both the addition of moisture to the surface through rainfall (measured) and the removal of moisture through evapotranspiration (calculated) need to be known (Holmes *et al.* 2022). Evapotranspiration is the combination of evaporation from the soil surface and transpiration from vegetation (Allen *et al.* 1998). Evapotranspiration is controlled by weather conditions (e.g. solar radiation, air temperature, humidity, and wind speed), and vegetation type and state. The Penman-Monteith equation is used to calculate the reference evapotranspiration (Allen *et al.* 1998), using data from the 1 km HadUK Grid, including daily minimum and maximum temperatures (Met Office *et al.* 2018). The other environmental parameters that can affect evapotranspiration are unavailable in this long-term dataset, so the default parameters described in Allen *et al.* (1998) are used. The reference evapotranspiration is multiplied by a crop coefficient to estimate actual evapotranspiration. The crop coefficient is assumed to be constant with a value of one, year-round; this is a commonly used simplification for grass-covered geotechnical assets (Smethurst *et al.* 2006; Helm *et al.* 2016). These simplifications may influence the absolute magnitude of evapotranspiration and short-term variability, particularly during extreme conditions, but do capture the seasonal cycles that force wetting and drying cycles in the near surface.

The soil moisture deficit (SMD) is derived using a simple bucket model to calculate the cumulative effect of rainfall and evapotranspiration (Allen *et al.* 1998; Clarke and Smethurst 2010). This model assumes that on the first day of monitoring in early November, $SMD = 0$, each day, rainfall (P) is added, and evapotranspiration (ET) is subtracted. If $SMD > 0$, we assume the excess rain leaves the site as runoff, and SMD returns to zero. However, if $SMD < 0$, the moisture deficit carries over to the following day. During dry periods, the SMD will become increasingly negative, but there is finite water within the rooting depth (assumed to be 1 m). For a typical silty clay, the total available water (TAW) within the rooting zone is $0.16 \text{ m}^3/\text{m}^2$ (160 mm) (Allen *et al.* 1998). When the SMD reaches 160 mm, the grass wilts, and evapotranspiration stops. Before SMD reaches 160 mm, the grass will become increasingly water stressed and the evapotranspiration rate will slow. Water stress occurs when the SMD exceeds the readily available

water (RAW). For pasture, RAW is assumed to be $0.6 \times \text{TAW}$ (Allen *et al.* 1998). To reflect the effect of water stress on the SMD when $\text{TAW} > \text{SMD} > \text{RAW}$, a modified crop factor (K_s) is used,

$$K_s = \frac{\text{TAW} - \text{SMD}}{\text{TAW} - \text{RAW}}, \quad (1)$$

to reduce the rate of evapotranspiration (Allen *et al.* 1998). Groundwater recharge is neglected in the bucket model (Clarke and Smethurst 2010), which may affect soil moisture conditions during wetter periods. However, during winter months the ground conditions will be near field saturation, and during summer drying conditions evapotranspiration dominates on clay materials so will have limited effect on surface drying.

Resistivity monitoring

An ERT monitoring system, PRIME (Proactive Infra-structure Monitoring and Evaluation), was installed along the levee. Here, the monitoring array comprised four lines, three perpendicular to the levee with a 1 m separation to form a 3D grid and one parallel located halfway up the river side face (Fig. 2d). The location of the parallel line was chosen to better image the impact of flood events on the levee slope, however there was no water against the levee during the monitoring period, so could not be investigated. Each line contained 64 stainless steel electrodes with a spacing of 0.5 m (perpendicular lines) or 1.5 m (parallel line). Each electrode is a 25 cm long rod, inserted vertically just below the turf. For each line, a dipole-dipole survey was used with dipole lengths of $a = 1-3$ electrode spacings and inter-dipole spacings na , where $n = 1-7$ (Loke *et al.* 2013). The dipole-dipole measurement configuration was chosen for its good image resolution and efficient use on a multichannel instrument, reducing overall power consumption (Dahlin and Zhou 2004). Over the monitoring period, ERT measurements were collected every 48 hours, resulting in 686 repeat measurement sets. Due to reduced power availability, the measurement frequency was changed to every 72 hours from January to March 2022. The data was sent to a remote server via a 4G mobile connection. During the monitoring period, water was never against the levee or covering the electrode array, so does not need to be considered during ERT processing.

ERT data processing, filtering and inversion used ResIPy (Blanchy *et al.* 2020), an open-source software wrapper and GUI for R3t, and R2, which are 3D and 2D inversion codes, respectively (Binley and Slater 2020; Blanchy *et al.* 2020). Measurements were removed prior to inversion if there was no reciprocal measurement or the reciprocal error exceeded 5% (Tso *et al.* 2017). A power law error model was fitted to the reciprocal errors at each time step; this was combined with a numerical modelling error estimate from the mesh using gaussian error propagation (Binley and Slater 2020; Blanchy *et al.* 2020). The 2D timelapse used a difference inversion, where the difference between the current time step and a baseline was inverted (LaBrecque and Yang 2000). The baseline was set to 20th April 2022 and was used to calculate resistivity change unless stated otherwise. This baseline was selected due to its good data quality and its intermediate values that highlight increases and decrease in resistivity compared to spring conditions. However, the selection of this dataset has very limited effect on the output of the difference inversion (Binley and Slater 2020, chap. 5). Overall, each time step converged with a mean χ^2 of 1.07 and a standard deviation of 0.16. The inversions were visually checked for consistency and artifacts.

Temperature modelling

Resistivity measurements are sensitive to changes in temperature. For soils at temperatures between 0-50°C, conductivity increases by ~2% for every 1°C increase in temperature (Ma *et al.* 2011). To reduce temperature-induced resistivity changes a simplified 1D seasonal temperature model can be fitted to the temperature array data (Fig. 3) (Brunet *et al.* 2010):

$$T(t, z) = T_{\text{mean}} + Ae^{-\left(\frac{z}{d}\right)} \sin\left(\frac{2\pi}{365.25}t + \varphi - \frac{z}{d}\right), \quad (2)$$

where $T(z, t)$ is the temperature at day t and depth z , T_{mean} is the mean annual temperature, A is the amplitude of the sinusoidal variation in yearly air temperature, d is the characteristic penetration depth of the temperature variations, φ is the phase offset and $(\varphi - z/d)$ is the phase lag. The resulting fitted parameters are listed in Table 2. This approach is now routinely used for temperature corrections (Chambers *et al.* 2014; Uhlemann *et al.* 2017; Jodry *et al.* 2019).

Parameter	T_{mean} (°C)	A (°C)	d (m)	φ (rad)
Value	9.95	6.42	3.13	-1.94

Table 2 Fitted parameters for the temperature model

However, in 2025, the spring and summer months were unusually warm. This caused a significant departure from the model (Fig. 3) to depths of at least 2.5 m. To account for this, we adopted an alternative approach, solving the 1D heat equation numerically using a Backward Time Centred Space (BTCS) finite difference scheme (BTCS is a stable implicit Euler method). The 1D model was split into seven depth domains, the first from the surface to the first temperature sensor, the second from the first to the second temperature sensor, and so on until the last domain which spanned from the sixth temperature sensor to a base depth (16 m) where the temperature was assumed to be constant.

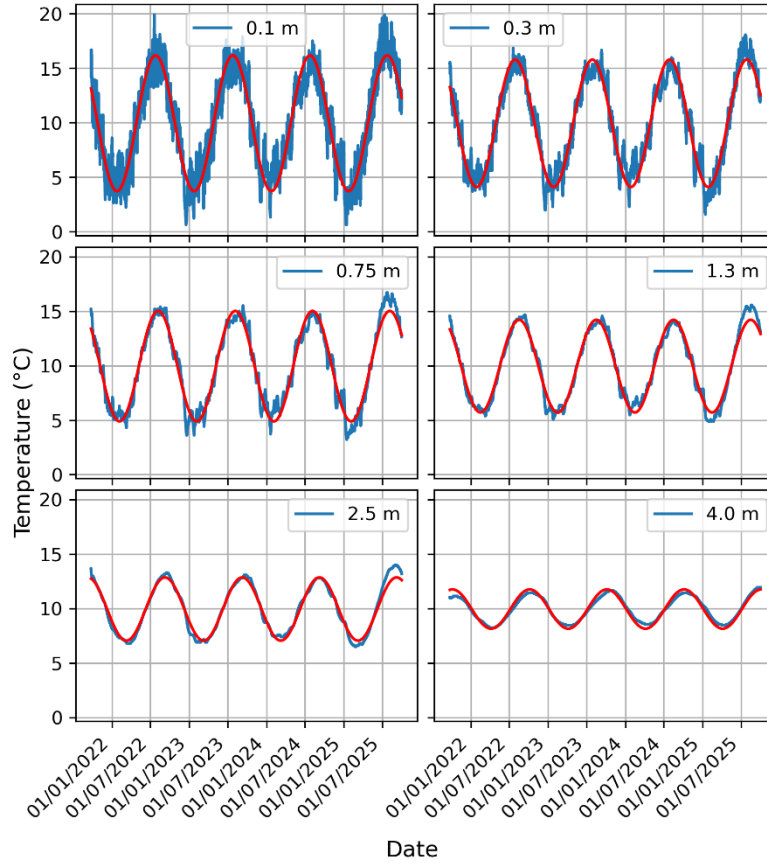


Fig. 3. Temperature data from the six sensors installed at different depths (blue) and the fitted 1D temperature model (red). © University of Bristol & British Geological Survey © UKRI

Each depth domain was discretised into 50 segments. The Dirichlet boundary conditions for each domain were set to the air temperature at the surface, the measured temperatures at the depths of each temperature sensor, and T_{mean} at the base depth. The thermal diffusivity was calculated from d , the characteristic depth fitted in the seasonal model (Equation 2) as $\alpha = \pi d^2 / 365.25$, and the initial temperature distribution was calculated from the seasonal model applied at the first time-step (2021/09/24 00:00). A time interval of 0.1 days was used to capture diurnal as well as longer period variations. The differences between the BTCS model and the seasonal model and are illustrated in Fig. 4.

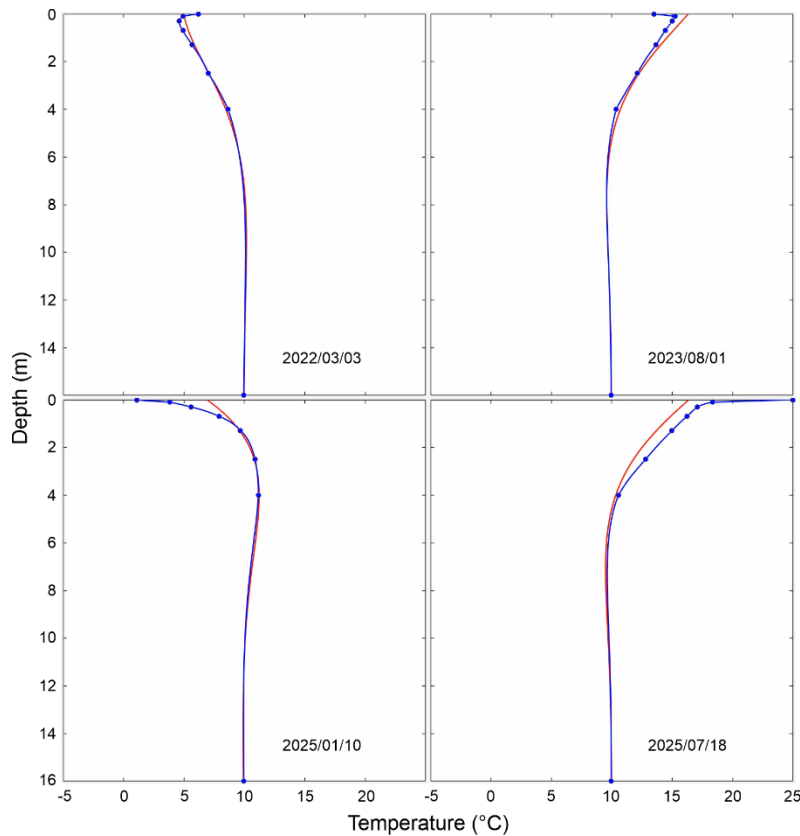


Fig. 4. BTCS (blue line) and seasonal (red line) temperature models. Blue dots indicate air temperature (depth = 0 m), measured ground temperatures (0.1 - 4 m), and T_{mean} (16 m). Note the greater departures from the seasonal model in 2025. © University of Bristol & British Geological Survey © UKRI

The temperatures for the centroid depth of every cell at each time step were interpolated from the BTCS temperature model results. The resistivity value of each cell was then adjusted to the mean annual temperature of 9.95°C, resulting in a maximum resistivity change of ~20%.

Results

Levee structure

To assess the structure of the levee, the baseline survey was inverted as a single 3D resistivity model (Fig. 5a). This confirms that the levee is relatively homogenous with a ~20 Ωm levee sitting on top of higher resistivity material. Where the perpendicular and parallel lines cross, there is a higher resistivity region, however, ERT inversions are affected by data distribution, offline topography, and isotropic smoothing, so we need to consider the reliability of this 3D model (Bièvre *et al.* 2018; Hojat 2024).

Comparing a cross-section along the central perpendicular line of electrodes (high data density) to a location away from the perpendicular electrodes (low data density) demonstrates a large difference in resistivity structure (Fig. 5a). The cross-section along the central perpendicular line of electrodes has higher resistivity values (~200 Ωm) in the foundation layer and closely matches a 2D model containing only the data of the same central perpendicular line, and the structure is consistent with the CPT-derived logs (Fig. 5b). In contrast, the cross-section away from the

perpendicular line of electrodes shows that the 3D model has a cylindrical resistivity distribution centred on the levee parallel line, and quickly converges to 100 Ωm , the starting resistivity value of the ERT model. This cylindrical resistivity distribution is a direct result of the levee parallel line being straight with no azimuthal sensitivity (i.e., it cannot discriminate between anomalies to either side or below) and an isotropic L2 smoothing regularisation. Therefore, the range of resistivity values from the foundation material will likely be underestimated away from the perpendicular ERT lines (White *et al.* 2024) (Fig. 5a).

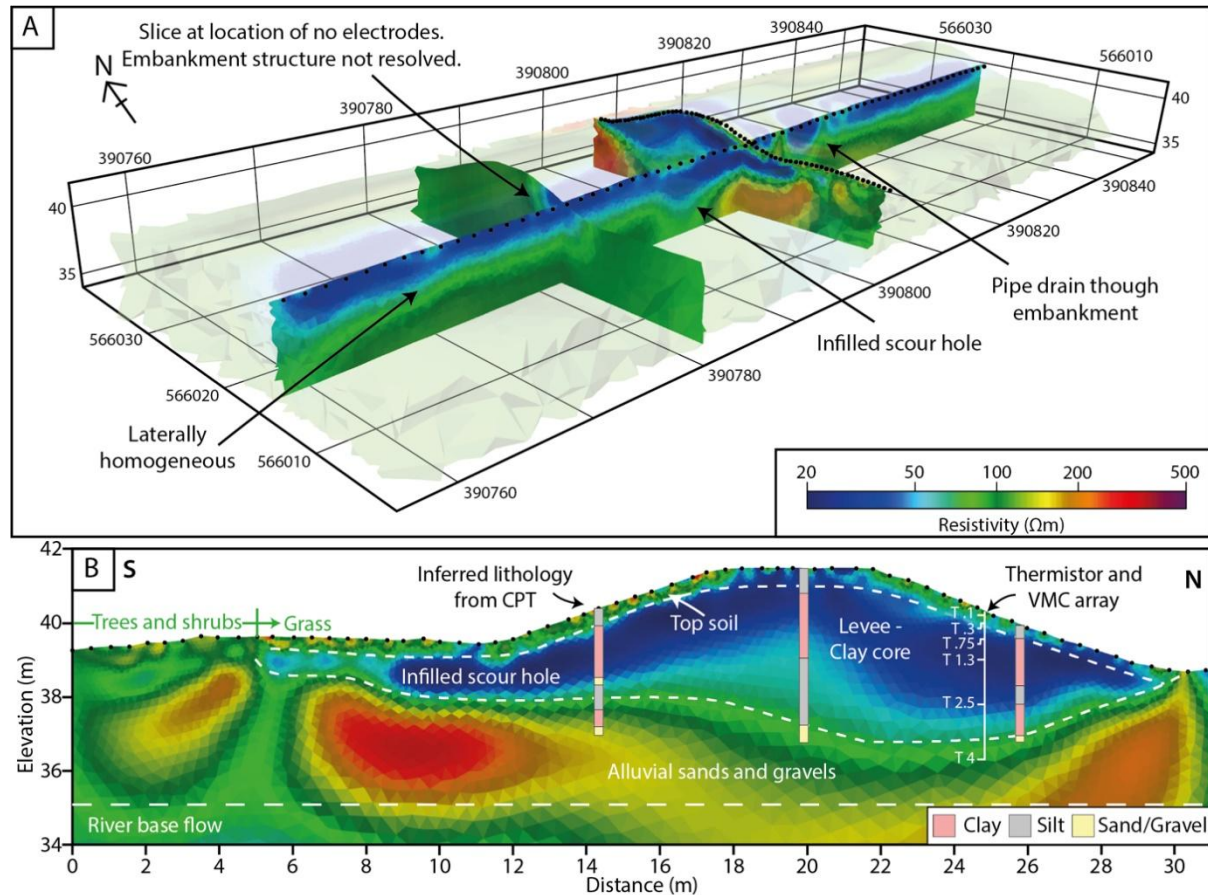


Fig. 5. ERT inversions of the baseline timestep (20th April 2022). **a)** 3D model of the levee. To aid visualisation, the 3D model has been sliced along the levee parallel line, the central perpendicular line, and a location away from the perpendicular lines. **b)** 2D model containing data from the central perpendicular line. The 2D inversion is overlain with CPT-derived logs with interpretation and the river level at a typical baseflow level. © University of Bristol & British Geological Survey © UKRI

The 3D model confirms that the levee is relatively homogeneous along the monitored section (when considering the effects of the array geometry) with small perturbations caused by the infilled scour hole and the drainage pipe under the levee (Fig. 5a). Therefore, due to the computational efficiency of the 2D inversion for time-lapse monitoring and its good agreement with the 3D model, we present the 2D inversion results from the central perpendicular line.

The baseline 2D resistivity model with the CPT-derived logs, where the soil behaviour type was calculated and simplified using the approach of Robertson (1990), suggests that the levee has three principal units (Fig. 5b): 1) a low resistivity unit of 20-50 Ωm representing the clay fill of the levee; 2) a surface layer with intermediate resistivity values (~100 Ωm) representing the layer of topsoil covering the levee; and 3) a high resistivity layer below the levee with values between

100-500 Ωm , highlighting the alluvial sand and gravel deposits. The low resistivity levee body cuts into the foundation layer, likely the result of topsoil removal during construction, following best practice guidance (CIRIA *et al.* 2013, fig. 10.26), and the infilling of the scour hole that formed during the original break.

Levee monitoring

Environmental monitoring

The hydrological and weather data show seasonal variations in rainfall, river level and soil moisture content over the monitoring period (Fig. 6). In the summer months, rainfall is lower and evapotranspiration is higher, resulting in drying of the levee surface. In the autumn, the evapotranspiration decreases and rainfall increases, wetting up the surface of the levee and causing elevated water levels in the river that fluctuate throughout winter. During the monitoring period river levels varied by 4.5 m within the river channel but at no point was there water against the levee (> 39.5 m).

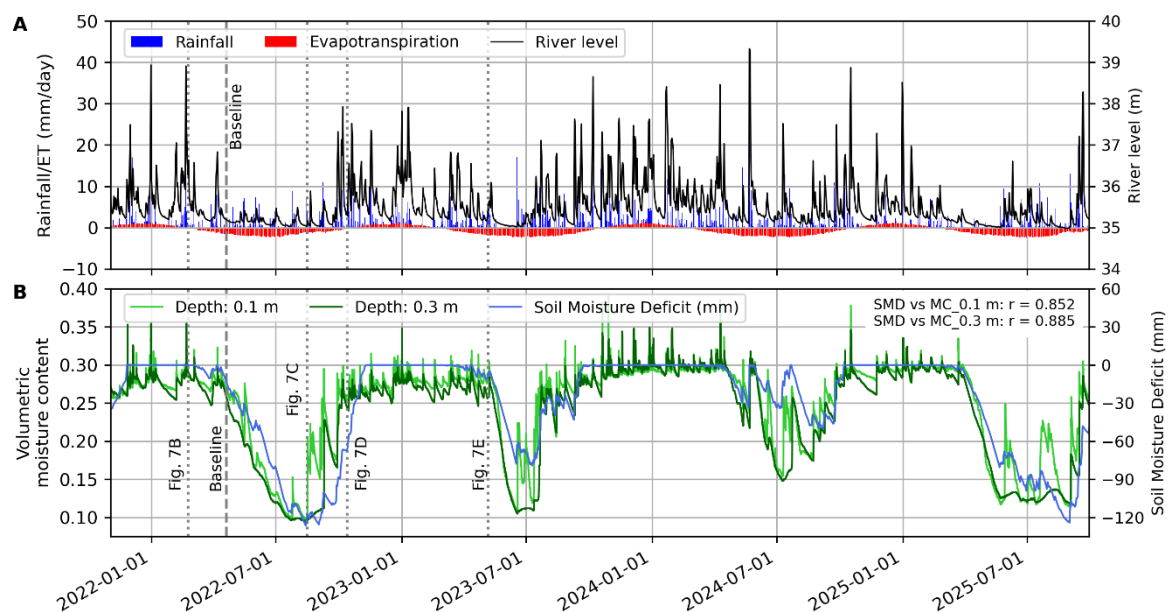


Fig. 6. Environmental monitoring of the field site . a) Plots of rainfall, evapotranspiration and river level. b) Plots of the volumetric moisture content at 0.1 m and 0.3 m depths and the soil moisture deficit (SMD) derived using the Penman-Monteith equation. r = Pearsons correlation coefficient. Vertical dashed lines are the datasets shown in Fig. 7. © University of Bristol & British Geological Survey © UKRI

Between autumn and spring, both moisture content sensors recorded average values of ~ 0.29 VMC (volumetric moisture content); this will approximate field saturation (Fig. 6), which is typical of UK earthwork infrastructure (Smethurst *et al.* 2012). Heavy rainfall can cause values to spike above 0.3 VMC followed by a rapid drop. During summer, VMC drops gradually, correlating with decreased rainfall and increased evapotranspiration; this is the main drying cycle. During the summer, there are rapid fluctuations in surface moisture content caused by summer rainfall that is rapidly removed through high evapotranspiration rates. In the autumn,

with the onset of more persistent rain, the surface appears to wet up rapidly, preceding the deeper VMC sensor.

Resistivity monitoring

During the monitoring period, repeat ERT inversions reveal resistivity changes that correspond to variations in moisture content driven by seasonal cycles, weather events, and fluctuations in river level within the foundation strata (Fig. 7). River levels were never high enough to place floodwater against the embankment, so we cannot assess the ERT response to flood loading of the levee. The results from 20th April 2022 are used as the baseline to calculate the resistivity difference. This baseline was selected because the levee was still relatively saturated, representing winter conditions, and the river stage was close to its baseflow level (Fig. 6). Baseflow is the typical streamflow between rainfall events.

To assess the resistivity changes in terms of moisture content values, all other effects such as temperature, pore fluid conductivity and structural changes (e.g. cracking) need to be negligible compared to moisture content changes. The temperature effects should be largely removed by temperature corrections. While pore fluid conductivity was not monitored during the study, it is often assumed to be constant in freshwater environments when petrophysical relationships are used (e.g. Waxman and Smits, 1968) to convert resistivity to moisture content (Chambers *et al.* 2014; Hojat *et al.* 2020; Holmes *et al.* 2022). This leaves structural changes such as cracking that we may expect to occur in the near surface as it dries out. Decreasing moisture content and any associated cracking both increase resistivity values and are inseparable with the data available to this study, so we chose not to apply a petrophysical relationship but interpret the resistivity model values. Surface drying and associated cracking from the baseline will be associated with increasing resistivity values, while increasing river levels or the water table result in decreasing resistivity values.

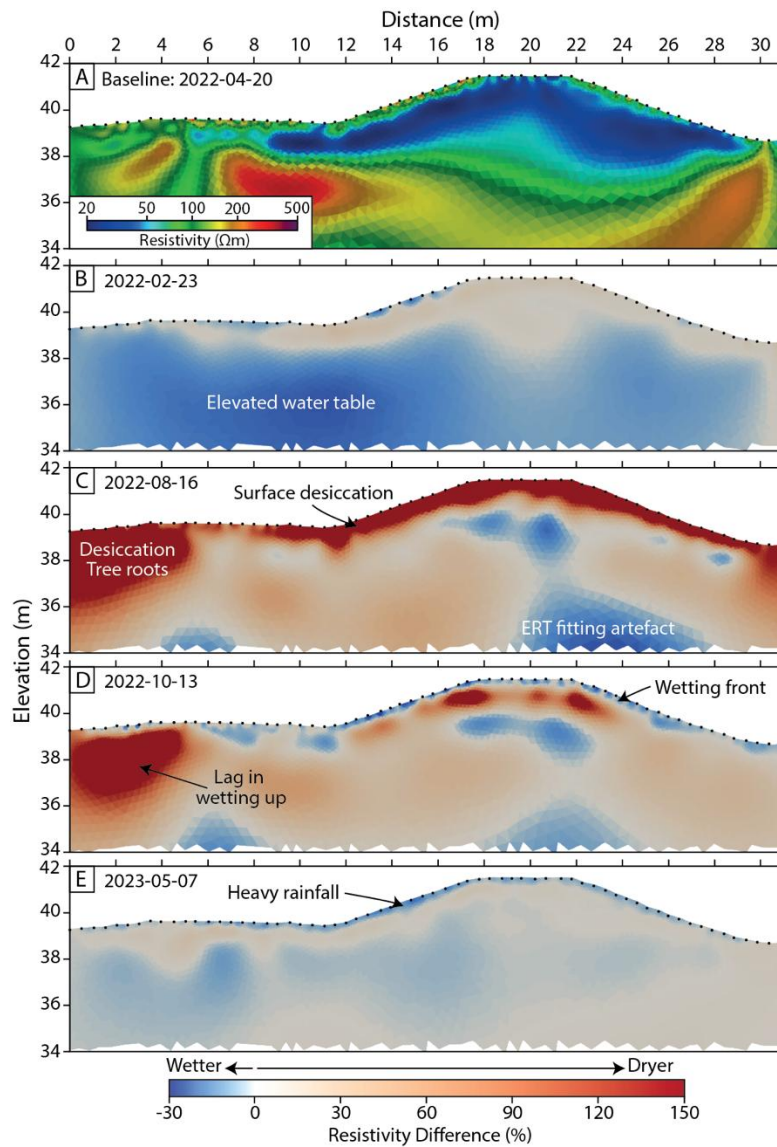


Fig. 7. Selected timesteps from the timelapse inversion, with the temperature correction applied, illustrating the key processes imaged during the monitoring period. **a)** Baseline resistivity distribution, 20 April 2022. **b)** Winter flood event with an elevated water table (no water against the levee). **c)** End of summer dry period, with little rainfall. **d)** Wetting up of the levee at the end of the summer. **e)** Effect of heavy rain on the near-surface. Fig. 6 shows their alignment with the measured environmental parameters. © University of Bristol & British Geological Survey © UKRI

In the winter, the resistivity values in the foundation strata decrease and after large rainfall events decrease below the baseline values (Fig. 7b). These decreases in resistivity span the width of the levee. During summer months, surface drying dominates, and at the end of the 2022 summer, after an extended period of dry weather, the surface shows large increases in resistivity values; these are deepest where there is woody vegetation (Fig. 7c). At the end of the summer, with the reduction in evapotranspiration, a wetting front develops, wetting the levee from the surface downwards (Fig. 7d). During heavy rainfall events, the near-surface records a transitory decrease in resistivity values associated with heavy rainfall (Fig. 7e). ERT inversions are not free of artefacts; Fig. 7c records a decrease in resistivity below the levee while the surface is very dry, this has been seen at other sites (Holmes *et al.* 2022), and is likely a result of slight overfitting of the data during the inversion.

Discussion

Levee variability: inferred failure mechanisms

To synthesise how the levee responds to changes in environmental conditions, the resistivity values from each cell in every time step can be combined by calculating the Coefficient of Variation (CV) (Boyd *et al.* 2021),

$$CV = 100 \frac{\sigma}{\mu}, \quad (1)$$

where σ is the standard deviation, and μ is the mean value of each cell. The CV statistic allows a comparison of the relative variability of each cell despite large variations in different mean resistivity values (Fig. 8). Cells with large variabilities must be associated with large fluctuations in moisture content. To facilitate these fluctuations these regions of the ground either have higher hydraulic conductivities than the surrounding areas facilitating moisture movement and/or are areas exposed to larger hydrological forcings driving moisture dynamics.

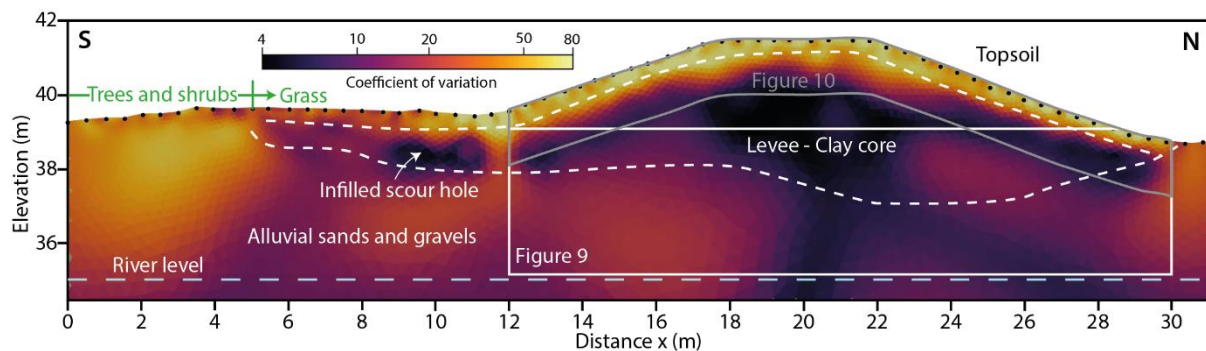


Fig. 8. A plot of the coefficient of variation for each cell in the resistivity model shows areas of high and low variability. Labels and line work from Fig. 5b. White and grey boxes show location of averaged data in Fig. 9 and 10. © University of Bristol & British Geological Survey © UKRI

The largest variabilities occur in the top ~1 m, which consists of a ~30 cm topsoil layer on top of the levee core. This region is directly exposed to fluctuations in surface conditions, so it will likely experience comparatively large hydrological forcings. Where there are trees and shrubs, this zone extends over 3 m deep but is slightly less variable than in the grass covered levee, which is consistent with the findings of Holmes *et al.* (2022). In contrast, the main levee body below ~1 m shows very little variability, indicating that the compacted clay must have low hydraulic conductivity and is protected from environmental extremes by the overlying soil. The levee foundations show intermediate variability likely driven by changes in river level and associated groundwater conditions. This highlights two regions of the levee, the near-surface and the foundation strata, that respond the most to external environmental forcing. These areas have large resistivity and therefore moisture content variations, so must facilitate moisture movement in response to environmental loading putting them potentially at risk of long-term deterioration.

Foundation resistivity variation

To investigate the cause of the elevated temporal resistivity variability within the levee foundations ($x = 12-30$ m, Fig. 8), changes in resistivity between time steps are compared to variations in river level. To summarise the resistivity data, resistivity values for discrete elevation

intervals are averaged then normalised by the corresponding baseline value and plotted as a time-elevation matrix (Fig. 9). Periods of elevated river level coincide with decreases in resistivity relative to the baseline. In addition, sustained decreases in resistivity are observed between March and May 2023 and between September 2023 and April 2024 that occur above the current river level. These correspond with above-average river levels (Fig. 9), higher rainfall totals and elevated near-surface VMC (Fig. 6). These observations suggest periods of wetter than baseline soil conditions between the river level and ~39 m.

During the summer, small increases in resistivity are seen throughout the foundation layer, consistent with dryer conditions. Short-lived peaks in river levels during these periods (e.g. October 2022) do not produce resistivity decreases sufficient to drop below baseline values, suggesting that significant air-filled porosity remains during short periods of elevated river levels. These resistivity variations are distinct from near-surface drying processes and indicate that foundation moisture dynamics respond to river level fluctuations independently of surface forcing.

Overall, despite the limitations of a 48-hour monitoring interval, the foundation resistivity appears to respond rapidly to increases in river levels. While the specific hydrological pathways cannot be resolved from geophysical data alone, the strong temporal correlation between river level and resistivity decrease, and the lateral continuity of the response under the levee (Fig. 5b) is consistent with transient foundation seepage. However, no sustained water loading occurred during the monitoring period, and there is no direct evidence of internal erosion or elevated pore pressures. Consequently, the observed response is interpreted as indicating hydraulic sensitivity and a potential deterioration pathway, rather than active piping or ongoing failure.

Given the upland location of this river, elevated water levels rapidly recede, so water is only against the levee for short periods of time, limiting the duration over which seepage could evolve into backward erosion or piping (Semmens and Zhou 2021). Inspection of the levee during and following flood events would therefore be necessary to identify any signs of internal erosion.

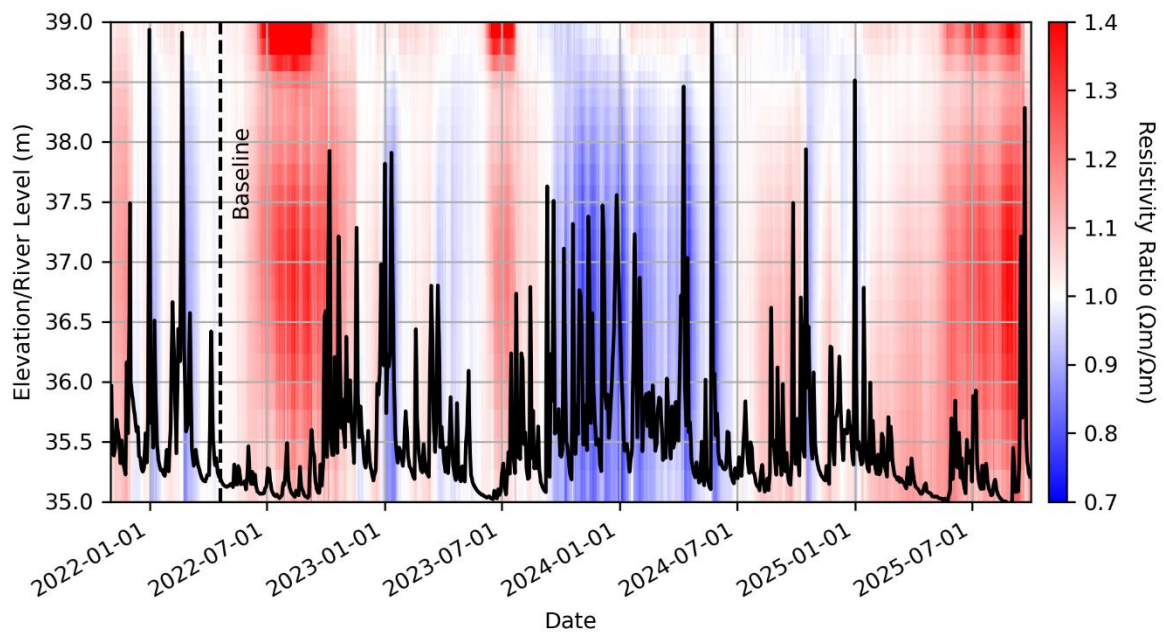


Fig. 9. Elevation-date plot comparing changes in the average resistivity difference at discrete depth intervals within the foundation layer (location shown in Fig. 8) to changes in river level for each time step. Red = drier, blue = wetter.
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Surface drying and cracking risk

To investigate the effect of surface drying on the levee, at each time step, the resistivity values for discrete depth intervals were averaged for the top 1.5 m of the levee ($x = 12\text{--}30$ m, Fig. 8), creating a series of 1D profiles. These profiles were normalised by the minimum mean resistivity value (i.e. approximately the highest moisture content) observed at each depth over the monitoring period (Fig. 10a). The resulting resistivity time series is dominated by a recurring seasonal cycle, characterised by a drying front that develops from spring into summer and a wetting front that develops autumn. Both fronts initiate at the surface and propagate downwards.

The drying front is picked using a resistivity change contour of $1.5 \Omega\text{m}/\Omega\text{m}$ (Fig. 10d). This threshold was selected as the minimum value that allows the surface driven drying to be separated from background variability associated with residual temperature anomalies, pore-fluid chemistry changes, small fluctuations in saturation, and from deeper floodplain aquifer processes (Fig. 10d). Extracting the drying depth from the resistivity models enables a comparison with weather derived SMD (Fig. 10b). The strong correlation between SMD and resistivity-derived drying depth ($r = -0.95$, Fig. 10c) indicates that, despite the simple evapotranspiration model, SMD provides a robust first-order prediction of seasonal drying depth at this site. The correlation enables us to explore the impact of future climate change of levee desiccation which we discuss below.

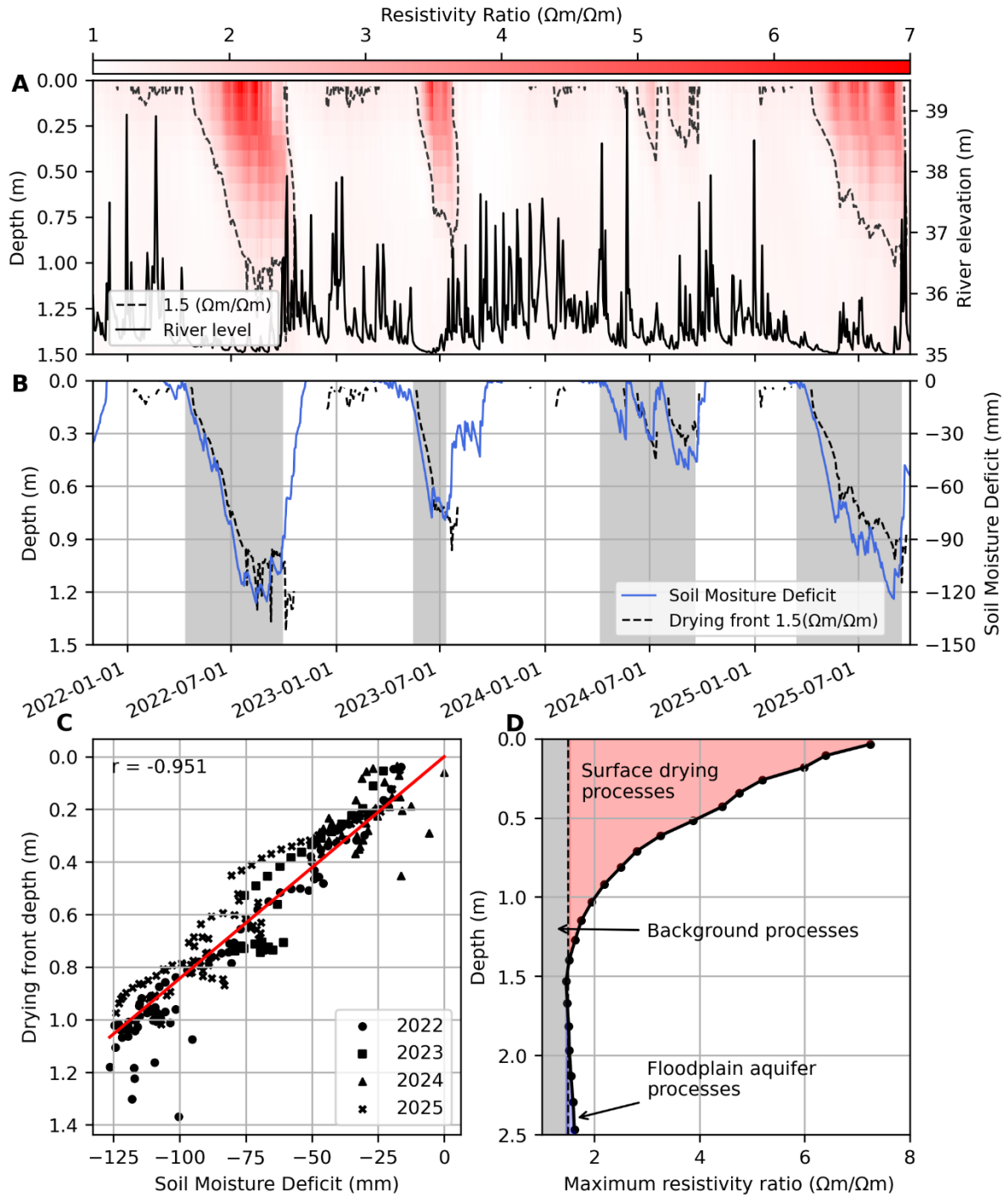


Fig. 10. **a)** Depth versus time plot for the average resistivity difference at discrete intervals (normalised to the minimum resistivity in each row) for the top 1.5 m of the levee, data cropped between 12-30 m (Fig. 8). The plot is overlain with the river level data. The black dashed line is the 1.5 $\Omega\text{m}/\Omega\text{m}$ contour, representing drying depth. **b)** Comparison of the resistivity-derived drying depth (1.5 $\Omega\text{m}/\Omega\text{m}$) to the soil moisture deficit (SMD). The drying depth is filtered to remove the 1.5 $\Omega\text{m}/\Omega\text{m}$ contour associated with wetting fronts. The shaded grey areas are used to correlate SMD with depth of drying front. **c)** Correlation plot between soil moisture deficit (SMD) and depth of drying front for each drying cycle that occurred within the three years. The days included are shaded grey in part B. The red line is a line of best fit, where r is the Pearson's correlation coefficient. **d)** Maximum resistivity difference at each depth of the model over the monitoring period. The top 1.5 m are shown in Panel A. © University of Bristol & British Geological Survey © UKRI

Desiccation of the upper soil layer does not compromise the performance of levees directly, but it is a necessary precursor for desiccation crack formation (Yu *et al.* 2021). Such cracks, if present, may increase hydraulic conductivity and facilitate seepage (Dyer *et al.* 2009). Desiccation can also stress vegetation, that reduces erosion resistance during overtopping events (Vannoppen *et al.* 2016). Direct observation of cracking within operational levees is challenging; existing methods can only characterise limited aspects of crack geometry and are known to underestimate the full crack network (Dyer *et al.* 2009; Yu *et al.* 2021; Apriyono *et al.* 2025). In contrast, imaging the seasonal drying depth provides a proxy for crack susceptibility, representing the maximum depth over which shrinkage cracking could potentially develop if soil properties (e.g. soil plasticity) permit. Importantly, drying depth alone does not imply the presence, continuity, or hydraulic activity of cracks.

Crack formation is strongly influenced by soil plasticity and mineralogy, with high-plasticity clays being most susceptible, although cracking has been documented in medium to low-plasticity glacial tills (Stirling *et al.* 2018; Yu *et al.* 2021). While no direct observations of cracks have been made at this site, the BIONICS test embankment, just 15 km away, is exposed to similar environmental loads, is constructed from similar materials, and has well-documented desiccation cracks (Hughes *et al.* 2009; Yu *et al.* 2021). It is reasonable to assume that cracks may form in the levee, in the absence of observations.

If cracks were to form within the near-surface layer, previous studies indicate that their closure may lag behind rewetting of the soil matrix, such that preferential flow pathways could persist into early autumn (Stirling *et al.* 2018; Jamalnia *et al.* 2020; Yu *et al.* 2021). At Warden, elevated river levels can occur (1st October 2022) before the levee has fully rewetted following summer drying (Fig. 10a) implying a period of increased susceptibility to near-surface seepage and reduced stability (Dyer *et al.* 2009). These are therefore potential deterioration pathways that may become relevant under certain environmental conditions.

Implications of climate change on levee performance

Since its construction in 2007, the Warden levee has performed as designed, including during the December 2015 flood, when it safely withstood water levels close to its designed height, while the adjacent floodwall overtopped (Environment Agency 2016). For this levee to be at risk of future failure, it must either experience a larger or more prolonged flood, or its performance must deteriorate over time. Climate change is projected to bring the hotter, drier summers and warmer, wetter winters across the UK (Lowe *et al.* 2018), altering flood recurrence intervals, drought duration and the magnitude of the seasonal wetting and drying cycles that drive long term deterioration processes in earthworks.

To explore how climate change may influence long-term levee deterioration, we established a relationship between seasonal drying depth and weather conditions. Comparison of resistivity-derived drying front depth with the weather derived SMD over four annual drying cycles shows a strong overall correlation, particularly during spring and summer drying (Pearson's $r = -0.95$; Fig. 10b, & Fig. 10c). Some discrepancies are evident, the most pronounced during summer 2023, when SMD remains around -30 mm while there is no observed drying front, and the measured VMC is near saturated conditions (Fig. 6a and Fig. 10a). These differences likely reflect the

simplified nature of the SMD calculation, which is driven primarily by air temperature and does not explicitly account for radiation, wind speed, humidity, or localised recharge processes. Despite these limitations, SMD captures the dominant seasonal control on drying depth at this site and provides a useful first order metric for extrapolation.

To extrapolate the drying front depth under future climate conditions, we use the local (2.2 km) UKCP18 convection permitting climate projections for the RCP8.5 emission scenario (Murphy *et al.* 2018). This dataset was selected because it is the closest match to the 1 km HadUK observational resolution, provides the required daily rainfall and temperature variables, and can more realistically represent the heavy summer rainfall events that strongly affect SMD (Fung *et al.* 2018). This local projection comprises 12 member ensemble, allowing a range of plausible future outcomes to be explored (Fung *et al.* 2018).

To apply the climate models at the site scale, each ensemble member was biased corrected to local HadUK observations for the period 1990-2020 following Fung (2018). Daily minimum and maximum temperatures were corrected using a mean additive approach (+0.73 °C and +1.74 °C respectively), while precipitation was adjusted using a multiplicative factor of 0.77. The bias corrected climate data was used to calculate SMD for each ensemble member which was translated into an estimated drying front depth using the empirically derived SMD–drying relationship. For each year, the maximum drying depth was extracted (Fig. 11). Importantly, evapotranspiration is limited by water stress within the SMD calculation, the maximum SMD is capped at 160 mm corresponds to a maximum possible drying depth of 1.35 m.

Five-year rolling averages suggest that maximum drying depths increase from ~0.6 m under recent climate conditions to greater than 1.0 m by around 2080 (Fig. 11), approaching or exceeding the current levee freeboard of ~0.6 m. These projections should be interpreted as relative, trend based estimates rather than an absolute prediction. They indicate an increasing susceptibility to climate driven drying rather than a specific threshold for failure.

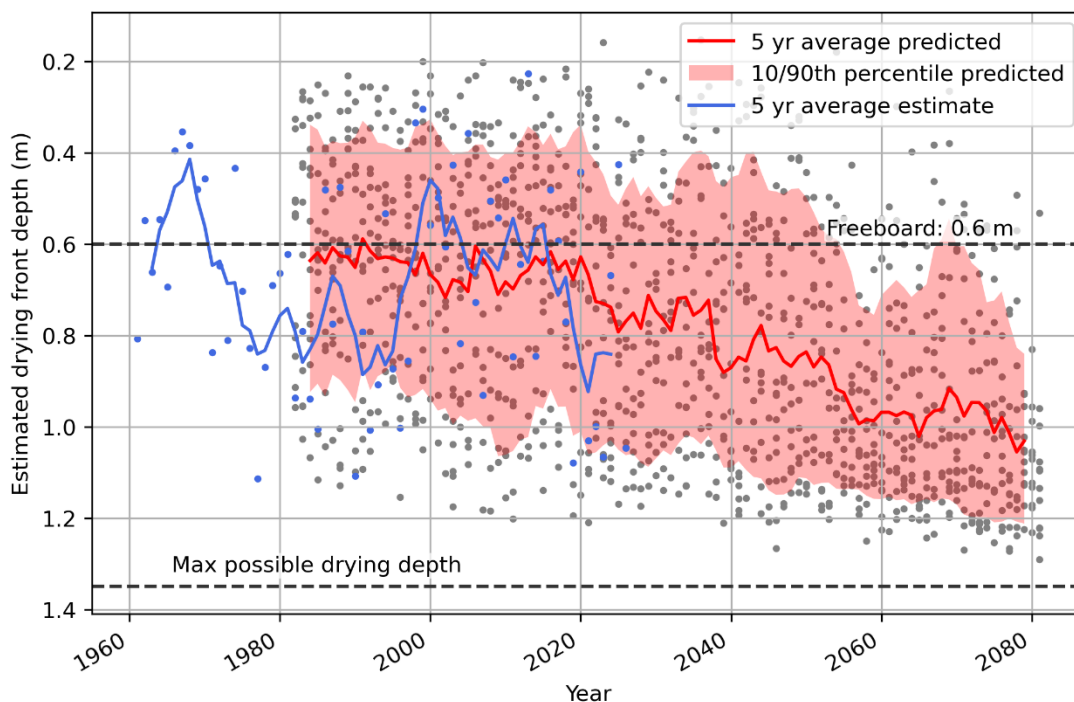


Fig. 11. Projection of drying depth under the RCP 8.5 climate scenario using the local (2.2 km) UKCP18 climate projection. Grey dots = predicted max drying depth for each year for each model. Blue dots = estimated drying depth from HadUK observations. Blue line = Rolling 5-year average of estimate drying depth. Red line = Rolling 5-year average of UKCP18 estimated drying depth. Freeboard at Warden is 0.6 m (Mott Macdonald 2019). The maximum drying depth is the maximum depth when SMD reaches 160 mm. © University of Bristol & British Geological Survey © UKRI

Mitigation measures

The UKCP18 climate models suggest a trend towards deeper seasonal drying at the Warden levee under future climate scenarios, increasing susceptibility to near surface desiccation and associated deterioration pathways. While fissures have not been directly observed at the site, the projected increase in summer soil moisture deficits suggests that conditions favourable for cracking may become more persistent and extend to greater depth. In this context, measures are discussed as potential responses to the risk of greater desiccation (Table 3).

Broadly, strategies to address desiccation related deterioration fall into two categories: 1) Mitigation measures that mitigate the consequences of fissuring if it occurs, and 2) Prevention measures that reduce the likelihood or severity of fissuring from occurring (Frith *et al.* 1997) (Table 3). One approach to mitigating the effects of fissuring is to increase levee freeboard so that any cracking develops above the designed level of protection. At Warden, accommodating the projected increase in average drying depth would require the crest height to be raised by 50 cm, which corresponds to a 50% increase in levee volume (and material needed). Alternatively, a cut off wall installed along the levee crest could limit seepage through cracked material without requiring height extension. Both options involve high capital cost, embodied carbon, and construction impact, which may limit their feasibility.

	Method		Pros	Cons
Mitigation	Increase levee freeboard		Likely can use locally available materials	Requires a lot of material; increases land take; enhance settlement issues; requires excavation of levee
	Cut off wall		Prevents seepage; relatively quick to install	High CO2 cost of steel
Prevention	Crack resistance	Place self binding material (e.g. Hoggin)	Crack resistant; can be used below design height.	Import specialist material; relatively expensive; requires excavation of levee
		Mix sand and gravel into clay levee	Less material required than using Hoggin; improves overtopping resistance	Likely import of materials; requires excavation and mixing levee soil
		Place Geogrid	Binds soil together; Reduces the macro cracks; may stop animal burrowing	Does not prevent fine cracking, requires excavation of levee surface
	Water loss	Impermeable geotextile	Prevent desiccation below membrane – reduce fissures;	Faster wilting and dying of vegetation; increased risk of overtopping erosion; shallow slope failure along membrane

	Soil vapour barrier	Reduce desiccation below membrane.	Likely import of materials
	Reseed with low water-use grass mix	Reduce evapotranspiration; relatively non invasive	Limited choice of native plants; impact on overtopping; biodiversity loss; root structure
	Shade levee	Reduced evapotranspiration by up to 30%; dual land use if photovoltaics used.	Likely expensive; large visual impact; scour risk around supports; impede grass mowing
	Irrigation of levee	Directly reduces the SMD	Effectiveness is uncertain; require water during droughts; has to be done regularly

Table 3. Mitigation and prevention methods for reducing the effect of drying conditions on levees and the formation of desiccation cracks (Frith *et al.* 1997; CIRIA *et al.* 2013, sec. 9.12.2) Financial considerations excluded.

Preventative measures aimed at reducing fissuring during dry conditions, offer a wider range of options and may be more adaptable to existing assets (Table 3). These include modifying the composition or structure of the near-surface layer to reduce shrink–swell behaviour, for example using self-binding aggregates, granular inclusions within clay, or geogrids to limit macro-crack development. Such measures may also provide additional benefits, including improved resistance to overtopping erosion (Sekine *et al.* 2020). Other approaches focus on reducing moisture loss during dry periods, for instance by installing subsurface barriers to evaporation, using engineered soil water barriers, selecting low water-use vegetation, or providing shade to reduce solar radiation (Garwood and Sinclair 1979; Frith *et al.* 1997; Marrou *et al.* 2013; Tsiampousi *et al.* 2024). While effective in principle, many of these interventions require removal of the existing surface layer and therefore represent invasive retrofit options. Finally, short term management responses such as irrigation may be used to limit cracking during extreme dry periods, as practised on some levee systems in the Netherlands (Van Lanen *et al.* 2016). However, for the Warden levee just removing a 120 mm SMD over the 600 m length would require 1296 m³ of water. This suggests that it may not be sustainable or widely applicable under future drought conditions due to water availability, cost and ethical considerations.

Taken together, these measures illustrate the range of possible adaptation strategies that may become relevant if climate driven drying trends continue. Their applicability will depend on site specific factors including material properties, geometry, exposure, and operational context. They should be considered within a broader risk-based asset management framework.

Conclusion

This study presents a four year time lapse electrical resistivity tomography (ERT) monitoring dataset from a clay levee constructed from glacial till in northern England, integrated with measurements of rainfall, evapotranspiration, river level, and near surface soil moisture. The monitoring provides direct observations of how subsurface resistivity evolves in response to seasonal climatic forcing and hydrological variability.

We found that resistivity changes are concentrated within two zones: the near surface active layer (upper ~1–1.5 m) and the levee foundation strata, while the compacted core shows low variability. The active layer undergoes progressive summer drying followed by rapid autumnal wetting, whereas the foundation exhibits coherent resistivity decreases associated with elevated river

levels, despite floodwater not acting directly on the levee face. These responses are repeatable and closely aligned with environmental observations, demonstrating seasonal moisture redistribution.

Two inferred deterioration pathways are identified from these observations. 1) Seasonal deepening of the drying front increases susceptibility to desiccation cracking within the crest and upper slopes, which may facilitate seepage during early autumn flood events before full rewetting occurs. 2) The sensitivity of foundation resistivity to river stage highlights a hydraulically responsive zone with potential longer-term vulnerability to piping-related failure mechanisms, under more severe or prolonged hydraulic loading.

This work establishes a relationship between resistivity derived drying depth within the levee and a SMD estimate from national gridded weather data (HadUK). Applying this empirically derived relationship to UKCP18 projections suggests a trend towards deeper summer drying at the site under future climate scenarios. Because SMD is calculated from nationally available gridded climate datasets, the relationship provides a potential pathway to extrapolate site scale geophysical insight beyond the monitored levee. Further work is required to test the robustness of this relationship across different levee materials, geometries, and hydraulic loading conditions. If shown to be transferable, the method could underpin the development of national scale susceptibility maps to help prioritise inspection, monitoring, and intervention across levee networks.

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Data Availability

The data are available from Adrian White (adwh@bgs.ac.uk) upon request.

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