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Multidisciplinary assessment of seasonal ground displacements at the Hatfield Moors gas storage site in a peat bog landscape

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The study aims to analyse ground displacement conditions observed over an Underground Gas Storage (UGS) site located at Hatfield Moors (United Kingdom), with a focus on understanding its implications for decarbonization efforts. The location serves as an active onshore storage site and was used as an analogy to assess ground motion implications around Carbon Capture and Storage (CCS) by the British Geological Survey (BGS) as part of the SENSE (Assuring integrity of CO_2 storage sites through ground surface monitoring) project. Given the value of continuous and real-time monitoring of ground movements induced by gas storage activities, the study leverages satellite Interferometric Synthetic Aperture Radar (InSAR) data to assess the environmental impact of UGS operations. Using free and open-source Sentinel-1 satellite data, ground motion patterns over Hatfield Moors are analysed, highlighting displacements ranging from − 5.0 to -10.0 mm/year within the peat bog. In addition, the Time Series (TS) of ground displacement from January 2018 to December 2022 reveals a seasonality in ground motion, with uplift observed in late winter and subsidence in late summer, showing a periodicity of approximately 1 year and a magnitude of +/-10.0 mm. Through in-depth analysis, the study highlights the need to understand the underlying causes of ground fluctuations at gas storage sites. This paper shows that InSAR has the versatility to integrate seamlessly with different monitoring tools and methodologies, opening avenues for comprehensive and holistic analyses. Cross-correlation analyses further elucidate temporal relationships between different datasets by evaluating InSAR time series, UGS injection/withdrawal data and piezometric data. This involves decomposing the TS into distinct components, including trend, seasonality and residuals. The case of Hatfield Moors shows a significant discrepancy between the UGS data and the InSAR TS, while also demonstrating a clear correlation between the groundwater data and the InSAR TS. By integrating insights from geology, hydrology and remote sensing technologies, the study navigates the complexities inherent in areas of overlapping phenomena. Accurate interpretation is essential for informed decision making, particularly at sites such as Hatfield Moors, where the convergence of natural peat motion and storage operations highlights the need for interdisciplinary analysis to understand the underlying causes of ground fluctuation.

Climate change, owing to a surge in atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases, poses an unprecedented challenge to public health, food security and biodiversity loss and requires immediate and concerted action on a global scale[1–5]. Over the past few years, innovative technological solutions, such as Carbon Capture and Storage (CCS), have represented a promising way pursued by governments, industries, and research organisations worldwide to mitigate CO_2 emissions and to counter global warming without an immediate phase-out of fossil fuels and emission-intensive industries, which is not feasible in the short term[6]. The CCS process involves capturing CO_2 from large emission sources, such as power plants or industrial facilities, before it reaches the atmosphere, and then transporting and safely storing it deep underground in specific geological formations. This three-step approach can help countries in achieving their climate change targets. However, despite its potential, CCS technology is still at an early stage of development and faces challenges such as high costs, regulatory complexity, public acceptance[7] and the need to provide environmental assurances. The last aspect covers potential environmental impacts associated with wells and

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storage integrity in the unlikely event of a storage site leak, optimal injection-withdrawal rate conditions and the detection of gas leaks[8].

Environmental monitoring of underground gas storage

Over the last three decades, Interferometric Synthetic Aperture Radar (InSAR) approach has represented a cost-effective and non-invasive solution to measure ground deformation[6,8] especially since 2014, with the availability of free satellite imagery through the Sentinel-1 constellation (from European Space Agency - ESA). Ground motion studies have greatly benefited from the InSAR approach. This capability is now part of a continental-scale service through the launch of the European Ground Motion Service (EGMS)[9–11].

InSAR data offer a valuable tool for providing insight into the kinematics of ground displacements observed over an Underground Gas Storage (UGS) site with millimetric precision and regular time intervals (in the order of weekly observations). The spatial resolution of Sentinel-1 data is 20 × 5 m at full resolution, and for EGMS products the data are resampled to a 100 × 100 m grid for both vertical and east-west displacements[9–11]. UGS operations can induce vertical ground displacements due to gas injection and withdrawal activities[6]. It is the interpretation of such displacements that is used to consider whether these fluctuations are directly caused by storage activities or not. These movements are primarily attributed to poroelastic effects, where the injection and withdrawal of gas changes the pressure within the reservoir, and this in turn can cause millimetre-scale deformations at surface[12–14]. Increased gas injection increases the pore pressure, resulting in uplift displacement, while gas withdrawal decreases the pore pressure, resulting in subsidence. These changes may indicate if the storage site is responding as expected to injection and withdrawal of gas[12]. If unexpected changes were detected, this could indicate that gas had migrated outside the expected area of storage[6,15,16]. This comprehensive monitoring approach ensures the integrity and safety of gas storage sites and enables proactive measures to address any emerging issue. In this paper, the Hatfield Moors (UK) case study is presented, focusing on the monitoring of an UGS site located below a peat bog area. This site provides a comprehensive analysis and interpretation of the ground dynamics observed at the UGS site, using InSAR data from the EGMS to identify displacement. Piezometric and ancillary data, together with detailed geological analysis, are then used to determine the root causes of this deformation. Precipitation plays a key role in influencing groundwater levels, which in turn affect vertical ground displacements in peatland areas. Peat soils are highly sensitive to changes in water content, exhibiting significant swelling during wet periods and deflation during dry periods[17,18]. This hydrogeological interaction between rainfall, groundwater levels and peat processes could drive seasonal variations in ground movement[17]. Hatfield Moors is used as a "prototype" site to demonstrate how this methodology can be used to address wider challenges in the monitoring of gas storage sites. The location serves as an active onshore analogue for a Carbon Capture and Storage (CCS) site used by the British Geological Survey (BGS) as part of the SENSE (Assuring integrity of CO_2 storage sites through ground surface monitoring) project[19].

The study collected multiple datasets, including precipitation patterns, groundwater levels, natural gas injection, and withdrawal data. These datasets, all in time series (TS) format, were analysed to establish meaningful correlations and provide valuable insights into the underlying dynamics that control these phenomena and, more generally, into best practices for monitoring UGSs.

Study area

Hatfield represents a remnant of a larger wetland area[20,21] located in South Yorkshire, England. The gas storage site is situated beneath the Humberhead Peatlands National Nature Reserve, which at 2,887 hectares is the largest area of raised bog wilderness in lowland Britain[22]. The land cover within Hatfield Moors is predominantly comprised of peat bogs (55%), non-irrigated arable land (17%), water bodies (6%), and inland marshes (4%)[23]. Terrains of this type often experience seasonal variations due to decomposition processes and weather conditions[19]. Beneath the surface of Hatfield lies a structure known as Hatfield anticline, with two high points called Hatfield Moors and Hatfield West (Fig. 1)[24]. The geological structure of Hatfield Moors was first disclosed in the 1960 during an exploration campaign by British Petroleum and the Gas Council to identify potential oil deposits[24,25]. Hatfield Moors and Hatfield West are two distinct gas fields with Initial Gas In Place (IGIP) of 173 million cubic metres and 68 million cubic metres respectively. Commercial gas production began in 1986 operated by Edinburgh Oil and Gas[26]. Then the company sought permission to convert the depleted Hatfield Moors reservoir for UGS activities[26]. This transformation required the construction of a processing plant and pipelines connected to the National Transmission System (NTS) with the site becoming operational in February 2000[25]. This marked the start of the first onshore depleted field storage facility in the UK and it was supported by a 25-year storage contract between Edinburgh Oil and Gas. The UGS site has three wellheads capable of injecting gas into the reservoir, although only two are used to withdraw gas from the subsurface. The storage capacity of the reservoir is approximately 116 million cubic metres and the gas storage site operates up to a maximum pressure of 44.82 bar[27]. The estimated total working gas is 70 million cubic metres[28,29]. During periods of low demand, gas is injected into the reservoir for storage; conversely, during periods of high demand, gas is withdrawn from the reservoir and transported via pipelines to the NTS[6]. This double process allows efficient management of the gas supply by ensuring both compliance to the fluctuations in energy demand and also contributing to the overall stability of the gas storage facility.

Gas storage at the Hatfield Moors site is facilitated by a layer of porous sandstone, surrounded by a band of solid rock that serves as a natural barrier to prevent the gas from leakage[26]. Natural gas is stored at a depth of around 450 m in the Oaks Rock Sandstone[26,27]. The shallow bedrock geology of the Hatfield Moors area consists of the Chester Formation, a thick sandstone of the Sherwood Sandstone Group, deposited during the Triassic. The geological characteristics of the superficial and shallow geology of the Hatfield Moors area are detailed in borehole SE70NW/9, located at Lindholme Hall (Fig. 2). The borehole reveals a top layer of 0.15 m of soil

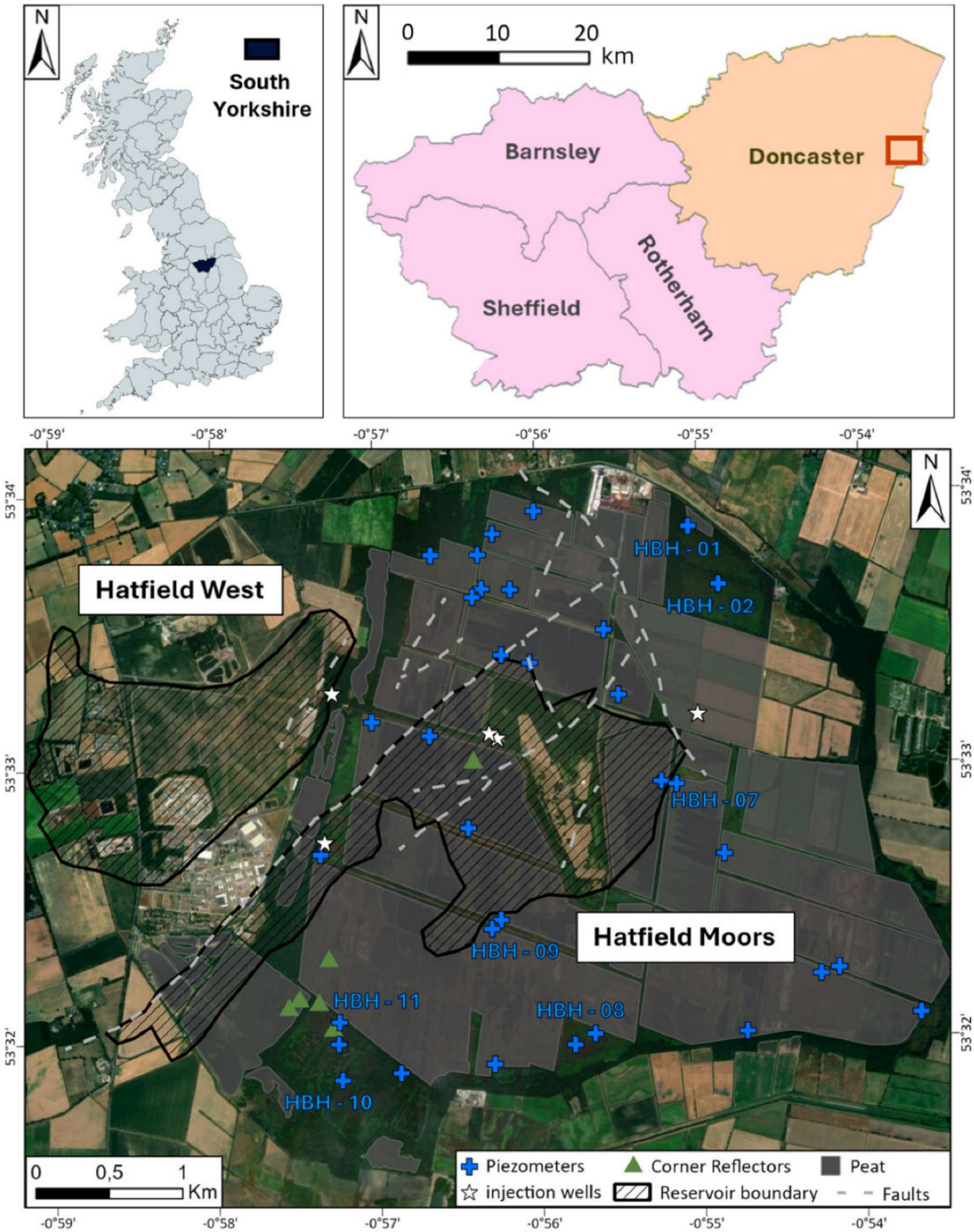

Fig. 1. Localization of the area of interest. Overview and location of the reservoirs, faults, piezometers, and injection wells beneath the Hatfield site. Sources of the background map: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community. The map was generated using ESRI ArcGIS PRO 3.3.0 (https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview).

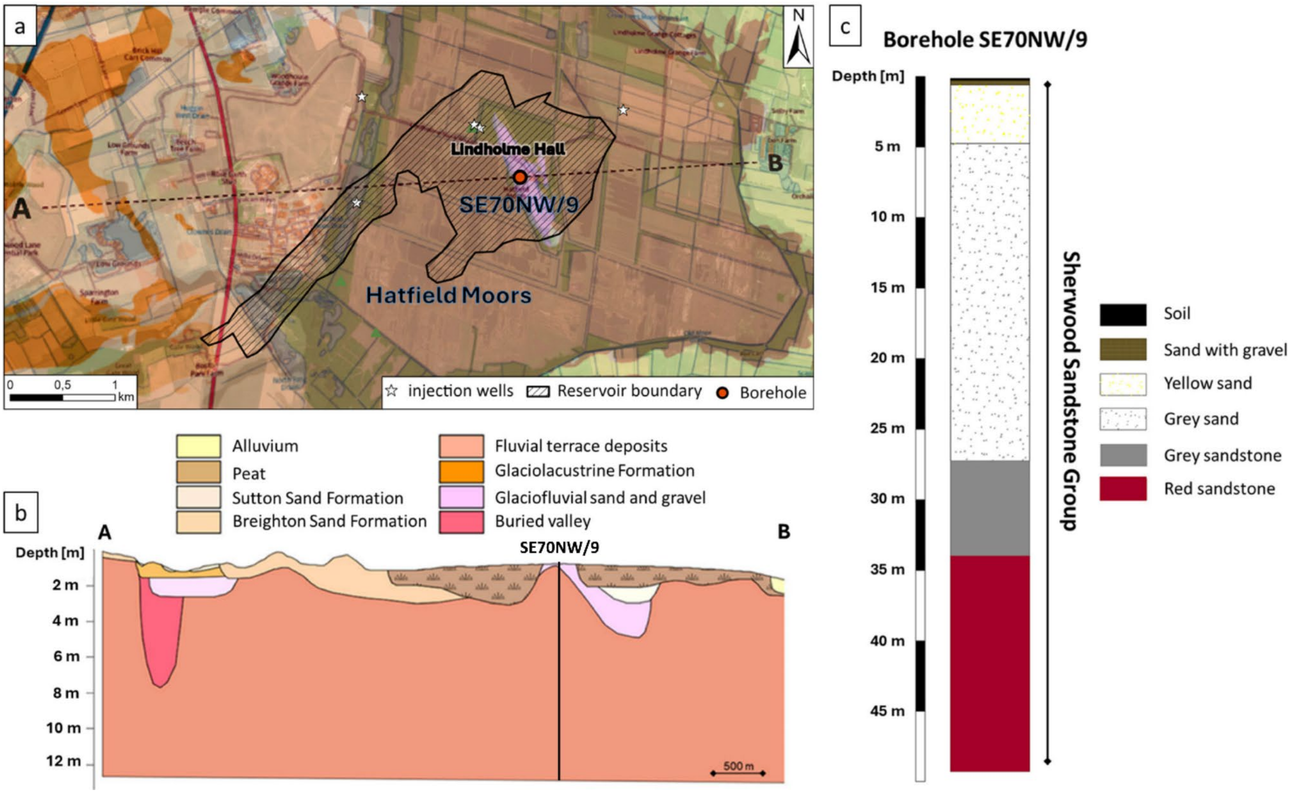

Fig. 2. Geological setting. Lithological map (**a**) and cross-section (**b**) (60x vertical exaggeration) showing the superficial deposits and shallow bedrock of Hatfield Moors. Lithological description of SE70NW/9 borehole (**c**). Contains British Geological Survey materials ©UKRI 2024. Contains OS data © Crown copyright and database rights 2024. OS AC0000824781 EUL. The map was generated using ESRI ArcGIS PRO 3.3.0 (https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview).

immediately followed by half a metre of sand and gravel of glacial origin alternated with alluvium and peat deposits[30]. Figure 2c reported several units of the Sherwood Sandstone Group.

Results

To understand the geological conditions behind the ground motion observed at Hatfield, a multidisciplinary approach involving the cross-correlation of InSAR data with ancillary datasets has been developed (Fig. 3).

InSAR results

The InSAR velocities, observed in both ascending and descending geometries, fall within the stability range (average displacement rates +/- 2.0 mm/year over a 5-year acquisition period) in the areas outside the peatland, where the signal to noise ratio is higher. However, within the bog where corner reflectors have been recently installed[31], most of the Measurement Points (MPs) show displacement rates between − 5.0 mm/year and − 10.0 mm/year (Fig. 4a and b).

Considering both vertical and horizontal components makes the interpretation easier compared to Line of Sight (LoS) data (Fig. 5a and b). This is because the displacement over the Hatfield Moors peatland is predominantly vertical, with a smaller horizontal component. This vertical displacement pattern is evident from the analysis of the TS data, which consistently show significant vertical displacement compared to horizontal displacement (Fig. 5c and d). The InSAR average velocity map of the vertical component shows a clear spatial correlation between the area covered by superficial peat deposits and the ground motion, although it is difficult to attribute the mean displacement directly to the gas storage area due to the uneven distribution of MPs. Overall, the average velocities of the vertical component fall within the stability range in the western areas outside the peat bog. Conversely, within the peat bog, most of the MPs show displacements in the range of -5.0 mm/year (Fig. 5a). Furthermore, it appears that the velocities do not show a discernible relationship with their location either within or outside the UGS area. In particular, MPs within the reservoir and within the peat show displacements, while those within the reservoir but outside the peat remain stable.

In addition to mean velocity, the EGMS produces TS of ground displacement for each MPs from January 2018 to December 2022, this offers critical information to reveal details not disclosed by the average displacements. Each MP over the peat reveals a seasonality, showing uplift in late winter and subsidence in late summer, with a periodicity of approximately 1 year. This observed seasonality is further confirmed by the average TS (Fig. 5c and d) respectively of the MPs enclosed by the two circles highlighted in white (Fig. 5a and b). This periodic

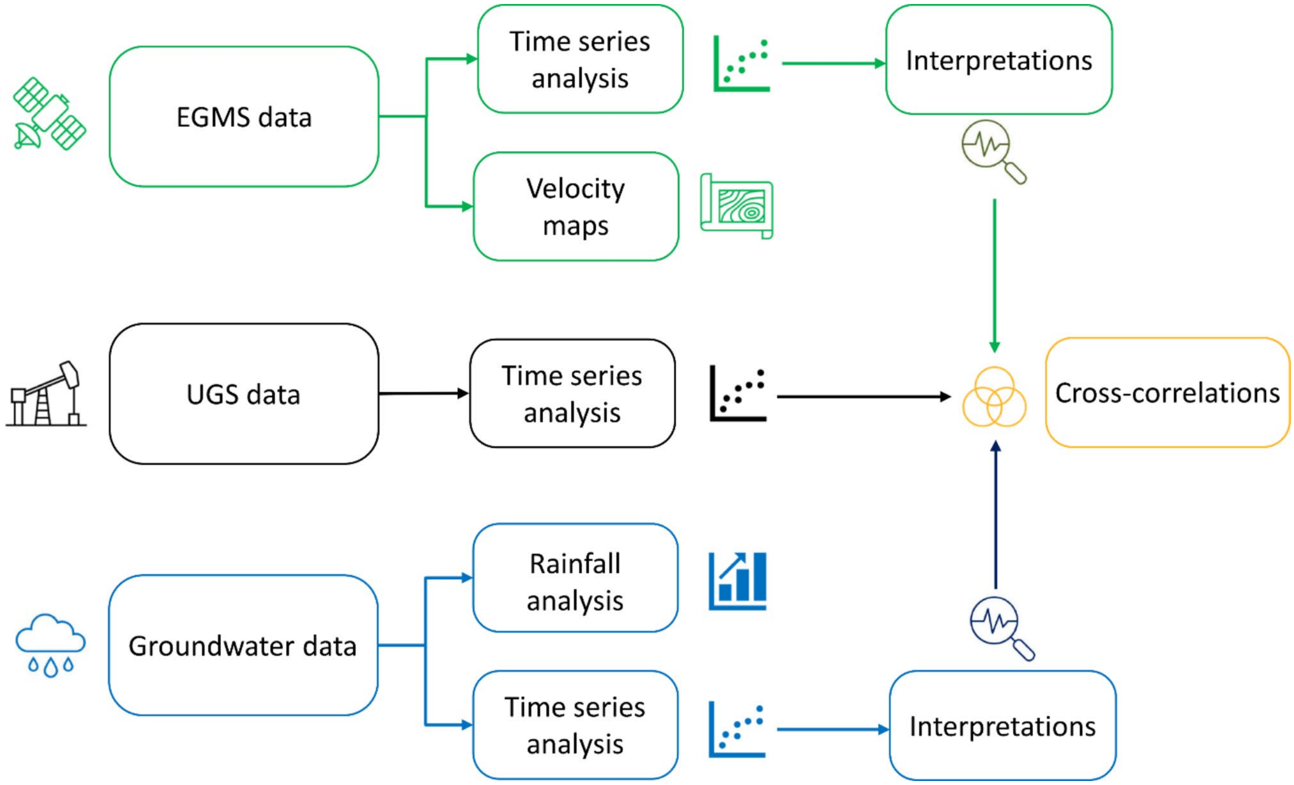

Fig. 3. Schematic workflow for identifying and understanding the factors contributing to the seasonal ground displacement observed at Hatfield Moors.

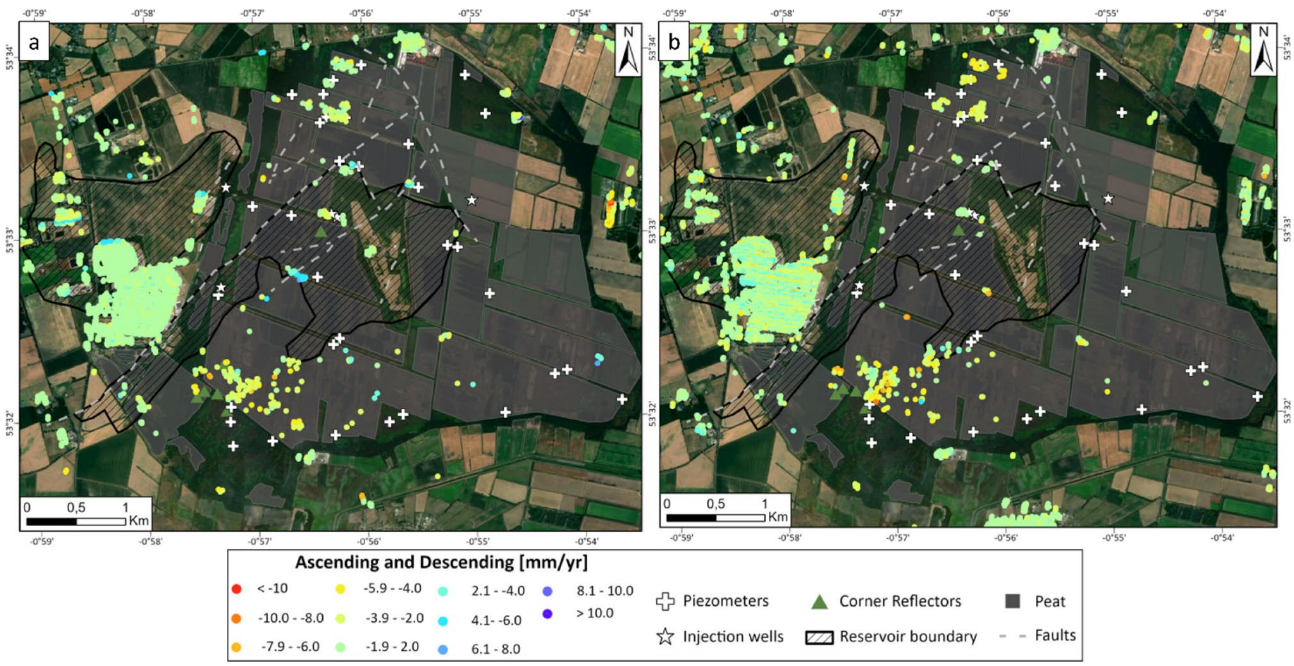

Fig. 4. InSAR-observed ground displacement in Hatfield Moors. Ascending (**a**) and descending (**b**) average velocity maps of ground displacement in the Hatfield Moors area and location of ground equipment. Sources of the background map: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community. The map was generated using ESRI ArcGIS PRO 3.3.0 (https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview).

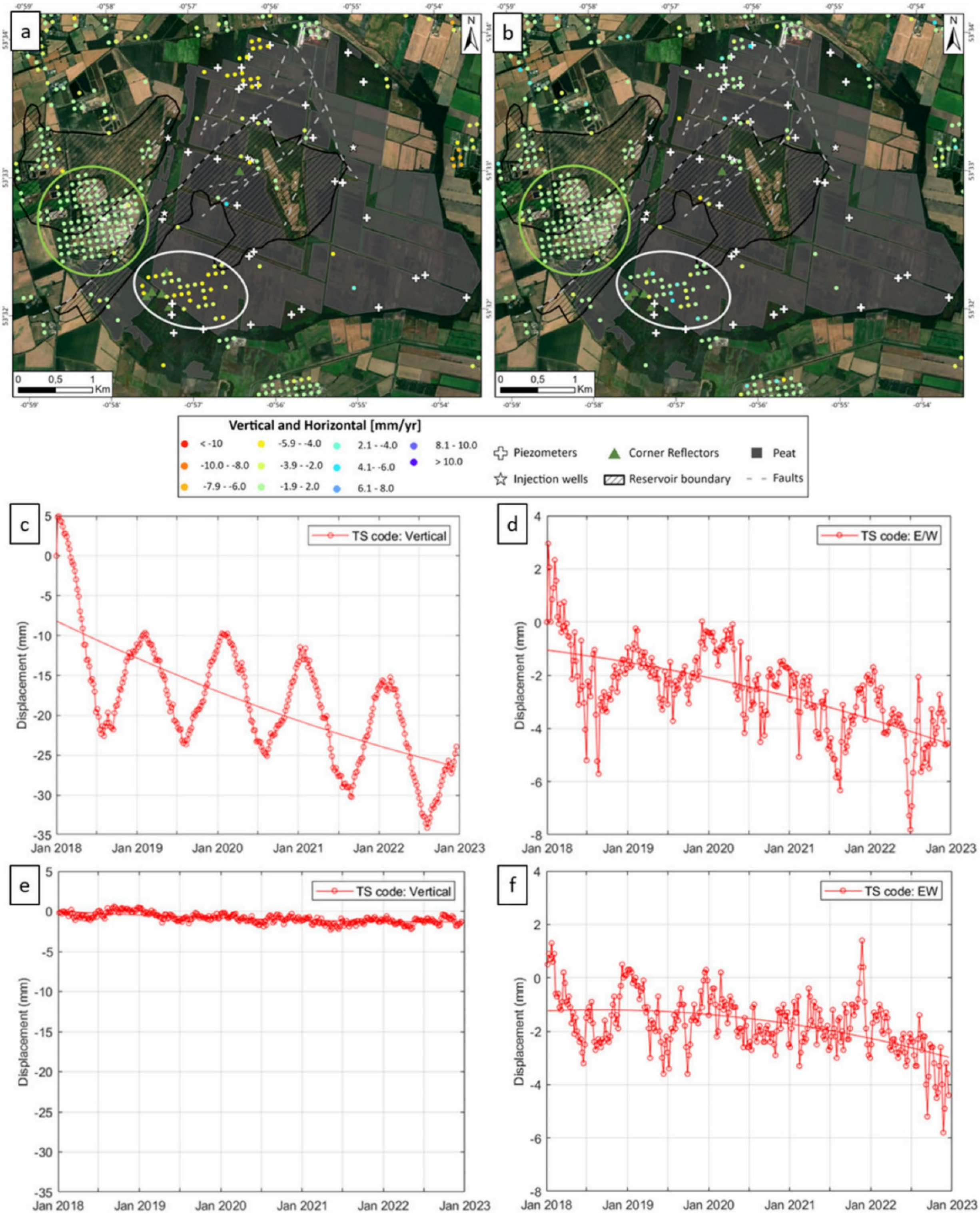

Fig. 5. Vertical and horizontal component of ground displacement in Hatfield Moors. Vertical (**a**) and horizontal (**b**) average velocity maps of ground displacement in the Hatfield Moors area and location of ground equipment. Negative values for horizontal movement indicate movement to the west, while positive values indicate movement to the east. The average TS of estimated ground displacement in vertical (**c**) and horizontal (**d**) components for the selected MPs inside the peat, which are enclosed within the two white circles shown in (**a**) and (**b**). The average TS of estimated ground displacement in vertical (**e**) and horizontal (**f**) components for the selected MPs outside the peat, which are enclosed within the two green circles shown in (**a**) and (**b**). The red line represents the regression curve. The map was generated using ESRI ArcGIS PRO 3.3.0 (https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview).

ground displacement, with a magnitude of +/-10,0 mm, could indicate "peat breathing" in response to either UGS activities or changes in the water content within the peat, as indicated in Alshammari et al. (2020)[32]. There is also a subtle seasonality in the TS of the MPs for the horizontal component (Fig. 5b), characterised by positive values in winter and negative values in summer (Fig. 5d). Furthermore, the average TS of estimated ground displacement for the selected MPs outside the peat bog shows that the observed seasonality is predominantly confined to peat bog areas (Fig. 5e and f).

Cross-correlations analysis

The detailed analysis of the gas injection and withdrawal data is important for the investigation of underlying cause of the seasonality observed in the InSAR TS. The analysis of the load/discharge curve of the Hatfield Moors reservoir reveals distinct patterns in gas withdrawal and storage activities. Gas withdrawal operations begin each year in January and continue until May, coinciding with the consistently observed minimum peak of gas in storage and the peak in energy demand in the northern hemisphere[6,25]. Conversely, gas storage activities begin each year in June and continue until November, when the maximum peak of gas in storage is consistently observed. Withdrawals and injections are not constant during these time periods, but instead are undertaken in phases depending on the demand. Theoretically, if UGS activities were influencing surface displacements, uplift in InSAR data during injection periods and subsidence during extraction periods should be observed[12,13]. This assumption is based on poroelastic theory, which describes how fluid pressure changes in a porous medium, such as a reservoir rock, cause elastic deformations[14]. According to this theory, the injection of gas increases pore pressure, leading to expansion and surface uplift, while extraction decreases pore pressure, resulting in contraction and subsidence[13]. The TS of ground surface displacement derived from the vertical InSAR data and the estimated cumulative injection and withdrawal curve were analysed by cross-correlation in order to show the temporal shift between the two datasets from January 2018 to December 2019 (Fig. 6). The TS was examined by selecting MPs both within the peat and above the reservoir at Hatfield Moors. This analysis involved decomposing the TS into distinct components, including trend, seasonality and residuals, using cross-correlation methods. The case of Hatfield Moors shows a significant discrepancy between the load/discharge curve and the InSAR TS curve during the period under investigation. The cross-correlation analysis provides two key values: (i) the maximum normalised correlation value, which represents the highest correlation between the two datasets after normalising the cross-correlation within a range of 0 to 1. This value assesses the extent to which the two TS coincide in terms of patterns or trends. (ii) the optimal lag, which is the time delay in months between the two datasets that maximises the correlation. A positive value indicates that the InSAR data lag behind the UGS data, while a negative value indicates the opposite.

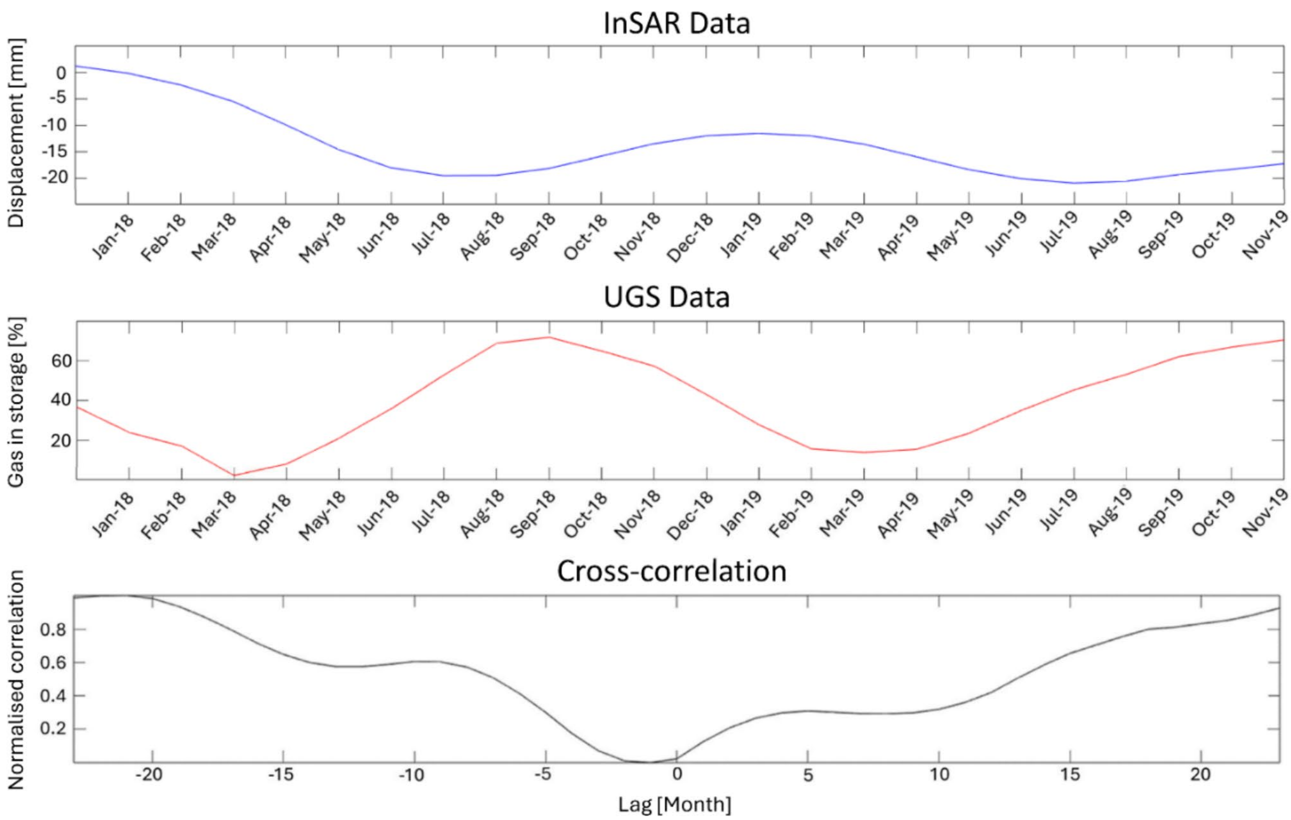

Fig. 6. Temporal cross-correlation analysis between InSAR data and smoothed UGS data. Cross-correlation analysis between the TS of ground surface displacement derived from InSAR data (in blue) and the cumulative injection and extraction curve (in red). The cross-correlation result is highlighted in black.

The result of the cross-correlation analysis considers the strength of the normalised correlation over time, where 0 represents the minimum correlation value and 1 the maximum, measured over different lag months. The normalised correlation is ~ 0.1 when lag time is 0 (the case of perfect time matching of the two time series), it stays low in any year window and would have its highest value at 21 months, so being out-of-phase with any seasonal signal.

In addition to the gas storage data, piezometric and rainfall data were analysed to investigate a possible correlation between seasonal surface displacements and peat water content using the same cross-correlation analysis described above. The groundwater level shows a clear seasonality during the analysed period (January 2018 to December 2019), with maximum peaks in winter and minimum peaks in summer (Fig. 7a), which is strongly consistent with the vertical InSAR TS (Fig. 7b). In addition, it is important to note that the vertical displacement TS from January 2018 to August 2018 shows a significant subsidence, exceeding that observed in subsequent years (see Fig. 5c). This evidence can be connected to an exceptionally dry summer of 2018 period with minimal precipitation affecting the whole country, which caused a significant drop in the water Tables[33,34].

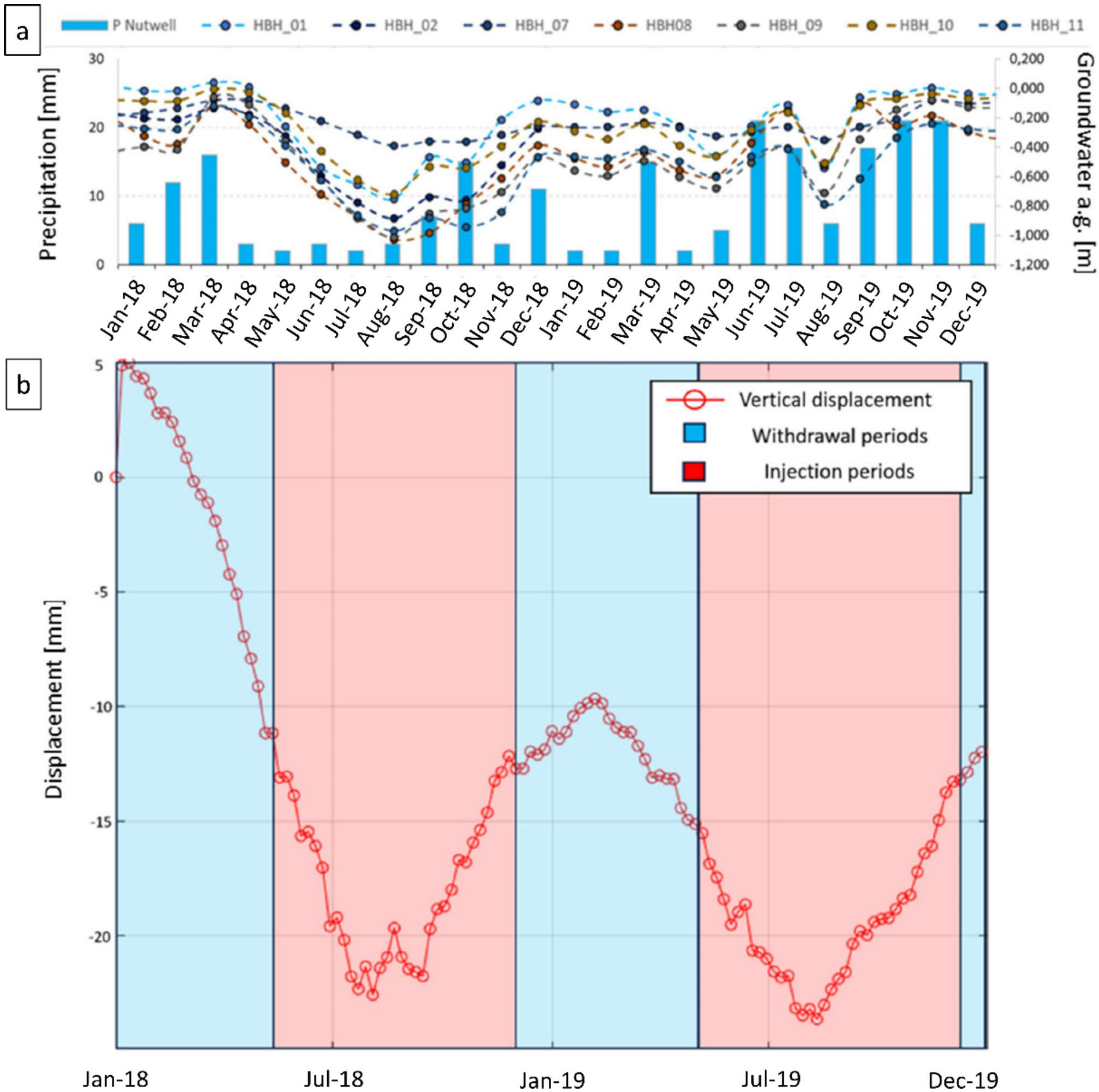

Fig. 7. Temporal correlation between seasonal variations in groundwater levels (**a**) and InSAR TS (**b**). Peaks in rainfall data and groundwater levels correspond to winter seasons, while troughs correspond to summer periods, showing a clear correlation with the observed satellite data trends.

This result supports the hypothesis that the seasonal ground displacement observed in the InSAR data may be related to the influence of the water content in the peat.

The cross-correlation analysis between the vertical TS of the surface displacement (Fig. 7b) and the TS of the groundwater level (Fig. 7a) in the peat was carried out for highlighting the temporal shift between the two datasets. The result of the cross-correlation analysis (Fig. 8) reveals an optimal lag, assessed with a coefficient of 0. The normalised correlation value is approximately 1, where 1 is the maximum correlation value. Therefore, the results of this analysis show a clear correlation between the two datasets.

Groundwater analysis

The groundwater analysis conducted in this study considered both satellite imagery and borehole measurements. Earth observation analysis relies on the Sentinel-2 imagery acquired on 5 April 2018 (Fig. 9a) and 5 August 2018 (Fig. 9b) allowed an assessment of the moisture conditions in the Hatfield Moors peatland area using the Normalised Difference Moisture Index (NDMI) as indicator[35]. NDMI values vary between − 1 and 1 with higher values indicating higher moisture levels in vegetation than lower values. The results mirrored the trends observed in the piezometric and rainfall data, reinforcing the evidence of an exceptionally dry period during summer 2018. NDMI shows a significant decrease in soil moisture, consistent with minimal rainfall during the period under investigation (Fig. 9c). This dry period coincided with a pronounced subsidence trend observed in the InSAR data from January 2018 to August 2018, highlighting the sensitivity of the peatland to fluctuations in water content.

The 3D groundwater model provides a means to reconstruct fluctuations in groundwater levels of the peatlands and within it. The data shows the difference in groundwater heights between the winter and summer seasons of 2018, a particularly dry year (Fig. 10a). In addition, the magnitude of the seasonal displacement is expressed through the seasonality factor which is evaluated on the TS residuals after applying a regression model consisting of a third-order polynomial and a sinusoidal seasonal component. The field value represents the amplitude of the seasonal oscillation, expressed in millimetres (mm)[36]. The seasonality factor of MPs within the boundaries of the Hatfield Moors reservoir shows an increase in the seasonality factor for MPs within the peat and a decrease for those located outside the peat but still within the reservoir (Fig. 10b). MPs located inside the peat show a seasonality factor varying between 2.1 mm and 10.0 mm while those outside the peat never exceed a value of 2.0. It is also noteworthy that the seasonality factor shows a significant increase with peat thickness. These results further confirm that the displacements detected by InSAR cannot be attributed solely to UGS activities, as the movement of the peatland has a significant impact (Fig. 10b).

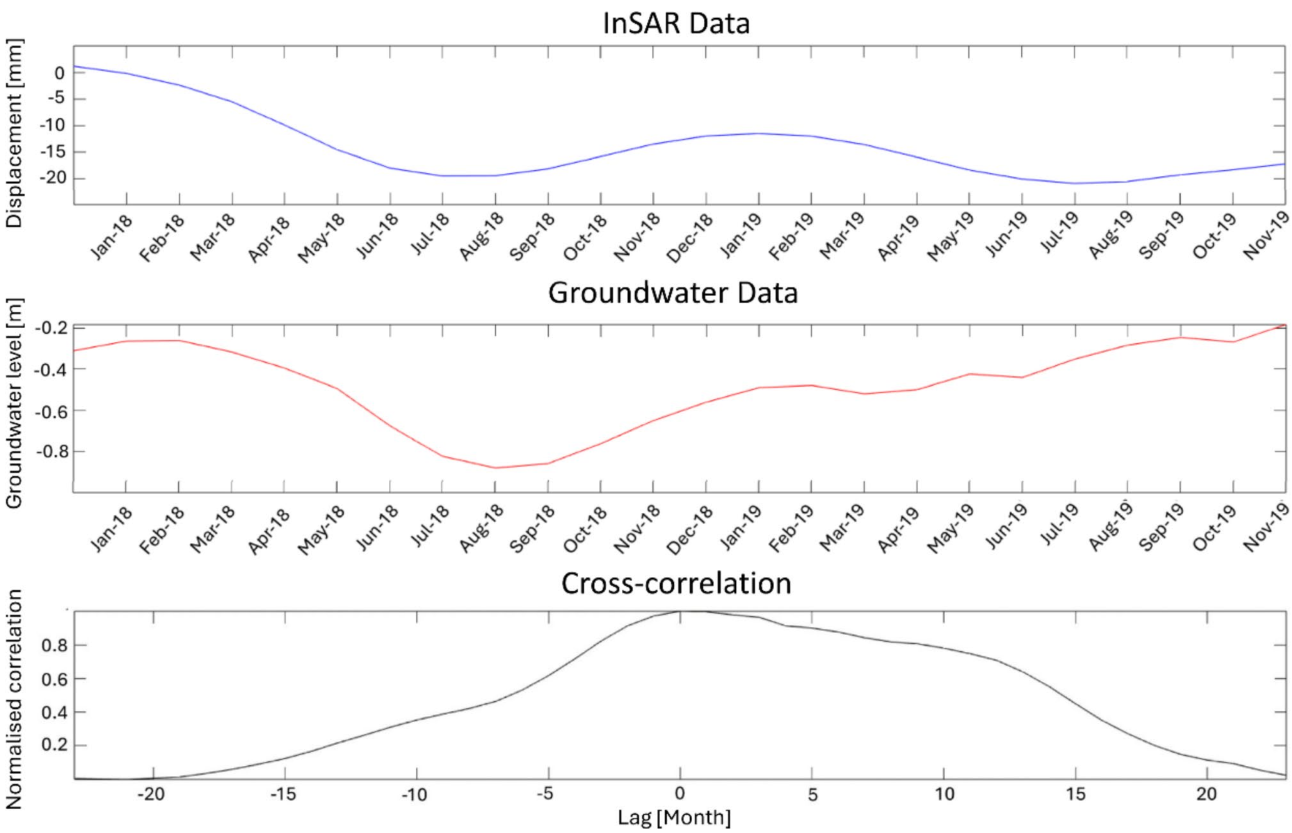

Fig. 8. Temporal cross-correlation analysis between InSAR TS and groundwater level in the peat bog. Cross-correlation analysis between the TS of the ground surface displacement derived from InSAR data (in blue) and the TS of the groundwater level in the peat bog (in red). The cross-correlation result is highlighted in black.

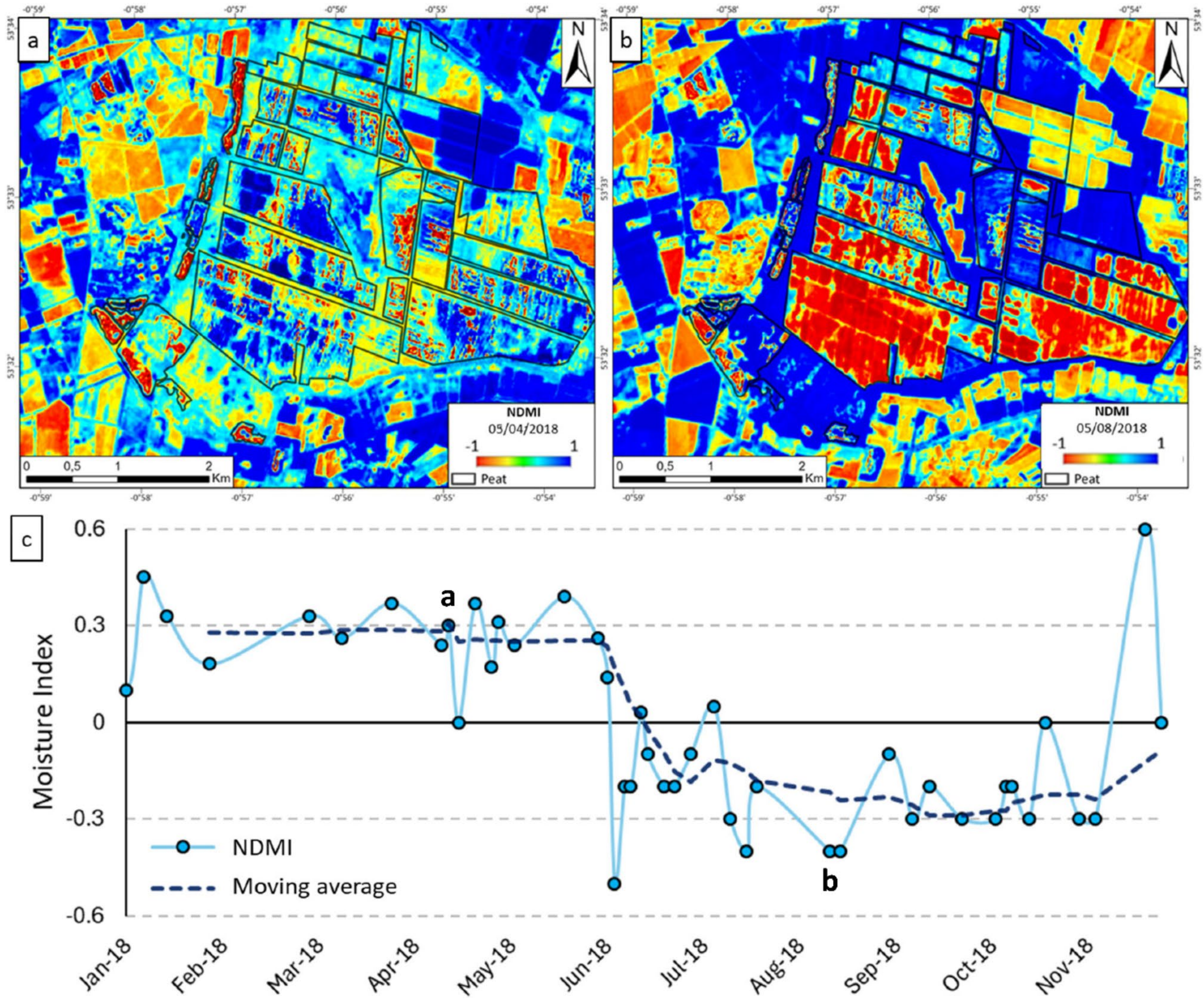

Fig. 9. Normalised difference moisture index analysis. NDMI analysis of two Sentinel-2 images acquired on 5 April 2018 (**a**) and 5 August 2018 (**b**). TS of the NDMI for the year 2018 using only images with a cloud coverage < 25% (**c**). The images from panels a and b are marked in the TS. The TS of the NDMI represents the average for the peat bog area. Contains modified Copernicus Sentinel data. The map was generated using ESRI ArcGIS PRO 3.3.0 (https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview).

Discussion and conclusions

InSAR analysis plays a key role in monitoring gas storage sites, providing valuable insights into ground displacement dynamics. The Hatfield Moors UGS site is as a prime example, showing the complexity of interpreting surface fluctuations observed via InSAR data. While it may be a possibility to attribute such deformations to gas injection and withdrawal activities, a comprehensive analysis reveals a different story. Contrary to expectations, the fluctuations observed in the surface are primarily driven by the absorption and release of water within the peat, rather than direct effects of UGS operations[17,18]. This interesting result can be attributed to several factors. Firstly, the volumes of gas involved in UGS activities are relatively small compared to the storage capacity of the reservoir, which is estimated at 70 million cubic metres of working gas out of a storage capacity of 116 million cubic metres[25]. In addition, the estimated injection and withdrawal volumes are relatively low[29] and the depth of operation, combined with the geological characteristics of the area, may not readily facilitate surface effects. Zhang et al., 2022[37], provide further elucidation on the multitude of factors that determine the detectability of surface displacements during gas storage activities via InSAR. These factors include several parameters such as gas injection and withdrawal volumes, operating rates, reservoir depth, and the geotechnical properties of the reservoir and overlying materials. Exploring the intricate relationship between surface fluctuations and the multiple factors influencing them at the Hatfield Moors UGS site reveals the imperative for a holistic approach. This approach integrates insights from geology, hydrology and remote sensing technologies to navigate the complexities inherent in areas of overlapping phenomena. Accurate interpretation is essential for informed decision making around subsurface storage, particularly in sites such as Hatfield Moors. The convergence of peat activities and storage operations highlights the need for interdisciplinary analyses. Relying solely on

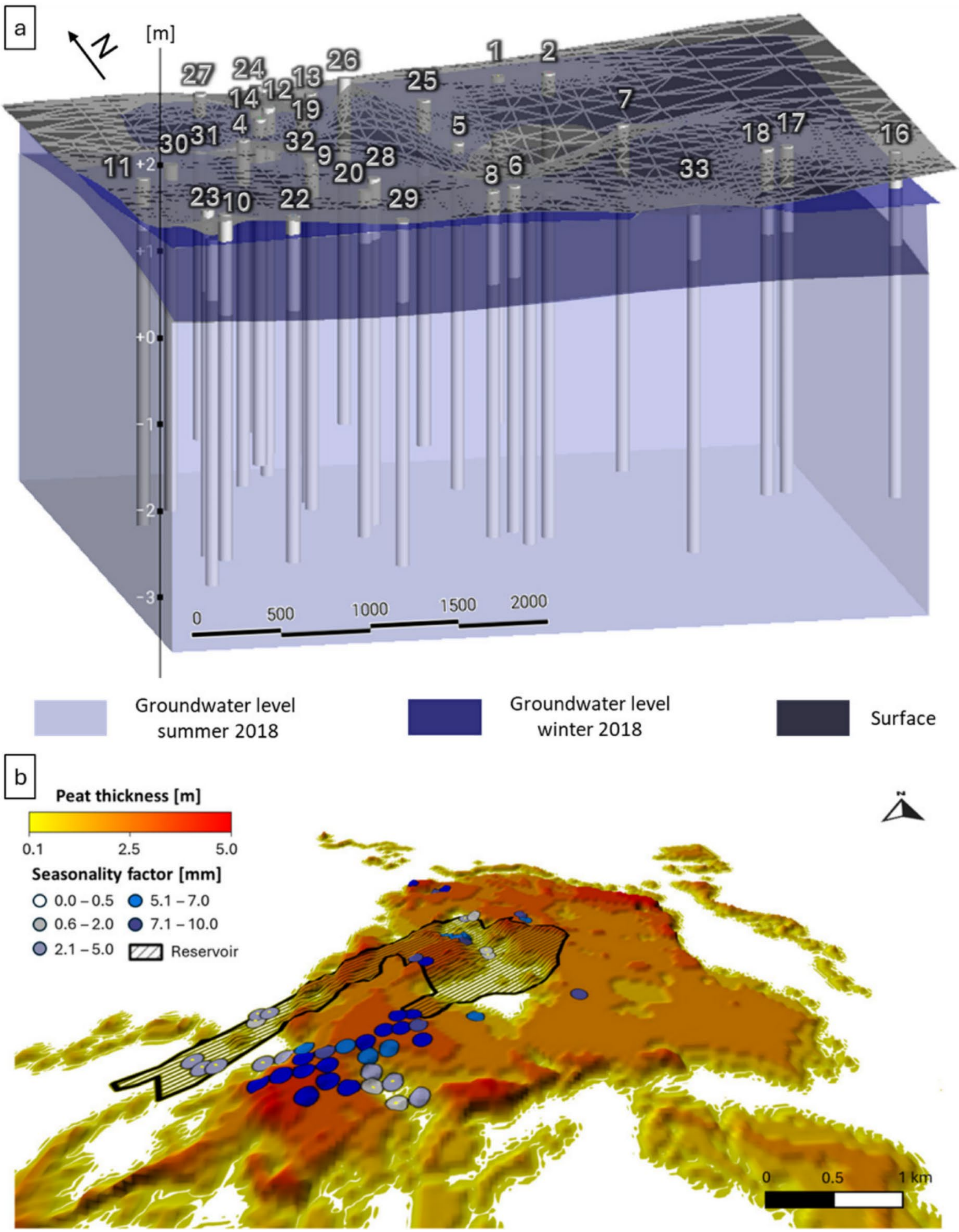

Fig. 10. 3D groundwater model and spatial correlation between seasonal ground displacement and peat thickness. The 2018 groundwater model incorporating piezometric data from wells close to the Hatfield Moors peat bog (**a**). The model was generated using Seequent Leapfrog Geo 2021.2.5 (https://www.seequent.com/products-solutions/leapfrog-geo/). The seasonality factor of MPs within the Hatfield Moors reservoir as a function of peat thickness (**b**). The map was generated using Golden Software Surfer 27.2.282 (https://www.goldensoftware.com/products/surfer/).

gas injection and withdrawal activities as the primary drivers of surface fluctuations overlooks crucial factors which could lead to incorrect assessments of reservoir behaviour at UGS or CO_2 storage sites and inappropriate mitigation measures.

This paper shows that InSAR has the versatility to integrate seamlessly with different monitoring tools and methodologies, opening avenues for comprehensive and holistic analyses. This adaptability allows for a synergistic approach, where InSAR data can be effectively combined with other monitoring techniques to improve the depth and breadth of understanding in different scientific fields. The integration of InSAR with complementary tools allows a more nuanced exploration of dynamic phenomena, providing researchers with a richer dataset and a more multidisciplinary perspective on the intricacies of surface processes. To elucidate the temporal relationships between different datasets, cross-correlation analyses evaluated InSAR TS, UGS injection/withdrawal data and piezometric data. The cross-correlation results showed a strong temporal correlation between InSAR TS and the seasonal peat dynamics driven by precipitation and consequent changes in groundwater levels, while highlighting a low correlation with UGS activities (Figs. 6 and 8). This correlation is supported by previous studies[17,18], which demonstrate the relationship between peat deformation and precipitation. These studies confirm that the observed displacement patterns are consistent with the expected behaviour of peatlands in response to changes in water content. In addition, the result of the spatial correlation between seasonal ground displacement and peat thickness suggests that the observed seasonal pattern could be influenced by the ability of the peat to absorb and release water rather than the UGS operations. The seasonality factor shows a significant increase with increased peat thickness, which also supports this hypothesis by indicating that areas with greater peat thickness exhibit a greater capacity to absorb water. This relationship is consistent both within and outside of the reservoir area, suggesting that the observed seasonal variations are primarily related to peat thickness rather than the reservoir operations (Fig. 10b). The 3D groundwater model supported this interpretation of peat response to groundwater level and helped validate the hypothesis that the detected displacements are not strongly correlated with the UGS activities. The difference in height between the winter and summer groundwater surfaces of 2018 supports the hypothesis that the peat dynamics are strongly influenced by the precipitation. This relationship highlights the impact of precipitation in regulating water table levels, thereby driving seasonal cycles of swelling and deflation (Fig. 10a). This finding confirms the conclusion that the observed ground displacements are primarily attributable to natural environmental factors rather than UGS activities (Fig. 11).

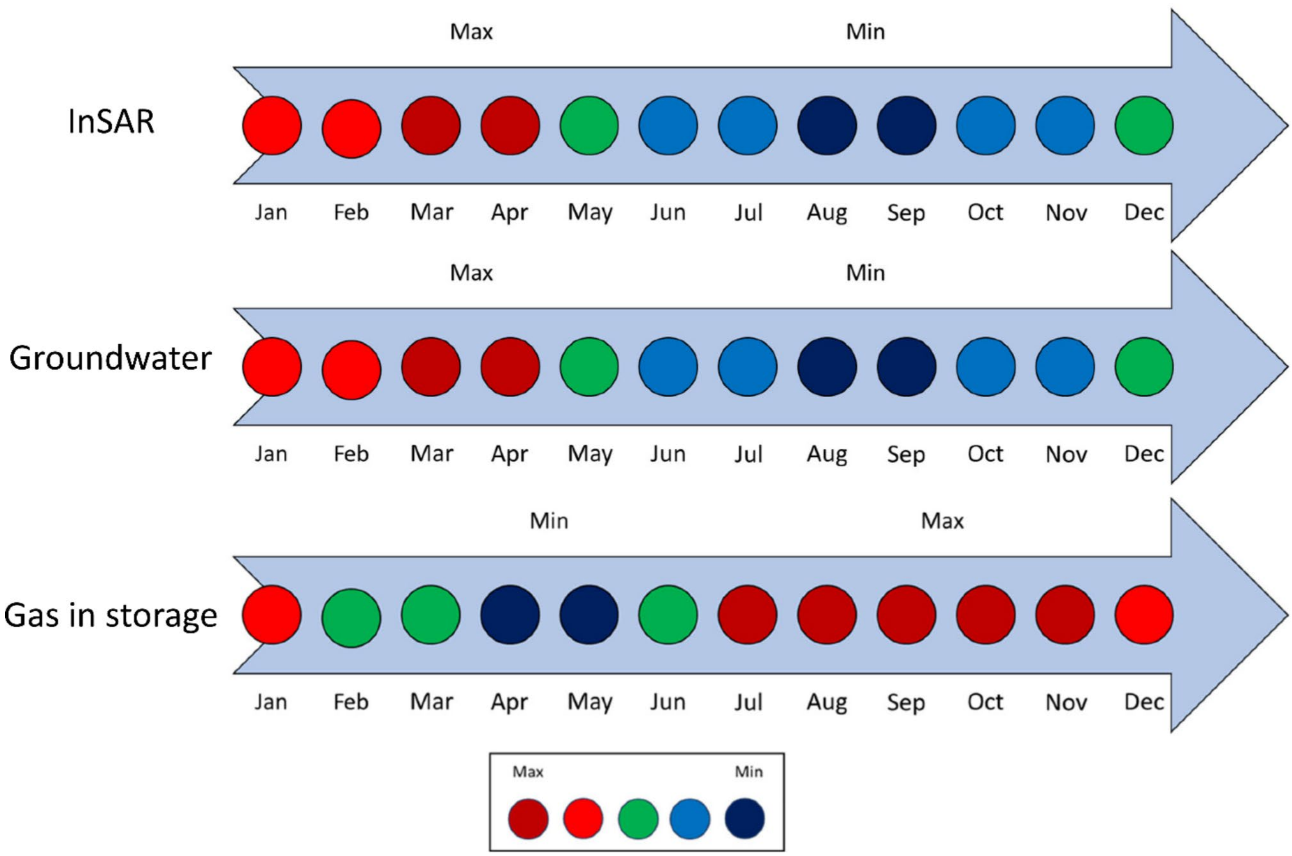

Fig. 11. Seasonal trend chart. InSAR trend at the top, groundwater trend in middle and injection/withdrawal trend at the bottom. The chart highlights months with peak and trough values, facilitating the visualization of correlations between different datasets.

Despite the significance of the results, it is important to recognise the limitations of the InSAR technology and the analysis carried out. A significant limitation lies in the inherent challenges associated with land cover characterisation, particularly in rural regions characterised by rough terrain and dense vegetation. The low phase coherence observed under such conditions can limit the spatial coverage and accuracy of InSAR measurements, potentially introducing uncertainties in the interpretation of surface deformations[38]. In addition, while the study attributes surface fluctuations primarily to peat activity, it is critical to acknowledge that a tiny contribution from UGS activities cannot be completely ruled out. A comprehensive geomechanical model incorporating factors such as gas volumes, daily injection and withdrawal rates and reservoir characteristics would be required to accurately quantify this contribution. Such a model could provide insight into the maximum and minimum displacements attributable to gas activities, allowing for a more nuanced understanding of surface dynamics. On the other hand, InSAR allows data acquisition even in contexts where information on working gas volumes and daily injection and withdrawal rates is not available, a common limitation in this field where published data on these specific aspects are scarce and information is often confidential. This paper focuses on the Hatfield Moors site where UGS activities do not have a significant impact on ground displacement, highlighting the value of the method in identifying natural environmental factors affecting displacement. However, InSAR may be particularly useful at other UGS sites where no other deformation mechanisms are at play, providing valuable insights into the relationship between UGS activities and ground displacement[6].

It is also noteworthy that peatlands provide a critical natural solution to the climate change challenges. Globally recognised, the restoration of peatlands historically affected by human activities is increasingly acknowledged as a key aspect of combating global climate change[17]. As long-term carbon reservoirs, peatlands play a key role in mitigating climate change by sequestering CO_2 from the atmosphere and storing it in waterlogged peat. Conversely, drained peatlands are a significant source of carbon emissions. Rewetting drained peatlands has been shown to reduce greenhouse gas emissions, aligning with international climate change agreements[17]. In addition, lowering the water table can trigger oxidation and decomposition of peat, which is an important subsidence mechanism[18]. Decomposed peat is not easily restored, highlighting the importance of maintaining stable groundwater levels to preserve peatland integrity. To ensure the survival of functional peatlands and the continuity of their valuable ecosystem services in a changing climate, maintaining good ecological condition is imperative to retain their water retention capacity[18]. InSAR monitoring is emerging as a tool that can facilitate the optimal management of these landscapes. Through its capabilities, InSAR contributes to informed decision making and sustainable practices, allowing for a more effective and targeted approach to peatland restoration efforts. This recognition highlights the importance of InSAR as a valuable asset in the wider strategy for environmental conservation and climate change mitigation.

Given that this study examines seasonal effects on the ground surface within a peatland environment overlying a depleted reservoir used for UGS activities, it is appropriate to highlight the potential applicability of this approach to CCS sites. This methodology can prove valuable during the preliminary assessment phase about the site potential conversion from UGS to CCS, helping to determine whether gas storage activities will have an environmental impact once they will be operational. However, it is important to note the differences between CCS and UGS activities. Unlike UGS, CCS involves the storage of CO_2 without the continuous cycles of injection and withdrawal that characterise UGS operations. In addition, the depth of the Hatfield Moors reservoir is significantly shallower compared to typical reservoirs used for CO_2 storage[5]. The conversion from a UGS site to a CCS facility requires extensive multidisciplinary investigation and the development of sophisticated geological, reservoir, geomechanical, geological hazard, and well models[15]. As a result, this study serves as a crucial preliminary analysis, suggesting that seasonal soil effects are due to peatland processes rather than to stockpiling activities, and demonstrating the effectiveness of InSAR technology as a suitable tool in the context of overlapping phenomena. Its capability to establish correlations between different datasets proves invaluable for optimal monitoring of these complex landscapes.

Methods

The data presented in this study, for the investigation of this notable case of UGS in a peatland landscape, are obtained through different monitoring and cross-correlations methodologies, shortly explained below.

EGMS products

The European Ground Motion Service (EGMS) is a groundbreaking initiative of the European Commission under the Copernicus Land Monitoring System[11]. The EGMS uses InSAR technology to monitor ground deformation across the European continent and provides full-resolution processing of Sentinel-1 satellite acquisitions. For this work, the Level 2b ascending and descending geometries, which are anchored to the GNSS reference network in a common reference frame, and the Ortho (Level 3) product, which includes horizontal and vertical components of ground displacement derived from the complementary ascending and descending geometries, were used. These products, accessible through the EGMS Explorer[16], are processed by the OpeRational Ground motion INsar Alliance (ORIGINAL) consortium[39]. This consortium ensures consistent quality through several processing algorithms, including PSP-IFSAR[40], SqueeSAR[41], GSAR-GTSI[42] and PSI performed with Integrated Wide Area Processor[43]. The extensive archive of InSAR data used in this study was extracted from the EGMS using the EGMStream application[44]. It includes calibrated Sentinel-1 ascending (A18-132) and descending (D16-081) data, as well as the vertical and horizontal displacement components. It is important to note that current satellite SAR sensors operate along near-polar orbits, and the angle between the orbit and the north-south axis is relatively small (<12 degrees), making InSAR relatively insensitive to measuring north-south motion components[41]. However, by combining InSAR datasets acquired along ascending and descending orbits, it is possible to retrieve vertical and horizontal (east-west) components, while neglecting the north-south component of the displacement[41]. The satellite data cover an area larger than the UGS Hatfield Moors facility.

Table 1 shows the main characteristics of the extracted Sentinel-1 datasets used to analyse ground displacements over the Hatfield Moors gas storage facility.

The Sentinel-1 data allowed TS analyses of ground displacement measurements from January 2018 to December 2022, with a temporal resolution of 6 days in both observation geometries (until the end of Sentinel-1B mission, which occurred on 23 December 2021). In addition, the seasonality factor extracted from EGMS was used in this study. It is evaluated on the TS residuals after applying a regression model consisting of a third-order polynomial and a sinusoidal seasonal component. The value of the field is the amplitude of the seasonal oscillation expressed in mm[36].

Underground Gas Storage data

Natural gas injection and withdrawal data for the Hatfield Moors UGS site were used to complement the radar imagery. In the absence of free daily injection and withdrawal rates, an estimate of the load/discharge curve, representing the cumulative volumes of natural gas injected and withdrawn was used, derived from free and open source relevant data[26–29]. This approach provided a comprehensive overview of the UGS operations and enhanced the analysis of the radar image interpretations. It should be noted that the process of injecting and withdrawing gas into/from the subsurface causes a change in pressure within the reservoir, which can then be transmitted to the surface[12–14,45]. In this context, this information was used to establish correlations between areas of ground displacement, identified by remote sensing data and the operational dynamics of the UGS facility. Relationships between surface displacement effects and UGS operations can be determined by juxtaposing the estimated injection/withdrawal curve of natural gas with InSAR data and considering the timing and amplitude of both curves.

Rainfall and groundwater data

The groundwater data analysis used information from 33 piezometer-equipped wells (Fig. 1) provided by Natural England, allowing data to be collected from January 2017 to March 2020. Daily rainfall data was made available by the Environment Agency for the Nutwell area (approximately 6 km to Hatfield Moors) over the same period. These datasets allowed a comprehensive TS of groundwater dynamics to be reconstructed. Correlations were then established between rainfall patterns, the TS of ground displacement and the UGS load/discharge curve. This multidisciplinary approach provided a holistic understanding of the interplay between environmental factors, gas storage activities and surface deformation phenomena.

Sentinel-2 data

The images from the Sentinel-2 constellation were used. This constellation consists of two twin satellites, Sentinel-2 A and Sentinel-2B, provided by the European Space Agency (ESA)[46] exclusively dedicated to Earth observation for research purposes. The Sentinel-2 constellation provides reliable global coverage of high-resolution optical multispectral data, which are freely available to end-users[47]. Specifically, two bands with a resolution of 20 m were used in this study: (i) Band 8a, known as Near InfraRed (NIR) and (ii) Band 11, known as Short-Wave InfraRed (SWIR). These 20-metre bands are designed to analyse the vegetation red edge, the spectral region where vegetation reflects most strongly, providing insight into the biological state and characteristics of plants. The images were collected using the Sentinel Hub EO Browser portal[48], allowing visualization, selection, and downloading of images and pre-compiled composites for the area of interest, with the capability to filter based on cloud cover. The images analysed correspond to 5 April 2018 and 5 August 2018. The two selected bands were used to calculate the Normalised Difference Moisture Index (NDMI) in order to detect the moisture content of the Hatfield Moors peat bog[35]. The NDMI ranges from -1 to $+1$, with the lowest values (white to light brown) indicating low water content in the vegetation and the highest values (in blue) corresponding to high water content. In other words, a decrease in the NDMI indicates water stress (i.e. lack of water), while abnormally high NDMI values could indicate waterlogging.

Cross-correlations

Groundwater data and UGS data were compared and juxtaposed with InSAR data to identify the cause of the seasonal displacements observed at the surface. A cross-correlation analysis was then performed in order to quantify the relationship between the curves. The results were normalised to a scale ranging from 0 to 1. The aim is to determine the maximum normalised correlation value and the optimal lag, providing an assessment of the relationship between the two curves.

3D groundwater model

The groundwater model was developed by incorporating piezometric data obtained from the groundwater wells (see Fig. 1). The ground surface was established using the elevation of the wellheads and two additional surfaces

Observation geometry	Layer name	Dataset	Scene	Time interval
Ascending right	Calibrated - level 2 A	(A18-123)	259	02/01/2018-31/12/2022
Descending right	Calibrated - level 2B	(D16-081)	269	05/01/2018-28/12/2022
Vertical component	Ortho - level 3	(vertical)	302	06/01/2018-17/12/2022
Horizontal component	Ortho - level 3	(east/west)	302	06/01/2018-17/12/2022

Table 1. Main characteristics of the Sentinel-1 datasets used in this study.

were created. The first surface represents the winter period of 2018, corresponding to the time when the water table reached its maximum level. Conversely, the second surface represents the summer period of the same year, during which the water table reached its minimum level. The model was created with Leapfrog 3D software[49], specifically using the Borehole Data Tool[50]. Leapfrog 3D software is a widely used tool for geological modelling and spatial analysis in hydrogeology. Borehole data, as used in this study, defines the physical 3D shape of boreholes and consists of several components: (i) a collar table, containing information on the location of each borehole; (ii) a survey table, containing information describing the deviation of each borehole from vertical and (iii) one interval table, containing measurements such as groundwater level data.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request. Groundwater level data were obtained from Natural England while rainfall data are available from the Environment Agency through the Open Government Licence (request id: EMD-283579). InSAR data have been obtained from the EGMS and thanks to the European Environment Agency.

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Author contributions
G.F., M.D.S. and A.N. conceived and supervised the project. G.F. analysis software. G.F. wrote the first version of the manuscript. M.D.S. and A.N. supervised the writing. G.F., M.D.S. and A.N. interpreted the results. L.B. and R.F. reviewed and improved the manuscript. All authors read and commented the final version of the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

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