remote sensing

Article

Lessons for Sustainable Urban Development: Interplay of Construction, Groundwater Withdrawal, and Land Subsidence at Battersea, London

Vivek Agarwal [1,*], Amit Kumar [2], Zhengyuan Qin [3], Rachel L. Gomes [4] and Stuart Marsh [4]

1 Engineering and Environment, Northumbria University, Newcastle upon Tyne NE1 8ST, UK
2 Centre for Ecology & Hydrology, Wallingford OX10 8BB, UK; amikum@ceh.ac.uk
3 College of Resources and Safety Engineering, Wuhan Institute of Technology, Wuhan 430223, China; 23029201@wit.edu.cn
4 Faculty of Engineering, Nottingham University, Nottingham NG7 2RD, UK; rachel.gomes@nottingham.ac.uk (R.L.G.); stuart.marsh@nottingham.ac.uk (S.M.)
* Correspondence: vivek.agarwal@northumbria.ac.uk

Abstract: The capacity of aquifers to store water and the stability of infrastructure can each be adversely influenced by variations in groundwater levels and subsequent land subsidence. Along the south bank of the River Thames, the Battersea neighbourhood of London is renovating a vast 42-acre (over 8 million sq ft) former industrial brownfield site to become host to a community of homes, shops, bars, restaurants, cafes, offices, and over 19 acres of public space. For this renovation, between 2016 and 2020, a significant number of bearing piles and secant wall piles, with diameters ranging from 450 mm to 2000 mm and depths of up to 60 m, were erected inside the Battersea Power Station. Additionally, there was considerable groundwater removal that caused the water level to drop by 2.55 ± 0.4 m/year between 2016 and 2020, as shown by Environment Agency data. The study reported here used Sentinel-1 C-band radar images and the persistent scatterer interferometric synthetic aperture radar (PSInSAR) methodology to analyse the associated land movement for Battersea, London, during this period. The average land subsidence was found to occur at the rate of −6.8 ± 1.6 mm/year, which was attributed to large groundwater withdrawals and underground pile construction for the renovation work. Thus, this study underscores the critical interdependence between civil engineering construction, groundwater management, and land subsidence. It emphasises the need for holistic planning and sustainable development practices to mitigate the adverse effects of construction on groundwater resources and land stability. By considering the Sustainable Development Goals (SDGs) outlined by the United Nations, particularly Goal 11 (Sustainable Cities and Communities) and Goal 6 (Clean Water and Sanitation), city planners and stakeholders can proactively address these interrelated challenges.

Keywords: PSInSAR; groundwater withdrawal; underground construction; sustainable urban development; Battersea London

check for updates

Citation: Agarwal, V.; Kumar, A.; Qin, Z.; Gomes, R.L.; Marsh, S. Lessons for Sustainable Urban Development: Interplay of Construction, Groundwater Withdrawal, and Land Subsidence at Battersea, London. *Remote Sens.* **2023**, *15*, 3798. https://doi.org/10.3390/rs15153798

Academic Editors: Norman L. Jones and Gustavious Paul Williams

Received: 31 May 2023
Revised: 25 July 2023
Accepted: 26 July 2023
Published: 30 July 2023

1. Introduction

Land subsidence, the gradual sinking or lowering of the Earth's surface, is a significant concern in urban areas worldwide [1–3]. Factors such as excessive groundwater withdrawal and extensive piling work during construction can contribute to land subsidence, leading to negative consequences such as damage to infrastructure, environmental impacts, and threats to human safety [4–7]. Piling work involves the installation of piles, which are deep foundations that provide support to structures. Piles can transfer loads to more stable layers of soil, improving the stability of the constructed structure. However, excessive piling work can exacerbate subsidence issues [8–10]. Unchecked and unplanned groundwater abstraction can result in a significant decline in aquifer levels [11], leading to compaction of aquifer sediments and further land subsidence [12,13]. To address these challenges and achieve sustainable and resilient cities, it is crucial to comprehensively assess the effects of land subsidence, piling work, and groundwater abstraction and identify suitable mitigation strategies.

This research focuses on the case study of Battersea, London, a prominent urban development area aligned with Sustainable Development Goal (SDG) 11 (Sustainable Cities and Communities), and it utilises interferometric synthetic aperture radar (InSAR) techniques to monitor subsidence and provide recommendations for future urban development practices. As populations continue to increase and migrate towards urban environments, there is a growing need to provide housing, infrastructure, and amenities to support thriving communities. Renovations and new developments in urban centres, such as Battersea, London, serve as pertinent case studies for understanding the complexities and interdependencies involved in meeting the evolving needs of urban dwellers while considering sustainability, liveability, and the achievement of the United Nations SDGs. Thus, the case study of Battersea, London, holds significant relevance in the context of global urban development and retrofitting endeavours. With its rapid urbanisation and ongoing infrastructure projects like the Battersea Power Station redevelopment and the Northern Line Extension [14], it becomes crucial to comprehensively assess the effects of land subsidence, piling work, and groundwater abstraction. By studying the interplay of these factors in Battersea, valuable insights can be gained to inform wider urban development practices, foster resilience, and support the achievement of SDG 11 on a global scale.

This research utilises Sentinel-1 [15] InSAR data covering October 2016–October 2020. The analysis also includes an assessment of groundwater extraction rates and construction projects involving piling work in Battersea. The utilisation of Sentinel data in this research is driven by their unique advantages that cater to the specific needs of land subsidence monitoring in Battersea, London. The continuous availability of data ensures uninterrupted monitoring, enabling the detection and analysis of subsidence patterns over time. The high spatial and temporal data quality facilitates a detailed assessment of land deformation processes. Moreover, the accessibility of free Sentinel data eliminates cost barriers and encourages widespread scientific collaboration. Integration with other data sources enhances the analysis, while the long-term monitoring capability allows for trend identification and informed decision-making in sustainable urban development practices.

Interferometric synthetic aperture radar (InSAR) is a remote sensing technique that has been widely used to monitor and measure land deformation with high precision [16–19]. By applying InSAR, the impacts of excessive groundwater withdrawal and extensive piling work on land subsidence in Battersea can be assessed, providing valuable insights for addressing this issue. Persistent scatterer interferometric synthetic aperture radar (PSInSAR) is an advanced remote sensing technique that uses radar satellite images to measure ground deformation with high precision [12,20–22]. It has been widely used to study land subsidence in urban areas by detecting ground movement through a series of satellite images taken over time. Given the urban fabric of the Battersea area, this method provides a valuable tool for quantifying subsidence rates and identifying potential contributing factors in this area.

Over the past decade, InSAR has gained prominence as a ground-monitoring tool for construction and tunnelling projects, particularly in London, due to the post-construction surveillance of the Jubilee Line Extension (1993–1999) and the Crossrail project [23]. The latter's tunnelling occurred from May 2012 to May 2015, resulting in a discernible settlement trough aligned east–west across central London [24,25]. In addition to the United Kingdom, InSAR has been utilised to monitor tunnelling projects in countries like India [26–29], China [30–32], Germany [33], Italy [34], Spain [35], the United States [36,37], Turkey [38], Vietnam [39], Poland [40–42], and others. Although researchers have utilised InSAR for studying surface deformation, and some of these studies have been summarised in Table 1, it is important to note that the list provided in the table is not exhaustive. While the majority of the studies have focused on surface deformation, there has been limited research conducted specifically on the interplay between construction, groundwater withdrawal, and land subsidence.

Table 1. Table summarising InSAR application in surface deformation studies.

Parameter Measured	Study Area	Observation Period	SAR Sensor/Other Data Used	Result	Reference
Land uplift due to groundwater variation	San Bernardino, California	1992–1993	ERS 1,2	0.87 cm/month	[43]
Land subsidence due to groundwater variation	Venice	1971–2002	ERS-1, 2 and others	3–5 mm/year	[44]
Land subsidence and groundwater variation	Kolkata, India	December 1992 to July 1998	ERS 1,2	5 mm/year	[26]
Subsidence in the geothermal fields	Taupo Volcanic Zone (TVZ), New Zealand	1996 to 2005	ERS 1,2 and Envisat	−10 and +15 mm/year	[45]
Surface deformation monitoring over a hydrocarbon reservoir	Middle East	2004–2007	Envisat satellite and Radarsat-1	Horizontal Deformations (1.8 mm/year), Vertical Deformation (4.8 mm/year).	[46]
Land subsidence due to groundwater and mining	Pangzhuang mining field, China	September 2004–December 2010	ALOS PALSAR	42 ± 15 mm	[47]
Ground motion over Coalfield	South Wales Coalfield, United Kingdom	1992 and 1999	ERS-1/2	Uplift at centre of coalfield 1 cm/year.	[48]
Land subsidence and groundwater variation	Wuhan, China	April 2015 to April 2016	Sentinel-1A	−82 mm/year to 18 mm/year	[49]
Groundwater depletion and land subsidence	Central Mexico	2006–2011	ALOS-1, GRACE, and others	3620 MCm/year	[50]
Structurally controlled land subsidence due to groundwater exploitation	Aguascalientes Valley, Mexico	1996–2020	ERS-1/2, ENVISAT, Sentinel-1	−10 cm/year to −14 cm/year	[51]

This research aims to investigate the effects of land subsidence, piling work, and groundwater abstraction on the stability of Battersea, London, using PSInSAR techniques to monitor subsidence and provide recommendations for future urban development in the area. This research contributes novelty by investigating the interplay between construction activities, groundwater withdrawal, and land subsidence in the context of urban development, shedding light on their interconnected impacts. Furthermore, it highlights the importance of considering the Sustainable Development Goals (SDGs) as a framework for addressing these challenges and achieving sustainable and resilient cities. Additionally, the application of statistical tests to evaluate the correlations between subsidence and groundwater withdrawal provides a fresh perspective on understanding their relationship.

The main objectives of this research are to (a) investigate the spatial distribution and magnitude of land subsidence in Battersea using InSAR data; (b) determine the correlation between excessive groundwater withdrawal and observed land subsidence patterns; (c) analyse the relationship between extensive piling work during construction and land subsidence patterns; and (d) provide recommendations for mitigating subsidence risks, such as sustainable groundwater management practices or improved construction techniques.

2. Study Area

Battersea is a district located in Southwest London, England, and is part of the London Borough of Wandsworth (Figure 1). It is situated on the south bank of the River Thames and is ~2.9 miles (4.6 km) southwest of Charing Cross [52–54]. Battersea is a primarily residential area, but it has experienced significant development and regeneration in recent years [55]. This has involved rapid urbanisation and development, with several high-profile projects such as the Battersea Power Station redevelopment and the construction of new residential and commercial buildings [56]. One of the most iconic landmarks in Battersea is the Battersea Power Station, a decommissioned coal-fired power station that has become an architectural symbol of London [57]. The power station is currently undergoing significant redevelopment, which includes the construction of new residential, commercial, and cultural spaces [56]. Battersea is also known for its parks, notably Battersea Park, which is a 200-acre (83-hectare) green space featuring gardens, sports facilities, a boating lake, and a children's zoo [55]. The park offers a serene and aesthetically pleasing environment for both residents and visitors, reflecting the growing significance of recreational spaces that contribute to the overall liveability of cities and align with the goals outlined by the United Nations Sustainable Development Goals (SDGs).

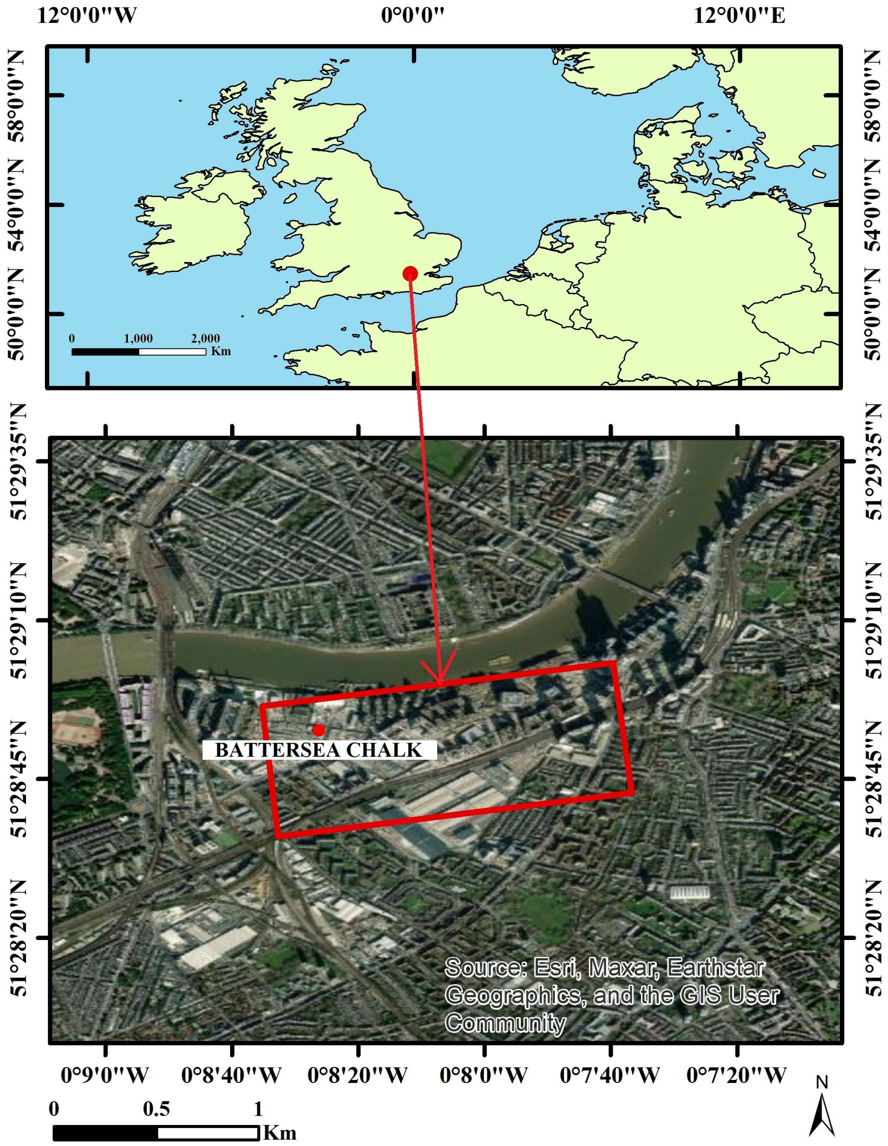

Figure 1. Study area. The Battersea chalk shows the location of the borewell used to study the groundwater variation.

Understanding the geological composition of Battersea and its correlation with the Greater London region is crucial for studying the potential impacts of groundwater extraction on land subsidence. The sedimentary layers and stratigraphy within the London Basin, which encompasses Battersea, play a significant role in hydrogeology [58]. The geological formations, such as the London Clay Formation, the Lambeth Group, the Thanet Sand Formation, and the Chalk Group, dictate the permeability and confinement of aquifers [14].

This information is pertinent for evaluating the relationship between groundwater extraction and land subsidence, providing insights into the potential risks and implications associated with the utilisation of the Chalk aquifer, a vital groundwater resource for the entire Southeast region.

The hydrogeology of the Battersea area in London is characterised by its unique geological composition and diverse groundwater systems. Figure 2, which shows a borehole cross section of Battersea Power Station, represents the local geology. Located along the River Thames, Battersea is underlain by a complex series of sedimentary layers, primarily composed of alternating layers of gravel, clay, sand, and silt. These strata, deposited over millions of years, are part of the Thames Group, consisting of the Lambeth Group, the Thames Gravel Aquifer, and the London Clay Formation. The Thames Gravel Aquifer, an unconfined aquifer, is the primary source of groundwater in the region. This permeable layer, consisting of gravel and sand, allows for water infiltration and storage, supporting the local ecosystem and supplying water for domestic and industrial use. The London Clay Formation, on the other hand, acts as an impermeable barrier, restricting the vertical movement of groundwater, thus influencing local groundwater flow patterns. Furthermore, the Battersea area's hydrogeology is significantly impacted by the River Thames, which plays a vital role in controlling groundwater levels and the interaction between surface water and groundwater resources [59].

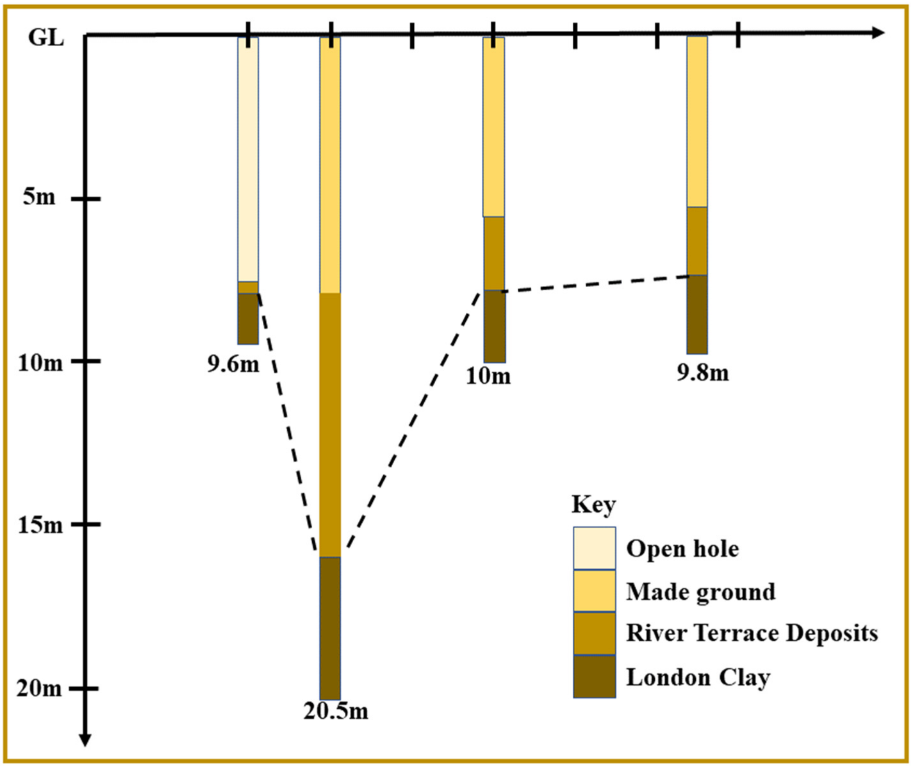

Figure 2. A typical cross section of the Battersea area. The vertical scale is shown at 5 m and the horizontal at 10 m. GL, ground level (adopted from [60]).

The geology of Battersea is crucial for evaluating land subsidence risks, as the area's hydrogeology and aquifer behaviour are influenced by the properties of these geological formations. Comprehending the local geology is crucial for efficiently managing groundwater resources and addressing the possible consequences of construction activities on land subsidence in the area. By considering the intricate geological composition described above, valuable insights can be gained into the hydrogeological characteristics of Battersea to make informed assessments regarding the potential impacts of groundwater extraction on land subsidence. This knowledge contributes to a comprehensive understanding of the complexities involved and aids in ensuring sustainable groundwater management practices aligned with the goals of urban development and the United Nations Sustainable Development Goals.

3. Materials and Methods

3.1. Land Subsidence

Land displacement information was obtained using the PSInSAR method [61] using the ENVI SARscape v5.4software [62]. Typically, the PSInSAR approach requires a minimum of 20 or more SAR image pairs to produce a trustworthy result [63]. We used a set of 99 Sentinel-1 C-band images, captured from October 2016 to October 2020 over Battersea, London, and employed for calculating land displacement. The data used are summarised in Table 2, while the methodology is summarised in Figure 3.

Table 2. Summary of data used.

Data	Description
InSAR data	99 Sentinel-1 SLC images, VV polarisation, Frame 422, Descending, IW Beam mode, Resolution: Azimuth: 20 m by Range: 5 m, Repeat Cycle: 12 days, Wavelength: 5.6 cm, C-band, Master Image: 1 November 2018, Time period: October 2016 to October 2020, Digital Elevation Model: SRTM V4, Software Used: ENVI SARscape, ArcGIS (ArcMap 10.2.2)
Groundwater Data	Borehole groundwater data from the United Kingdom Environment Agency
Piling Data	Projects by sheet piling and Martello piling

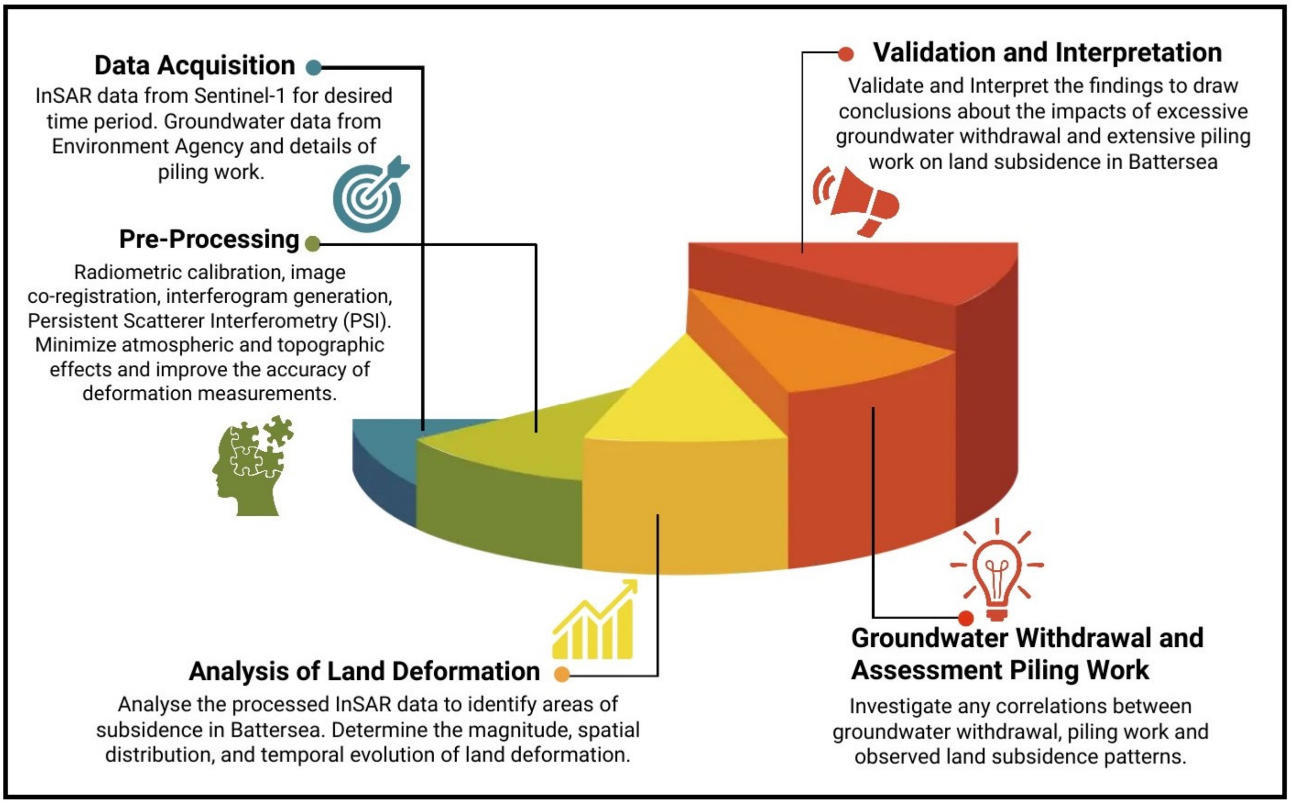

Figure 3. Methodology used to correlate land subsidence, groundwater withdrawal, and underground construction works.

The time period from October 2016 to October 2020 was chosen for this study due to several reasons. Firstly, it aligns with the significant construction activities and groundwater extraction that occurred during the renovation and redevelopment of Battersea, allowing for a comprehensive analysis of their impacts. Additionally, consistent Sentinel InSAR (interferometric synthetic aperture radar) data and groundwater data from the Environment Agency (EA) were available for this period, facilitating a robust examination of the interdependencies between land subsidence, piling work, and groundwater levels. By utilising data from this timeframe, the study ensures a thorough evaluation of the long-term trends and dynamics associated with these factors, enhancing the reliability and relevance of the findings.

The SARscape module facilitates PSInSAR processing of SAR data using a multi-step, semi-automatic process [64]. The first step involves selecting a master image, to which all the other slave images are co-registered. The master image is chosen based on the stack's smallest average baseline, guaranteeing an ideal spatio-temporal position compared to the slave images. This process enhances coherence and data co-registration, as minimal baselines exhibit reduced sensitivity to volume de-correlation [62]. Upon co-registration, interferograms are generated from master–slave pairs, and flattening is accomplished by implementing a reference digital elevation model (SRTM DEM V4).

SARscape divides the entire study area into overlapping subsets for PSInSAR analysis if the area surpasses a predefined threshold. Each subset is independently analysed, with each having its own reference point. This step is undertaken to improve atmospheric estimation accuracy, and in the end, all separate areas are merged. The predetermined threshold area is known as the "Area for Single Reference Point (sq km)" [62]. In this study, the threshold was set at 25 km^2, resulting in 238 subsets. The permanent scatterers' density, which is used for deriving land motion measurements, depends on the coherence threshold chosen for the PSInSAR analysis. A higher coherence threshold leads to superior quality and a smaller number of PS points, and vice versa. As a result, an optimum balance between the quality and quantity of PS points should be achieved when selecting the coherence threshold. The first inversion step was conducted to obtain coherence, displacement velocity, and residual topography, which were subsequently used for flattening complex interferograms. Then, a second inversion step addressed atmospheric phase components of linear model products originating from the first inversion. Ultimately, geocoding was executed to display average (linear) velocity and displacement time-series maps for the observation period.

3.2. Groundwater Variation

The groundwater variation data for the Battersea chalk borehole were obtained from the England and Wales Environment Agency [65]. The correlation between groundwater withdrawal and observed land subsidence patterns was investigated. The units for land displacement (mm/year) and groundwater levels (mAOD) are different, and thus, comparing the absolute values is not meaningful. Instead, the focus was on analysing the trends of both variables to understand the relationship between them. The methodology used is explained below:

- The time-series dataset for groundwater levels and subsidence in the Battersea area were aligned for the same time periods. To align the time periods, the missing values were filled using ARIMA (autoregressive integrated moving average) [66], which combines three components: autoregression (AR), differencing (I), and moving average (MA).
- The data were normalised for both variables (groundwater level and subsidence) by converting the values into relative changes or percentage changes. This made the trends of both variables more comparable without being affected by the difference in units.
- The moving average was calculated for both variables to smooth the time-series data and highlight the underlying trends.
- Cross-correlation analysis [67]: The cross-correlation function was computed between the normalised time-series data for groundwater levels and subsidence rates. This

helped to assess the strength and direction of the relationship between the two variables, as well as the time lag between them, if any.

- Granger causality test: A Granger causality test was performed to determine whether changes in groundwater levels can predict changes in subsidence rates, or vice versa. This test helped to establish a causal relationship between the two variables [68,69].
- Based on the results of the trend analysis, cross-correlation analysis, and Granger causality test, the relationship between the temporal trends of groundwater levels and subsidence in the Battersea area was interpreted.

By focusing on the trends of both variables and normalising the data, a robust analysis of the relationship between the temporal distribution of groundwater levels and subsidence in the Battersea area was conducted.

3.3. Construction Work Assessment

Our study delved into the construction projects taking place in the Battersea area, with a specific focus on projects like the Northern Line Extension and the associated piling work. To gain comprehensive insights, we collected detailed information regarding various aspects of these construction projects. In terms of foundation depth, we examined the depths to which the foundations were laid during the construction activities. This information allowed us to understand the extent to which the underlying soil layers were impacted by the construction process. Furthermore, we investigated the piling techniques employed in the projects by sheet piling and Martello piling. These details provided us with a deeper understanding of the construction processes and their potential influence on the surrounding environment.

With the gathered information, we then proceeded to examine the relationship between the piling work undertaken and the land subsidence patterns observed in the InSAR data. By conducting analysis of the geospatial and temporal correlation between the construction activities and the detected land subsidence, we aimed to identify any potential causal links or associations. This comprehensive investigation allowed us to assess the impact of the construction projects, particularly the piling work, on the observed land subsidence patterns in the Battersea area. By integrating detailed information about the construction activities and analysing their relationship with the InSAR data, we aimed to gain valuable insights into the interplay between construction processes, piling techniques, and resulting land subsidence.

3.4. Trend Analysis

Because the units for land displacement and groundwater levels are different, comparing the absolute values is futile. Instead, we focus on analysing the trends of both variables to understand the relationship between them. For this analysis, a model is created in the R programming language, and the approach used is described below:

Data collection and preparation: We obtain a time-series dataset for groundwater levels and subsidence in the Battersea area and align the time periods for both variables.

Normalisation: Then, data for both variables are normalised by converting the values into relative changes or percentage changes. This will make the trends of both variables more comparable without being affected by the difference in units.

Trend analysis: A moving average is calculated for both variables to smoothen the time-series data and highlight the underlying trends. The moving averages for groundwater levels and subsidence rates over time are plotted to visualise their trends and observe any apparent relationship between the two variables.

Cross-correlation analysis: The cross-correlation function is computed between the normalised time series data for groundwater levels and subsidence rates. This will help assess the strength and direction of the relationship between the two variables, as well as the time lag between them if there is any.

Granger causality test: Finally, a Granger causality test is performed to determine whether changes in groundwater levels can predict changes in subsidence rates or vice versa. This test will help establish a causal relationship between the two variables.

4. Results and Discussions

4.1. Land Subsidence

The processed InSAR data revealed the spatial distribution and magnitude of land subsidence in Battersea, London (Figure 4). The subsidence statistics are summarised in Table 3. An average subsidence of −6.8 ± 1.6 mm/year was observed at Battersea from 2016 to 2020 and can be attributed to several factors, which may have occurred individually or in combination. These include groundwater withdrawal, underground construction activities, and tunnelling activities. The study area has two tunnels underneath it, viz., the Tideway and the Northern Line Extension [14,70,71].

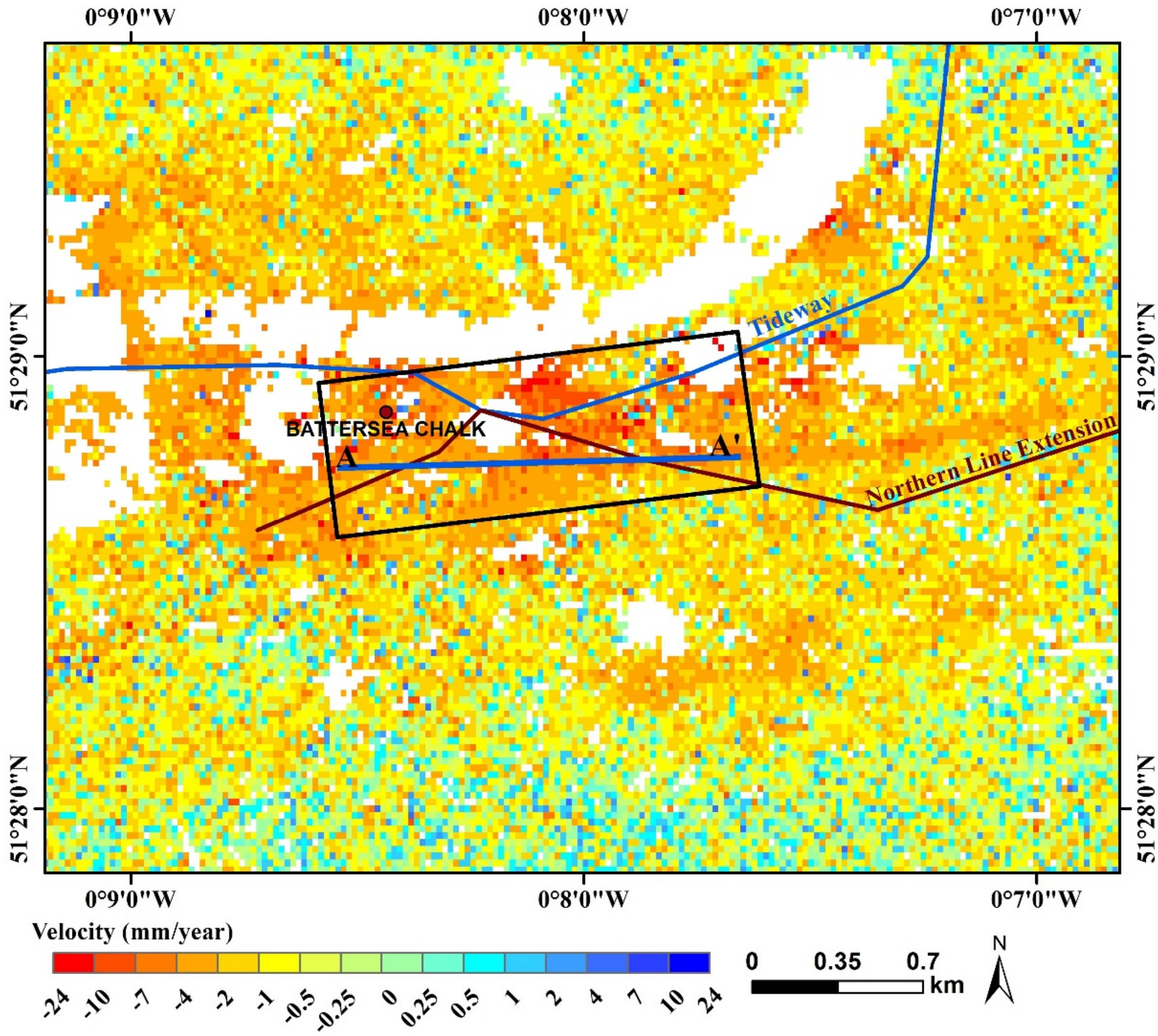

Figure 4. Spatial distribution of subsidence around Battersea, London. The Battersea chalk is the location of the borehole used in the study. The section A-A′, is used to show subsidence profile's interaction with the Northern Line Extension (NLE), shown in Figure 5.

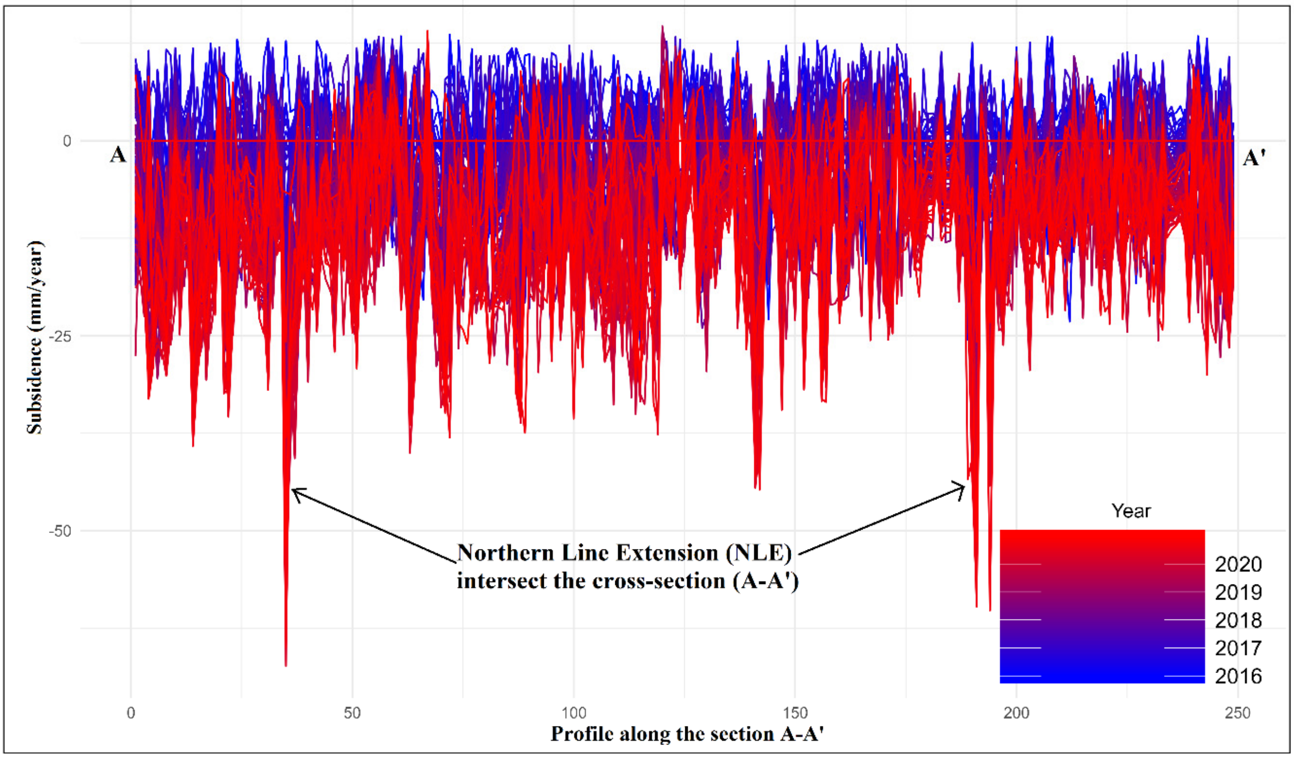

Figure 5. Subsidence profile variation across the profile A-A′ (marked on Figure 4). Red to blue lines show the subsidence varying from 2020 to 2016.

Table 3. Statistics of land subsidence for Battersea area.

Location	Area (km^2)	No. of PS	PS Density	Land Deformation (mm/year)			
				Max	Min	Mean	St. Dev.
Battersea	0.72	8124	11,745	0.5	−18.71	−6.8	1.6

The Northern Line Extension (NLE) is a significant infrastructure project in London that extends the existing Northern Line from Kennington to Battersea [71]. The project aims to improve transportation in the region, support the ongoing redevelopment of the Vauxhall, Nine Elms, and Battersea areas, and promote economic growth. The construction of the Northern Line Extension began in 2015, and the new stations were initially expected to open in 2020 [72]. However, due to various delays and challenges, the expected opening has been pushed back. Most of the construction work was conducted between 2016 and 2020, the time-period observed in this study. Figure 5 shows section A-A′ passing along the Northern Line Extension. The subsidence variation along the section A-A′ for each year shows maximum displacement near the location of the NLE. This highlights that subsidence is highly influenced by underground construction activity, with the maximum subsidence near the NLE site on the order of 75 mm (Figure 5).

This ground settlement has been caused by NLE construction activities, such as tunnelling and excavation, which can alter stress distribution in the overlying soil and rock layers. It is essential to consistently examine and track subsidence patterns during and post-construction to guarantee long-term infrastructure stability. Additionally, the intricate geology and hydrogeology of Battersea, including clay formations like the London Clay, could contribute to ground subsidence. It is necessary to comprehensively study and manage the behaviour of these formations under the added stress from construction activities to reduce land subsidence risks. Moreover, extracting groundwater from the Chalk aquifer or other shallow aquifers in Battersea could cause ground settlement due to reduced pore water pressure in soil layers. Proper monitoring and management of groundwater abstraction are critical for mitigating these land subsidence risks.

Significant subsidence in Battersea could potentially damage infrastructure such as buildings, roads, and utilities and jeopardise the safety and stability of the NLE and nearby structures [73]. Consequently, it is crucial to continuously monitor subsidence rates and patterns for the long-term safety and functionality of the infrastructure. To tackle land subsidence issues in Battersea and along the NLE, it is necessary to apply appropriate mitigation measures. Techniques like InSAR and other remote sensing methods can continuously observe land subsidence, while construction methods and groundwater management practices are adjusted to minimise ground surface impacts. Effective management of subsidence risks in the area requires collaboration among stakeholders, including engineers, geologists, and local authorities [3,63,74].

By leveraging remote sensing techniques, both retrospectively as a source of valuable lessons and currently during ongoing projects, it is possible to bolster the alignment of urban planning and delivery with the United Nations Sustainable Development Goals (SDGs). This entails employing non-invasive sensing approaches to holistically assess the broader ramifications on factors such as liveability, ecosystem health, and urban connectivity, thus fostering sustainable urban development under SDG 11 (Sustainable Cities and Communities).

4.2. Correlation with Groundwater

Figure 6 shows the variation of land subsidence and groundwater in the Battersea area. The groundwater variation is shown by the blue line, and the values are represented on the left-hand vertical axis. The groundwater level is in mAOD (meters above ordnance datum) and varies between −18 and −30 mAOD. The negative values represent the groundwater level being below the reference point, which is the ordnance datum. In the United Kingdom, the ordnance datum is the mean sea level at Newlyn in Cornwall. This can happen due to various factors such as local geological conditions, groundwater extraction, or natural fluctuations in groundwater levels. In some cases, a negative groundwater level could be associated with potential issues such as land subsidence or the need for more sustainable water management practices. The subsidence variation is shown by the red line, and the values are represented on right-hand vertical axis. The subsidence varies between −0.5 mm and −13 mm over the observed time period. The negative values indicate that the ground is moving away from the sensor and so indicate that land subsidence is occurring.

Clearly, both the groundwater and ground-surface levels are decreasing, but the units for land displacement (mm/year) and groundwater levels (mAOD) are different; thus, comparing the absolute values is not meaningful. Instead, we focus on analysing the trends of both variables to understand the relationship between them in subsequent sections.

4.2.1. Cross-Correlation Analysis

Cross-correlation is a measure of similarity between two time series as a function of the time lag applied to one of them. It helps to identify how much one time series influences another at various time lags. The cross-correlation between two time series at different lags is shown in Figure 7, utilising the ACF (autocorrelation function) versus the lag plot for cross-correlation analysis. From this, the relationship between the two time series at different time lags can be visualised. Figure 6 indicates a strong correlation between groundwater and subsidence, especially around the lag of 0–2. An ACF value of 0.4 indicates that an increase (or decrease) in groundwater will bring about a corresponding decrease (or increase) in subsidence. As the lag increases, we can see a negative correlation, which indicates that with an increase in lag (difference in the observation period of the two phenomena), the dependence of one variable on other decreases, and other factors might become more dominant in affecting these phenomena. The lag with the highest cross-correlation value is the lag at which the two time series are most strongly related. This lag can provide insights into the timing or lead–lag relationship between the two time series. Thus, it can be concluded that for Battersea, there is a direct effect of groundwater withdrawal on land subsidence.

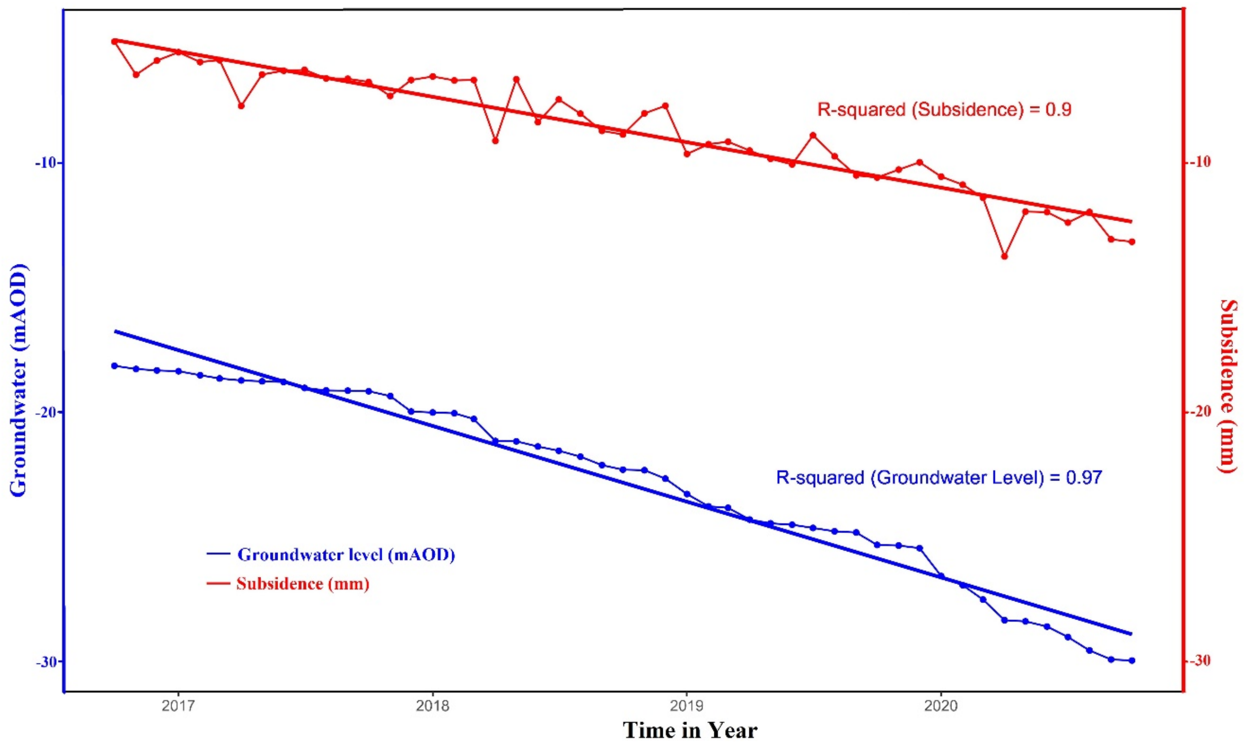

Figure 6. Temporal variation of groundwater and subsidence. The blue line is for groundwater, and the red line is for subsidence. Both the groundwater level and land-surface level are going down with time for Battersea, London.

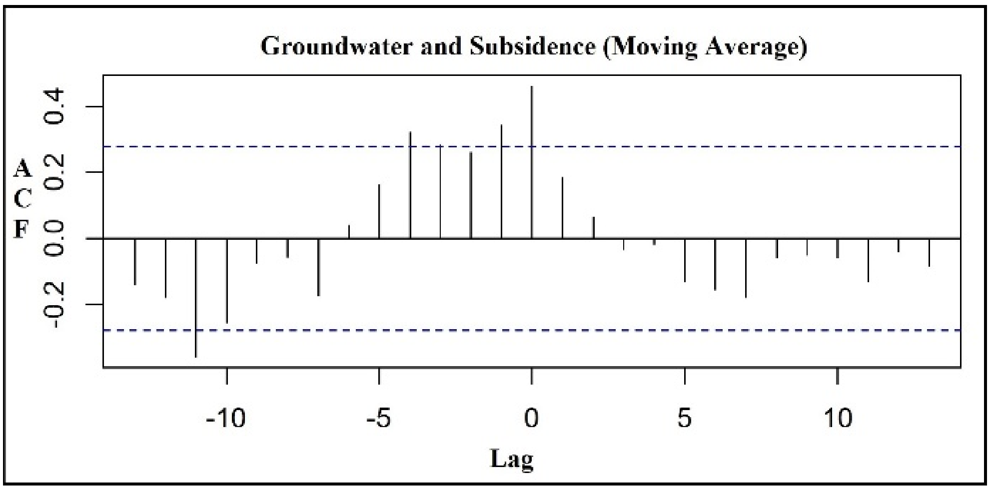

Figure 7. ACF (Autocorrelation function) versus lag plot for cross-correlation analysis between groundwater and subsidence.

4.2.2. The Granger Causality Test

The Granger causality test is used to determine if one time series (groundwater levels) can predict or "Granger-cause" another time series (land subsidence). In this study, we have used two models:

Model 1: Groundwater (moving average) is explained by its own values and the values of subsidence (moving average).

Model 2: Groundwater (moving average) is explained only by its own values.

The test compares the two models to determine if including the values of groundwater in Model 1 provides a better explanation of the variation in subsidence compared to Model 2, where only the lagged values of groundwater are included. This test aims to demonstrate the interconnected nature of groundwater and subsidence and their potential influence on each other within the study area.

The result of the Granger causality test is given in the form of an F-statistic and its corresponding p-value [68]. Table 4 shows the F-statistic is 6.5242, and the p-value is 0.01477 (indicated by the '*' symbol, which means it is significant at the 0.01 level). Because the p-value is less than 0.05 (a common threshold for statistical significance), we can reject the null hypothesis that subsidence does not Granger-cause groundwater. This means that there is evidence to suggest that past values of subsidence have a predictive power in explaining the variation in groundwater (and vice versa). Including the lagged values of subsidence in the model significantly improves the model's ability to predict groundwater compared to using only the lagged values of groundwater. Furthermore, the positive correlation between the moving average plot of subsidence and groundwater (Figure 8), highlights the strong interdependence of the two phenomena on each other.

Table 4. Granger causality test statistics to summarise relation between groundwater and subsidence.

Granger Causality Test				
Model 1: Groundwater~Lags (Groundwater, 1:1) + Lags (Subsidence, 1:1)				
Model 2: Groundwater~Lags (Groundwater, 1:1)				
	Res.Df	**Res.Df**	**F**	**P r (>F)**
1	38			
2	39	−1	6.5242	0.01477 *

Significant. codes: 0.01 '*' 0.05 '.' 0.1 ' ' 1.

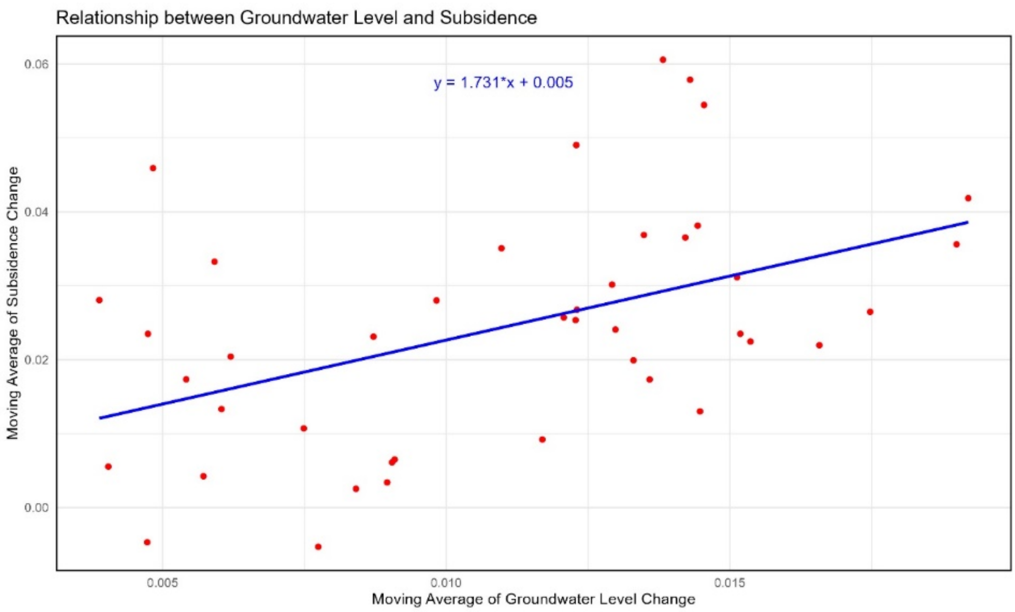

Figure 8. Groundwater–subsidence relationship. The graph shows the pattern of interdependence of groundwater and subsidence.

4.2.3. Correlation of Subsidence with Construction (Piling) Work

Several underground construction activities took place at and nearby the Battersea area during our observation time period [58,60]. Two of the notable projects were the Battersea Power Station redevelopment [57] and the Northern Line Extension [14]. Piling work was a crucial part of the construction process for these developments, as it involved installing deep foundations to support the weight of the new buildings and infrastructure. Long, slender column piles made of materials such as concrete, steel, or timber were driven or drilled into the ground to transfer the load of the structure to the underlying soil or rock layers. The Northern Line Extension project was proposed in 2010, and after a series of consultations and approvals, the United Kingdom Secretary of State for Transport granted planning permission in November 2014. The construction work on the Northern Line Extension began in 2015 and involved tunnelling and station building; it also involved piling work to ensure the stability and safety of the new infrastructure [75,76]. Figures 4 and 5 clearly show the impact of NLE on the subsidence profile of the area.

Construction projects like the Battersea Power Station redevelopment and the Northern Line Extension can have an impact on groundwater during the construction phase, particularly when they involve excavation, tunnelling, or piling work [14,56,57,72,77]. These activities can potentially disrupt the natural flow of groundwater or change the distribution of groundwater in the area. During construction, it may be necessary to manage groundwater levels to ensure the safety and stability of the structures being built. This can involve dewatering, which is the process of extracting groundwater from the construction site to lower the water table temporarily and create a dry, stable environment for construction. Dewatering can affect groundwater levels in the immediate vicinity of the construction site, but it is generally a temporary measure and unlikely to have a long-term impact on the overall groundwater quantity in the area. Moreover, construction projects in the United Kingdom, especially large-scale ones like the Battersea Power Station redevelopment and the Northern Line Extension, are subject to stringent environmental regulations and assessments. These assessments aim to identify potential impacts on the environment, including groundwater, and outline measures to minimise and mitigate those impacts.

Furthermore, advanced construction techniques and monitoring systems are employed to ensure the stability of the structures being built and to minimise any adverse impacts on the surrounding environment. For example, the tunnelling work for the Northern Line Extension utilised tunnel-boring machines (TBMs) that are designed to minimise ground movement and reduce the risk of subsidence. In addition, extensive monitoring systems were put in place to detect any signs of ground movement during and after construction. It is also worth noting that environmental regulations and assessments are in place to ensure that the potential risks associated with land subsidence are carefully considered and mitigated during the planning, design, and construction phases of these projects.

In conclusion, while the Battersea Power Station redevelopment and the Northern Line Extension projects have the potential to cause land subsidence, and indeed our study detects such movement, this is expected. The risks are typically well-managed through comprehensive geotechnical investigations, advanced construction techniques, and adherence to environmental regulations. It is important, however, that construction practices adhere to environmental regulations and best practices to minimise any potential adverse effects on groundwater resources.

5. Conclusions

This study aimed to investigate land subsidence in Battersea, London, using interferometric synthetic aperture radar (InSAR) techniques. The results revealed the spatial distribution and magnitude of land subsidence in the area and identified correlations with potential contributing factors, such as excessive groundwater withdrawal and extensive piling work during construction.

The implications of these findings highlight the need for sustainable groundwater management practices, improved construction techniques, and informed urban planning and infrastructure management in Battersea. By addressing the issue of land subsidence proactively, local authorities, urban planners, and engineers can minimise the risk of damage to infrastructure, protect the environment, and ensure the safety and well-being of the community.

The study also emphasises the importance of ongoing research to better understand the long-term trends and impacts of land subsidence in Battersea and other urban areas facing similar challenges. Expanding the analysis to other regions and assessing the effectiveness of various mitigation strategies can contribute to a broader understanding of land subsidence and its implications for urban planning and development worldwide.

In summary, this study demonstrates the value of using InSAR techniques to investigate land subsidence in urban areas like Battersea, London, and provides a solid foundation for future research and the development of effective mitigation strategies.

Author Contributions: Conceptualization, V.A., A.K., Z.Q., R.L.G. and S.M.; data curation, V.A. and A.K.; formal analysis, V.A., Z.Q. and S.M.; investigation, V.A., A.K. and Z.Q.; methodology, V.A.; software, V.A., A.K. and S.M.; supervision, R.L.G. and S.M.; validation, V.A., Z.Q., R.L.G. and S.M.; visualization, V.A. and R.L.G.; writing—original draft, V.A., A.K., Z.Q., R.L.G. and S.M.; writing—review and editing, V.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors would like to thank L3Harris Geospatial for providing access to the SARscape software for the processing of InSAR data. We would also like to thank the Environment Agency for providing the groundwater data.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Werner, C.; Wegmüller, U.; Strozzi, T.; Wiesmann, A. Interferometric Point Target Analysis for Deformation Mapping. In Proceedings of the IGARSS 2003. 2003 IEEE International Geoscience and Remote Sensing Symposium, Toulouse, France, 21–25 July 2003. [CrossRef]
2. Mora, O.; Mallorqui, J.J.; Broquetas, A. Linear and nonlinear terrain deformation maps from a reduced set of interferometric SAR images. *IEEE Trans. Geosci. Remote Sens.* **2003**, *41*, 2243–2253. [CrossRef]
3. Cigna, F.; Jordan, H.; Bateson, L.; McCormack, H.; Roberts, C. Natural and Anthropogenic Geohazards in Greater London Observed from Geological and ERS-1/2 and ENVISAT Persistent Scatterers Ground Motion Data: Results from the EC FP7-SPACE PanGeo Project. *Pure Appl. Geophys.* **2015**, *172*, 2965–2995. [CrossRef]
4. Changming, L.; Jingjie, Y.; Kendy, E. Groundwater exploitation and its impact on the environment in the North China Plain. *Water Int.* **2001**, *26*, 265–272. [CrossRef]
5. Guppy, L.; Uyttendaele, P.; Villholth, K.G.; Smakhtin, V. *Groundwater and Sustainable Development Goals: Analysis of Interlinkages*; UNU: Shibuya, Japan, 2018.
6. Massonnet, D.; Feigl, K.L. Radar interferometry and its application to changes in the earth's surface. *Rev. Geophys.* **1998**, *36*, 441–500. [CrossRef]
7. Zhou, X.; Chang, N.B.; Li, S. Applications of SAR interferometry in earth and environmental science research. *Sensors* **2009**, *9*, 1876–1912. [CrossRef]
8. Zeevaert, L. Foundation problems related to ground surface subsidence in Mexico City. In *Field Testing of Soils*; ASTM International: West Conshohocken, PA, USA, 1962.
9. Hannigan, P.J.; Goble, G.G.; Thendean, G.; Likins, G.E.; Rausche, F. *Design and Construction of Driven Pile Foundations—Volume I*; Office of Technology Applications, Federal Highway Administration: Washington, DC, USA, 1998.
10. Sandanayake, M.; Zhang, G.; Setunge, S.; Thomas, C.M. Environmental emissions of construction equipment usage in pile foundation construction process—A case study. In Proceedings of the 19th International Symposium on Advancement of Construction Management and Real Estate; Springer: Berlin/Heidelberg, Germany, 2015; pp. 327–339.
11. Kumar, M.; Panday, D.P.; Bhagat, C.; Herbha, N.; Agarwal, V.; Jain, V. Demystifying the decadal shift in the extent of groundwater in the coastal aquifers of Gujarat, India: A case of reduced extent but increased magnitude of seawater intrusion. *Sci. Total Environ.* **2023**, *898*, 165451. [CrossRef]
12. Agarwal, V.; Kumar, A.; Gee, D.; Grebby, S.; Gomes, R.L.; Marsh, S. Comparative Study of Groundwater-Induced Subsidence for London and Delhi Using PSInSAR. *Remote Sens.* **2021**, *13*, 4741. [CrossRef]
13. Agarwal, V.; Kumar, A.; Gomes, R.L.; Marsh, S. Monitoring of Ground Movement and Groundwater Changes in London Using InSAR and GRACE. *Appl. Sci.* **2020**, *10*, 8599. [CrossRef]
14. Toms, E.; Mason, P.J.; Ghail, R.C. Drift-filled hollows in Battersea: Investigation of the structure and geology along the route of the Northern Line Extension, London. *Q. J. Eng. Geol. Hydrogeol.* **2016**, *49*, 147–153. [CrossRef]
15. SLC. Sentinel-1A. 2020. Available online: https://sentinel.esa.int/web/sentinel/user-guides/sentinel-1-sar/resolutions/level-1-single-look-complex/ (accessed on 25 September 2020).

16. Kang, Y.; Lu, Z.; Zhao, C.; Xu, Y.; Kim, J.W.; Gallegos, A.J. InSAR monitoring of creeping landslides in mountainous regions: A case study in Eldorado National Forest, California. *Remote Sens. Environ.* **2021**, *258*, 112400. [CrossRef]
17. Kang, Y.; Zhao, C.; Zhang, Q.; Lu, Z.; Li, B. Application of InSAR techniques to an analysis of the Guanling landslide. *Remote Sens.* **2017**, *9*, 1046. [CrossRef]
18. Even, M. Advanced InSAR processing in the footsteps of SqueeSAR. In Proceedings of the Fringe Workshop, Frascati, Italy, 23–27 March 2015.
19. Ferretti, A. *Satellite InSAR Data: Reservoir Monitoring from Space*; EAGE Publications: Dubai, United Arab Emirates, 2014.
20. Peltier, A.; Bianchi, M.; Kaminski, E.; Komorowski, J.C.; Rucci, A.; Staudacher, T. PSInSAR as a new tool to monitor pre-eruptive volcano ground deformation: Validation using GPS measurements on Piton de La Fournaise. *Geophys. Res. Lett.* **2010**, *37*. [CrossRef]
21. Gonnuru, P.; Kumar, S. PsInSAR based land subsidence estimation of Burgan oil field using TerraSAR-X data. *Remote Sens. Appl. Soc. Environ.* **2018**, *9*, 17–25. [CrossRef]
22. Karanam, V.; Motagh, M.; Garg, S.; Jain, K. Multi-sensor remote sensing analysis of coal fire induced land subsidence in Jharia Coalfields, Jharkhand, India. *Int. J. Appl. Earth Obs. Geoinf.* **2021**, *102*, 102439. [CrossRef]
23. Scoular, J.; Ghail, R.; Mason, P.J.; Lawrence, J.; Bellhouse, M.; Holley, R.; Morgan, T. Retrospective InSAR analysis of East London during the construction of the Lee Tunnel. *Remote Sens.* **2020**, *12*, 849. [CrossRef]
24. Milillo, P.; Giardina, G.; DeJong, M.J.; Perissin, D.; Milillo, G. Multi-temporal InSAR structural damage assessment: The London crossrail case study. *Remote Sens.* **2018**, *10*, 287. [CrossRef]
25. Giardina, G.; Milillo, P.; DeJong, M.J.; Perissin, D.; Milillo, G. Evaluation of InSAR monitoring data for post-tunnelling settlement damage assessment. *Struct. Control Health Monit.* **2019**, *26*, e2285. [CrossRef]
26. Chatterjee, R.; Fruneau, B.; Rudant, J.; Roy, P.; Frison, P.-L.; Lakhera, R.; Dadhwal, V.; Saha, R. Subsidence of Kolkata (Calcutta) City, India during the 1990s as observed from space by Differential Synthetic Aperture Radar Interferometry (D-InSAR) technique. *Remote Sens. Environ.* **2006**, *102*, 176–185. [CrossRef]
27. Malik, K.; Kumar, D.; Perissin, D. Assessment of subsidence in Delhi NCR due to groundwater depletion using TerraSAR-X and persistent scatterers interferometry. *Imaging Sci. J.* **2019**, *67*, 1. [CrossRef]
28. Malik, K.; Kumar, D.; Perissin, D.; Pradhan, B. Estimation of ground subsidence of New Delhi, India using PS-InSAR technique and Multi-sensor Radar data. *Adv. Space Res.* **2022**, *69*, 1863–1882. [CrossRef]
29. Mishra, V.; Jain, K. Satellite based assessment of artificial reservoir induced landslides in data scarce environment: A case study of Baglihar reservoir in India. *J. Appl. Geophys.* **2022**, *205*, 104754. [CrossRef]
30. Qin, Z.; Agarwal, V.; Gee, D.; Marsh, S.; Grebby, S.; Chen, Y.; Meng, N. Study of Ground Movement in a Mining Area with Geological Faults Using FDM Analysis and a Stacking InSAR Method. *Front. Environ. Sci.* **2021**, *9*, 787053. [CrossRef]
31. Ge, D.; Zhang, L.; Li, M.; Liu, B.; Wang, Y. Beijing subway tunnelings and high-speed railway subsidence monitoring with PSInSAR and TerraSAR-X data. In Proceedings of the 2016 IEEE International Geoscience and Remote Sensing Symposium (IGARSS), Beijing, China, 10–15 June 2016; pp. 6883–6886.
32. Jiang, H.; Balz, T.; Cigna, F.; Tapete, D. Land subsidence in Wuhan revealed using a non-linear PSInSAR approach with long time series of COSMO-SkyMed SAR data. *Remote Sens.* **2021**, *13*, 1256. [CrossRef]
33. Heimlich, C.; Gourmelen, N.; Masson, F.; Schmittbuhl, J.; Kim, S.-W.; Azzola, J. Uplift around the geothermal power plant of Landau (Germany) as observed by InSAR monitoring. *Geotherm. Energy* **2015**, *3*, 1. [CrossRef]
34. Arangio, S.; Calò, F.; Di Mauro, M.; Bonano, M.; Marsella, M.; Manunta, M. An application of the SBAS-DInSAR technique for the assessment of structural damage in the city of Rome. *Struct. Infrastruct. Eng.* **2014**, *10*, 1469–1483. [CrossRef]
35. García, A.J.; Marchamalo, M.; Martínez, R.; González-Rodrigo, B.; González, C. Integrating geotechnical and SAR data for the monitoring of underground works in the Madrid urban area: Application of the Persistent Scatterer Interferometry technique. *Int. J. Appl. Earth Obs. Geoinf.* **2019**, *74*, 27–36. [CrossRef]
36. Dzurisin, D.; Lisowski, M.; Wicks, C.W. Continuing inflation at Three Sisters volcanic center, central Oregon Cascade Range, USA, from GPS, leveling, and InSAR observations. *Bull. Volcanol.* **2009**, *71*, 1091–1110. [CrossRef]
37. Liu, L.; Millar, C.I.; Westfall, R.D.; Zebker, H.A. Surface motion of active rock glaciers in the Sierra Nevada, California, USA: Inventory and a case study using InSAR. *Cryosphere* **2013**, *7*, 1109–1119. [CrossRef]
38. Akcin, H.; Kutoglu, H.S.; Kemaldere, H.; Deguchi, T.; Koksal, E. Monitoring subsidence effects in the urban area of Zonguldak Hardcoal Basin of Turkey by InSAR-GIS integration. *Nat. Hazards Earth Syst. Sci.* **2010**, *10*, 1807–1814. [CrossRef]
39. Dang, V.K.; Nguyen, T.D.; Dao, N.H.; Duong, T.L.; Dinh, X.V.; Weber, C. Land subsidence induced by underground coal mining at Quang Ninh, Vietnam: Persistent scatterer interferometric synthetic aperture radar observation using Sentinel-1 data. *Int. J. Remote Sens.* **2021**, *42*, 3563–3582. [CrossRef]
40. Solarski, M.; Machowski, R.; Rzetala, M.; Rzetala, M.A. Hypsometric changes in urban areas resulting from multiple years of mining activity. *Sci. Rep.* **2022**, *12*, 2982. [CrossRef] [PubMed]
41. Przyłucka, M.; Herrera, G.; Graniczny, M.; Colombo, D.; Béjar-Pizarro, M. Combination of conventional and advanced DInSAR to monitor very fast mining subsidence with TerraSAR-X data: Bytom City (Poland). *Remote Sens.* **2015**, *7*, 5300–5328. [CrossRef]
42. Nádudvari, Á. Using radar interferometry and SBAS technique to detect surface subsidence relating to coal mining in Upper Silesia from 1993–2000 and 2003–2010. *Environ. Socio-Econ. Stud.* **2016**, *4*, 24–34. [CrossRef]

43. Lu, Z.; Danskin, W.R. InSAR analysis of natural recharge to define structure of a ground-water basin, San Bernardino, California. *Geophys. Res. Lett.* **2001**, *28*, 2661–2664. [CrossRef]
44. Carbognin, L.; Teatini, P.; Tosi, L. Eustacy and land subsidence in the Venice Lagoon at the beginning of the new millennium. *J. Mar. Syst.* **2004**, *51*, 345–353. [CrossRef]
45. Hole, J.K.; Bromley, C.J.; Stevens, N.F.; Wadge, G. Subsidence in the geothermal fields of the Taupo Volcanic Zone, New Zealand from 1996 to 2005 measured by InSAR. *J. Volcanol. Geotherm. Res.* **2007**, *166*, 125–146. [CrossRef]
46. Klemm, H.; Quseimi, I.; Novali, F.; Ferretti, A.; Tamburini, A. Monitoring horizontal and vertical surface deformation over a hydrocarbon reservoir by PSInSAR. *First Break* **2010**, *28*, 5. [CrossRef]
47. Fan, H.D.; Cheng, D.; Deng, K.Z.; Chen, B.Q.; Zhu, C.G. Subsidence monitoring using D-InSAR and robability integral prediction modelling in deep mining areas. *Surv. Rev.* **2015**, *47*, 438–445. [CrossRef]
48. Bateson, L.; Cigna, F.; Boon, D.; Sowter, A. The application of the Intermittent SBAS (ISBAS) InSAR method to the South Wales Coalfield, UK. *Int. J. Appl. Earth Obs. Geoinf.* **2015**, *34*, 249–257. [CrossRef]
49. Zhou, L.; Guo, J.; Hu, J.; Li, J.; Xu, Y.; Pan, Y.; Shi, M. Wuhan surface subsidence analysis in 2015–2016 based on sentinel-1A data by SBAS-InSAR. *Remote Sens.* **2017**, *9*, 982. [CrossRef]
50. Castellazzi, P.; Longuevergne, L.; Martel, R.; Rivera, A.; Brouard, C.; Chaussard, E. Quantitative mapping of groundwater depletion at the water management scale using a combined GRACE/InSAR approach. *Remote Sens. Environ.* **2018**, *205*, 408–418. [CrossRef]
51. Cigna, F.; Tapete, D. Satellite InSAR survey of structurally-controlled land subsidence due to groundwater exploitation in the Aguascalientes Valley, Mexico. *Remote Sens. Environ.* **2021**, *254*, 112254. [CrossRef]
52. Block, F.M.; Kho, T.-S. Engineering an icon or the probabilistic-based structural fire engineering of the battersea power station. *Struct. Fire* **2016**.
53. Penz, F.; Reid, A.; Thomas, M. Cinematic Urban Archaeology: The Battersea Case. In *Cinematic Urban Geographie*; Springer: Berlin/Heidelberg, Germany, 2017; pp. 191–221.
54. Bowler, C.; Brimblecombe, P. Battersea Power Station and environmental issues 1929–1989. *Atmos. Environ. Part B Urban Atmos.* **1991**, *25*, 143–151. [CrossRef]
55. Smith, A. Justifying and resisting public park commercialisation: The battle for Battersea Park. *Eur. Urban Reg. Stud.* **2019**, *26*, 171–185. [CrossRef]
56. Suckling, T.P.; Gates, S.J. Challenging Piling Works Within Battersea Power Station. In *Piling 2020: Proceedings of the Piling 2020 Conference*; ICE Publishing: London, UK, 2021; pp. 97–102.
57. Edgell, G.; Brooke, P.M. The rehabilitation of Battersea power station. In Proceedings of the International Masonry Society Conferences, Milan, Italy, 9–11 July 2018; pp. 917–935.
58. Newman, T.; Hueso, O.; Goirigolzarri, M.M. Effects of changing geology on the performance of a tunnel boring machine for the Thames Tideway Tunnel, London, UK. In Proceedings of the Institution of Civil Engineers-Geotechnical Engineering; ICE Publishing: London, UK, 2022; pp. 1–14.
59. Morley, M. The Battersea Channel: A former course of the River Thames? *Lond. Archaeol.* **2010**, *12*, 7.
60. Flynn, A.; Collins, P.; Skipper, J.A.; Pickard, T.; Koor, N.; Reading, P.; Davis, J.A. Buried (drift-filled) hollows in London—A review of their location and key characteristics. *Q. J. Eng. Geol. Hydrogeol.* **2021**, *54*, 3. [CrossRef]
61. Ferretti, A.; Prati, C.; Rocca, F. Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry. *IEEE Trans. Geosci. Remote Sens.* **2000**, *38*, 2202–2212. [CrossRef]
62. Sarmap. PS Tutorial. 2014. Available online: http://www.sarmap.ch/tutorials/PS_Tutorial_V_0_9.pdf (accessed on 12 June 2023).
63. Kim, J.; Kim, D.-J.; Kim, S.-W.; Won, J.-S.; Moon, W.M. Monitoring of urban land surface subsidence using PSInSAR. *Geosci. J.* **2007**, *11*, 59–73. [CrossRef]
64. Sarmap. SARscape Help Manual. 2014. Available online: http://sarmap.ch/tutorials/Basic.pdf (accessed on 10 June 2023).
65. EA. *Management of the London Basin Chalk Aquifer*; Environment Agency of England and Wales, Thames Region: Hertfordshire, UK, 2022.
66. Ho, S.L.; Xie, M. The use of ARIMA models for reliability forecasting and analysis. *Comput. Ind. Eng.* **1998**, *35*, 213–216. [CrossRef]
67. Podobnik, B.; Stanley, H.E. Detrended cross-correlation analysis: A new method for analyzing two nonstationary time series. *Phys. Rev. Lett.* **2008**, *100*, 84102. [CrossRef]
68. Lopez, L.; Weber, S. Testing for Granger causality in panel data. *Stata J.* **2017**, *17*, 972–984. [CrossRef]
69. Maziarz, M. A review of the Granger-causality fallacy. *J. Philos. Econ. Reflect. Econ. Soc. Issues* **2015**, *8*, 86–105. [CrossRef]
70. Ward, E.J.; Dimitriou, H.T.; Wright, P.; Dean, M. Application of policy-led multi-criteria analysis to the project appraisal of the Northern Line Extension, London. *Res. Transp. Econ.* **2016**, *58*, 46–80. [CrossRef]
71. Ward, E.J. *Phase 2 Desk Study Report of Northern Line Extension*; UCL Discovery: London, UK, 2014.
72. Christine, H. Community, authenticity and newness: Obscuring financial motivations in transport and development projects through discourse at Battersea Power Station. In *Discourse Analysis in Transport and Urban Development*; Edward Elgar Publishing: Cheltenham, UK, 2023; pp. 199–211.
73. Agarwal, V. Study of Groundwater Properties and Behaviour Using Geospatial Techniques. Ph.D. Thesis, University of Nottingham, Nottingham, UK, 2022.

74. Grebby, S.; Sowter, A.; Gluyas, J.; Toll, D.; Gee, D.; Athab, A.; Girindran, R. Advanced analysis of satellite data reveals ground deformation precursors to the Brumadinho Tailings Dam collapse. *Commun. Earth Environ.* **2021**, *2*, 1–9. [CrossRef]
75. Findeisen, F. Financing the Northern Line Extension: The politics of governing Greater London. *Territ. Politics Gov.* **2022**, *10*, 608–627. [CrossRef]
76. Hannigan, C. Financialisation in Planning: Examining the Planning and Funding of the Vauxhall Nine Elms Battersea Opportunity Area and Northern Line Extension. Ph.D. Thesis, UCL (University College London), London, UK, 2019.
77. Transport for London. Northern Line Extension—Transport for London. 2021. Available online: https://tfl.gov.uk/corporate/publications-and-reports/northern-line-extension (accessed on 21 May 2023).