Limitations of Persistent Scatterer Interferometry to measure small seasonal ground movements in an urban environment

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Abstract: London Clay, which underlies the majority of Greater London, has a high shrink-swell potential that can result in damage to foundations and surface infrastructure due to seasonal expansion and contraction of the clay. Currently, surface movement as a result of shrink-swell is not monitored in London, meaning that the magnitude and cyclicity of these movements is poorly understood. Persistent Scatterer Interferometric Synthetic Aperture Radar (PSI) data provide high-precision line-of-sight displacement measurements at a high point density across urban areas, offering the possibility of routine shrink-swell monitoring across whole cities. To test this, PSI data derived from TerraSAR-X (TSX) observations for the period from May 2011 to April 2017 were analysed for shrink-swell patterns across three areas of London in Hammersmith, Muswell Hill and Islington. A consistent cyclicity and amplitude was detected at all sites and the number of cycles is comparable with those identified in rainfall data. The amplitude of these cycles is smaller than anticipated, most probably because of the resisting effect of roads and pavements. The Cranfield University Leakage Assessment from Corrosivity and Shrinkage (LEACS) database was used to subdivide the PSI data and the average velocity and amplitude of each class statistically tested for significant differences between classes. The results show that it is not possible to statistically isolate possible soil shrink-swell movement in TSX PSI data in London.

Shrink-swell of clays is known to cause structural damage to buildings and infrastructure and is a major cause of water main pipe bursts (Boyle et al. 2000). It poses the highest cost and subsequent risk to infrastructure systems in the UK, with the potential to exceed the economic costs of flooding if climate change predictions are accurate (Pritchard et al. 2013). The National House Building Council (NHBC), report that approximately 80% of foundation related claims it receives are due to clay soil volume change (Driscoll & Crilly 2000). The UK climate projections UKCP09 predict hotter drier summers in southern England, with summer rainfall decreasing by 12% and wetter winters, with an overall yearly increase in rainfall, leading to more substantial shrink-swell cycles (Murphy et al. 2009). All clays are subject to shrink and swell, but those with a higher proportion of expansive clay minerals, such as smectite, experience much higher ratios of shrink-swell (Jones & Terrington 2011). In addition, tree cover, soil exposure, urbanisation and surface drainage factors, weather, and atmosphere all influence the magnitude of wetting-drying cycles and hence the degree of shrink and swell (Boyle et al. 2000). Clay-rich soils in the UK are most common in the south-east of England (Harrison et al. 2009). London clay is particularly susceptible to shrink-swell and has long been the cause of significant damage to foundations and infrastructure (Jones & Terrington 2011).

Despite its importance, there is a surprising lack of shrink-swell data for London Clay. Standard methods for investigating such properties, such as BS 1377, 1990: Part 2, tests 6.3 & 6.4, Shrinkage Limit and 6.5, Linear Shrinkage and Part 5, test 4, Swelling Pressure (British Standards Institution 1990), rarely form part of a routine site investigation in the UK (Jones & Terrington 2011).

The Volume Change Potential (VCP) of a soil is the relative change in volume to be expected with soil moisture content flux, and is reflected in subsequent shrinkage and swelling of the ground (Jones & Terrington 2011). Prior to Jones & Terrington (2011) there had been few studies on the VCP of London Clay, except chapters covering the Plasticity Index (PI) in Burnett & Fookes (1974), Forster (1997), Hight et al. (2003), Driscoll & Crilly (2000) and Pantelidou & Simpson (2007). Typical values of

PI for the London Clay are 46% to 63%, which equates to a High/Very High VCP (Driscoll & Crilly 2000).

Surface movement caused by shrink-swell in London Clay is also poorly quantified; in situ measurements typically being restricted to infrastructure assets or areas in the vicinity of ongoing construction and recorded for a limited time period only. Techniques such as levelling, total station surveying, and GPS can provide accurate measurements of deformation, but can be costly if a high density of measurements is required over a large area.

Precision GPS has been used to study ground movements in London but the spatial density of GPS stations is low; only 26 in total, of which just 3 are relevant to clay shrink-swell (Ashkenazi et al. 1998). Boyle et al. (2000) used differential InSAR from ERS-1 and -2 to map surface movement in London but the results were inconclusive and not validated. North et al. (2017) applied PSI to C-band (5.6 cm) Sentinel-1 data to study the response of roads and railways to seasonal soil movement at 6 locations in the UK. Deformation was observed across all sites, with spatial and temporal patterns caused by variations in regional water use and shrink-swell potential of the different soil types. Agar (2018) identified swelling of Jurassic clays up 10 mm/yr over an 8 month period in an area near Bath, UK, using PSI applied to Sentinel-1 but the low PS point density (1063 PS/km^2) limited interpretation to the identification of regional trends (over a 50 x 40 km area), rather than local patterns.

High resolution Persistent Scatterer Interferometry (PSI) from X-band (3.1 cm) satellites can provide a high density of high precision measurements over large areas. Although the shrink-swell signal is anticipated to be smaller in urban compared to rural areas, the improved resolution of TerraSAR-X (TSX) over Sentinel-1 or ERS should assist identification. This study investigates whether seasonal cyclic movements in urbanised areas can be detected by TSX SAR data, processed by TRE Altamira using SqueeSAR™. It uses statistical significance tests between detected ground movements and different shrink-swell classes.

Materials and Methods

PSI data were obtained from TSX SAR data, processed by TRE Altamira using SqueeSAR™ (Ferretti et al. 2011). TSX has a repeat period of 11 days and data for London were acquired in StripMap mode in descending geometry at a spatial resolution of 3 m by 3 m (range and azimuth). Displacement along the line of sight (LOS, incidence angle 37°) can be measured to better than 1 mm on PS characterised by very consistent radar returns (Ferretti et al. 2001), with a standard deviation of 0.1 mm/yr on range displacement rates. Apart from the consistency of the radar targets, the accuracy of the measurements depends on the distance from the reference point and the quality of the filtering of the atmospheric components in the interferograms (Colesanti et al. 2003; Ferretti et al. 2007a; Ferretti et al. 2007b).

The data used in this study covers the time period from 1st May 2011 to 28th April 2017 (a total of 150 images, Figure 1) and have a minimum coherence of 0.8. Coherence is a measure of the phase noise affecting the radar targets and ranges from 0, where the interferometric phase is just noise, to 1, where there is an absence of phase noise (Ferretti et al. 2007b). By selecting points exhibiting a coherence value greater than 0.8, the standard deviation of the noise affecting each measurement is expected to be better than 0.7 mm (Colesanti et al. 2003). Atmospheric filtering techniques in multi-temporal InSAR analyses can mitigate the impact of these phase noise components on range displacement data. However, some atmospheric leakage should always be considered. Atmospheric disturbances are spatially correlated and cannot be reduced by spatial averaging. The decorrelation distance of atmospheric components affecting SAR interferograms is about 4 km (Ferretti 2014). Such errors can be reduced only by means of filtering procedures based on the statistical characterisation of both the atmospheric disturbance and the signal of interest (Ferretti et al. 2001;

Ferretti et al. 2011). It should be noted that the atmospheric filtering procedure applied to the data-set used in this work was not based on any pre-selected cyclic model for displacement of the radar targets, to avoid creating a bias in the results. This TSX dataset has been validated with levelling data (Bischoff 2019).

GIS vector point files, containing Persistent Scatterer (PS) velocity data, were supplied for three areas in London (Hammersmith, Muswell and Islington); chosen to provide a good representative sample of clays with different shrink-swell properties and differing long term ground movement trends (Figure 2). The point density for each area was 3840 PS/km^2, 1930 PS/km^2 and 3830 PS/km^2 for Hammersmith, Muswell and Islington respectively.

The National Soil Resources Institute (NSRI) holds the soil data for England and Wales in the Land Information System (LandIS) database. Using topographic, climatic and LandIS soil data, Cranfield University developed the Leakage Assessment from Corrosivity and Shrinkage (LEACS) database, aimed specifically at the water industry, with soil shrink-swell recorded as just one of its parameters (Dufour et al., 1998; Jarvis, 1999) in a GIS point vector file (Figure 2). Shrink-swell potential is categorised from Very Low (1) to Very High (5), based on the predicted volumetric shrinkage that occurs at soil suctions between 5 and 1500 kPa, as a percentage of the volume at 5 kPa (Hall et al. 1977; Jones & Hollis 2014). The thickness of superficial sequences, depth to rockhead and thickness of London Clay were determined from borehole records from the British Geological Survey (BGS) and Superficial Deposit Thickness data (British Geological Survey 2010), which was input into GIS with the TSX data.

As the ground surface, rather than infrastructure, was the focus for this study, only PS points on roads were used for analysis. PS points on buildings were discarded since they may be affected by thermal dilation, may not be representative of surface motion depending on foundation depth and because there is uncertainty as to where on the building the PS point is located. The location of roads has been identified from the OS VectorMap District (Ordnance Survey 2018), which is a vector line map of roads, input into GIS. The width of roads has been determined from the World Topographic Map (1:1000) (Esri 2018) and the road lines of the OS VectorMap enlarged to that width. The PS points were input into GIS and the overlapping road points were selected using the *Intersect* function with the enlarged OS VectorMap. The number of road points in each area was approximately 7,500 for Hammersmith, 1,500 for Muswell Hill and 30,000 for Islington, which reduces the point density in each area to 1520 PS/km^2, 500 PS/km^2 and 1440 PS/km^2 respectively.

The PSI data were detrended, which removes the average secular ground movement of each area over the entire time period. This was done because the focus is for short period ground movements, not long-term trends. Processes that effect long term patterns of deformation in south-east England include glacio-isostatic adjustment, tectonic processes, changes in groundwater levels, natural compaction of alluvial deposits and anthropogenic loading or excavation (Bingley et al. 1999; Aldiss et al. 2014; Mason et al. 2015). The number of cycles per year and the average amplitude of these cycles, for each area, was calculated using the *Rainflow* function in Matlab (ASTM International 1985 (2011)), which detects a change in gradient from positive to negative or vice versa, with the number of cycles per year being half the number of gradient changes. The Lomb Scargle method (Lomb 1976) was used to test for periodicity to identify seasonal patterns in the PS data. This method is similar to a Fast Fourier Transform (FFT) but it does not require equally spaced samples and allows for missing data points.

Hourly rainfall data were acquired for the Heathrow weather station (station ID: 708) for the period 2011 to 2017, from the Met Office Integrated Data Archive System (MIDAS) through the Centre for Environmental Data Analysis (CEDA) Web Processing Service (WPS) (Met Office 2006). The hourly totals have been combined to obtain a daily rainfall total for the period midnight to midnight. As the displacement measurements are every 11 days, a moving average of rainfall with a window size of 10 days is used and the value of this average, on the date where there is a displacement measurement, are used in the comparison. Daily temperature data for Heathrow were also acquired from MIDAS. A maximum and minimum temperature is recorded for the period with the end time 09:00 (overnight) and 21:00 (daytime). The maximum temperature during the daytime (9am to 9pm) was used for temperature analysis in this study. To compare rainfall and displacement, the datasets were first standardised by subtracting the mean and dividing by the standard deviation. Cross correlation was performed using the *correlate*, function in the *Signal* module of *SciPy*, in Python 3.6 (Jones et al. 2001). Periodicity in rainfall and temperature was tested using the Lomb Scargle method (Lomb 1976).

To test for a statistical significance in the average velocity and amplitude of PS points in different shrink-swell units, points were group-selected according to their LEACS shrink-swell potential and a one-way analysis of variance (ANOVA) test was applied to compare the averages across different mapping units. The ANOVA test determines whether there are statistically significant differences between two or more groups (the null hypothesis is that there is no difference in the means). If the p value of the ANOVA test is significant, a post-hoc Tukey test is applied to determine exactly which units are significantly different. A confidence level of 0.05 is used in all statistical tests.

Results

Average Ground Movements, Cyclicity and Periodicity

Each area has a different long-term trend (Figure 3). Hammersmith has subsided by *ca* 4 mm over the 6 years, whereas Muswell has uplifted by ca 2 mm and Islington has remained stable. The detrended signals for each area show similar patterns of peaks and troughs, and magnitude of movement that might imply common environmental controls on cyclicity, such as rainfall or temperature.

The number of cycles per year is consistent between the sites, with an average of 8.5 per year over the 5-year period (Table 1). The average amplitude between sites is also consistent at between 0.34 and 0.37 mm. An annual periodicity is evident only in Hammersmith, with a peak at 365 days (Figure 4), but all sites show a periodicity approximately at the two-year mark (600 to 700 days). There are no other dominant signals at periods shorter than 365 days in any of the areas.

Comparison of detrended displacement with rainfall and temperature

The Lomb-Scargle periodogram of daily rainfall reveal a weak annual periodicity but a strong spike in power spectral density at approximately two years (Figure 5). The periodogram of daily temperature reveal a clear annual periodicity (Figure 5).

The standardised displacement and 10-day rainfall moving average (Figure 6) suggest displacement may be weakly correlated with rainfall but with a lag of just over a month. When this correlation is statistically tested using Spearman's Rank, the correlation coefficients are very small: 0.089, 0.067 and 0.071 for Hammersmith, Muswell and Islington respectively. Cross correlation analysis between rainfall and displacement reveal no significant correlation at any lag time (Figure 7).

The average number of rainfall cycles from the Heathrow dataset is 8 per year, which is comparable to the number identified in the ground movement data (Table 1).

Comparison of Shrink-swell mapping units

Velocity

Table 2 shows the areas with a statistically significant ($p < 0.05$) difference between shrink-swell potential classes. If PS velocity correlated strongly with shrink swell, each class should be significant.

In Hammersmith there is a statistically significant difference between the Very Low and Low classes ($p = 0.022$), which equates to 0.02 mm/yr. In Muswell, the differences in velocity are greater, for example, the average velocity for both the Moderate and the Very High shrink-swell potential are significantly larger than the Very Low shrink-swell potential ($p < 0.001$ for both). The difference in velocity is approximately 0.14 mm/yr but the difference between Moderate and Very High at Muswell is not significant.

In Islington, the difference in average velocity for the shrink-swell potential between the High and Very Low classes is significant ($p < 0.001$), but the Low and Very Low classes are not significant.

Amplitude

The average amplitude for the shrink-swell potential classes is not significant in all areas (Table 3). Hammersmith has a significant difference between the Low and Very Low shrink potential classes ($p < 0.001$). Conversely, in Islington none of the shrink-swell units (High, Low and Very Low) are significantly different ($p > 0.05$). If shrink-swell had a noticeable effect on amplitude, a significant difference would be expected between each unit.

Additionally, not all areas that had a statistically significant difference in velocity exhibited a significant difference in amplitude, such as the Islington High and Very Low classes. It is important to note that many of the significant differences equate to very small ground movements, e.g. the difference between the statistically significant Very Low and Moderate shrink-swell classes in Muswell is just 0.08 mm, which is below the resolution of the data and therefore questionable.

Different areas of the same class

The average amplitudes of different areas in the same shrink-swell class are also compared (Table 4). The data show a significant difference between the Low and Very Low ($p < 0.001$ and $p = 0.006$, respectively) in Hammersmith and Islington. This is unexpected as areas in the same shrink-swell class should show ground movement of a similar magnitude, but comparisons could only be made for four of the areas.

Discussion

Cyclic ground movements are successfully identified in PS data but the amplitude of these cycles is smaller than anticipated. This could be due to a non-perfect filtering of atmospheric phase components in the InSAR analysis, but we deem it partly due to the location of the points, in that all lie on the road surface, so any clay movement is likely resisted by Made Ground beneath. In London, Made Ground thickness varies from <1 m to >10 m (Howland 1991). Additionally, with a temporal resolution on the measurements of just 11 days, short-term periodicity may not be detected.

The number of cycles per year in the PS data is consistent with the number of cycles in the rainfall data which suggests a connection between the two variables. Visual inspection of rainfall moving average and displacement reveals a weak relationship between the two variables, with displacement appearing to lag approximately one month behind rainfall. Despite this, neither Spearman’s Rank or cross-correlation analysis identify a statistically significant relationship between them.

There are many factors affecting the potential connection between these variables. The rainfall measurement, at Heathrow, is approximately 15 to 25 km away from the study areas, so some local variation is likely. Surface water drainage patterns have not been considered and there are other factors which may affect road surface movements, such as thermal expansion. Additionally, the correlation is performed on a moving average of total rainfall and the detrended displacement is an average across thousands of points over an area of between 3 and 20 km^2.

The reason that only Hammersmith demonstrates an annual periodicity remains unclear. Its proximity to the River Thames may lead to a larger surface water flow or a stronger tidal influence on groundwater that increases the shrink-swell of the clays, and this may be further amplified by subsidence from groundwater abstraction (Figure 2). Of the three areas it also has the thickest alluvium and river terrace deposits (as determined from boreholes records and the BGS *DigiMap* Superficial Deposits (British Geological Survey 2010)), although it has only moderate thickness of London Clay. Muswell has the thickest London Clay, at 42 m (BGS borehole TQ28NE9), with Hammersmith 38 m (TQ27NW419, TQ27NW87 and TQ27NW233) and Islington 19 m (TQ38SW497, TQ38SW4239 and TQ38SW4048) but all areas have an approximately two-year periodicity, consistent with rainfall.

These results suggest that shrink-swell is not detectable with PSI over London, despite the greater sensitivity and PS density in urban areas, compared to rural areas. Urban drainage and the road base structure reduces the amplitude and therefore suppresses the signal of shrink-swell movements to below detectable limits. Additionally, the areas of interest are relatively small, which can make it difficult to separate the signal of interest from spurious atmospheric components and only one area was categorised as having a high shrink-swell potential; thus AOI size may be a limiting factor in successful identification. Furthermore, the cyclicity detected may not actually be caused by shrink-swell at all. Alternative causes for that cyclicity are not fully clear, but a relationship between small-scale cyclic ground movements and rainfall has been demonstrated.

Conclusions

This study identifies a cyclicity in detrended ground movement from PSI in London. There are on average 8 cycles of movement per year with amplitudes between 0.34 and 0.38 mm. Although these figures are close to the precision of the data set, the number of cycles is consistent with annual rainfall cycles. Detrended ground movements and rainfall data also show a statistically significant two-year periodicity. The effect of shrink-swell classification on velocity and amplitude of ground movements is inconclusive, some areas exhibit a statistically significant difference between classes, but others do not. While some cyclical signal is apparent, monitoring shrink-swell in London using TSX PSI data from road surfaces is not yet practicable but may be achievable using future constellations of high-resolution SAR instruments with much shorter revisit times, and with improved techniques for detecting complex, non-linear ground movements.

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Figure Captions

Fig. 1. Distribution of the TerraSAR-X images over the time period May 2011 to April 2017. Notable gap in data acquisition between January and July 2013.

Fig. 2. Study areas: (**a**) Hammersmith (**b**) Muswell and (**c**) Islington overlain on the LEACS shrink-swell potential map (Natural Perils Directory Cranfield University) and the TerraSAR-X points overlain onto the World Topographic Map (Esri 2018).

Fig. 3. Ground movement over the period May 2011 to April 2017 for Hammersmith (red), Muswell (blue) and Islington (green) and the detrended average ground movement for each burst site.

Fig. 4. Lomb Scargle plot of detrended displacement suggesting an annual periodicity at Hammersmith and a two-year periodicity at all sites.

Fig. 5. Lomb Scargle plot of daily rainfall and daily temperature at Heathrow weather station for the period May 2011 to April 2017. Rainfall has a small peak at approximately one year, but a more pronounced peak at approximately two years, similar to that of the detrended displacement. Temperature has a strong annual periodicity (note the difference in strength of power spectral density between the two graphs).

Fig. 6. Comparison of standardised rainfall with a moving average window of 10 and detrended displacement for Hammersmith, Muswell and Islington.

Fig. 7. Result of cross-correlation analysis for Hammersmith, Muswell and Islington.

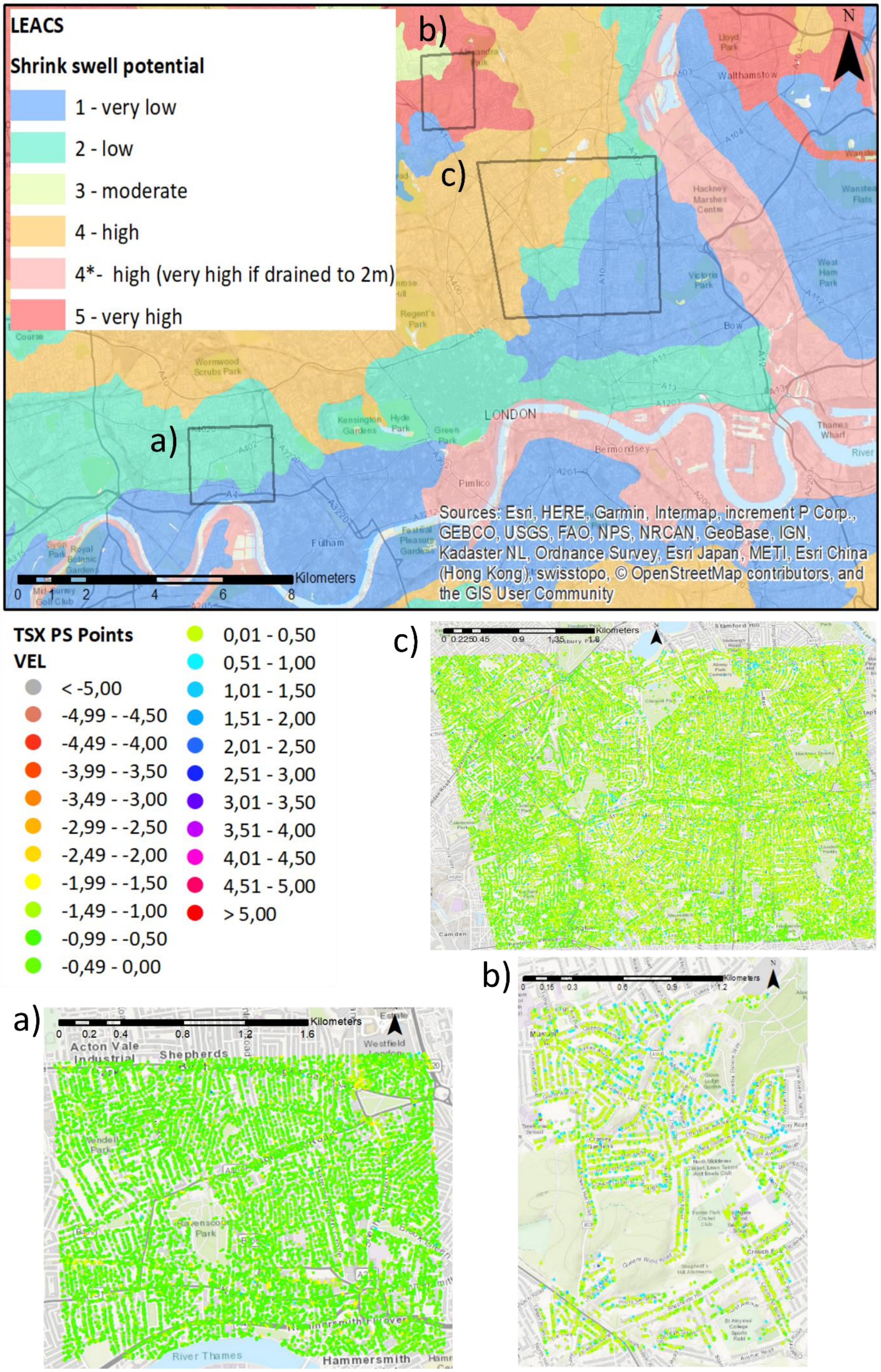
Table 1 *Average number of cycles per year for each area (upper table) and average cycle amplitude per year (mm) for each area (lower table)*

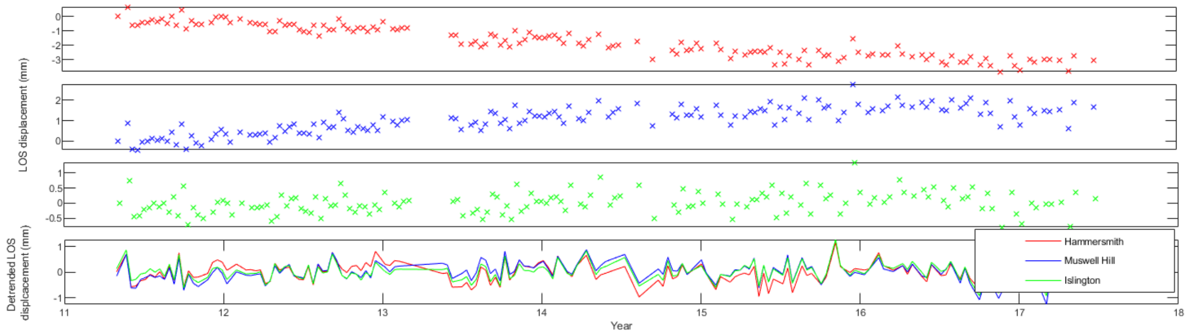
Table 2 *Results of ANOVA and Tukey statistical tests comparing velocity between shrink-swell potential classes. A result of $p < 0.05$ in the Tukey test implies the shrink-swell classes are significantly different*

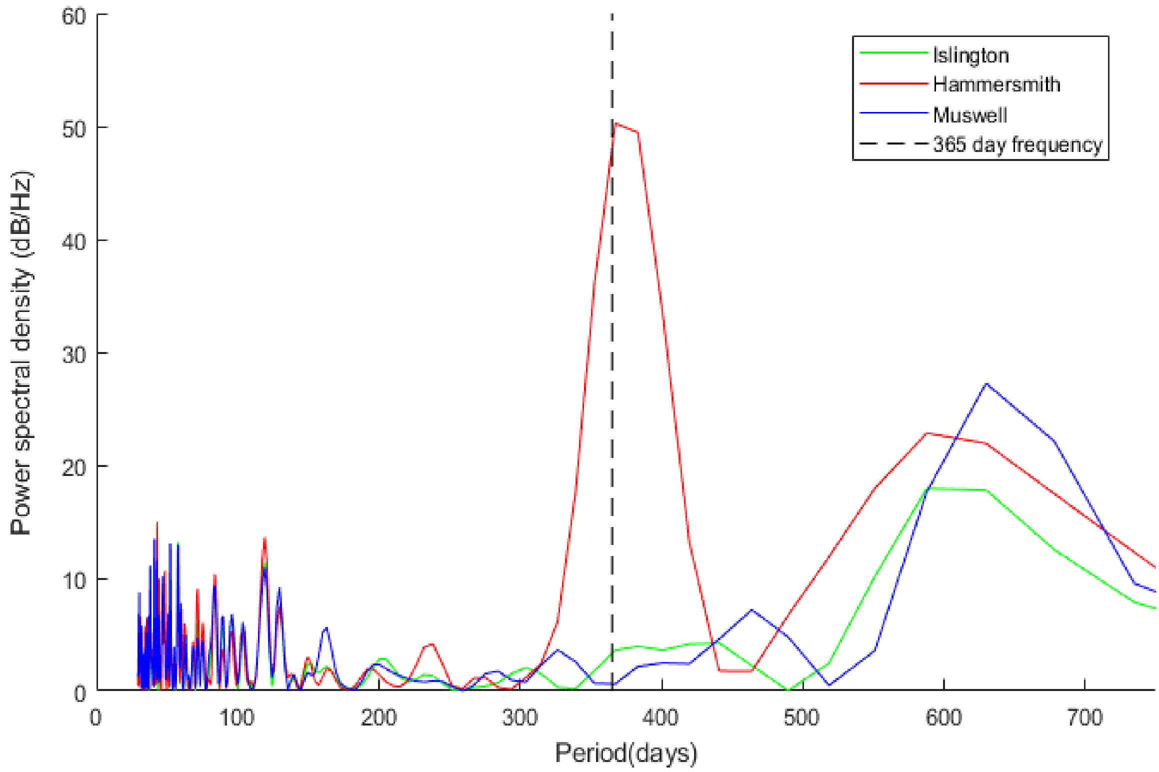
Table 3 *Variations in statistical significance of average amplitude for shrink-swell classes*

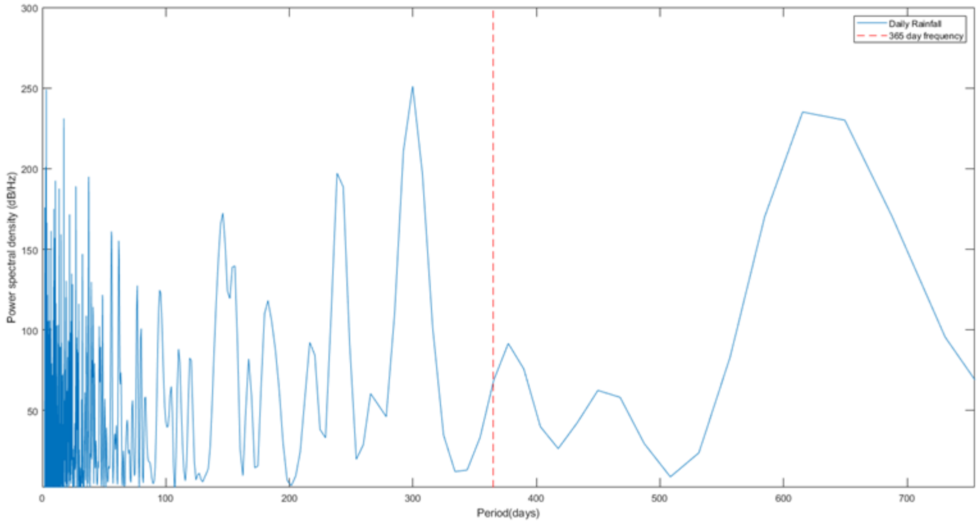
Table 4 *Significance of the difference in average amplitude for the same shrink-swell potential in different areas*

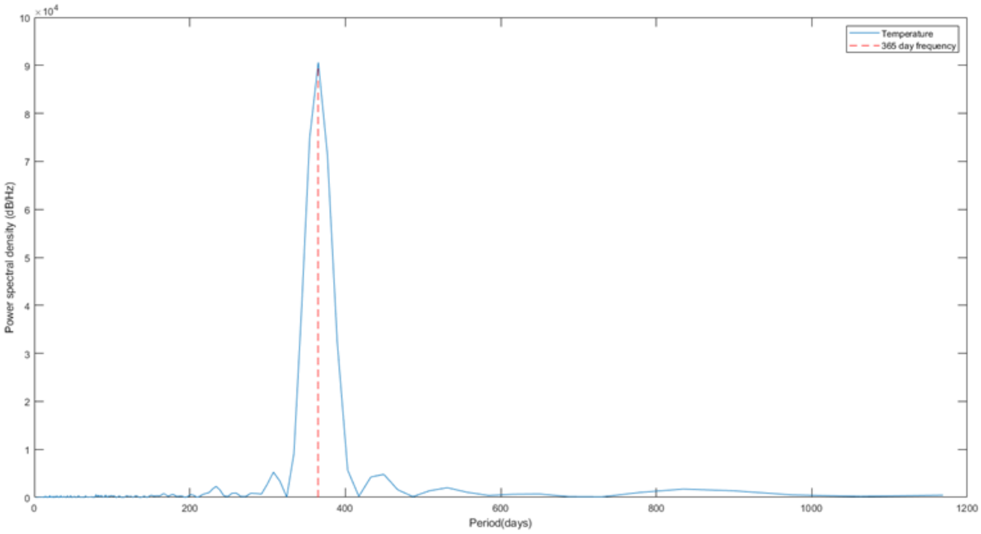

01/05/2011
17/11/2011
04/06/2012
21/12/2012
09/07/2013
25/01/2014
13/08/2014
01/03/2015
17/09/2015
04/04/2016
21/10/2016
09/05/2017

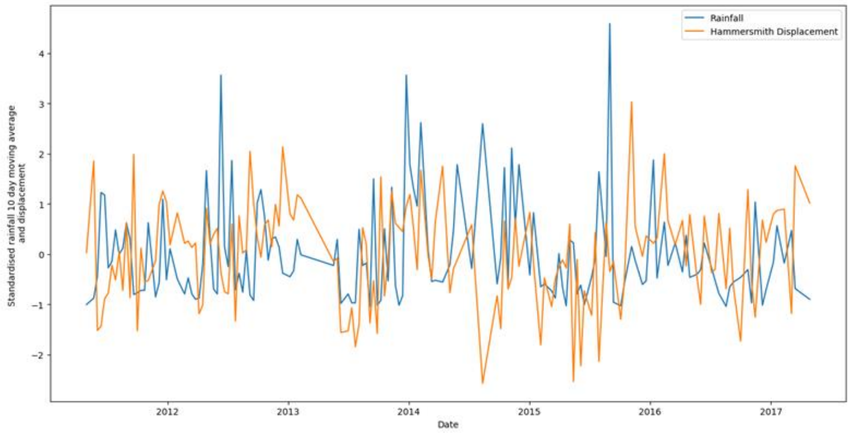

LEACS
Shrink swell potential
1 - very low
2 - low
3 - moderate
4 - high
4*- high (very high if drained to 2m)
5 - very high
a)
b)
c)
LONDON
Kilometers
0 2 4 6 8
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community
TSX PS Points
VEL
< -5,00
-4,99 - -4,50
-4,49 - -4,00
-3,99 - -3,50
-3,49 - -3,00
-2,99 - -2,50
-2,49 - -2,00
-1,99 - -1,50
-1,49 - -1,00
-0,99 - -0,50
-0,49 - 0,00
0,01 - 0,50
0,51 - 1,00
1,01 - 1,50
1,51 - 2,00
2,01 - 2,50
2,51 - 3,00
3,01 - 3,50
3,51 - 4,00
4,01 - 4,50
4,51 - 5,00
> 5,00
Kilometers
0 0.225 0.45 0.9 1.35 1.8
0 0.15 0.3 0.6 0.9 1.2
0 0.2 0.4 0.8 1.2 1.6
River Thames
Hammersmith

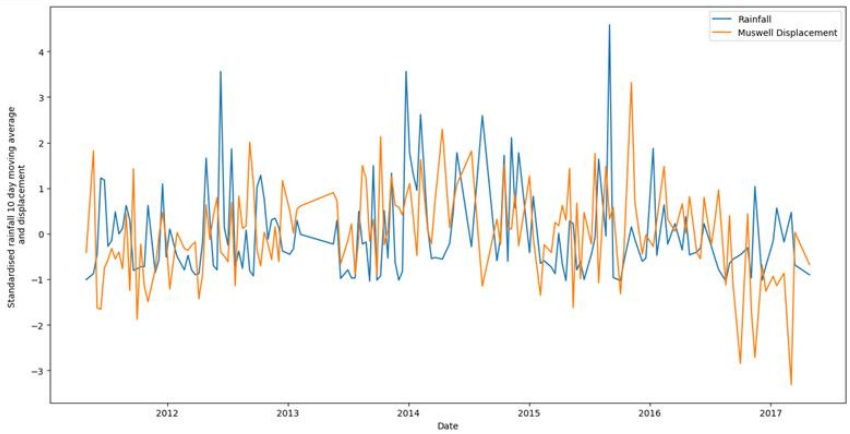

LOS displacement (mm)
Detrended LOS displacement (mm)
Year
Hammersmith
Muswell Hill
Islington

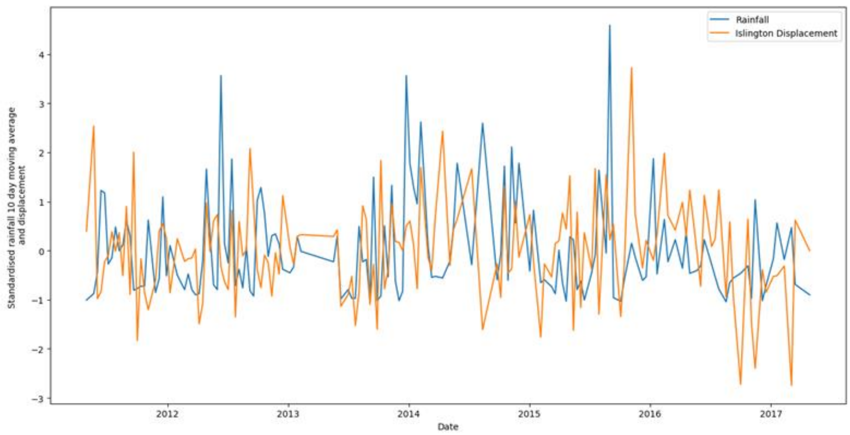

Islington
Hammersmith
Muswell
365 day frequency
Power spectral density (dB/Hz)
Period(days)

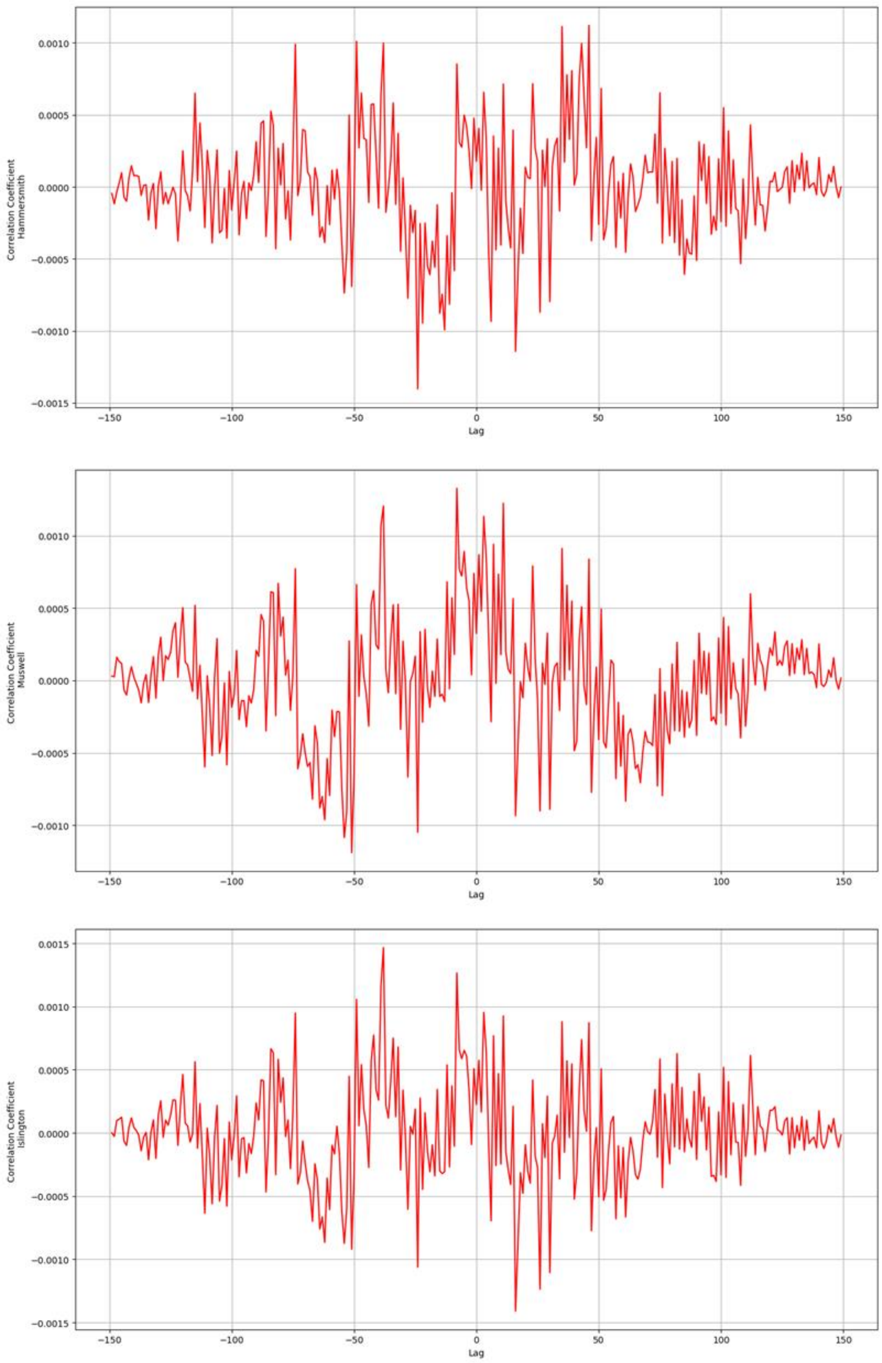

Daily Rainfall
365 day frequency
Power spectral density (dB/Hz)
Period(days)


Temperature
365 day frequency
Power spectral density (dB/Hz)
Period(days)


Rainfall
Hammersmith Displacement
Standardised rainfall 10 day moving average and displacement
Date
2012
2013
2014
2015
2016
2017


Rainfall
Muswell Displacement
Standardised rainfall 10 day moving average and displacement
Date
2012
2013
2014
2015
2016
2017


Rainfall
Islington Displacement
Standardised rainfall 10 day moving average and displacement
Date
2012
2013
2014
2015
2016
2017


Correlation Coefficient
Hammersmith
Lag
Correlation Coefficient
Muswell
Lag
Correlation Coefficient
Islington
Lag

Year	Hammersmith	Muswell	Islington	Rainfall
2012	10.5	9.5	9.5	8.5
2013	8	7	8	8.5
2014	6.5	6.5	6.5	7
2015	10	11	10	8.5
2016	8	8	8	7
Average	8.6	8.4	8.4	7.9

Year	Hammersmith	Muswell	Islington
2012	0.31	0.29	0.27
2013	0.40	0.31	0.28
2014	0.38	0.38	0.35
2015	0.45	0.42	0.40
2016	0.32	0.43	0.39
Average	0.37	0.36	0.34

Variable 1	Variable 2	Mean 1	Mean 2	f-Anova	p-Anova	p-Tukey	Significant (Y/N)
Islington High	Islington Low	0.26	0.25	9.44	0.00	0.62	N
Islington High	Islington Very Low	0.26	0.24	9.44	0.00	0.00	Y
Islington Low	Islington Very Low	0.25	0.24	9.44	0.00	0.17	N
Muswell Very Low	Muswell Moderate	0.27	0.40	21.84	0.00	0.00	Y
Muswell Very Low	Muswell Very High	0.27	0.40	21.84	0.00	0.00	Y
Muswell Moderate	Muswell Very High	0.40	0.40	21.84	0.00	0.99	N
Hammersmith Low	Hammersmith Very Low	0.57	0.59	5.24	0.02	0.02	Y

Variable 1	Variable 2	Mean 1	Mean 2	f-Anova	p-Anova	p-Tukey	Significant (Y/N)
Muswell Very Low	Muswell Moderate	1.01	1.09	6.27	0.00	0.00	Y
Muswell Very Low	Muswell Very High	1.01	1.09	6.27	0.00	0.00	Y
Muswell Moderate	Muswell Very High	1.09	1.09	6.27	0.00	0.92	N
Islington High	Islington Low	1.03	1.03	0.47	0.62	-	N
Islington High	Islington Very Low	1.03	1.02	0.47	0.62	-	N
Islington Low	Islington Very Low	1.03	1.02	0.47	0.62	-	N
Hammersmith Low	Hammersmith Very Low	1.06	1.00	46.50	0.00	0.00	Y

Variable 1	Variable 2	Mean 1	Mean 2	f-Anova	p-Anova	p-Tukey	Significant (Y/N)
Hammersmith Low	Islington Low	1.06	1.02	45.97	0.00	0.00	Y
Muswell Very Low	Hammersmith Very Low	1.01	1.00	4.88	0.01	0.83	N
Muswell Very Low	Islington Very Low	1.01	1.02	4.88	0.01	0.83	N
Hammersmith Very Low	Islington Very Low	1.00	1.02	4.88	0.01	0.01	Y