2nd Year Group Research Project (GEOG20011)

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The Avon Partner Project 2020

Investigating the presence of standing water at the highest point of elevation on Troopers Hill Field

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Words = 7,891

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ABSTRACT

The issue of standing water, due to inhibited infiltration of precipitation, has been studied comprehensively; nevertheless, it remains a problem on Troopers Hill Field's point of highest elevation during winter. Through investigating the subsurface layer and collecting data upon the water's stagnation, a dense clay cap was revealed at the test site. At both the test site of standing water, and control site, infiltration capacity experiments across 93minutes provided rates of 0mm/hr, and 3mm/hr respectively. Here, the impact of soil type and depth on the infiltration of rainwater was investigated using soil and water samples. The results subsequently generated from laboratory methods were represented graphically, and further compared to relevant research papers. Hence, the relatively impermeable characteristics of clay, coupled with compaction from walkers and high winter rainfall events, explains why minimal infiltration and the resulting standing water occurs at the point of highest elevation on Troopers Hill Field.

1 Introduction

Soil moisture is a crucial factor in several biogeochemical cycles and can help to dictate land use, productivity and landslides *(McColl, et al., 2017)*. Studies of soil moisture in the natural land of urban areas is limited, despite it being an important factor in determining land use. Although there are numerous papers investigating the compaction of soils, such as *Pitt, et. al., (2002)* most paid greater attention to the impact of cattle and agricultural machinery *(Mulholland, et al., 1991)*, as opposed to human impacts of trampling.

This report thoroughly investigates the causes behind the standing water that materialises every winter at the point of highest elevation on Troopers Hill Field, a local nature reserve located in the East of Bristol. In the past, Troopers Hill has been used for smelting, mining, and quarrying of the underlying Pennant Sandstone *(Friends of Troopers Hill, n.d.)*. Additionally, Troopers Hill Field was used as a landfill site for tipped rubble, and visual evidence shows the area to be covered over with a clay cap, although there is no information about the location or design of this cap.

These former activities could have verifiably had an impact upon the structure and metal content of the soil, plausibly causing problems for Troopers Hill Field today. Currently, Troopers Hill is used as a recreational area; including a nature reserve and a recently installed children's play park. The standing water that occurs during the winter months has created an area of concentrated bogginess which currently restricts people from easily walking across this specific region of the field. Therefore, this investigation aims to identify the causes behind this standing water, in order to allow access to all sections of Troopers Hill; similar to its use in summer.

The main task, as set out by the partner's request, was to determine whether the source of standing water was natural or treated. Treated water would arise from a leaking pipe beneath the surface; whereas, water from a natural source may be upwelling from a spring, or from precipitation that exceeds the infiltration rate.

Troopers Hill Field is a relatively small local nature reserve and most likely unknown to the wider public, but for the local community there is a high level of interest relating to the issue that this report addresses. During our investigation we were in regular contact with the Friends of Troopers Hill – a group with over 1600 followers on social media. Subsequently, this investigation made it to front cover of a local newspaper, the "St George & Redfield Voice", due to its rising interest within the local community *(Acton-Campbell, 2020)*.

During our study we took soil and water samples that were extracted for laboratory analysis in order to determine the source of the water. In addition to this, theta probe measurements of soil moisture in quadrants at both the test and control site allowed investigation into whether the water was coming from a point source. Furthermore, tests for heavy metals, alongside ion chromatography were both performed in order to evaluate whether treated water may have upwelled from a broken cast iron pipe through comparing results to secondary sources, namely *Bristol Water*. Lastly, we measured the infiltration rate at the test and control site to deduce whether soil type and characteristics were impeding the flow of infiltration.

2 Research Question and Hypotheses

Based on the problem of standing water, this report aims to investigate the source of water, as *natural* or *treated*, and determine the causes for its lack of infiltration. The investigation is motivated by two research questions.

RQ1: Does the water chemistry reflect <u>treated</u> water coming from a broken pipe at the point of highest elevation on Troopers Hill Field?

> *H_1: If the water chemistry contains proportionate concentrations of ions in reference to Bristol Water's standards for treated water, a broken pipe is the source.*

RQ2: To what extent does the <u>natural</u> water that has fallen as precipitation receive restrictions from the clay cap, and thus prevent it from infiltrating into the ground?

> *H_2: If the infiltration capacity is lower at the site of the clay cap than the control site, clay has a greater influence than other soil types on restricting infiltration.*

Under the circumstances of H_2, the test site soil moisture profile would be representative of a non-point source, with low heavy metal concentrations in the soil and low ion contents in the water samples in accordance with that of natural water from precipitation, thus concurrently disproving H_1.

3 Literature Review

There are multiple research papers in the field of soil moisture as a synoptic topic, for instance *McColl, et al., (2017)*, yet no soil moisture studies have been previously conducted on Troopers Hill Field. In particular, there are very few papers that have studied the impacts of human trampling on soil moisture properties, with much greater attention paid to exploring the impacts of cattle and agricultural machinery, both of which lead to an increase in runoff and compressed zones in the soil *(Mulholland, et al., 1991)*. Studies of the human consequences of soil compaction are concentrated in special eco-regions, such as Antarctica, beaches, and forests, but there is limited research in urban environments investigating the same topic. A study about long-term and short-term effects of human trampling in suburban forests showed a decrease in plant cover and height, as well as species loss due to the human impact *(Kissling, et al., 2009)*. Furthermore, in the literature it is understood how changes in the infiltration capacities of soils have had a noticeable impact on surface runoff, especially in cities *(Yang, et al., 2011)*.

As Troopers Hill Field was also used as a tipping location, it is especially important to investigate the clay layer used to cover the landfill. *Johnson, et al., (1985)* found that a clay cap that is too close to the surface can lead to increased erosion of the soil. This is corroborated by *Li, et al., (2009)*, which showed that there is a correlation between the clay content and the infiltration capacity, whereby the greater the clay content of the soil, the lower the infiltration capacity.

The research therefore demonstrates the human influence on infiltration capacities of clay caps in urban soils leading to increased runoff, which could be further investigated with additional studies at different locations. Thus, a model could be created that explains the relationship between the compaction of soils by human trampling, and infiltration capacities.

4 Sample Collection and Analyses

4.1 Study Area

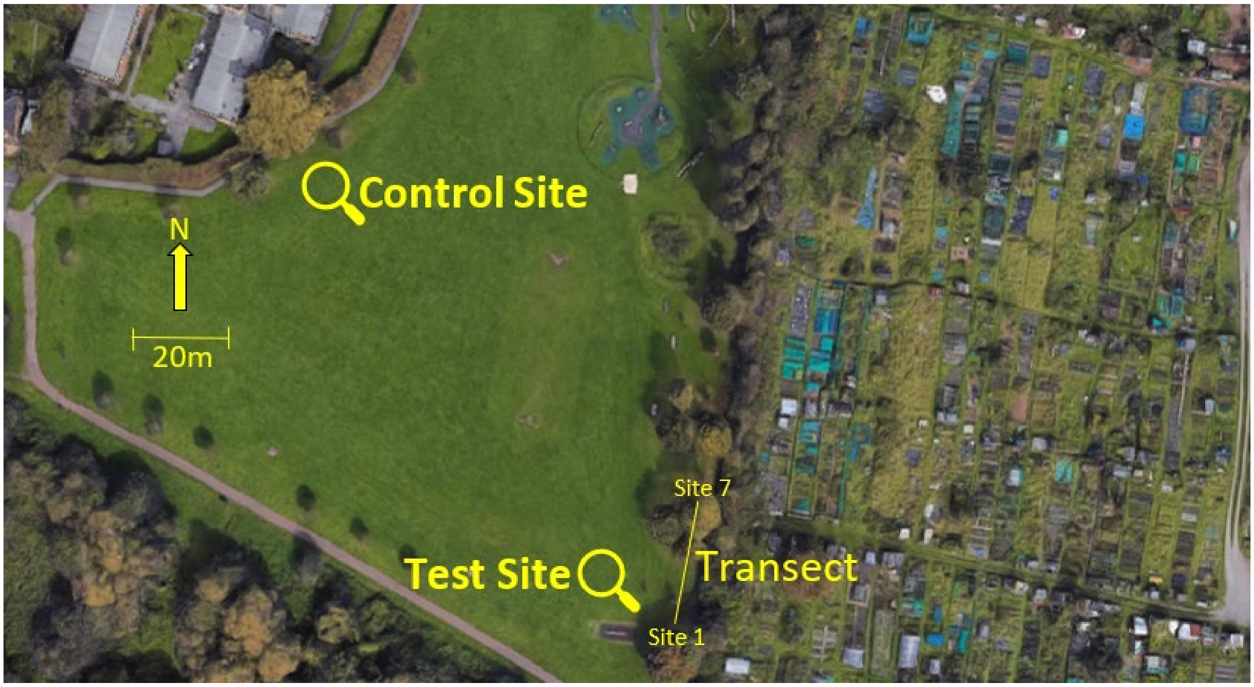
Map 1. *Map of Troopers Hill in relation to Bristol. Troopers Hill Field identified as the red circle.*

Troopers Hill Field is 4 acres of recreational ground, mainly covered by grass, located in the Bristol ward of St. George Central, in the East of the city. The area of greatest elevation on the field is approximately 70m a.s.l., whilst the lowest point of elevation is approximately 62m a.s.l..

4.2 Sampling Sites

The test site was located by the partner, who identified an unusually boggy area at the South-West, most elevated point of Troopers Hill Field. In order to compare the test site samples against a typical dry area of the field, a representable control site was identified at a lower elevation, 100m North-West of the test site.

In addition to this, a transect was established running parallel to the boundary at the East side of Troopers Hill Field on the test site (*Map 2*). The transect consisted of seven sites, each being 4m away from the previous. The first four sites along the transect are classified as being wet due to the visible standing water (*Appendix H*), while the remaining three were classified as being relatively dry due to the absence of any standing water.



Map 2. *Map of the site location on Troopers Hill Field. Transect sites all located in a line at four metres equidistance.*

4.3 Sample Collection

At each site along the transect, and at the control site, a 30cm cube pit was dug in the soil - due to the public use of this area, larger pits were not permitted. The soil and clay from each pit were individually well-mixed in order to give a more representative sample of the sites. This large stock sample was later split into three sub-samples of approximately 10g in order to test the variability of the data.

In addition to this, two water samples were collected by placing a bottle in the standing water. One sample was taken at site 4 on the transect, and another was taken from within the test site, in order to analyse the presence of white liquid in the water.

Raw data for soil drying available in Appendix B

4.4 Field Tests

4.4.1 Theta Probe Quadrant

Soil moisture can be determined by a direct measurement in the field with a Delta-T theta probe. The probe uses a sinusoidal signal from four rods, which are inserted into the ground, in order to measure the impedance of the soil. To measure the distribution of moisture at our test and control site, two 10x10m quadrants, with breaks every 2m, were set up. At each break along the grid, a measurement for the moisture was taken, resulting in 36 measurements of moisture over the 100m^2 grid.

Raw data for Theta Probe Quadrants available in Appendix A.

4.4.2 Infiltration Capacity

It can be difficult to determine the infiltration capacity, defined as the maximum rate of infiltration of the soil, as the water can simultaneously infiltrate into the soil and travel laterally. To prevent the water from travelling laterally, a cylinder infiltrometer is fixed into the ground. By pouring water into the physically restricted soil, the amount of infiltration over a previously determined set duration can be measured. This apparatus used for this process can be seen in *Image 1.* After conducting this practical in the field, laboratory analysis had to be undertaken in order to gauge the true infiltration rate, as opposed to the total volume that infiltrated into Troopers Hill Field.

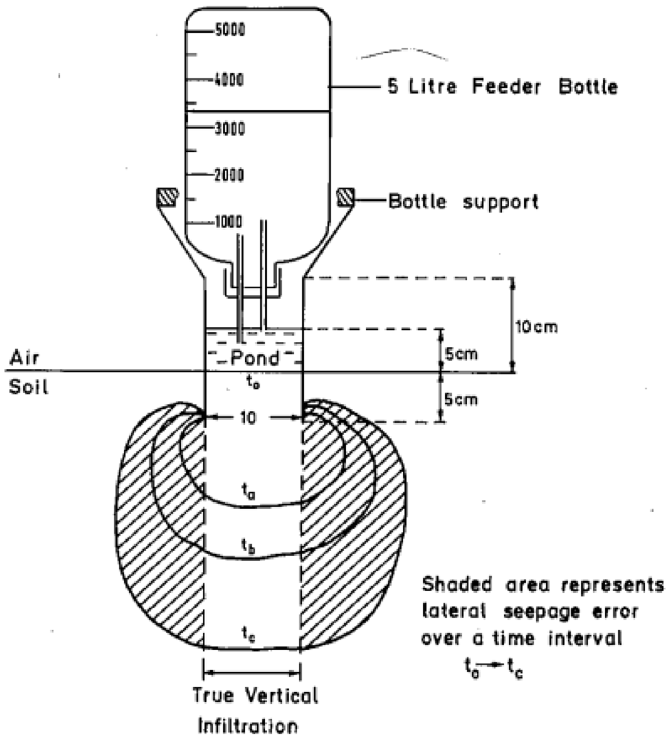


Image 1. *Ring cylinder infiltrometer used to measure infiltration capacity. (Wilcock and Essery, 1984).*

4.5 Lab Analyses

4.5.1 Soil Drying

The eight soil samples that were collected in the field had high water contents which would severely interfere with laboratory results. The three soil sub-samples from each site, weighing approximately 10g, were measured for their precise weight before being dried in a laboratory oven at 50°C for 5 days. After which, the precise weight of each sub-sample was measured in order to obtain the gravimetric soil moisture. Calculating the difference between the initial and dried weight provides an alternative measurement of soil moisture, which presents greater accuracy to the measurements given by the Delta-T theta probes due to their instrumental limitations. By calculating the gravimetric soil moisture threefold for each site, the variability of soil moisture can be examined. All future mention of soils in this report will have undergone this drying process.

Raw data for soil drying available in Appendix B.

4.5.2 Heavy Metals Test

Using inductively coupled plasma mass spectrometry, the heavy metal concentrations of the soil at the eight sites were measured. For each site, 0.02g of soil was ground and combined with 4.4mL of digestion mixture and mixed well. Following this, the solution was heated on a hot plate at 360°C until it was colourless, before the sample was diluted with 50mL Milli-Q water. Lastly, the diluted sample was filtered through a Whatman no. 42 filter paper into a 100mL volumetric flask, along with enough Milli-Q water to fill the flask.

Raw data for heavy metals available in Appendix C.

4.5.3 Soil Grainsize analysis

To determine the grainsizes of the soil, three of the soil sub-samples from each site were run through the Mastersizer 3000. Samples were passed through a 2mm sieve in order to remove grains larger than sand, as they would not be detected in the Mastersizer results. Following this, samples were ground with a mortar and pestle to homogenize the samples, making them more representative of the stock soil.

By adding small amounts of sample with a spatula, each sub-sample was scanned 5 times, giving 15 replicates per site.

Grainsize categories were determined using Tucker's (1987) *Sedimentary Petrology*, in which:

- Clay: ≤ 0.004 mm median diameter
- Silt: 0.0041mm to < 0.06 mm median diameter
- Sand: 0.06 to < 2mm median diameter

4.5.4 Soil pH Analysis

By combining 5g of soil and 45mL of Milli-Q water in a tube and shaking hard for 10 seconds, followed by leaving the solution to stand for 10 minutes, the pH of the soil and water solution can be taken. By directly measuring the pH of the water, the acidity of the soil can be identified. Due to the heterogenous conditions of the soil at each site, an investigation into the precision of the data must be undertaken. This was accomplished by performing two repetitions of this analysis in order to work out the range of soil pH between all the sites.

Raw data for Soil pH is available in Appendix E.

4.5.5 Ion Chromatography

The concentrations of many chemicals within water can be measured simultaneously with ion chromatography using a separator column. To prepare the two water samples for ion chromatography, they must be passed through a 0.45μm filter into a 1mm autosampler vial. Following this, the vials are loaded into the ion chromatographer where ions are separated using an ion exchange resin and concentrations are measured by an electrical conductivity cell. Again, the variability of data was investigated by performing three repetitions for each water sample. Chemicals that were measured during the ion chromatography include fluoride, chloride and magnesium.

Raw data for Ion Chromatography can be seen in Appendix D.

4.6 Statistical Tests

Several statistical tests were conducted throughout the investigation in order to determine the nature of relationships between measured variables. Firstly, a multiple regression was performed in order to determine the extent of each grainsize's influence on the associated soil's moisture. Secondly, a linear regression was performed in order to explore the specific nature of the two continuous variables and their relationship. Due to both the limited number of sites along the transect, and the number of samples taken at each site, normal distributions were not expected in the data. As such, non-parametric statistical tests such as Spearman's Rank Correlation were used to define relationships between soil moisture and grainsize.

5 Results

5.1 Theta Probe Moisture Grid

In order to make the results of both sites comparable and interpretable, each point has been assigned a classification for its associated moisture, as measured by the Delta-T theta probe. The soil classification is performed through specifying defined intervals of 10%; leading to four classifications of moisture between 45 and 85%, as seen in *Figure 1*.

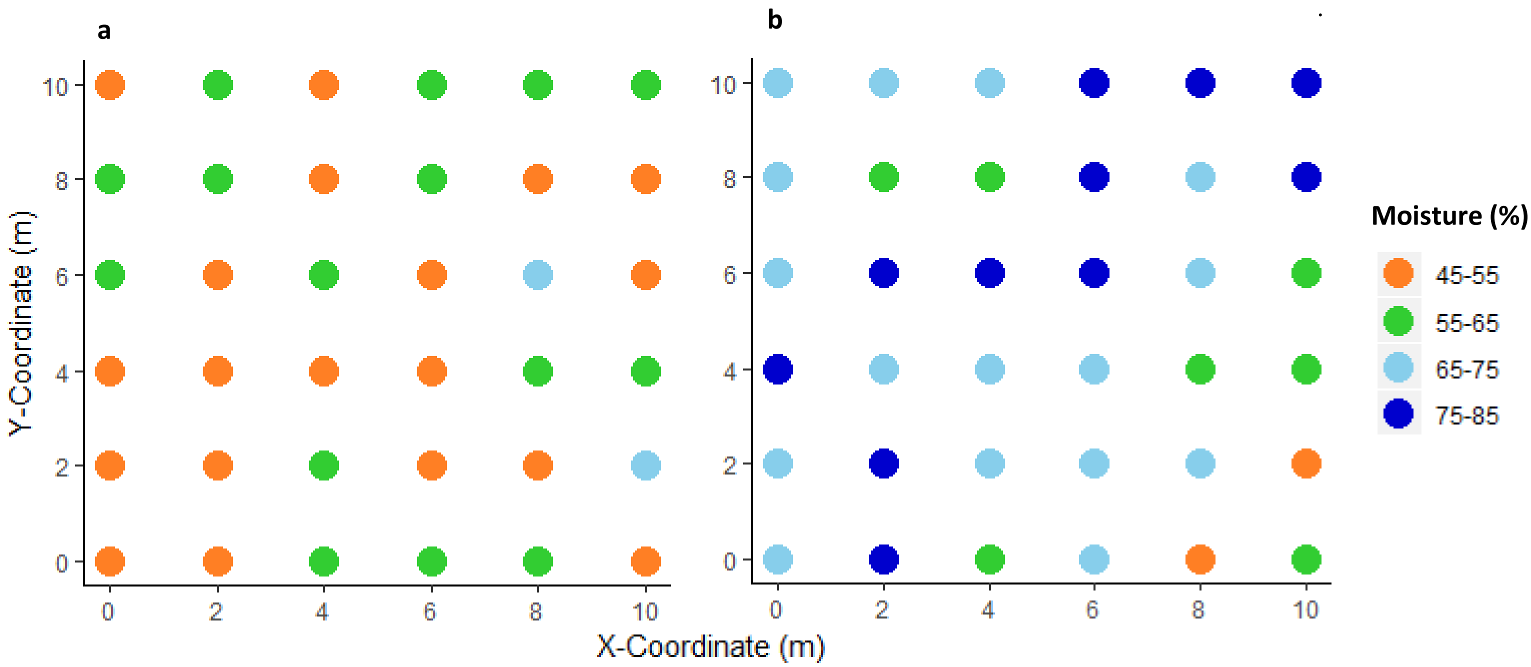


Figure 1. *Map of the Delta-T theta-probe soil moisture quadrant at for the:*

a) Control site
b) Test site

There are only two points across the entire control site quadrant which has a soil moisture of over 65%; furthermore, the quadrant had no points with moisture above 75%. On the other hand, there are only two points in the test site with moisture values below 55%. In addition, 11 of the 36 points at the test site are classified as the wettest class, whereas there was none under the same classification in the control site. This shows that there is a significantly higher amount of moisture at the test site, despite being at a greater elevation.

5.2 Water Chemistry

The concentrations of ions and elements from the ion chromatography can be seen in Table 1.

Table 1. *Water chemistry data comparing mains water, rainwater and sample water. Mains water from Bristol Water (2020), rainwater from Reynolds, et al. (2017) and sample water from mean ion chromatography results. Fluoride results for sample water exclude sample 1 as results were beyond limit detection (0.05 mg/L).*

	Calcium (mg/L Ca)	Chloride (mg/L)	Fluoride (mg/L)	Magnesium (mg/L Mg)
Mains Water	81	48	0.11	7.1
Rainwater	0.26	3.5	N/A	0.24
Sample Water	34.8	13.6	0.04	3.66

All concentrations for sample water were lower compared to mains water and higher compared to rainwater. Chloride, for example, saw mains water concentrations that were approximately 250% higher compared to sample water. Rainwater chloride concentrations were approximately 75% lower compared to sample water.

5.3 pH and Heavy Metals

Comparisons between soil pH and iron content showed no discernible trend along our transect, as seen in *Figure 2*.

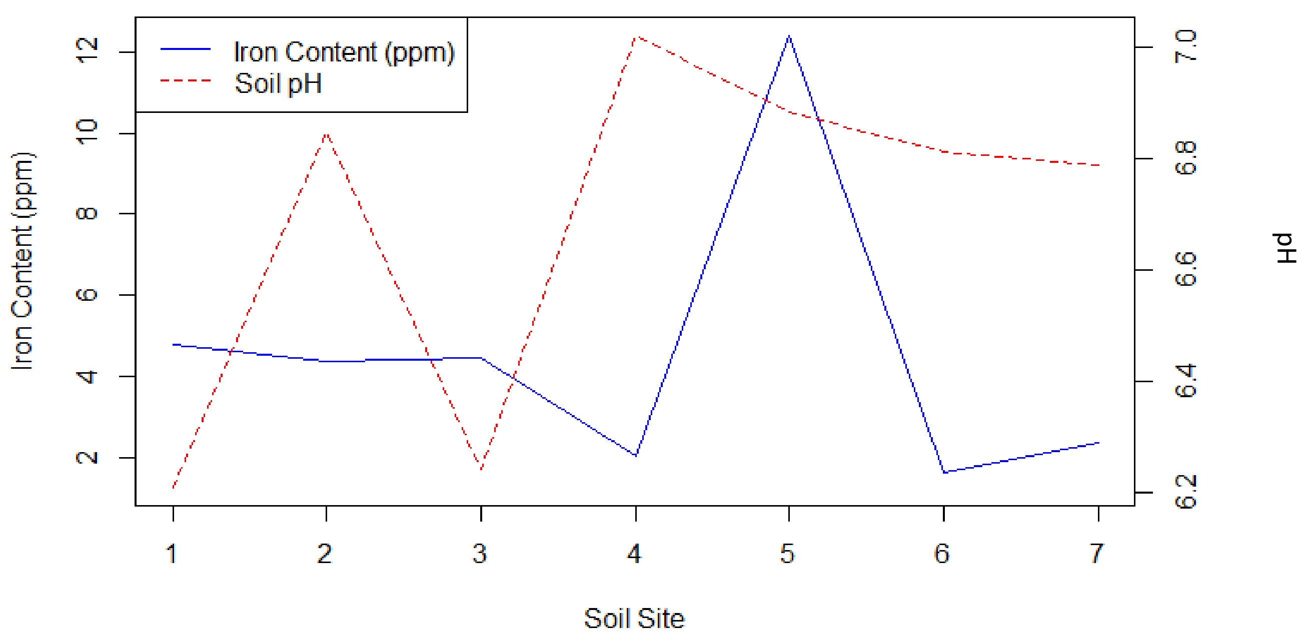


Figure 2. *Changes in pH and iron content (ppm) for soil samples taken along Troopers Hill Field transect. Blue trendlines represent the changes in iron content whilst the red trendlines represent changes in soil pH.*

pH values along the transect give indications of neutral to slightly acidic soil at Troopers Hill Field, ranging between 6.2 and 6.9, peaking at site 4, with no significant trend observed between sites. Iron content ranged between 1 ppm and 12.5 ppm, peaking at site 5, again with no significant trend between sites.

5.4 Soil Grainsizes

Data retrieved from the master sizer grainsize analysis can be found in Table 2.

Table 2. *Mean grainsize data along transect obtained from Mastersizer analysis, given in % composition. Soil type also listed, determined using Figure 3. Mean gravimetric soil moisture data given in %.*

Site	Standing Water Type	Sand Content (%)	Silt Content (%)	Clay Content (%)	Soil Type	Soil Moisture (%)
1	Wet	15.8	72.4	11.2	Silt Loam	21.2
2	Wet	28.9	57.9	12.1	Silt Loam	23.4
3	Wet	26.3	60.4	13.3	Silt Loam	27.8
4	Wet	26.8	54.1	15.6	Silt Loam	23.8
5	Dry	35.2	57.7	7.03	Silt Loam	22.0
6	Dry	38.8	51.9	9.29	Silt Loam	13.2
7	Dry	41.7	49.9	8.44	Silt Loam	13.3

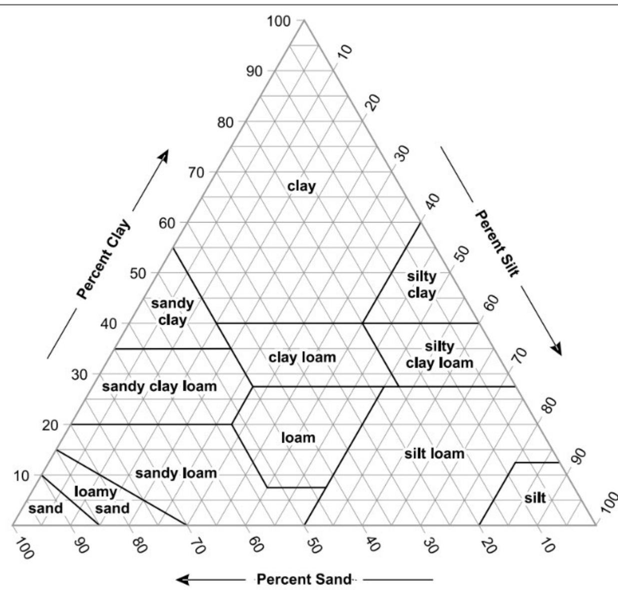


Figure 3. *Soil textural triangle used to identify soil types based on grainsize compositions. Sourced from United States Department of Agriculture (2017).*

Despite all sites being classified as silt loam soil, there is still variation in both grainsize compositions and soil moisture. For example, wet sites tend to show a higher clay and silt composition compared to dry sites, displayed visually in *Figure 4*. Average clay contents at wet sites (13.05%; n=4) were 4.8 percentage points higher than dry sites (8.25%; n=3). Average silt contents at wet sites (61.2%;

n=4) were 8 percentage points higher than dry sites (53.2%; n= 3). Average soil moisture at wet sites (24.05%; n=4) were 7.85 percentage points higher than dry sites (16.2%; n= 3).

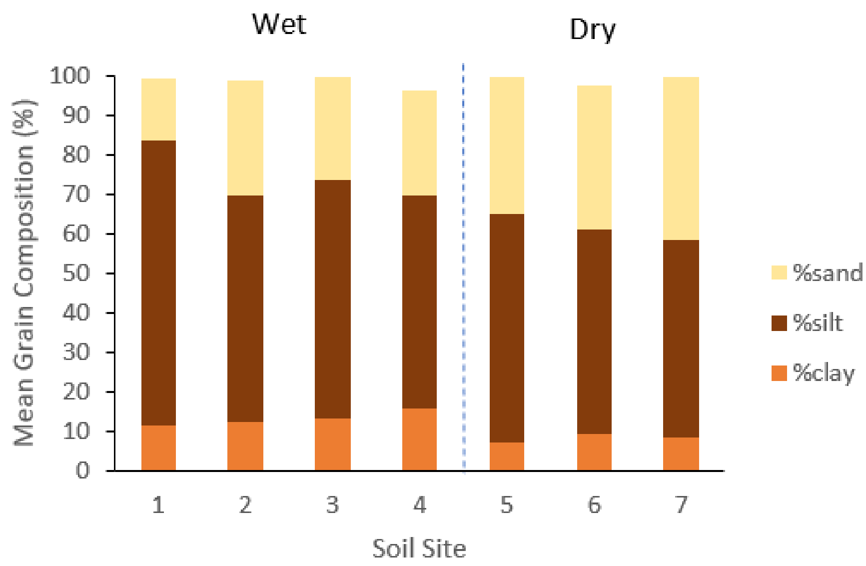


Figure 4. *Stacked bar chart of grainsize compositions for each site along transect. Clay and silt proportions of wet sites (1-4) were higher compared to dry sites (5-7).*

A multiple regression was run to determine the relationship between soil moisture and grainsizes, as depicted in *Table 3*.

Table 3. *Multiple Regression data of mean gravimetric soil moisture (Intercept) against mean sand, silt and clay content for transect soils. Multiple R^2square value also listed.*

	Estimate	Std. Error	t value	p value
(Intercept)	-62.581	271.38	-0.231	0.832
Sand Content (%)	0.550	2.68	0.205	0.851
Silt Content (%)	0.815	2.60	0.314	0.774
Clay Content (%)	1.765	3.70	0.478	0.666

R^2= 0.534

Although positive correlation between soil moisture, sand, silt and clay (R^2= *0.534 Table 3*) was observed, all p-values exceeding 0.05 suggests that there is no significant difference between variables.

Linear regression between soil moisture and clay content can be seen in *Figure 5*.

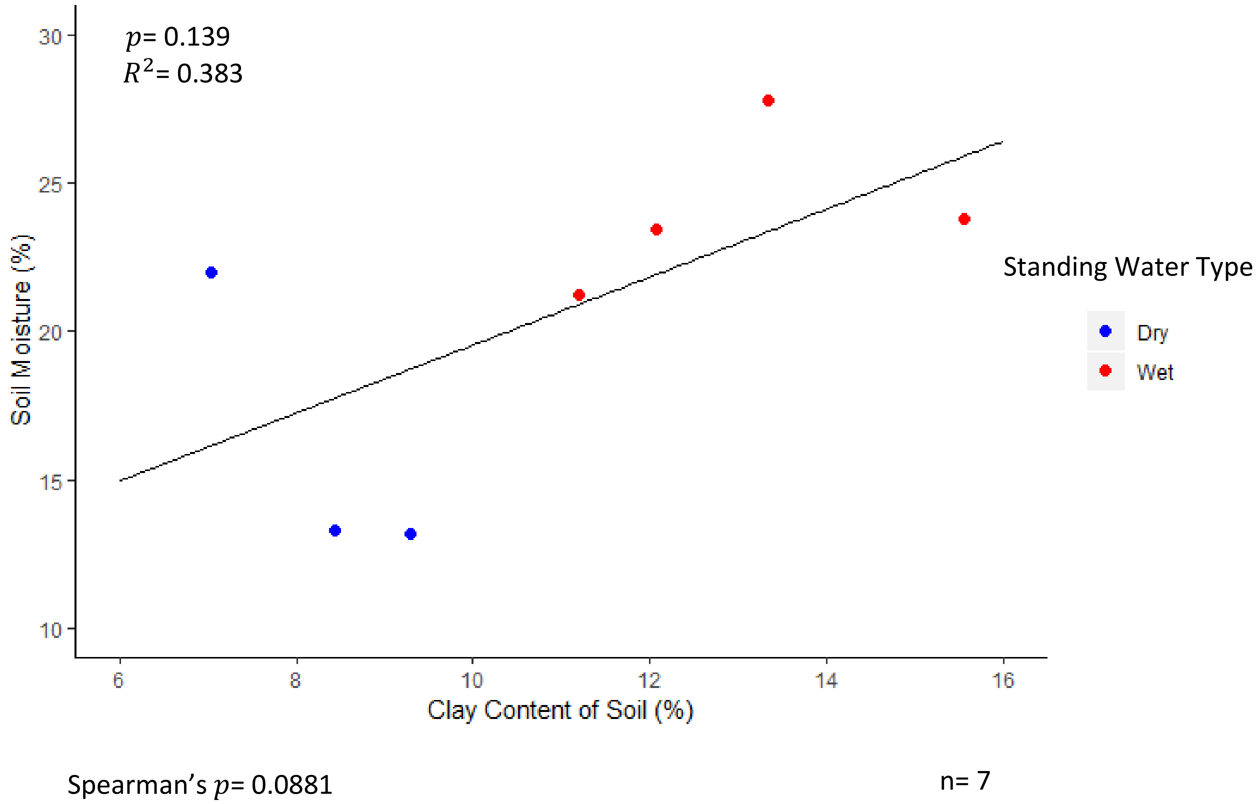


Figure 5. *Linear regression plot for mean gravimetric soil moisture against mean clay content. p and R^2 values for linear regression listed, along with Spearman's rank correlation and sample number. Wet sites are displayed in red, whilst dry sites are displayed in blue.*

Despite positive correlation observed in the regression model (*R^2= 0.383)*, the lack of a statistically significant regression p value (*p= 0.139)* and a weak Spearman's p value (*Spearman's p= 0.0881)* suggests a weak relationship between soil moisture and clay.

A linear regression was also carried out between soil moisture and combined silt and clay contents, seen in *Figure 6*.

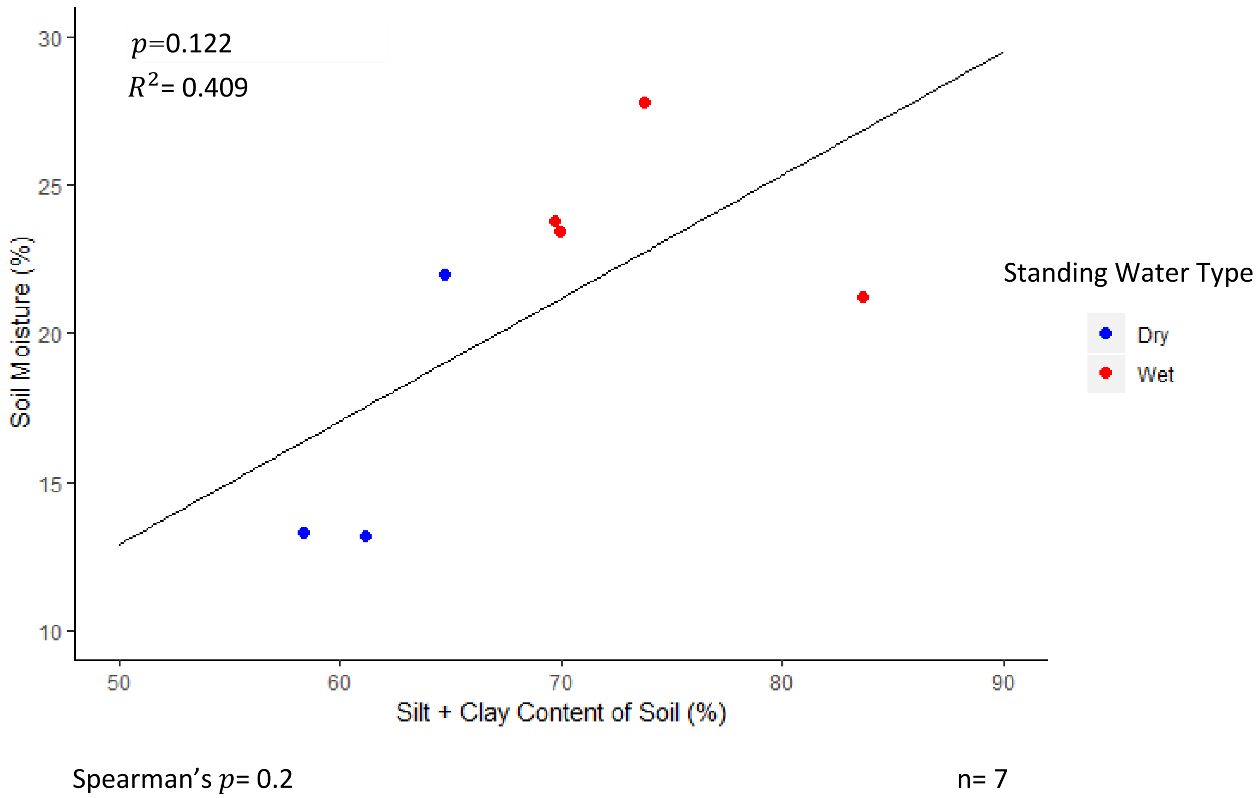


Figure 6. *Linear regression plot for mean gravimetric soil moisture against mean silt + clay contents. p and* R^2 *values for linear regression listed, along with Spearman's rank correlation and sample number. Wet sites are displayed in red, whilst dry sites are displayed in blue.*

Positive correlation was also observed in the regression model between soil moisture and silt + clay contents (R^2= *0.409*), yet the lack of a statistically significant p value (*p=0.122*) remained. The Spearman's p value (*Spearman's p= 0.2*) showed slight positive correlation between variables.

5.5 Infiltration Capacity

Infiltration results gathered from field test can be seen in Table 4.

Table 4. *Infiltration data obtained from field tests, including grainsize results from control/ test sites and soil types. Soil types determined using Figure 3.*

	Total water infiltrated (mm)	**Infiltration Rate (mm/hr)**	**Sand Content (%)**	**Silt Content (%)**	**Clay Content (%)**	**Soil Type**
Control Site	46	3.0	49.9	46.1	3.97	Sandy Loam
Test Site	0	0	26.3	60.4	13.3	Silt Loam

The control site's sandy loam soil saw a total of 46mm of infiltrated water over a 93 minute period, producing an infiltration rate of 3.0 mm/hr. The test site, however, saw 0mm of water infiltrating into its silt loam soil, thus an infiltration rate could not be determined.

6 Discussion

6.1 Hypothesis 1

H_1: If the water chemistry contains proportionate concentrations of ions in reference to Bristol Water's standards for treated water, a broken pipe is the source.

Investigating whether a broken pipe is feeding water into the subsurface of Troopers Hill Field and consequently forcing standing water to develop requires meaningful results to confirm the pipe's presence. These can be obtained through ion chromatography, heavy metal analysis, soil moisture readings and pH values, and can be validated through secondary data research, namely *Hornung, et al*., *1984* and *Pitt, et al., 2002.*

Analysis of water chemistry

In order to make drinking water safe for human consumption, concentration standards of certain ions must be set at both minimum and maximum requirements; by interpolating these values from sources such as Bristol Water, H_1 can be evaluated. This is through comparing Bristol's treated water ion concentrations to the ion chromatography results of the water samples collected. After conducting laboratory experiments, it was found that the ion concentrations were significantly lower in the surface water samples analyzed from Troopers Hill Field, in comparison to the Stapleton, St. George and Coombe region's treated water ion concentrations *(Bristol-Water, 2020)*. Bristol Water's report, published in 2020, shows chloride levels at 48 mg/L, whereas the Troopers Hill Field water samples display a noticeably lower average of 13.6 mg/L *(Table 1)*, as provided through the ion chromatography results. The other ion concentrations follow the same trend as chloride, with calcium levels of 81mg/L being the treatment standard for Bristol Water, yet in our analysis the calcium levels were found at an average of 34.8mg/L *(Table 1) (Bristol-Water, 2020)*.

Contrary to this first hypothesis, the findings of the ion concentrations found on our surface water samples correlates closely to levels found in natural rainfall in the UK. Collected over a two-year period and calculated as an arithmetic mean, chloride levels in the water falling as precipitation in an upland region of Mid-Wales came to 3.5 mg/L, with the range being between 0.5mg/L to 18mg/L *(Hornung, et al., 1984)*. *Ward, et al., (2009)* explores the physiochemical properties of rainwater within the proximity of the University of Exeter's Innovation Centre, to test whether a Rainwater Harvesting system (RWH) could be installed to reduce mains water consumption *(Ward, et al., 2009)*. This paper thus studies the water chemistry properties of rainfall in Exeter, in South-Western England, in order to determine if the water is safe; chloride levels were found ranging between 3 mg/L to 28 mg/L, when collected in 2009 *(Ward, et al., 2009)*. Both examples do not only correlate with the surface water sample averages, but also gives a significantly lower chloride concentration to that of the treated water in the location in Bristol. Thus, omitting the broken pipe to be the main problem and giving a justification to disprove H_1. More likely, the results from our tests, alongside the evidence from these research papers, suggests that the surface water has *not* undergone the treatment process; therefore, the standing water on Troopers Hill field must be coming from another water source.

Analysis of Theta probe test

To gain supporting evidence for the broken pipe hypothesis, presence of water entering from the subsurface layer in the region of highest elevation must provide results to indicate a point-source origin.Opposingly, the control site is expected to show less uniform soil moisture results due to the origin being non-point in the form of precipitation. Therefore, in order to determine whether the test site was of a non-point origin, we compared these results to that taken from the control site. Within the test site quadrant where site 3 is the origin, the soil moisture content measurements range from 52.3% to 83.6% *(Figure 1b)* with no visible pattern to suggest that a pipe is dispersing water into one particular area.

However, *Figure 1b* does show a relationship across the quadrant, displaying markedly higher moisture contents represented by a diagonal pattern in red. This diagonal configuration correlates to a commonly used unofficial walkway that pedestrians follow when walking across the field towards the exit at Summerhill Terrace. The increased frequency of walking along this diagonal pathway may have caused heightened compaction of the soil, making it difficult for water to infiltrate into the ground. This finding is significant for debating whether rainwater is one of the contributing problems on Troopers Hill Field, as it suggests that compaction is preventing excess precipitation from infiltrating into the ground, thereby causing the standing water to develop.

In accordance with the *Pitt, et al., (2002)* paper, soils with high clay proportions received "little effective infiltration" *(Pitt, et al., 2002, p.9)* when compaction was prominent in conjunction with high saturation levels. *Figure 1b* at the test site shows this pathway to have significantly high soil moisture values ranging between 77.6% and 83.6% which confirms the idea that water is unable to fully percolate into the subsurface layers due to the excessive compaction. This theory is supported by the infiltration capacity experiments conducted in the *Pitt, et al., (2002)* paper where lower extents of compaction exerted on silty loam soil types produces faster rates of infiltration; light compaction gives a rate of 4.318 mm/hr and harder compaction gives rates of 0.3556 mm/hr. This supports the notion that excessive compaction along this diagonal transect is restricting effective infiltration, thus causing higher surface soil moisture concentrations along this pathway.

Analysis of the heavy metals test

Another supplementary method to accept H_1 was the heavy metals test, specifically for iron content found in the soil samples along the transect at the test site. Prior to the 1960s, the water supply pipes in Bristol were constructed of lead, or most likely iron; due to no knowledge that an underground pipe was installed after this year at Troopers Hill Field, it can be inferred that any pipe beneath the boggiest region on the field would be cast iron *(Bristol-Water, 2020)*. The iron content at all the sites stayed relatively consistent, with the lowest recorded value being 1.24ppm, reaching a peak of 12.42ppm at site 6 *(Figure 2)*. In reference to *Irmak, et al., (2008)* the iron concentration readings from Troopers Hill Field are in coherence with values collected under another investigation, where iron concentrations range from 6.96ppm to 12.70ppm in the Cukurova region of Turkey. Rather, many of the results generated fell below the critical threshold value required for iron in soils *(Irmak, et al., 2008),* exemplifying how Troopers Hill Field soils may even be iron deficient. Accordingly, this shows the iron content of the soils analyzed at Troopers Hill Field do not contain high enough values to be categorized as contaminated by objects consisting of cast iron; such as pipes.

Furthermore, despite the fluctuations in soil pH readings along the test site transect, all the pH readings were found within the range of 6.2 and 7.0 *(Figure 2)*. Due to its proximity to the allotments, this is consistent with the expected pH values for agricultural land in the UK, with a pH of 5 typically occurring for unlimed mineral soils and a pH of 7.5 being associated with chalky, limestone soils *(Goulding, 2016)*.

This suggests absence of intense heavy metal pollution from iron, as acidic soils below a pH of 6.0 are expected to exist, contrary to the results we have obtained. Correspondingly, there is a low mobility of iron due to the neutral pH results, as more acidic environments have the most significant impact upon heavy metal release *(Krol, et al., 2020)*. Hence, the data seems to reject H_1, the process of water upwelling from a broken pipe. This is due to the minimal metal concentrations detected in the soil samples, alongside the pH results showing negligible acidity levels.

In summary, collating results in order to consider the presence of a broken pipe under H_1 can be disproven. There is notable evidence to suggest that treated water has not infiltrated Troopers Hill Field and contaminated the water lying upon the surface: soil moisture readings exhibit no distinct pattern to suggest a point source is present; low concentrations of iron, proportionate to other research papers, fails to indicate the presence of a cast iron pipe; and neutral pH values do not suggest the existence of a broken pipe in the subsurface. Most significantly, the water samples display substantially lower ion concentrations for minerals that are present at notably higher concentrations in Bristol's treated water.

6.2 Hypothesis 2

H_2: If the infiltration capacity is lower at the site of the clay cap than the control site, clay has a greater influence than other soil types on restricting infiltration.

Determining whether the clay cap is restricting infiltration and drainage and therefore allowing for the accumulation of standing water at the point of highest elevation on Troopers Hill Field can be validated by various methods. For instance, experiments examining visual depth, infiltration capacity, grainsize analysis and soil moisture concentrations.

Analysis of visual depth

Although not a statistical method, visual analysis allowed for the formation of an alternative hypothesis encompassing the impact of clay, and its depth, on the presence of standing water. The choice of methods in this section, and their subsequent interpretation, was based on findings of a dense clay cap not 30cm beneath the surface, as displayed in *Image 2.* Repetition of identical clay pits were located along a transect of 7 sites at 4m intervals, with the test site classified as silt loam, and the control site classified as sandy loam, with minimal clay findings.

Image 2. *Photograph of the soil pit dug at site 3 along the transect at the test site.*

The clarity of this image observes the density of the clay cap, as well as the compaction of the topsoil layer, both of which significantly decrease permeability of the silt loam and reduces infiltration of intense precipitation in winter. This, coupled with knowledge that the South-West region of England, including Bristol, is prone to rare but heavy rainfall events *(Environment Agency, 2020)* promotes meaningful evidence in support of H_2. Relatively impermeable clay should reduce rapid infiltration (*Rhys Thomas and Rees, 1990)* in combination with heavy monthly rainfall in the South-West regions of 161mm and 58mm in December 2019 and January 2020, (*Environment Agency, 2020)* respectively. Visual analysis strongly correlates with reliable statistical findings through infiltration capacity and grainsize analysis in supporting the second research question.

Analysis of grainsize

The grainsize composition table (*Table 2)* categorises all test sites as silt loam, with clay content ranging between 7.03% and 15.6%, based on the grainsize triangle (*Figure 3),* by which clay percent can reach a maximum of 27%. The relatively high clay content, as well as its categorisation as a silt loam, reflects lower water availability within the soil, and further, its ability to become saturated quicker, leading to saturation excess overland flow. Soil type and structure strongly influence the capacity of soils to retain available water (*Jamison, 1961)*, lowering their winter rainfall acceptance potential *(Wilcock and Essery, 1984).* According to *Salter and William, (1965),* available-water content of soil decreases from medium-textured soils to moderately fine and fine-textured soils, i.e from sand or coarse silt, to fine silt or clay. 53.4% of the variation of soil moisture is accounted for by the grainsize values (*Table 3)*, as depicted by the R^2 value of 0.534. However, the p-value shown in the multiple regression model (*Table 3)* is rather large, and therefore implies no significance between grainsize and soil moisture. In addition, '%sand' has the smallest p-value implying its greater significance on the impact of grainsize on soil moisture. This challenges H_2 providing minimal statistical evidence supporting the concept that clay has greater influence than other soil types on restricting infiltration and hence increasing soil moisture.

The linear regression model presented in *Figure 5* clearly displays a positively correlated relationship between clay content of the soil (%) and soil moisture (%), with an R^2 value of 0.385, further indicating a positive relationship. Yet, following a very weak Spearman's correlation (Spearman's p=0.0881) and a statistically insignificant regression p-value (p=0.139), this positive correlation cannot be substantiated. Site 3, of 13.3% clay represents the site with greatest soil moisture, at 27.8%. This soil moisture statistic has been taken from the Mastersizer process, rather than the less reliable Delta-T theta probe. Resistivity is a measure of resistance of a material to conduct electricity and can be used as a proxy when undertaking soil moisture measurements. A paper investigating the influence of soil moisture content and grainsize characteristics on field resistivity (*Abidin, et al., 2014)* compared nicely to the linear regression model results. It explains findings that the lowest resistivity was found at the point containing highest moisture content and highest proportion of fine soil, and therefore the lowest proportion of coarse soil (*Abidin et al., 2014)*. However, the test site has been categorised a silt loam, and contains between 49.9% and 72.4% clay. Therefore, a linear regression representing *both* silt *and* clay content of soil (%) must be evaluated (*Figure 6).* Comparatively, this linear model has a stronger positive relationship between the two variables, with a higher R^2 value of 0.409, and Spearman's p-value of 0.2, implying that the combination of both silt and clay has a stronger impact on soil moisture. Yet, the lack of a statistically significant regression p-value (0.122) prevents the validation of these results, as the null hypothesis cannot be rejected. This therefore contests the hypothesis that clay has a greater influence than other soil types, but certainly supports the notion that clay *does* has an impact on soil moisture.

Analysis of infiltration capacity

Infiltration rates at both the control and test site were instrumental in investigating the relative permeability of subsurface soil, with the results and methodology correlating highly to *Wilcock and Essery's 'Infiltration Measurements in a Small Lowland Catchment'.* As revealed in *Table 4,* 0cm of total water infiltration and 0mm/hour infiltration rate at the test site, are dissimilar to findings at the control site which exhibited 4.6cm of total water infiltration and an infiltration rate of 3mm/hour. Infiltration results show a notable significance, supporting the correlation of soil type and permeability, and can be highly comparable to *Wilcock, et al.*, (*1984).* Their site 11, classified as a sandy loam, compares nicely to the control site at Troopers Hill Field, with infiltration rate of 3.44mm/hour and 3mm/hour, respectively *(Wilcock, et al., 1984, p.195)*. Moreover, *Salter and Williams, (1965),* undertook experiments to understand the influence of texture on the moisture characteristics of soil, and found that silt loam held the largest volume of available water in 2 of the 3 cases *(Salter, et al., 1965, p.313)*. Therefore, it could be found that following heavy monthly rainfall during winter months, the silt loam located at the test site may have become saturated, being able to hold a large volume of available water. Precipitation would be unable to infiltrate, as demonstrated by 0cm of water infiltrating, and surface water and runoff would succeed. Infiltration capacity results uphold H_2 , with 9.33% greater clay content (T*able 4)* at the test site relative to the control site, and 0cm of infiltration occurring. The assumption can hence be made that clay has a greater influence than other soil types on restricting infiltration. Nonetheless, there is 14.3% greater silt content, and 23.6% lesser sand content. The impact that these proportional changes in soil type have on restricting infiltration cannot be ascertained, and hence infiltration capacity does not corroborate H_2.

To summarise, results derived from visual depth, grainsize analysis and infiltration capacity support the concept behind H_2, but cannot authenticate its claims. There is visual evidence to prove the existence of a dense clay cap, and statistical confirmation of grainsize in the subsurface soil layer which hinders the ability for precipitation to infiltrate, as corroborated by secondary research. However, this evidence is not substantial in justifying clay's 'greater influence than other soil types on restricting infiltration'. Hence, H_2 cannot be wholly proven without greater soil analysis, as mentioned below in 'Future Work'.

6.3 Limitations

Analysis of the water sample's chemical composition, Delta-T theta probe soil moisture measurements and heavy metal ion chromatography tests are suitable and effective methodologies to infer whether a point-source is present, specifically a cast iron pipe below the subsurface layer of Troopers Hill Field. Despite this, the results generated through these experiments could be made more reliable by knowing the precision that the individual instruments have when collecting raw data. This is in conjunction with increasing the amount of soil and water samples collected from each site along the transect in order to increase the accuracy.

When conducting the heavy metals analysis to generate iron concentrations for each site, the detection limit is vital in terms of portraying the precision of the instrumental response *(Thompson & Ramsey, 1999)*. The detection limit given for the iron concentrations under this analysis is 10ppb; this value is the lowest concentration of the analyte that can be detected with certainty *(Thompson & Ramsey, 1999)*. Despite no iron concentrations being below this value, it must be considered that one of our results was found under the detection limit at site 2 for the lead analysis, and hence generated no result *(see Appendix C).* Furthermore, the ion chromatography tests taken on our water samples omitted half the results for fluorine due to their concentrations being below the limit detection of the instrument; at 0.5ppm *(see Appendix D)*. However, according to Bristol Water, fluorine has never been added to their treated water as low levels are detected naturally; so, the results were irrelevant nonetheless *(Bristol-Water, 2016)*. If this investigation were to be conducted in another county of the UK, this may have been an issue for the analysis, allowing for inaccurate results to appear.

Accurately recording soil moisture measurements with the Delta-T theta probe has proved problematic in terms of maintained reliability, and is inconsistent under conditions where soil is spatially heterogeneous and moisture conditions vary temporally *(Paige & Keefer, 2008)*. Mineral and organic soils have calibration equations associated with their theta probe measurements, in order to gain the ±5% accuracy; although the manufacturer suggests using site-specific calibration in order to make the probes more accurate *(Paige & Keefer, 2008)*. This on-site calibration was not conducted on Troopers Hill Field, which may explain why some results could be inaccurate, most notably the highest results between 77.6% and 83.6% recorded from the test site (*Figure 1b*). Essentially, this means that the percentage of pore spaces in these particular soil samples are filled with water approximate to full saturation, which is improbable.

For this study, the use of the Mastersizer was pivotal in order to determine grain size fractions, to then classify the soil and thus draw conclusions in relation to their infiltration capacities. The results showed significantly smaller grainsize fractions of clay, to that expected when visually analyzing the soil pits. Large proportions of clay were present due to the cap introduced to cover the antecedent tipping of quarry waste on the hill *(Bristol-City-Council, n.d.) (Image 2).* Despite this, some reports encounter experiences where the Mastersizer underestimates the finer fraction of clay with the use of the laser diffraction technique *(Sochan, et al., 2012)*. This underestimation has arisen due to "the shape of clay particles being different than spherical", in conjunction with typical problems occurring in terms of the optical parameters used for clay fractions *(Sochan, et al., 2012, p.99)*. In addition, the grainsize composition did not equate to 100% as some grains were larger than 2mm, which is beyond the threshold capable for detection in the Mastersizer. Consequently, these grains did not fall within the boundaries of sand, silt or clay. Therefore, the grainsize analysis must be examined with some level of uncertainty due to the limitations affiliated with the instrument.

Perhaps, the most substantial limitation is due to the time restrictions preventing greater replicates of the soil samples to be taken; especially focusing on the boggiest region of the field more extensively. Unfortunately, this meant an in-depth statistical analysis could not be conducted. Statistical significance of the results would have been optimised had there been a longer time frame to complete this investigation, thus raising its reliability.

6.4 Future Work

Taking into account both limitations and hindsight, the process taken to evaluate the standing water at Troopers Hill Field could be improved in the future. In particular, analysis of grainsize in both topsoil and subsurface soil layers, compaction test analysis, further infiltration capacity tests and collection of water samples from within soil pits. This study would have been deeply enriched had these ideas been implemented earlier on.

For this study, experiments and analysis into the distinct dichotomy of grainsize in the topsoil layer and grainsize in the subsurface clay cap, as separate entities, would allow greater scrutiny around the infiltration of precipitation in both soil layers. This is exhibited in *Image 2,* through showing how the hindrance of percolation deeper into the soil profile occurs. For example, a particle size distribution analysis was done by *Gamvroudis and Alevizos (2012),* and a method similar to this would prove more appropriate and beneficial, especially for the confirmation of research question 2.

Following on from this, a compaction test would prove valuable for the topsoil layer. *Pitt, Clark and Chen, (2002),* performed "low-head laboratory infiltration tests for various soil textures and densities" ensuing 'hand, standard and modified' compaction to investigate the influence of compaction on infiltration rates and evaluate their contrasts. A compaction test would be suitable in determining its influence on infiltration rate, as a result of the footpath along the transect at the test site, and hence help propose implications, or solutions, of the results. Similarly, a 'Soil Proctor compaction test' (*Gamvroudis, et al., 2012)* was investigated by *Gamvroudis and Alevizos*, *(2012)*, in order to determine the optimal water content at which soil can reach its maximum dry density and determine soil compaction properties. A compaction test could further evaluate whether soil type, as a silt loam, or compaction had greater influence in the lack of infiltration at the test site.

In addition, infiltration capacity measurements across the whole transect, rather than just site 3, which was the boggiest area and as such had less infiltration, would be more reliable. Although, the entire test site was classified 'silt loam', the variations in sand, silt and clay content may have had a significant impact on the infiltration capacity experiment. Further analysis incorporating this experiment can be undertaken, such as producing a linear regression model explaining the relationship between soil content across all dimensions, and infiltration rate. This method will help validate the acceptance of H_2.

The inability for soil pits to fill up with water after extraction from the saturated topsoil layer, prevented extended water experiments and analysis. By obtaining water samples from within each of the soil pits, rather than simply taking two samples from the surface, more reliable and thorough pH, heavy metal and water chemistry tests could have been utilised in our evaluation of results. Analysis of water from the soil would permit further investigation into H_1.

6.5 Solutions

Based on our findings we suggest several possible causes of action in order to minimize the problem of standing water at the point of highest elevation on Troopers Hill Field moving forward. The first suggestion is to add a layer of soil above the wettest areas of the field. This would not only increase the infiltration capacity of the soil but might also help disperse water into other areas by increasing the gradient – although this may be impractical for those using the field. The second suggestion is to implement a land drain in order to take water away from the area. However, if installed, the land drain would need to be placed above the clay layer, but given the very thin layer of soil present, this would not be possible. Therefore, this is something that could be used in conjunction with adding more topsoil. It is also worth noting that any new land drains, alongside the existing one, should be periodically checked and maintained to ensure they do not become blocked up by mud, rocks or sediment which would affect their efficiency.

There are currently plans in place to build a path running through this area. Careful thought must be placed into the design of the path to ensure that water is drained away from it effectively, so that the problem is not exacerbated. A raised path, similar to ones that are regularly built in floodplain areas, would ensure that the path does not become flooded – thereby defeating the very point of using it in the first place.

7 Conclusion

This study aimed to determine whether the source of the standing water present on Troopers Hill Field in Bristol was natural or treated. The results showed that the standing water is from a natural source and is present due to the low infiltration capacity, coupled with the subsurface clay cap layer beneath. H_1, that the water is from a broken pipe, and therefore treated, was rejected due to low ion chromatography results, which displayed values beneath Bristol Water's treated water values and soil moisture results, which suggest a non-point source. This idea was compounded by heavy metal results of the soil which did not display any unusually high values indicative of a cast iron pipe being present. The infiltration capacity results suggest that the water is from precipitation that is unable to infiltrate into the ground. This might be explained by the presence of a thick clay layer which was visible during the fieldwork and is supported by the grainsize analysis of the soil. However, due to the limited time frame of this investigation it was not possible to take the number of samples and replicates needed to fully analyse the statistical significance of the results; more infiltration tests at more sites would increase this significance. To minimize the effects of this issue in the future, more soil could be added to enhance storage capacity, assisted by an appropriately placed land drain. This would prevent the standing water occurring on Troopers Hill Field every winter.

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Appendices

Appendix A. *Theta probe moisture data for test and control site*

X Coordinate	Y Coordinate	Wet Site Moisture (%)	Dry Site Moisture (%)
0	0	68	54.3
0	2	72.6	55
0	4	82	54.8
0	6	65.5	57.8
0	8	68.1	58.1
0	10	68.7	54.3
2	0	77.2	52.6
2	2	80.3	52.6
2	4	72.3	52.2
2	6	79.6	50.2
2	8	62.6	59.5
2	10	72.3	60.9
4	0	58	61.4
4	2	66.3	61.6
4	4	67	49.3
4	6	83.6	59.2
4	8	65	53.4
4	10	70.1	53.7
6	0	70.7	62.8
6	2	71.2	48.3
6	4	73.3	50.2
6	6	78.6	52.5
6	8	78.4	60.1
6	10	75.3	57.1
8	0	52.3	60.3
8	2	66.6	48.9
8	4	64.8	59.1
8	6	68.4	66.2
8	8	68.8	54.3
8	10	80.7	63.2
10	0	56.2	53.8
10	2	53.3	66.1
10	4	57.4	57.1
10	6	64.2	50.1
10	8	82.5	54.8
10	10	80.7	60.8

Appendix B. *Soil drying data for transect sites and control site*

Site	**Dish Weight (g)**	**Soil+Dish Weight (g)**	**Soil + Dish Weight after 5 days (g)**	**Change in Weight (g)**	**Weight Loss (%)**
Site 1.1	0.679	10.645	8.339	2.307	21.670
Site 1.2	0.668	11.679	9.302	2.377	20.352
Site 1.3	0.660	11.534	9.031	2.503	21.702
Site 2.1	0.674	10.858	7.810	3.048	28.073
Site 2.2	0.666	10.776	8.514	2.263	20.996
Site 2.3	0.675	11.719	9.232	2.487	21.218
Site 3.1	0.662	10.622	7.442	3.180	29.941
Site 3.2	0.663	10.662	7.745	2.916	27.354
Site 3.3	0.583	10.596	7.829	2.767	26.114
Site 4.1	0.670	10.401	7.907	2.493	23.973
Site 4.2	0.673	10.079	7.668	2.411	23.920
Site 4.3	0.669	12.054	9.219	2.835	23.517
Site 5.1	0.670	11.529	9.328	2.201	19.091
Site 5.2	0.666	12.067	9.279	2.787	23.099
Site 5.3	0.664	11.533	8.782	2.751	23.850
Site 6.1	0.664	14.956	13.789	1.167	7.800
Site 6.2	0.666	12.424	10.451	1.974	15.887
Site 6.3	0.662	11.847	9.978	1.868	15.771
Site 7.1	0.672	10.745	9.189	2.201	19.091
Site 7.2	0.672	11.331	10.116	2.787	23.099
Site 7.3	0.664	10.967	9.350	2.751	23.850
Control 1.1	0.679	9.671	7.438	2.233	23.089
Control 1.2	0.680	9.504	7.505	1.999	21.028
Control 1.3	0.674	9.956	7.693	2.263	22.734

Appendix C. *ICP heavy metal data for transect sites and control site. Detection limits also included.*

Site	Fe (ppm)	Cu (ppb)	Pb (ppb)	Zn (ppm)
Site 1	4.77	83.63	22.89	0.19
Site 2	4.40	46.86	BLD	0.10
Site 3	4.49	78.90	71.70	0.29
Site 4	2.04	20.75	19.27	0.10
Site 5	12.46	52.99	59.91	0.21
Site 6	1.62	25.30	58.18	0.13
Site 7	2.39	12.48	31.29	0.17
Control	1.27	85.16	40.15	0.69

Element	Detection limit
Cu	1ppb
Fe	10ppb
Pb	100ppb
Zn	1ppb

Appendix D. *IC water chemistry data for surface water samples. Detection limits for Fluoride= 0.5 ppm.*

Sample	Na (ppm)	K (ppm)	Mg (ppm)	Ca (ppm)	F (ppm)	Cl (ppm)	SO4 (ppm)
1.1	3.38	12.93	3.40	34.82	BLD	12.63	0.44
1.2	3.99	12.97	3.43	36.00	BLD	12.58	0.31
1.3	3.75	13.06	3.46	35.63	BLD	12.50	0.31
2.1	5.40	10.41	3.90	35.03	0.02	14.00	1.23
2.2	5.07	10.52	3.78	34.27	0.04	14.12	1.15
2.3	5.95	10.34	4.00	32.82	0.07	15.68	1.20

Appendix E. *pH data for transect sites and control sites.*

Site	pH
1	6.21
2	6.85
3	6.24
4	7.02
5	6.88
6	6.81
7	6.79
Control	6.74

Appendix F. *Infiltration bottle used at control site for infiltration capacity.*

Appendix G. *Test site for infiltration capacity*

Appendix H. *Surface water located over test site*

Appendix I. *Example of dry site along transect (Site 7)*