Conserving World Heritage in climate change(d) futures: Building understanding of precipitation impacts through innovative hydrological-based solutions.

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Abstract

Heritage landscapes are under threat from a change in precipitation regimes. However, there is little understanding of the surface and subsurface hydrological interactions of heritage landscapes. Establishing the surface and subsurface hydrological interactions will allow for a greater understanding of the potential impact that changes in rainfall could bring to heritage landscapes. It is important to understand these interactions to equip heritage practitioners to make informed decisions about site hydrological management and undertake interventions to create climate-enabled sites. This research aims to build a baseline to develop an understanding of surface and subsurface hydrological networks of three World Heritage Sites (WHS) in Scotland, Ring of Brodgar Heart of Neolithic Orkney, Rough Castle on the Antonine Wall, and St Kilda. In addition, this study examines the influence that key visitor features are having on the subsurface hydrology at Ring of Brodgar and Rough Castle through the novel application of Microwave Moisture Sensor (MMS). MMS highlighted the influence of footpaths and signboards across two heritage landscapes. At Ring of Brodgar, the main footpath influenced soil properties across a wide area to each side of the path, whilst a line of desire had a narrow impact on soil properties. At Rough Castle, the influence of main footpaths, signboards and lines of desire were well defined within the MMS data. With increased precipitation, the effects of footpaths on soil properties may become more pronounced and could be damaging to buried archaeology. Hydrological modelling was carried out using 0.25m resolution LiDAR data to determine the surface hydrological networks of three WHS sites. The hydrological networks at the Ring of Brodgar show the controlling influence of archaeology and footpaths. At Rough Castle, hydrological modelling demonstrated the full extent of the drainage of the fort top and the effect of archaeological defensive ditches on controlling the hydrology. On St Kilda, hydrological modelling shows the influence of upstanding archaeology on hydrological networks. All sites demonstrate the influence of upstanding archaeological features in the higher-order stream networks, and on St Kilda, the lower-order hydrological flows show the legacy of the cultivated farmland in controlling hydrological networks. Climate change precipitation projections (RCP 8.5) for each site were used in conjunction with hydrological modelling and MMS to suggest how sites may become affected through changes in precipitation. For Ring of Brodgar, this highlighted the possible increase in overland flow and the potential increase in soil saturation. For Rough Castle, the potential increase in standing water for longer periods and the erosion of the Antonine Wall and Ditch. St Kilda showed a potential increase in erosion surrounding upstanding archaeology and an increase in soil repellency. The application of MMD required further development but is suitable for understanding the subsurface interaction surrounding key visitor features. Hydrological modelling could be applied to any

heritage landscape which has a suitable DEM/DSM from LiDAR data. Overall, this research has established a baseline approach for determining surface hydrological networks and the influence of visitor pressures on the subsurface in three WHS across Scotland, and in the wider heritage sector.

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Commonly used acronyms, words, and their descriptions

Word/ Acronym	Definition
PIC	Property in the Care of Historic Environment Scotland
SMC	Scheduled Monument Consent
MMDC (Section 42)	Metal and Mineral Detection Consent
OUV	Outstanding Universal Value
MMS	Microwave Moisture Sensor (Moist 350) used for determining relative moisture in stone.
LiDAR	Light Detection and Ranging.
Hydrological Network	In this study, Hydrological Network refers to the stream networks generated through hydrological modelling using LiDAR.
Preferential flow	A stream order that is not visible on the ground but determined through hydrological modelling, can be an ephemeral stream.
Line of Desire	A chosen footpath through a landscape which often follows the topography and has not been designated or forms part of the formal path network.
Heritage landscape	In this study, an area defined by a scheduled monument and the area of land that is situated within the PIC boundary and/or until the neighbouring land reaches a bounding geographical feature, within the LiDAR surveyed areas, which contains upstanding and/or buried archaeology.
HES	Historic Environment Scotland
CCRA	‘Climate Change Risk Assessment’ carried out by HES on PICs
DSM	Digital Surface Model- represents both the built and natural surface of the environments - showing artificial and natural features
DEM	Digital Elevation Model- bare earth models not natural (trees) or built features included
DTM	Digital Terrain Model - augments a DEM by including vector features of the natural environment

Chapter 1. Introduction

1.1 Heritage and climate change

WHS are heritage landscapes of the past and present (UNESCO, 2016a). Climate change poses a known threat to heritage landscapes, yet there is little understanding of the specific pressures heritage landscapes will face by 2080 (Historic Environment Scotland, 2017). As site management practice adapts to climate change, there is an increasingly important need to understand the impacts that climate change and management strategies will have on heritage landscapes (Harvey and Perry, 2015). Climate change has become one of the biggest threats to cultural heritage as it has many unknown implications for future management (Sabbioni, 2008, Heathcote et al., 2017), and it is now recognised as a major threat that heritage practitioners must work to protect against (Bonazza et al., 2009, UNESCO, 2016a, UNESCO, 2016b).

Achieving this is challenging, as there is a current lack of understanding by site managers of both site hydrology and soil moisture regimes and the impacts visitors may be having on buried archaeological structures and soils. Therefore, this thesis explores and offers an evidence-based approach for three WHS in Scotland to determine the current subsurface soil moisture impact from visitor footpaths and the surface hydrological networks present on site. This research provides a baseline approach for further monitoring and research.

A greater understanding of climate data (Murphy, 2018) and the effects climate change could have on heritage will only be achieved through an interdisciplinary approach, which will create a more resilient heritage sector (UNESCO, 2016a). Through a better understanding of how changes in rainfall regimes will impact a heritage landscape, a foundation of practical information can be developed for heritage practitioners to allow them to maintain a site more effectively.

1.1.1 Site vs Landscape scale approach

The concept of site and landscapes is complex and the use of each term can be used interchangeably. There are two scales of approach that can be used when studying upstanding or buried archaeological heritage- site or landscape. The first is a site scale approach; this typically can include a monument, upstanding or buried archaeology and can be defined by a PIC boundary. The second is at the landscape scale; this is where all surface features of an area that surrounds a monument or upstanding archaeology are included. The site approach can generate a monument-centric view when looking at the care and management of heritage, whereas a landscape approach allows for connections between a monument, site, and its surrounding areas to be considered.

Landscapes are the foundations in which our heritage sits (López Sánchez et al., 2020). The landscape setting of our iconic heritage is important because it provides context for the visitor and environmental processes affecting the site, which are not constrained by a property boundary. Understanding the histories of our landscapes can help us form narratives around landscape development and change (Renes et al., 2019). By understanding how landscapes have been impacted by changing climates in the past it becomes possible to recognize their long-term changes and not only aid conservation in the present but adaptations for the future (Renes et al., 2019, Tengberg et al., 2012).

The definition of heritage landscape used within this study is all the components of an area that surrounds cultural structures, monuments, buildings or buried archaeology that can be altered to have a positive or negative impact on archaeological features.

1.1.2 Climate threats to heritage landscapes

There is a huge spatial variability, climatic regions and interregional variability affecting WHS and heritage sites around the world (Collette, 2007, World Heritage Centre, 2014, UNESCO, 2016a). Thus understanding the impact climate change will have on cultural heritage could form the basis of adaptive strategies to minimise the impact of climate change and highlight the importance of gaining a greater understanding (Ezcurra and Rivera-Collazo, 2018) of the effects that changes in pluvial regimes will have on cultural heritage.

There has been research into the effects of climate change on built heritage throughout Europe and the United Kingdom (UK), with a building or monument focus. Further research has been carried out on the effects of climate change on largescale cultural heritage throughout the rest of the world, for example, a Cultural Heritage Risk Index for Australia (Forino et al., 2016), coastal sea-level rise in Puerto Rico (Ezcurra and Rivera-Collazo, 2018). However, the focus has been on the effect that climate change will have on built cultural heritage relating to individual buildings (Brimblecombe, 2014, Fatorić and Seekamp, 2017, Orr et al., 2018). Additionally, in Europe, there is a growing body of research into the effects climate change will have on the wider heritage landscape, and the effects mitigation measures may have on heritage landscapes and the monuments they contain (Orr et al., 2021).There has been research into the effects of climate change on built heritage throughout Europe and the United Kingdom (UK), with a building or monument focus. Further research has been carried out on the effects of climate change on large-scale cultural heritage throughout the rest of the world, for example a Cultural Heritage Risk Index for Australia (Forino et al., 2016), and coastal sea-level rise in Puerto Rico (Ezcurra and

Rivera-Collazo, 2018). However, the focus has been on the effect that climate change will have on built cultural heritage relating to individual buildings (Brimblecombe, 2014, Fatorić and Seekamp, 2017, Orr et al., 2018). Additionally, in Europe there is a growing body of research into the effects climate change will have on the wider heritage landscape and the effects mitigation measures may have on heritage landscapes and the monuments they contain (Orr et al., 2021).

There is, however, an overall lack of literature on climate change and heritage at a landscape scale. In addition, research into climate change impacts on non-heritage asset landscape elements, such as soil, has tended to explore its effects on industry and agriculture, such as lengthening or shortening growing seasons, increased soil erosion etc. (Bonazza et al., 2009) rather than the potential effects this has on a heritage landscape.

In the last six years, systematic literature reviews by Fatorić and Seekamp (2017), Orr et al. (2021) have identified a growing field of research on the impacts of climate change on cultural heritage. Despite an ongoing focus on built structures and interiors for the presentation and preservation of heritage, there is also a clear increase in research focusing on the landscape that cultural artefacts sit in and the impacts that climate change may have on them, from sea-level rise (Howey, 2020) to flooding (Miranda and Ferreira, 2019, Kittipongvises et al., 2020) to undermining of buildings (Torabi et al., 2018). The growing field of heritage landscape and climate change research is where this thesis aims to add understanding.

In Scotland, there has been the initial stages of identifying the risk posed to heritage by climate change through a recent study undertaken by Historic Environment Scotland (HES) (Historic Environment Scotland, 2017). This has resulted in HES being more advanced in understanding of the threats posed to some of its heritage sites. The report ‘A Climate Change Risk Assessment’ (CCRA) looks at HES’s Properties in Care (PIC), but there is limited consideration of the connections to the wider landscape, and it only includes PICs. However, the CCRA can be built upon to develop connections to the wider heritage landscape. The CCRA provides a building block for further research to be carried out and enhance our understanding of the historic environment in Scotland.

The CCRA uses national databases that are widely available for factors such as terrain, rainfall, and land boundaries, but has minimal consideration of alteration, remediations or prevention measures currently in place on sites but provides a starting point when looking at climate change impacts. The report does, however, highlight that a change in pluvial regimes may be one of the most significant single factors affecting sites. Therefore, in this study, the hydrological networks by which water moves across a heritage landscape have been chosen as a starting point for investigation.

Determining the current surface hydrological flow networks within a heritage landscape is likely to be of value, as this will allow for accurate mapping and understanding of the impacts that an increase in rainfall will have on heritage landscapes. The CCRA highlights the impacts that current river systems may have on heritage landscapes through fluvial flooding (Historic Environment Scotland, 2017) the CCRA only considers flooding in terms of pluvial, fluvial and coastal, without considering the surface hydrological networks and drainage patterns of the heritage landscape. Gaining a greater understanding of the direction and scale of hydrological networks across a site is imperative to understand the impacts that changes in pluvial regimes may have on a heritage landscape.

Besides the movement of water across a heritage landscape, the impact that visitors have on the subsurface soils and buried structures is also considered in this study. Visitor interactions are known to have a visual impact on the landscape, particularly through that of footpaths (Ballantyne and Pickering, 2015) and understanding how these footpaths are impacting the subsurface is important. Understanding the impact of footpaths could influence their location in order to protect subsurface archaeology. Combining a consideration of the surface hydrology and subsurface impacts of visitor interactions will build a better understanding of the impacts that changes in pluvial regimes may have on heritage landscapes.

1.1.3 Current Predictions for climate change and heritage landscapes in Scotland

The CCRA provides a starting point for understanding the climate change influences that will affect PICs, which will in turn, aid the understanding of the wider historic environment. One factor that repeatedly occurred throughout the CCRA was that of water inundation, whether it be from rainfall, groundwater, fluvial or coastal or causing landslides. HES has found a number of their sites are at increasing risk from flooding through pluvial, fluvial or groundwater forces (Historic Environment Scotland, 2017), both currently and in future climates. These factors pose a threat to PICs either through flooding buildings or monuments, potentially causing irreversible damage or destruction and loss of a historic monument. Neither outcome is desirable for a PIC or heritage landscape. Identifying the different sources of threat will result in a better understanding of which factors will affect sites in light of a climate-changed future. From this, it is clear that one of the biggest factors affecting heritage landscapes is water.

Although the CCRA indicates water inundation is a factor that will affect PICs due to climate change (Historic Environment Scotland, 2017) (See section 3 of CCRA), it does not identify the pathways by which water enters, moves or leaves a PIC. The CCRA does not identify the site scale connections between a PIC and the surrounding landscape.

From the CCRA (Historic Environment Scotland, 2017) and the review by Fatorić and Seekamp (2017) it is clear cultural heritage is not generally considered at a landscape scale, instead, the focus is on individual monuments (Dupont and Van Eetvelde, 2013). It is important to be aware of how altering/mitigating climate change impacts at a monument scale for protecting cultural heritage monuments and how this may have an adverse effect on the landscape (Dupont and Van Eetvelde, 2013). In addition, focusing on site and monument interventions prevents acknowledgement of the connection so the wider landscape and the potential impact this will have on surface and soil water movement. From the CCRA (Historic Environment Scotland, 2017) and the review by Fatorić and Seekamp (2017) it is clear cultural heritage is not generally considered at a landscape scale, instead the focus is on individual monuments (Dupont and Van Eetvelde, 2013). It is important to be aware of how altering/mitigating climate change impacts at a monument scale for protecting cultural heritage monuments and how this may have an adverse effect on the landscape (Dupont and Van Eetvelde, 2013). In addition, focusing on site and monument interventions prevents acknowledgement of the connection to the wider landscape and the potential impact this will have on surface and soil water movement.

It is widely accepted that Scotland’s precipitation regime will be altered as a result of climate change (Figure 1 and Figure 2) (Wignall et al., 2018, Afzal et al., 2011, Afzal et al., 2015), yet there is little understanding of the effects these changes in precipitation patterns will have on heritage landscapes. Several theoretical studies have been conducted exploring the threat posed to Geodiversity in Scotland (Prosser et al., 2010, Wignall et al., 2018) and HES has highlighted the threats that their PICs will pose face as a result of climate change (Historic Environment Scotland, 2017). Although the risk to each PIC has been identified, ranging from pluvial inundation to landslips to coastal erosion, the likely specific onsite impacts have not yet been established or identified.

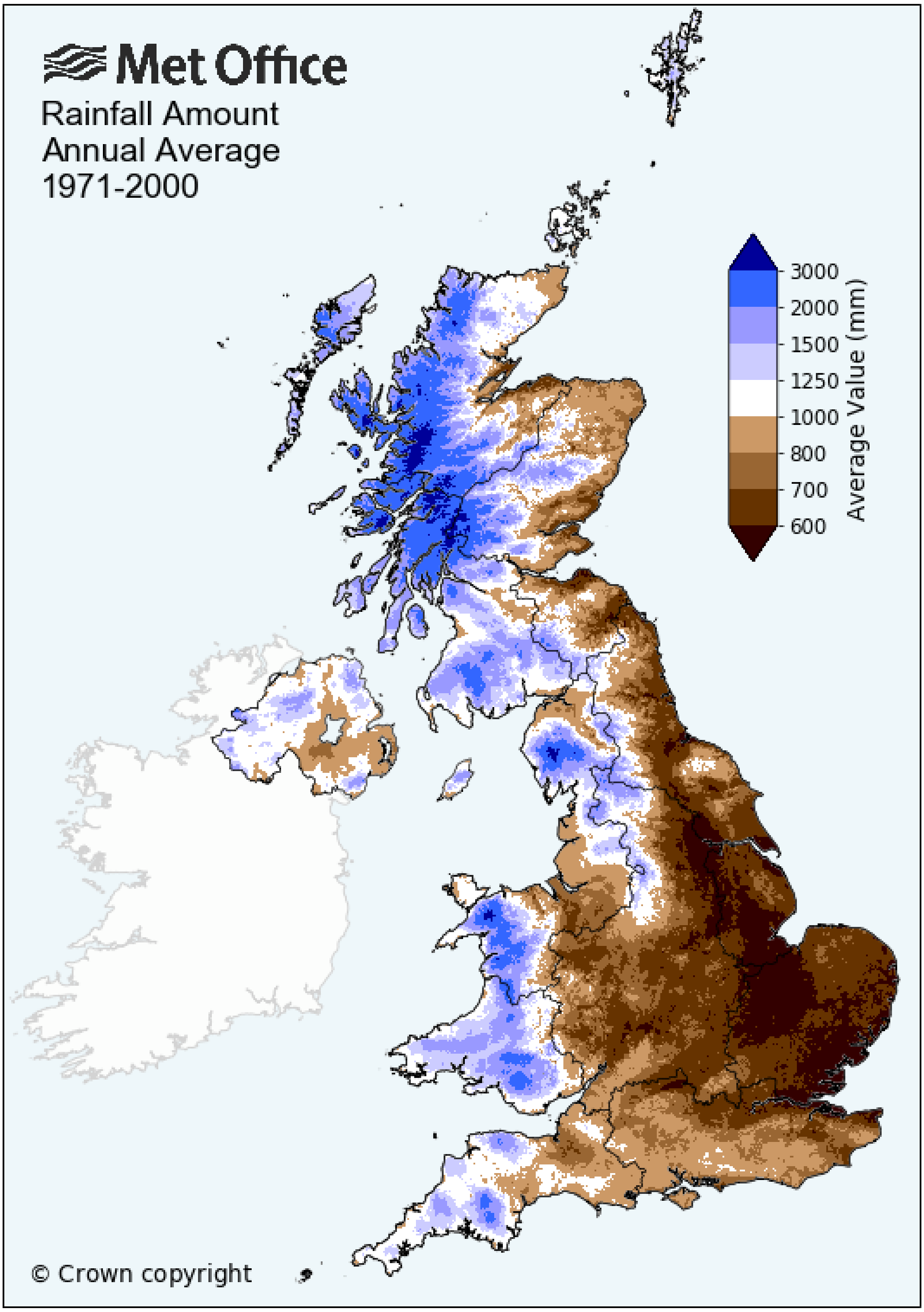

Figure 1 Precipitation average from 1971-2000 based on the 1km resolution HadUK-Grid dataset derived from station data (Met Office, 2019).

There have been two sets of UK climate projection data (Murphy et al., 2010, Met Office, 2020) The first is the UKCP09 data set, this data set allows for 25km regional daily prediction to 30-year averages over a 25km region. This data set focuses more on regions and variations between the regions. The second is the UKCP18 data set. The UKCP18 has several scales of data that can be used for determining the climate changes; they range from 60km global daily predications to 2.2km variations in local rainfall intensity and duration. The UKCP18 data set provides a higher resolution of regional data and updated predictions from the UKCP09 data set. The latest predictions include regional variation in climate that may be affected by local topography; the finer scale data sets further have a day-to-day breakdown and inter-day weather patterns. For this research, the breakdown of the UKCP18 data sets at a regional scale, which provides local variations in precipitation regimes, will be used. This will allow the rainfall variation and its impacts on heritage landscapes to be better understood.

The UKCP18 further details how weather patterns may change seasonally (Met Office, 2020). This is important when looking at heritage landscapes and understanding the effects seasonality of weather and visitor effects will have on a heritage landscape. As Scotland has distinctive climate regions (North, East and West) and significant differences between seasons, the fine-scale differences within the regions will allow for greater accuracy when predicting the local effects of changes in rainfall on sites and the impact this may cause (Figure 2).

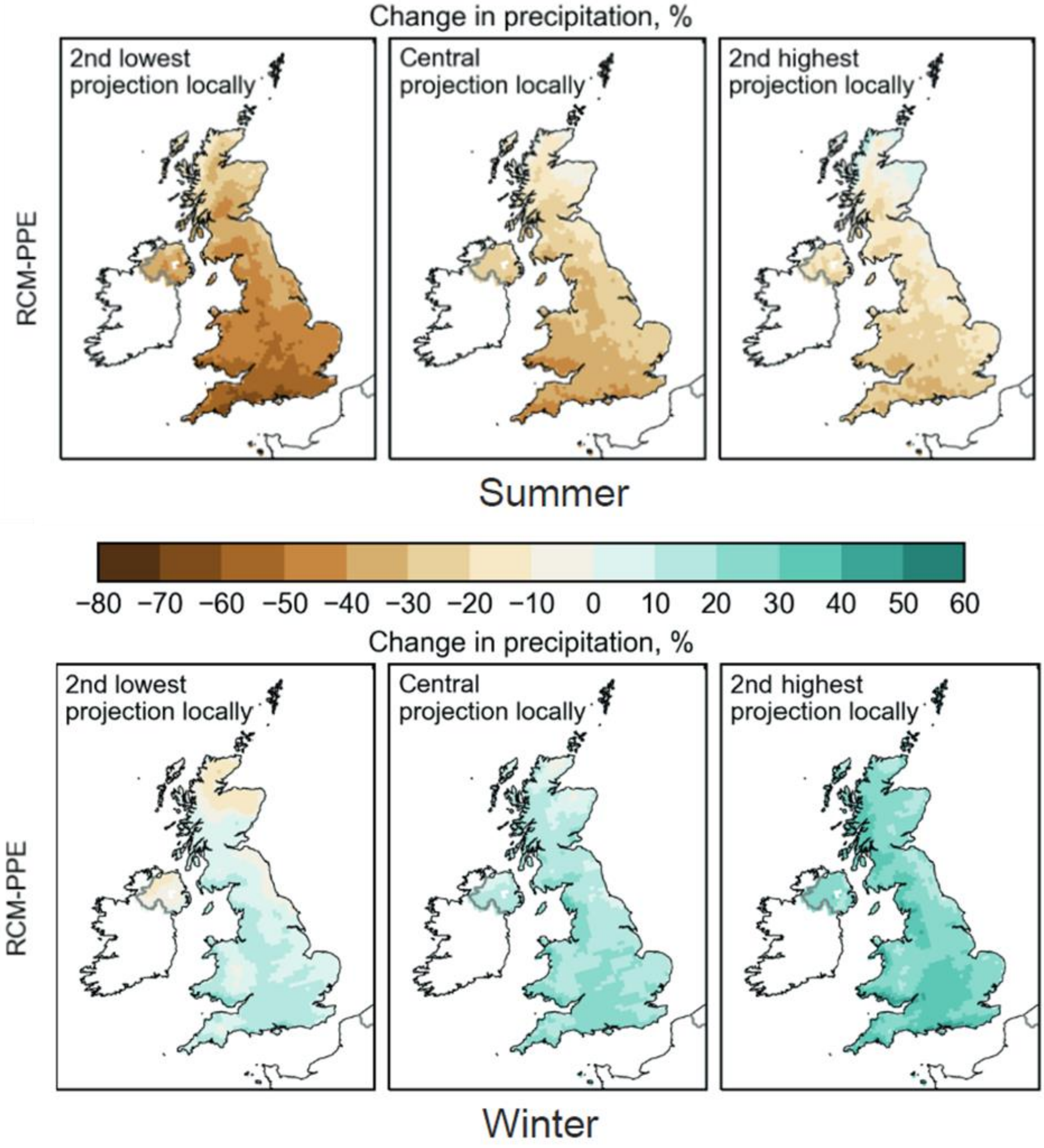

Figure 2 The spatial pattern of change to 2061-2080 shows detailed structure over the UK (RCP8.5). Compare SE England and N Scotland. (Met Office, 2020)

Current climate change predictions for Scotland are that rainfall will occur for shorter more intense periods, coupled with longer dry spells, along with wetter winters (Figure 1 and Figure 2) (Orr et al., 2018, Historic Environment Scotland, 2020), all of which could have detrimental impacts to cultural heritage. Therefore, viewing heritage at a landscape scale allows for potential mitigation and interventions to be considered within the wider landscape and allows for maintaining hydrologic connections across a landscape.

The predicted change in rainfall regimes, resulting in more rainfall and more periods of intense rainfall, could cause damage to heritage landscapes (Werritty and Sugden, 2012, Orr et al., 2018). The changes in pluvial regimes will directly impact heritage sites at a landscape scale through changes in soil wetting and drying cycles (Historic Environment Scotland, 2017) and erosion, which could be detrimental. Changes in soil moisture can lead to enhanced deterioration either through wetting and drying cycles or changes in the ambient soil aeration and moisture regimes (Historic England, 2016). The wetting and drying of soils, including the fluctuations in the water table, could lead both to soil compaction and to erosion (Historic Environment Scotland, 2017). Changes in soil moisture could lead to management and conservation issues from hidden degradation of a heritage landscape, such as deterioration of buried archaeology, through to the visible erosion of soil. Therefore, understanding the surface hydrological networks and soil moisture changes within a heritage landscape is essential. It could inform areas that may become more at risk, either from receiving increased soil moisture or from drying soils.

1.2 Why is soil moisture important to heritage?

Every heritage landscape is unique and has distinct elements, including monuments, archaeology, soil and geographical location; each will also differ in the number of visitors it receives annually and the visitor infrastructure that is present. However, this research will focus on the subsurface soil interactions underlying and adjacent to key visitor features, such as footpaths and signboards, and how surface hydrological networks are affected by upstanding archaeology. Soil properties, footpaths and upstanding archaeology are site dependent and can vary across sites; therefore, understanding how the different components of soil properties throughout a profile interact is essential.

Soils play an important role in regulating soil moisture and hydrological interactions and are important in heritage landscapes as soil moisture has a significant role in the preservation, or deterioration, of buried archaeology. Being able to detect changes in soil moisture regimes is key as changes in soil moisture can impact the soil geochemistry, including the anaerobic and aerobic conditions of waterlogged archaeology (Cassar and Pender, 2005, Agapiou et al., 2020).

Understanding soil moisture regimes is also essential to understanding the threat from pluvial and groundwater flooding that was identified in the CCRA. Upstanding archaeology is unique to each WHS site, and their influence on site hydrology will be site-specific. However, are the site-specific controlling factors that affect hydrological networks on different WHS and their effect on site hydrology are less well understood.

1.2.1 Soil Properties Relating to Soil Hydrology

Soil moisture forms a regulating factor of the hydrological cycle (Shaukat et al., 2022, Zhang et al., 2015). The influence soil moisture has on the hydrological cycle is mainly understood through the impacts that variable soil moisture has on agriculture (Shaukat et al., 2022, Zhang et al., 2019) and there is little understanding of the impacts change in soil moisture has on heritage landscapes. By understanding how soil moisture affects soil structure (Brady and Weil, 2008) and vice versa, we can then begin to understand how a change in pluvial regimes could affect soil profiles.

There are three key, interrelated soil properties that affect soil moisture regimes; these are soil texture, soil structure, and soil porosity. Together these three soil properties regulate not only the behaviour of soil moisture, but also influence soil stability and cohesion and, thus, the potential for erosion and compaction. Understanding these key soil properties and their distribution and development within a heritage landscape could help predict the impact that changes in pluvial regimes will have on soil hydraulic conductivity (Brady and Weil, 2008).

Soil texture is determined by the relative proportion of sand (0.05mm to 2mm), silt (0.002mm to 0.05mm), clay (less than 0.002mm), and organic matter in the soil. Drainage capacity is dependent on the percentage abundance of sand, silt, and clay in the soil and, therefore, the structure of the soil. A higher percentage of sand within a horizon means the soil is more freely draining as the spaces between the sand grains are larger, whilst a high percentage of clay will inhibit drainage due to the smaller pore space the particle composition creates (Brady and Weil, 2008). Silt and clay can also fill larger pore spaces created by sand particles, inhibiting drainage. Organic matter concentration is also important to understand as it can affect the water-holding capacity of a soil (Brady and Weil, 2008) along with the maximum saturation, and hygroscopic capacity of a soil. Therefore, understanding the differences in soil composition across a heritage landscape can give a theoretical indication of the potential variations in hydrological interactions that could occur.

Structure is how particles of sand, silt, clay and organic matter aggregate into different shaped and sized structures such as crumbs, blocks, prisms, columns or plates (Figure 3). This is influenced by a range of abiotic factors such as clay type and content and the presence of other potential cements such as calcium carbonate and iron oxides, as well as biotic factors such as the presence of gums and mucilage from the decomposition of organic matter or as released in the gut of soil organisms, and the actions of plant rootlets and fungal hyphae that can act like a mesh to bind particles together. Very sandy soils with low organic matter and low biological activity tend to be poorly structured and may be single-grain. Whilst clay-rich soils can also be structureless if they have low organic matter and little biological activity or through chemical composition such as high concentrations of sodium (Na^+) ions, which neutralise the cohesion between clay particles and through compaction. Soil structure can determine how the soil responds to different stressors (Brady and Weil, 2008) and in relation to this research, how it responds to hydrological stressors such as droughts, flooding, and other external stressors, such as visitor pressures.

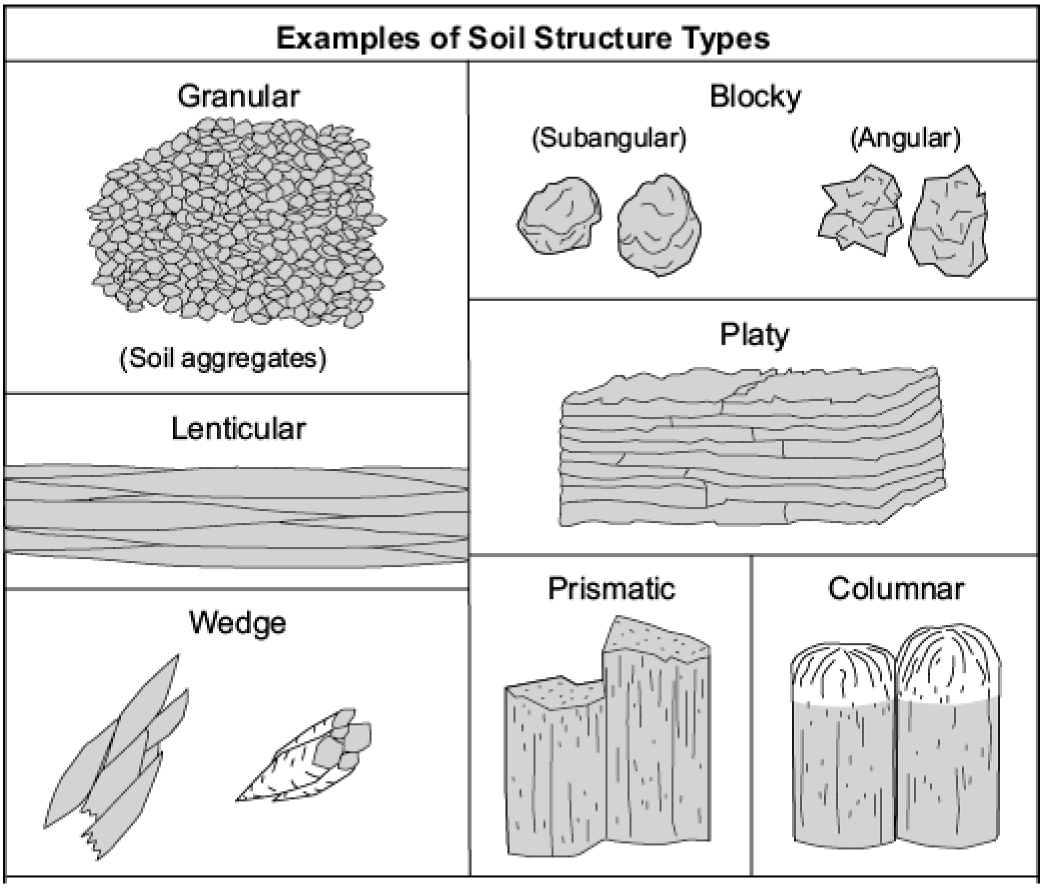

Figure 3 Examples of soil structure types from USDA-NRCS (Moorberg and Crouse, 2021).

Soil porosity is linked to the structure of the soil and is the void space between the particles and soil aggregates (Indoria et al., 2020). Porosity plays a fundamental role in the ability for a soil to respond to changes in moisture conditions. This porosity of a soil affects its ability to store water and directly influences the hydraulic activity of the soil. In addition to the porosity is the size and connectivity of the pore space, which plays an important role in the moisture regulation of a soil (Figure 4). Large pore spaces can hold more soil moisture; however, if they are poorly connected, the ability for water to infiltrate is limited. Small pore spaces can have the opposite effect with increased infiltration and have, but also has a similar soil moisture capacity.

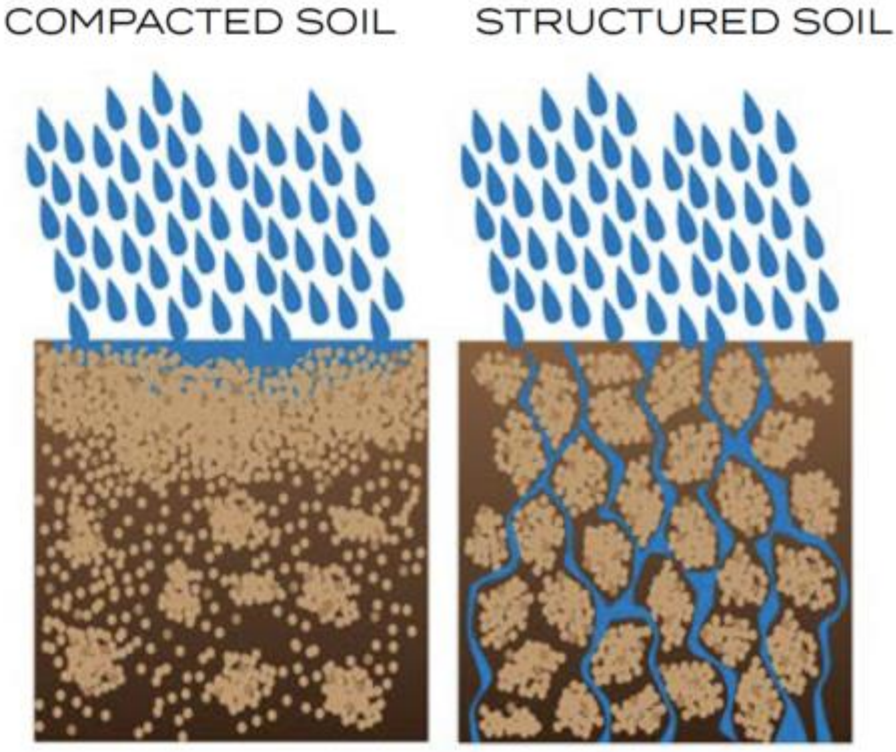

Figure 4 Simple soil porosity diagram indicating smaller pore space with less capacity for infiltration. Image from Urth Agriculture (Urth Agriculture, 2021).

Understanding the texture and structure of a soil, along with its porosity, is the basis for understanding soil hydrology. However, soil properties can also vary with depth through the soil profile. Therefore, it is essential to establish the different percentages of sand, silt and clay within different soil horizons. If there is a significant change in soil texture between soil horizons, this can inhibit vertical infiltration rates due to the consequent change in pore space (Brady and Weil, 2008) or induce lateral subsurface flow. Recognising these natural interfaces between soil horizons throughout a profile can aid in understanding vertical drainage and lateral subsurface flow.

Soil structure, texture, and porosity affect soil hydrology and, in turn, processes such as wetting and drying, cohesion and compaction. The following section will look at these factors in more detail in relation to a heritage landscape.

It is important to establish the maximum retentive capacity to predict when a site may reach maximum saturation capacity but also the point at which hygroscopic water is reached, where soil dryness will affect the infiltration rates, capacity, and structure (Gray, 1967). The hygroscopic point is when the moisture within the top layer of the soil reaches a critical level that does not facilitate infiltration of above-ground moisture. This is an issue for heritage landscapes, as soil that has reached its hygroscopic point has an increased surface flow and potential for entrainment of soil particles, thus, is susceptible to erosion during intense rainfall events. Furthermore, the lack of soil moisture leads to a lack of cohesion in soil structure, which can lead to increased compaction rates.

The maximum retentive capacity is when a soil reaches maximum saturation capacity and does not support moisture infiltration. This is correspondingly detrimental to soil structure as it can lead to the breakup of said structure, which can lead to soil compaction during these conditions. Within these conditions, there can be significant changes in the soil composition, including an increased concentration of fines at the surface due to the loss of silt and sand which, can be easily eroded without the cohesive properties of clays. There can also be structural collapse at the surface due to rain splash, which can prevent the infiltration of moisture. Thus, it could be detrimental to heritage landscapes, particularly for areas used as footpaths and those surrounding them. Site flooding, through soil saturation, is likely to increase due to the increase in rainfall (Historic Environment Scotland, 2017). Furthermore, soil saturation can cause enhanced deterioration of unique artefacts and monuments (Wang, 2015). Soil saturation can come in many formats, rise in groundwater level, fluvial, pluvial, and coastal inundation (Historic Environment Scotland, 2017), all of which will have different implications for a site, from changes in soil moisture, to changes in soil and water geochemistry which can impact archaeology in different ways (Cassar and Pender, 2005).

Soil dryness is likewise a concerning factor at cultural heritage sites. Dry soils can be more susceptible to erosion by wind and intense rainfall events. When a soil loses moisture, hydrophobic surfaces can develop, resulting in infiltration rates during extreme rainfall events being inhibited due to a reduction in the capillary tension that transports water (Gray, 1967). The reduction in infiltration during intense rainfall events can result in overland flow and an increase in the erosion of soil across a site. Additionally, there is the preservation or deterioration of below-ground archaeology resulting from a reduction in soil moisture; although not investigated explicitly here, this should still be considered.

There is a reduction in soil moisture during the summer months (Calanca et al., 2006), resulting in different mechanisms of water infiltration into the soil becoming active at different times. These mechanisms range from gravity-filled pore spaces to capillary forces. Soils that are very dry can increase infiltration due to increased pore size but are friable and lack cohesion. This could result in soils becoming increasingly susceptible to erosion due to the lack of infiltration capacity and the intensity of precipitation events (Gray, 1967, Märker et al., 2008).

The water content of soil has the greatest effect on soil cohesion (Wei et al., 2018) and therefore plays a significant role when considering the impacts of climate change. Soil cohesion is vital for the strength and consistency of soil. Brady and Weil (2008) have highlighted the importance of understanding the relationship between soil moisture and cohesion, as it can affect the capacity and structures of soils in different conditions. Predicted changes in rainfall regimes mean it is important to understand how rainfall will interact with the soil (Alaoui, 2017) within a heritage landscape. For a heritage landscape, soil cohesion is directly related to soil stability, particularly when soils lose cohesion due to saturation or inversely when it becomes too dry.

There is an increased focus in the literature on understanding the effects of soil erosion in the context of land management and the loss of soil from landscapes (Nosrati, 2017, Dymond and Vale, 2018, Mehri et al., 2018). The projected increase in rainfall and intensity of events could lead to increased erosion rates within heritage landscapes. To determine the potential extent of soil erosion due to intense rainfall events, the hydrological networks of the heritage landscape first have to be established.

Soil compaction occurs when an external force, such as footfall, is placed upon the soil, causing a reduction in pore space. Once a soil has been compacted, it has a reduced capacity for water infiltration. Soil compaction can happen very quickly, particularly in wet soil and can result in a legacy effect that can be detected in soils decades after the compaction has ceased (Alaoui et al., 2018). Alaoui and Diserens (2018) show that understanding the mechanisms of soil compaction and mapping its extent is important for understanding the short- and long-term fluctuations for top- and sub-soil moisture. Compaction alters the function of water transport through a profile and can cause extensive land degradation (Obour et al., 2017). Understanding the extent of soil compaction in the surface and subsurface is important for understanding soil permeability (Veronesi et al., 2012).

Peng et al. (2012) found that soil shrinkage was independent of soil compaction and that soil compaction reduced the size of the structural pores but not textural pores. This contrasts with soil shrinkage that is linked to soil texture. This could have a significant effect on a heritage landscape due to the effects of infiltration, soil structure and water-holding capacity, which could lead to a deterioration in the soil profile and in turn, be detrimental to upstanding and buried archaeology.

1.2.1.1 Soil Properties Summary

Due to the complex interactions between soil and water, it is important to understand the factors that could enhance water storage capacity within soils and increase the infiltration rate to limit the extent of the wetting and drying cycles. Soil moisture plays a significant role in the capacity of sites to respond to changes in rainfall events. Therefore, understanding the maximum saturation and the volume of water a soil can hold against gravity and water movement through a site makes it possible to promote the development of good soil structure with a high saturation capacity. Understanding soil porosity in heritage landscapes is important (Peng et al., 2012) as heritage landscapes have a long use and visitor history, and soil compaction will already be prevalent on most sites. Predicted increase in precipitation has been suggested to have an impact in soil erosion which is likely to increase in severity during winter months (Kundzewicz et al., 2007). There has been little research within the heritage sector on the erosion of soils and the trends that are likely to occur with changes in precipitation patterns (Jiménez-Cisneros et al., 2014). Understanding soil properties and soil processes can create a better understanding of the soil dynamics that exist in a heritage landscape and the potential pathways for remediation. Through gaining an understanding of soil water movement and compaction, this study will demonstrate the effects that increased rainfall may have on heritage landscapes. This understanding can also be used for monitoring changes as a result of climate change.

1.2.2 Heritage landscape infrastructure- footpaths

When looking at heritage landscapes regarding existing visitor infrastructure, it is important to remember heritage landscapes are key to site management (Ballantyne and Pickering, 2015). Footpaths are key for allowing visitors to move around a heritage landscape (Ballantyne and Pickering, 2015). Understanding how visitors interact with heritage landscapes makes it possible to help improve these visitor footpaths to reduce their potential negative impacts and aid visitor interaction with cultural heritage.

This understanding can influence site management practices, for example, by developing appropriate footpath surfaces to support active conservation of areas and prevent damage by visitors (Canteiro et al., 2018)). Further, awareness of visitor site use can lead to better monitoring and sustainable management of site visitors (Canteiro et al., 2018).

Having a clear understanding of soil properties is important as they can determine the impact that visitor pressures will have on a profile through compaction as well as water infiltration rates and storage capacities of the soil profile (Defossez and Richard, 2002). Pre-Covid19 patterns of global tourism growth towards the end of this century are expected to increase in the summer, with less tourist activity in the spring and autumn (Kovats et al., 2014), along with a push from VisitScotland to encourage visiting all year round (Visit Scotland, 2022). This could be a concern for heritage landscapes due to the increase in footfall during drier months leading to soil alteration.

Due to visitors interacting with a site, soil alteration has been widely studied, particularly in China (J. Gong, 2009, K. Zhang, 2009). Soil porosity and water holding capacity declined in the upper most layers of the soil of trampled areas, and soil water saturation content could reduce by 75% in severely impacted sites (J. Gong, 2009, K. Zhang, 2009), found that the effects of soil compaction can be seen up to 15m away from paths, with the highest impact at 5m from a path. From their study, Zhong et al. (2011) found that tourists adversely affect soil water infiltration, this leads to increased runoff through trampling, which has, in turn, increased erosion. Although these studies have been conducted in China, they highlight a very real and important factor that can affect all heritage landscapes. This further demonstrates the importance of knowing site-specific features such as designated footpaths, lines of desire and site use for understanding of the soil hydraulic capacities throughout a heritage landscape.

Visitor footpaths affect the surrounding vegetation (Hill and Pickering, 2009) and therefore have an indirect impact on the soil composition, which can have an effect on soil compaction and their susceptibility to erosion(Farrell, 2001, Nepal and Nepal, 2004). For example, the recovery of vegetation surrounding a path (Lemauviel and Rozé, 2003), the type of variety of uses a path was subject to (Olive and Marion, 2009), or the effects that informal and formal paths had on soil loss, compaction and footpath widening (Ballantyne et al., 2014, Ballantyne and Pickering, 2015). These studies have found unhardened footpaths have a greater susceptibility to erosion and run-off and were subject to greater compaction rates (Ballantyne and Pickering, 2015). This finding is particularly important as it can aid understanding how lines of desire and unhardened path systems could impact a heritage landscape. Visitor footpaths affect the surrounding vegetation (Hill and Pickering, 2009) and therefore have an indirect impact of the soil composition which can have an effect on soil compaction and their susceptibility to erosion (Farrell, 2001, Nepal and Nepal, 2004). For example, the recovery of vegetation surrounding a path (Lemauviel and Rozé, 2003), the type and variety of uses a path was subject to (Olive and Marion, 2009), or the effects that informal and formal paths had on soil loss, compaction and footpath widening (Ballantyne et al., 2014, Ballantyne and Pickering, 2015). These studies have found unhardened footpaths have a greater susceptibility to erosion and run-off and were subject to greater compaction rates (Ballantyne and Pickering, 2015). This finding is particularly important as it can aid the understanding of how lines of desire and unhardened path systems could impact a heritage landscape.

When considering the impact of climate change on a heritage landscape, understanding the different ways visitors use a site will allow for better predictions on how infiltration may be affected during intense rainfall events; particularly through understanding the impacts that visitors have on the designated (footpaths) and chosen routes (lines of desire) can help us to understand the impact on soil moisture. Ballantyne and Pickering (2015) have highlighted that the soil structure and composition around walking trails had greater compaction and higher erosion than areas around designed and designated routes. They further highlighted those trails with a bare surface had greater compaction and erosion susceptibility. This is important when considering the impact of climate change and the consequences changing rainfall regimes may have on soil structure and stability in heritage landscapes. The predicted changes in rainfall regimes (Werritty and Sugden, 2012) and bare trails/paths, which have greater compaction surrounding (Ballantyne and Pickering, 2015) them could lead to an increase in flooding due to lack of permeability into the soil (Brady and Weil, 2008) and erosion. This impact on a heritage landscape is currently unknown and further research is required to understand the interaction between footpaths, soil, and water.

Gaining a better understanding of how soil compaction can increase or decrease the water capacity of soil is an important factor in interpreting the stresses visitors put on different sites under different precipitation conditions. Along with understanding how different types of footpaths affect soil moisture movement and compaction is essential for reducing visitor impacts on a heritage landscape.

1.2.3 Soil moisture monitoring techniques

Soil moisture varies across a landscape and is controlled by soil properties such as texture, organic matter, bulk density, and pore size (Zhao et al., 2011) (1.2.1 Soil Properties Relating to Soil Hydrology), along with vegetation, topography, and land use. The spatial variability of soil moisture is often estimated across a landscape (Doolittle and Brevik, 2014). The level of spatial and temporal variation makes monitoring difficult as the data is typically noisy, and long-term trends are difficult to identify; one of these long-term trends is climate change which may increase the temporal variability in soil moisture (Zhao et al., 2011).

Increasingly understanding and monitoring soil moisture content is via the use of remote sensing techniques (satellite data and UAVs), and the development of on-ground techniques to determine and monitor soil moisture. The following section explores the different methods and techniques available for monitoring soil moisture.

1.2.3.1 Remote sensing techniques for soil moisture

More accessible satellite data, particularly that of Sentinel- 1, is becoming more prevalent to derive soil moisture (Zeyliger et al., 2021). Remote sensing techniques use several software applications to extract satellite data in the format of radiometer and scatterometer data to determine soil moisture (Pulvirenti et al., 2018). This is in addition to emerging research on the scale and resolution of areas being mapped (Peng et al., 2021). Furthermore, the scale (25- 50km) at which soil moisture is being monitored is not yet at a sufficient resolution for use within a heritage landscape. Limiting factors to using satellite data for soil moisture measurement in heritage landscapes, is that satellite data only measures soil moisture in the top few centimetres of a soil profile and can be limited by vegetation growth (Pulvirenti et al., 2018). The depth of archaeological remains can vary, and thus only being able to monitor the top few centimetres of the soil is not beneficial for determining changes in soil moisture at depth. The interpretation and access of the results from satellite-derived data require specialist knowledge. The increased use of UAVs and specialist equipment (multi-spectral imaging) is emerging (Wu et al., 2019, Wigmore et al., 2019, Floreano and Wood, 2015) and will increase the potential for remote monitoring of soil moisture variation. However, for these emerging techniques to be successful, there needs to be a better understanding of how soil moisture can vary at small spatial scales as well as with depth. This field looks promising and could be applied widely within the heritage sectors with the correct knowledge and application of techniques.

1.2.3.2 On ground techniques for soil moisture monitoring

There are a variety of techniques that can be used to determine and monitor soil moisture, such as Time Domain Reflectometry (TDR), Electromagnetic Induction (EMI), Ground Penetrating Radar (GPR), and Neutron Moisture Meters (NMM). Uses, benefits, and drawbacks to these methods can be found in Table 1 and the following section. These techniques all have their own specific characteristics and advantages and disadvantages for use and deployment within the field. They often require specialist knowledge for either operation or interpretation of results, or both.

Time Domain Reflectometry (TDR), can give near real-time determination of soil moisture with minimal destruction to the soil profile (Zanetti et al., 2015). TDR measures reflections of an emitted signal along a conductor. TDR can determine soil moisture by analysing the reflected signal's magnitude, duration, and shape of the reflected signal (Table 1). Metal probes 10-30cm long are required to be embedded into the soil for TDR to be effective.

Electromagnetic Induction (EMI) is a contactless sensor that measures the soil's electrical conductivity, which can be controlled by soil moisture, organic matter, salts and texture. Itcan also be affected by stratigraphy, bedrock and bulk density (Table 1) (Shaukat et al., 2022, Barca et al., 2019, Moghadas et al., 2017, Moghadas et al., 2019, Doolittle and Brevik, 2014).

Ground Penetrating Radar (GPR) full waveform and inversion methods can be used to determine soil moisture (Grossi et al., 2007, Wu et al., 2018). GPR has been demonstrated to be an effective non-invasive method for monitoring soil moisture (Klotzsche et al., 2018), however, it requires a highly knowledgeable skill set to operate and interpret (Table 1). GPR is a growing discipline for understanding the hydrological component dynamics of soil (Doolittle, 2008) and has a growing importance for the use of non-invasive techniques when understanding hydrological soil dynamics (Doolittle, 2008) on culturally significant sites. GPR is highlighted as being one of the few soil moisture monitors that has no impact on the measured soils (Huisman et al., 2001) and offers a larger range capacity than that of point sampling and depending on equipment, can range from 0.5 to 30m^3 (Huisman et al., 2001). GPR performance relies heavily on the electrical conductivity of the soil (Doolittle et al., 2007) therefore soil type can greatly affect the viability of GPR as a single source for understanding soil moisture, particularly clay rich soils (Algeo et al., 2016).

Neutron Moisture Meters (NMM) can measure soil moisture with a high level of accuracy, at a predetermined intervals (Table 1). A permanent vertical shaft is installed into the soil, and a neutron probe is inserted. This probe can then measure the total moisture content of the soil.

Due to these techniques for monitoring soil moisture within the archaeology sector requiring specialist knowledge and training, they are inaccessible for most heritage practitioners.

Table 1 Summary of commonly used on ground methods for monitoring soil moisture

Method	How it is used	Positives for soil moisture	Negatives for soil moisture
Time Domain Reflectometry (TDR)	• Indirect measurement of soil water content	• Depth can be specified • Repeatable • Rapid measurements • Near real-time readings	• Dependent on dielectric properties • Requires probe (10-30cm long) insertion into soil • Calibration of equipment require for each soil type
Electromagnetic Induction (EMI)	• Characterization of the spatial variability of soil moisture • Measures electrical conductivity of the soil	• Rapid • Characterisation of soil properties • Determine flow patterns • Non-invasive • Time-lapse to infer hydrological processes	• Complex soil profiles can affect results • Costly to purchase and run equipment • Require development of Inversion algorithms
Ground Penetrating Radar (GPR)	• Detecting buried archaeology • Developmental technique in soil moisture	• Non-invasive • Repeatable • Can cover large areas	• Difficult to interpret results • Needs specialist knowledge to operate • Costly

			- Waveform processing requires development
Neutron Moisture Meters (NMM)	- Soil moisture	- Long term monitoring - High level of accuracy - Repeated visits	- Requires a permanent vertical hole and access shaft for the probe (invasive) - Requires radiological safety process and procedures

Being able to determine estimates of soil moisture for a given point is possible with the techniques outlined in Table 1. However, their robustness depends on knowledge of soil composition and other factors controlling soil moisture, along with taking repeated samples for soil moisture content verification. Having representative soil samples from across a landscape that correlates with the locations of the moisture readings can support understanding of the influence that soil composition and soil structure may have on a soil moisture sensor's result. In addition to the composition is soil structure. Soil structure varies across a landscape and influences the moisture capacity of the soil (Brady and Weil, 2008). Therefore, exact values can be misleading if soil composition and structure are not considered. Within a heritage landscape, it is not desirable to take repeated soil samples at the point of measurement for soil moisture determination (for techniques used in Table 1), therefore, a representative scale can be a better approach.

In addition, these techniques are either invasive or measure at specific depths; the ability to depth profile moisture changes and variations is important when understanding the potential impacts changes in soil moisture may have on buried archaeology (Cassar and Pender, 2005). The research into the direct effects of changes in soil moisture and archaeological preservation is still growing, however, being able to non-invasively monitor soil moisture around these features would be a step in the right direction to allow for non-invasive monitoring.

1.2.3.3 Emerging technology: Microwave Moisture Sensor.

A new and novel technique which is quick and easy to deploy is Microwave Moisture Sensors (MMS), Moist 350b. MMS are a non-invasive technique that is inserted to the surface and uses deploys microwaves to determine the relative moisture properties of the substrate. MMS has three attachable sensors that can measure depths of 3cm, 11cm and 30cms. This allows for repeat sampling to be carried on in the same location without disturbing the surface or subsurface of the material being sampled.

MMS has traditionally been used for detecting moisture within stone and building fabric (Blaeuer and Benedicte, 2009, Møller and Olsen, 2011, Kurik et al., 2017, Orr et al., 2019), but not exclusively (Goller, 2006). Blaeuer and Benedicte (2009) conducted an initial study on the use of MMS on built cultural heritage. Their study advised that MMS were unsuitable for use in built cultural heritage, when determining exact moisture within walls. However, a recent study by Orr et al. (2019) has demonstrated that calibration curves for water content can be established using dry and known wet weighs of distinctive building stones used throughout the UK. This method provides a calibration for specific stone types and is affordable. The calibration was carried out on stone blocks suitable for laboratory handling. The testing in a controlled situation allowed for the difficulties and potential inconsistencies that may be found in the field, such as irregular distribution of moisture within the stone, to be controlled. Orr et al. (2019) further highlight that it is possible to develop material-specific calibration for different geo-materials, which give a material- specific characterised understanding of moisture.

Although the procedures for measuring moisture in stone using MMS are well established in cultural heritage, this non-destructive technique is not as well developed for monitoring soil moisture. Non-invasive detection of moisture within soil is becoming increasingly important, especially for monitoring heritage landscapes. MMS has been developed to make non-destructive surveying accessible (Goller, 2006) and therefore is considered an alternative to the techniques outlined in Table 1 (Section 1.2.3 Soil moisture monitoring techniques).

It is important first to establish the effects of a homogenous substance and the relationship between soil and moisture when using MMS moisture sensors (Kurik et al., 2017). Establishing this baseline is important as it can then be used to identify boundaries and causes for anomalies from MMS readings. By using a range of sensor heads at various depths, it then becomes possible to determine boundaries that affect moisture movement (Kurik et al., 2017). This is important for heritage landscapes as identifying areas or boundaries that prevent the movement of soil moisture could indicate areas required for further investigation or additional works to assist with preserving and protecting monuments, archaeology, and buildings.

The dynamic nature of heritage landscapes and the complex nature of their soils and buried artefacts, and cultural sediments makes heritage landscapes complex and often difficult to understand. Several high-technology techniques can be used to monitor soil moisture, but they are not appropriate for this study due to their inaccessibility for heritage practitioners (Table 1). In addition, repeat samples are often required, and invasive probes or access shafts need to be installed for the techniques outlined in Table 1 to be effective. From the use of MMS in buildings (Orr et al., 2019), it is predicted that MMS could potentially be used to identify subsurface moisture variation within heritage landscapes. As MMS is repeatable and non-invasive, it can facilitate repeat sampling to create an accurate representation of seasonal changes in soil moisture. However, the technique is untested but offers good opportunities to be widely applied within the heritage sector.

1.3 Hydrological Modelling.

Hydrological modelling is the determination of hydrological networks based on a topographic model. It can be used to determine subsurface hydrological movements through a soil profile or across a landscape's surface. Heritage landscapes Table 1 have many complex features, such as upstanding archaeology, visitor access and anthropogenic influences, which create micro-topographies within these landscapes. Understanding how these micro-topographies and hydrological networks interact and are influenced is important for determining the potential impact of climate change.

Hydrological modelling is increasingly recognised as an important management protection tool for cultural heritage sites, particularly with the development of information databases and GIS systems (Oikonomopoulou et al., 2017). Understanding soil surface moisture movement across a site makes it possible to determine the hydrological networks and how they interact and are influenced by archaeology. This is important as changes in rainfall regimes may lead to a change in these hydrological networks. However, there is little currently understood about the location and extent of these hydrological networks within heritage landscapes, along with the ability to model these landscapes using LiDAR-derived topographic models due to the intricate nature of these landscapes.

Once the hydrological networks of a heritage landscape have been identified to gain, a greater understanding of surface and subsurface water movement is possible. From knowing the physical soil properties and theoretically understanding how the properties will affect soil moisture movement, it is then possible to incorporate this knowledge into a model to map the potential movement of water. This results in establishing surface hydrological networks, which will provide insight of the potential movement of water across a heritage landscape, which can be coupled with soil properties to predict subsurface water movement.

Gaining an understanding of the surface hydrological interactions within a landscape will provide the potential to understand the impact that changing or altering a feature within a landscape will have on the hydrological networks (Christensen et al., 2004). Landscape surface hydrological models have various forms and scales and are at different levels of development (Jackson et al., 2013, Fatichi et al., 2016, Lewis et al., 2018). Landscape hydrological models have been used at a catchment scale to establish threats from flooding and how land use changes can affect flooding throughout a catchment (Jackson et al., 2013). There have also been models to establish the effect of urban development on flooding Fatichi et al. (2016), Lewis et al. (2018) highlight the variety and breadth of models, and emphasise the impact that small-scale ‘backyard’ models have and the benefits of stakeholder responsibility for land use changes. Gaining an understanding of the surface hydrological interactions that happen within a landscape will provide the potential to understand the impact that changing or altering a feature within a landscape will have on the hydrological networks (Christensen et al., 2004). Landscape surface hydrological models have a variety of different forms, scales and are at different levels of development (Jackson et al., 2013, Fatichi et al., 2016, Lewis et al., 2018). Landscape hydrological models have been used at a catchment scale to establish threats from flooding and how land use changes can affect flooding throughout a catchment (Jackson et al., 2013). There have also been models to establish the effect of urban development on flooding (Lewis et al., 2018). The variety and breadth of models is highlighted by Fatichi et al. (2016) who emphasise the impact that small-scale ‘backyard’ models have and the benefits of stakeholder responsibility for land use changes.

These landscape hydrological models could give a good overview of a site and provide the ability to model specific parts of a landscape from above and below ground. However, little is understood about the surface hydrological networks within a heritage landscape due to their micro-topographies and upstanding archaeology. Therefore, establishing a baseline of hydrological networks is essential before landscape scale modelling and interventions can be made.

Hydrological network modelling requires a good topographic model, and there are several different options for generating these models (Vivoni et al., 2004). Aerial documentation of the historic environment has had a rich history (Luo et al., 2019). Different techniques implemented to capture the historic environment from the air include hot air balloons, aircraft, drones and satellites(Luo et al., 2019) and continues to change with the advancement in technologies (Guo et al., 2019). LiDAR is a frequently used method of capturing large landscape areas associated with a monument (Wulder et al., 2012, Cowley, 2011). LiDAR can penetrate vegetation cover to give a true topographic profile (Li et al., 2015) and traditionally, LiDAR has been used to identify sites of archaeological interest (Hannon, 2018, Luo et al., 2019, Chase et al., 2012), within the cultural heritage sector, however, it has been much more widely used in the agricultural and oceanology sectors (Luo et al., 2019). LiDAR topographic models have also been widely used to create surface hydrological models for landscapes and basin catchments (Jones et al., 2008). LiDAR derived datasets have been shown to produce accurate hydrological models (Miller and Shrestha, 2013). Whilst fine-scale LiDAR data is commonly collected for archaeological documentation, it is not currently used to determine hydrological networks within heritage landscapes. Combining these two uses of LiDAR data sets could allow the development of small-scale hydrological models for heritage landscapes to aid the conservation and management of these unique landscapes. Hydrological network modelling requires a good topographic model and there are a number of different options for generating these models (Vivoni et al., 2004). Aerial documentation of the historic environment has had a rich history (Luo et al., 2019). Different techniques implemented to capture the historic environment from the air include, hot air balloons, aircraft, drones and satellites (Luo et al., 2019) and continue to change with the advancement in technologies (Guo et al., 2019). LiDAR is a frequently used method of capturing large areas of a landscape that is associated with a monument (Wulder et al., 2012, Cowley, 2011). LiDAR can penetrate vegetation cover to give a true topographic profile (Li et al., 2015) and traditionally LiDAR has been used to identify sites of archaeological interest (Hannon, 2018, Luo et al., 2019, Chase et al., 2012), within the cultural heritage sector, however it has been much more widely used in the agricultural and oceanology sectors (Luo et al., 2019). LiDAR topographic models have also been widely used to create surface hydrological models for landscapes and basin catchments (Jones et al., 2008). This use of LiDAR derived datasets has been shown to produce accurate hydrological models (Miller and Shrestha, 2013). Whilst fine scale LiDAR data is commonly collected for archaeological documentation, it is not currently used to determine hydrological networks within heritage landscapes. Combining these two uses of LiDAR data sets could allow development of small-scale hydrological models for heritage landscapes to aid conservation and management of these unique landscapes.

One of the benefits to using LiDAR data sets compared to traditional topographic terrains, such as 5m or 1m digital terrain models (DTM), is that of micro-topographies, areas of discrete hydrological influence, can be determined (Jones et al., 2008). When using traditional DTMs these discrete features are often smoothed over due to the lack of resolution in the topographic capture, and their influence on surface hydrology is reduced. For this reason, using LiDAR datasets with a fine-scale resolution is beneficial. Using a resolution at which archaeological features are captured would be desirable for heritage landscapes, as this will capture the anthropogenically generated micro-topographies within a complex landscape. Currently LiDAR derived topographies are between 0.5m and 0.25m resolution within heritage landscapes, making it suitable for determining hydrological networks and understanding micro-topographies' influence on water movement. Within heritage landscapes, these discrete and intricate features create micro-topographic features and may play a more significant role in the influence of hydrological networks than the overall general topography.

This factor is important in this research, which aims to understand these micro-topographies' influence on hydrological movement across discrete heritage landscapes. Thomas et al. (2017) further highlights that the finer resolution data gives a clearer understanding of the key factors of water movement, which further highlights the need to use a fine-scale definition of data. Heritage landscapes can have complex topographies; therefore, exploring the options and scales of currently available data will aid understanding in this sector.

Once LiDAR data is collected, it requires processing before it can be used as a base topography model. LiDAR data requires basic processing to transform the data from a point cloud into a topographic model. A widely used method of doing this is to use a Triangulated Irregular Networks (TIN). These can be used to create effective surface models that can be used for hydrological processing (Freitas et al., 2016). One factor Freitas et al. (2016) highlights is that TIN models can often minimise hollows, dips, and flat areas. This could pose a problem when understanding hydrological flows on complex archaeological landscapes, where these features are often abundant. Despite this Freitas et al. (2016) further go on to highlight that TIN models are efficient at predicting the locations of hydrological networks, which align with present drainage networks found within a landscape.

LiDAR data has a high accuracy and spatial resolution and can also be used to generate accurate Digital Elevation Models (DEM). Using an increase in the resolution of DEMs can also increase the micro-features that influence hydrological regimes (Thomas et al., 2017, Clarke and Archer, 2009). However, as archaeological features are present within the LiDAR data these will show the effects of archaeological features on hydrological networks.

Therefore, it is important to consider the influence that the DEM resolution will have when studying the overall hydrological influences of a heritage landscape. DEM creation is not without its flaws and is highly dependent on the source data that is used to create them (Goulden et al., 2016). Hydrological modelling has been carried out on LiDAR derived DEMs with relative success, but also acknowledged errors (Goulden et al., 2016). , the resolution of data can greatly affect the accuracy of the outputs required. Fine scale DEMs have been used to establish soil loss and flow accumulation (Eagleston and Marion, 2020). The scale of the DEMs affected the accuracy and the representation of soil erosion, as when this was looked at in the larger scale the detail was lost (Eagleston and Marion, 2020). Eagleston and Marion (2020) further highlights that a resolution of less than 0.5m would allow for an accurate determination of local influencing factors of soil loss on footpaths.

Further to the overall quality of the data sets is the topography of the landscape, areas of high relief (Goulden et al., 2016) and low relief (Amatya et al., 2013, Poppenga and Worstell, 2013), as both of these extremes can create errors with in the hydrological modelling. However, identifying that these areas cause influence within low relief areas is essential, and the influence that they exert on hydrological flows within heritage landscapes is important to understand.

Early hydrological network models developed by Beven and Kirkby (1979) have been widely accepted and further developed. There is a now a variety of hydrological flow regime models, D8 being the most common and widely used (Ariza-Villaverde et al., 2015) in GIS modelling.

The D8 technique has been successfully used in areas of low relief (Amatya et al., 2013, Poppenga and Worstell, 2013). Common errors that are associated with D8 modelling in low topographies are those of wrong river direction(s) on convex slopes, along with those of parallel flows (Jones, 2002, Paz et al., 2010). Both of these errors can be easily identified through the visual output that the hydrological mapping process generates and can be taken into consideration at each stage of the process. Despite this D8, it is the most accurate widely used technique that is available for developing a base understanding of hydrological mapping within heritage landscapes.

Persendt and Gomez (2016) have further described the use of several different methods for determining drainage networks in areas of low topography. After the initial processing of LiDAR data at a 2m resolution, the use of the D8 algorithm for determining stream orders was effective. This highlights the suitability of using already derived algorithms to determine drainage networks in heritage landscapes.

1.4 Introduction Summary

Soil properties play a key role in the regulation of water movement within a landscape. This is also true for a heritage landscape. However, soil properties are not the only factor that controls water movement. Visitor infrastructure, upstanding buried archaeology along with modern infrastructure also play a role in how water can move through a heritage landscape.

Soil properties along with surface topography can affect the movement of water over and through heritage landscapes. It is understood that visitor pressures affect soil properties through infrastructure and their movements across a heritage landscape. Therefore, it is important to understand the areas affected by visitor pressures to understand the effects it has on subsurface hydraulic networks across a site. This is important as with increased rainfall, the hydrological networks across a heritage landscape may change over time.

It is important to gain a baseline understanding of surface hydrology networks within a heritage landscape to understand the effects that changes in pluvial regimes may have. LiDAR is widely used within the heritage sector for documenting heritage. Through using fine-scale data sets it is possible to map the hydrological networks of a heritage landscape and determine the potential interactions between the hydrological networks and archaeological features. Thus, a base line understanding of the current hydrological networks within the heritage landscape can be developed. From this, areas that are perceived to be at greatest threat from changes in pluvial regimes can be identified and monitored, along with measures put in place to mitigate the effects of increased rainfall.

1.5 Research aims and objective

From the gaps identified within the literature, this research will address the potential impact of changes in precipitation on heritage landscapes. This research will use the UKCP18 data sets to understand regional variability in precipitation regimes to 2080. It will also address the ability to non-invasively monitor changes in soil properties by using a new technique (MMS). In addition, it will look at the ability to use topography data derived from LiDAR to map the hydrological networks within heritage landscapes and the influence of upstanding archaeology and visitor infrastructure.

The overall research aim of this study is to determine hydrological networks within heritage landscapes and how visitor footpaths and upstanding archaeology influence this. The research of this project falls into two distinct threads. Firstly, can MMS be used to determine near subsurface soil moisture impacts from visitors? Secondly, can LiDAR data be used to determine surface hydrological networks within a heritage landscape, especially in areas of low topography or where no stream network is present? Finally, this data will be used to highlight areas within the heritage landscapes, which we predict may see more pronounced change as a result of altered pluvial regimes due to climate change.

This study will consider soil compaction and its location within a heritage landscape. The study aims understand the subsurface hydraulic activity in areas subject to compaction, which is determined through a non-invasive method.

The objectives of this research are specific and directly focused on key components of the heritage landscape.

1. Develop a new technique to determine the near surface impact of visitor pressures on site, using Microwave Moisture meters (MMS).
    a. Develop an infield technique for use of MMS focussed on determining the impact of key visitor features (footpaths, signboards and lines of desire) (Chapter 3. Methods and methodological development)
    b. Determine the impact of key visitor features on soil properties in two different WHS landscapes (Chapter 4. MMS field surveys for the applicability of using MMS for landscape scale monitoring of soil moisture).

2. Hydrologically model three WHS using topography derived from DEMs to understand the influence of upstanding archaeology and visitor infrastructure. (Chapter 5. Hydrological modelling of WHS for determining hydrological networks to establish the effects of upstanding archaeology and visitor infrastructure in heritage landscapes.)
    a. Explore hydrological modelling of stream and stream-less heritage landscapes to create a baseline understanding for different heritage landscapes (Chapter 5. Hydrological modelling of WHS for determining hydrological networks to establish the effects of upstanding archaeology and visitor infrastructure in heritage landscapes.).
    b. Determine the impact of upstanding archaeology on hydrological networks (Chapter 5. Hydrological modelling of WHS for determining hydrological networks to establish the effects of upstanding archaeology and visitor infrastructure in heritage landscapes.).
    c. Determine the possibility of combining MMS and hydrological networks data sets (Chapter 6- Exploring the connections between MMS and Hydrological Networks).
3. Explore the predicted changes in precipitation patterns by 2080 and the influence this might have on hydrological networks within heritage landscapes.
    a. Establish the predicted changes in pluvial regimes at three WHS and the theoretical impact this will have on the hydrological networks (Chapter 7. Climate Change: Precipitation and its Hydrological Implications for Heritage Landscapes).

This research will produce a baseline understanding of hydrological networks and soil properties around key visitor features of three WHS in distinct geographic and climate regions within in Scotland. This exploratory study will develop approaches that can be applied to other heritage landscapes.

Chapter 2. Site Selection and Research Design

This study aims to determine hydrological flows within heritage landscapes with two distinct strands, using MMS for near-surface soil moisture and surface hydrological mapping using LiDAR. This chapter will introduce the three selected study sites, and the impact of Covid-19 on this research will be outlined.

2.1 Research Design

Three WHS have been selected throughout Scotland to explore the aims outlined in Section 1.6. They are the Ring of Brodgar, Heart of Neolithic Orkney; Rough Castle, The Antonine Wall; and St Kilda (Figure 9). These landscapes were chosen because they vary in location, topography, geology and soil type, as well as the archaeological time periods and features. This approach will give an understanding of the impact that footfall, hydrology, and changes in pluvial regimes will have on a wider range of different heritage landscapes. In addition, they are located in three separate regions that are predicted to have different changes in rainfall regimes by 2080. It is important to understand the impacts that changes in precipitation regimes will have on different regions of Scotland and its heritage.

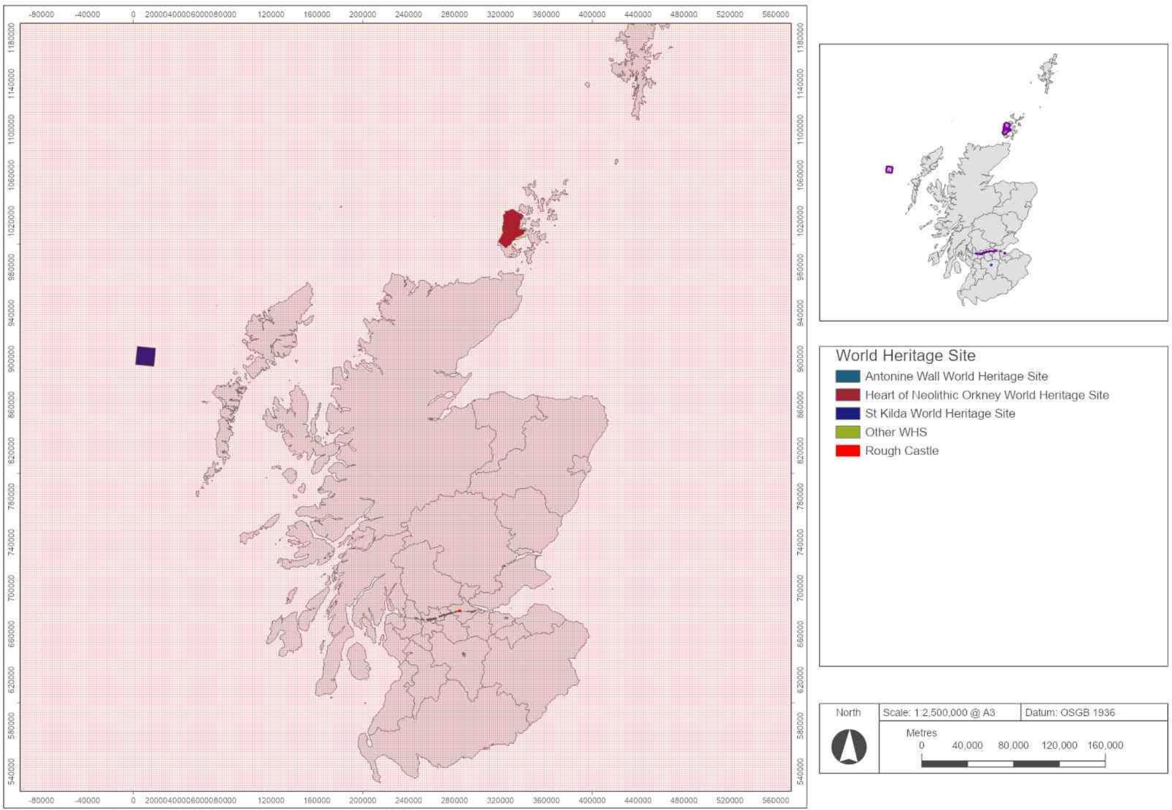

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Figure 5 Map of Scotland showing the locations of World Heritage Sites

Determining a baseline for hydrological interactions in heritage landscapes through non-invasive techniques is a unique approach for aiding site understanding. Developing two techniques that are novel in their application, both to heritage landscapes and the scale at which they are being applied, makes the application of this research distinctive. Developing two techniques that are non-invasive and can capture the above and below- ground hydrological interactions, will result in approaches that can be used to monitor heritage landscapes and determine the possible impacts of climate changes. Additional impacts could come from visitor interactions on- site, or hydrological networks, or a combination of both. Having two complementary techniques that do not disturb the hydrological networks will allow for the continual monitoring of these impacts without further disturbance to the landscape taking place. Within the context of this study focus will be on key visitor features and hydrological networks.

Both techniques will establish a baseline for understanding the hydrological networks that are currently present within a heritage landscape. It is important to establish this baseline within this research, to demonstrate the current location of these hydrological networks and to allow for their future monitoring. This baseline research is important due of these hydrological networks. Due to mapped hydrological networks not having been established on heritage landscape previously and the small geographical areas that they are being applied to, makes this baseline even more important. Through this baseline, it will become possible to develop a greater understanding of the hydrological networks in PICs and on site, how these interact with features within the landscape, along with and how future works may impact them. This baseline will allow heritage practitioners to gain an understanding of what is currently happening with the hydrological networks within a heritage landscape.

Further to the non-invasive nature of the techniques is that MMS is a relatively low-cost piece of equipment. In comparison, LiDAR data is costly to capture, although there are more methods are coming on to the market that can be used for a variety of different applications within the heritage sector. There are national datasets of LiDAR data that can be accessed; however, these are limited in coverage of Scotland and only captured part of one site within this research, Rough Castle.

Ring of Brodgar and Rough Castle will be used to explore Objective 1. Develop a new technique to determine the near surface impact of visitor pressures on site, using Microwave Moisture meters (MMS). In order to achieve this, MMS will be used to establish the impact that visitor footfall is having on the current path network. All three sites will be used to explore Objective 2, Hydrologically model three WHS using topography derived from DEMs to understand the influence of upstanding archaeology and visitor infrastructure. (Chapter 5. Hydrological modelling of WHS for determining hydrological networks to establish the effects of upstanding archaeology and visitor infrastructure in heritage landscapes.). This will establish the small-scale interactions between archaeological features and hydrological movement across a heritage landscape. Through carrying out the first two objectives on the sites, it will then be possible to address Objective 3, Explore the predicted changes in precipitation patterns by 2080 and the influence this might have on hydrological networks within heritage landscapes. As all three sites are expected to have different changes in rainfall regimes, it will be possible to explore the potential impacts that these changes will have on these sites, as well as the wider heritage landscape.

Table 2 Connections between Sites, Techniques and Objectives

Site	MMS Survey	Hydrological mapping	Objective
Ring of Brodgar	Yes	Yes	1, 2, 3
Rough Castle	Yes	Yes	1, 2, 3

St Kilda	No	Yes	2, 3

2.1.2 COVID-19 Impacts and Schedule Monument Consent

COVID-19 (subsequently abbreviated to ‘Covid’ in the narrative text) has impacted this research in two ways. The first of which was the cessation of field work. MMS is an experimental technique, and the aim was to use it at Rough Castle and Ring of Brodgar for seasonal surveying to determine changes in soil moisture and the applicability of using this technique. The field work at St Kilda was planned for one week in 2020 to monitor the impact of upstanding archaeology on soil moisture. However, the inability to travel outside council areas prevented any field work. Additionally, once lockdowns had been lifted, the university limited the ability to travel throughout Scotland, and timescales were not sufficient to enable repeated field visits before the end of the funding period. The second way that Covid impacted this research was due to the change away from developing an understanding of the impacts that technosol installation in a heritage landscape could have on soil hydraulic activity. Due to the inability to access a laboratory to conduct initial research at the start of covid; this research section quickly changed to hydrological mapping. Hydrological mapping was not planned initially within the research, and as a result, the skills, knowledge and support for processing LiDAR data and hydrological modelling has been self-taught, with minimal support from the University of Stirling.

Scheduled Monument Consent (SMC) was required before sampling could take place at Rough Castle or Ring of Brodgar. The process takes around 13 weeks once an application has been submitted. Prior to this, there was three months of discussions with different departments within HES. These ranged from architects to site managers and the Planning, Consents and Advice Service. Overall, this process set the project back six months. MMDC was also applied for at this time but was subsequently not required. As this research is part funded by HES, it would be advised that the SMC process is started, or a different type of research consent is made available, prior to PhD programmes commencing.

2.2 Study Sites

Table 3 provides an overview for the three study sites and their characteristics along with their general period of classification.

Table 3 An overview of the three study sites

Site	Period	Archaeology	Geology	Soil	Visitor Pressure

Ring of Brodgar	Neolithic	Standing Stones, Burial mounds, ditch	Upper Stromness flagstone, overlain by superficial Devensian	Brown Earth	Cruise ships- summer Short high intensity footfall
Rough Castle	Roman	Turf Wall, Ditch, buried Military Way and structures	Scottish lower coal measure formation	Mineral Podsol	General public- dog walkers John Muir Way
St Kilda	Modern	Stone buildings, Farming systems	Igneous	Plaggic	Tour boats- summer Short intense footfall

2.2.1 Ring of Brodgar

2.2.1.1 Archaeology

The Ring of Brodgar forms one of the monuments included in the Heart of Neolithic Orkney (HONO) inscribed as a WHS (UNESCO, 2005). The HONO provides a fundamental understanding of the Neolithic period and illustrates the complex social structures of this period. The lack of urban development within the Orkney landscape allows the formal connections between HONO monuments to be studied and understood, of which Ring of Brodgar is one.

The Ring of Brodgar (Canmore ID: 1696) consists of a ring of 36 standing stones that is bordered by a ditch and has burial mounds located throughout the PIC (Canmore ID’s: 1701, 1702, 1703) (Figure 6). The Ring of Brodgar is bound on the west by a sea loch and the east by a road and freshwater loch, with agricultural fields to the north and south (Figure 6). Ring of Brodgar’s prominent position within the landscape and being located on a narrow strip of land makes it iconic and recognisable.

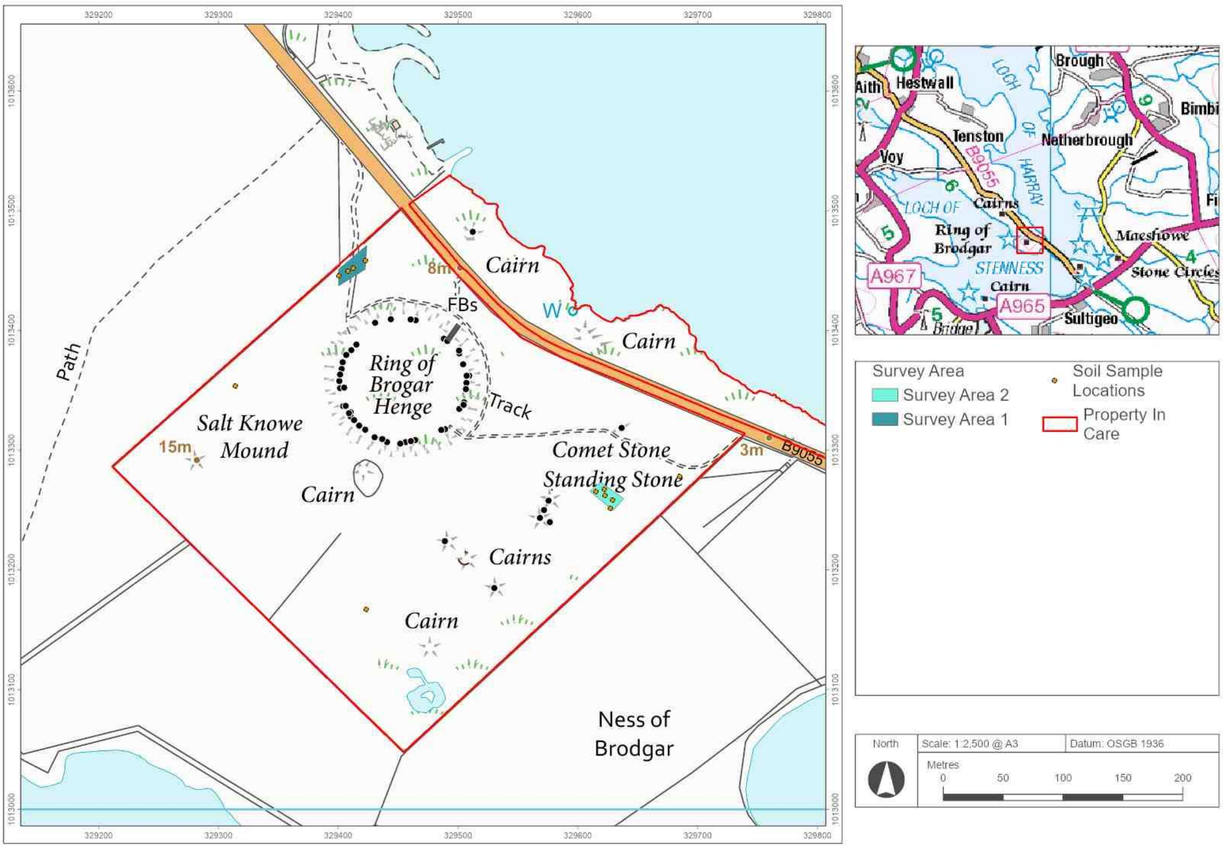

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Figure 6 Ring of Brodgar PIC (highlighted in red) with the key archaeological features, along with the main access path to the north and the path exiting the site to Stones of Stenness to the east. Survey Area 1 is in the north of the PIC, with Survey Area 2 in the east. Soil sample locations are shown by points.

2.2.1.2 Visitor pressures

Ring of Brodgar attracts large numbers of visitors each year, and pre-Covid saw around 125,000 visitors annually. This is due to an increase in tourism in Orkney, partly driven by an increase in cruise ships. The arrival of cruise ships results in large numbers of people visiting the site for short, intense periods of activity. This created a concentrated time constraint of on-site interaction and in specific areas of a site. This increase in visitor pressure is not unique to the Ring of Brodgar; however, the ability to monitor the number of people accessing the site and the locations makes it ideal for carrying out research on the impact that this level of visitors is having on a heritage landscape.

2.2.1.3 Geomorphological setting

The Ring of Brodgar is located 10m above sea level, with the highest point of the heritage landscape reaching 16m (Canmore ID: 1701). The general topography of the site is gently rising undulating ground from the east and west from sea level to 16m (Figure 7). The land from the south and north also gently rises to 16m in the centre of the PIC. The burial mound (Canmore ID: 1702) is the highest location at 16m within the area being surveyed to the north and south. As the site is boarded by a sea and freshwater loch on the east and west, the distances to the highest points have not been included, as they are outside the area studied.

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Figure 7 Topography of Ring of Brodgar, PIC highlighted in red, and neighbouring landscape. Highest elevation point is 16m found to the south of Ring of Brodgar.

2.2.1.4 Soil and geology

The Geology underlying the Ring of Brodgar is sedimentary Upper Stromness flagstone, which is overlain by a superficial Devensian (British Geological Survey, 2021). The dominant local soil type is a brown earth (The James Hutton Institute, 2021) (Figure 8); however, the soils within the PIC at Ring of Brodgar are freely and imperfectly drained podzols (The James Hutton Institute, 2021). Geology underlying the Ring of Brodgar is sedimentary Upper Stromness flagstone, which is overlain by a superficial Devensian (British Geological Survey, 2021). The dominant local soil type is a brown earth (The James Hutton Institute,

2021) (Figure 8), however, the soils within the PIC at Ring of Brodgar are freely and imperfectly drained podzols (The James Hutton Institute, 2021).

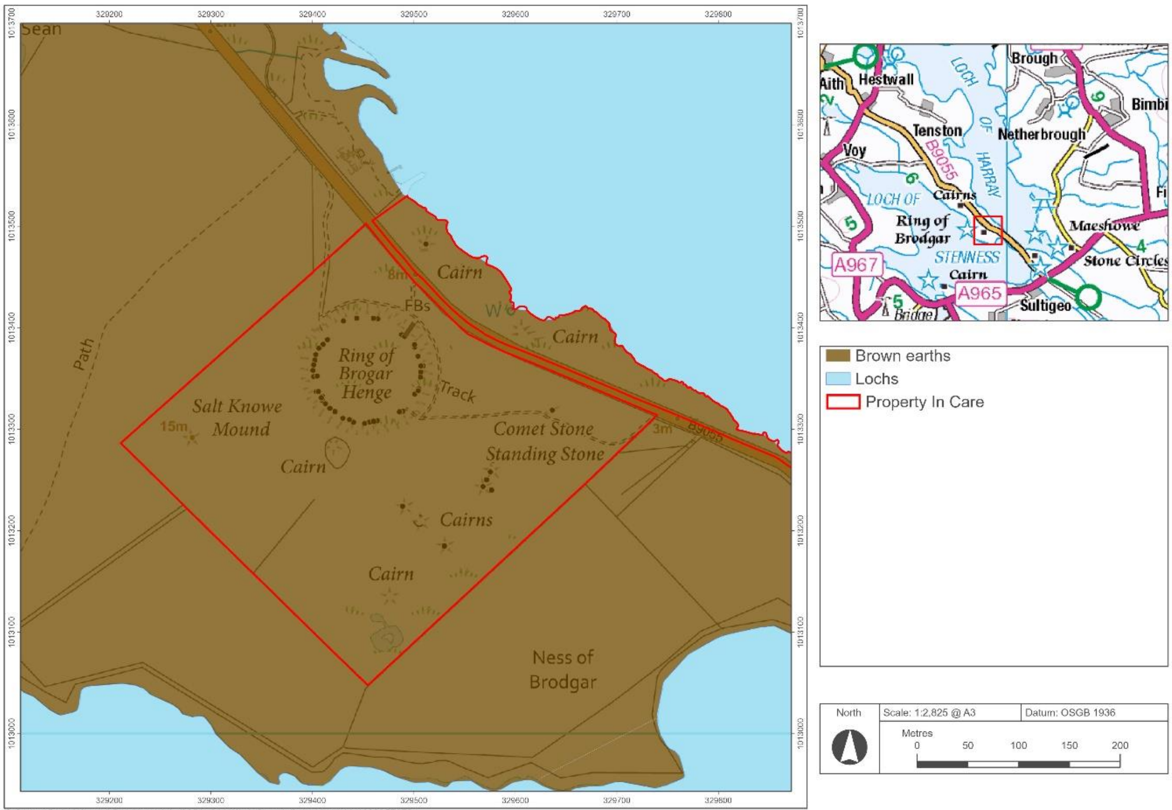

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Figure 8 Brown earths are the soil type for the Ring of Brodgar PIC area and surrounding landscape.

2.2.1.5 Climatological setting

The closest weather recording station to the Ring of Brodgar is the Met Office recording station in Kirkwall (Met Office, 2019). The averages have been taken from the 30-year period 1991-2020, to indicate the current climate in Orkney. In general, the Ring of Brodgar receives 1,048 mm per year of rainfall, with October to February being the wettest months where there is rainfall recorded on more than 20 days of the month. The driest months are May and June, with less than 15 days of rainfall. May receives the most sunshine (193.49 hours), with July recording the highest temperatures averaging 16 ^{o}C.

The projected changes in climate for Orkney by 2050 are a 20% increase in precipitation during the winter months, with summer months receiving similar rainfall. The temperatures of both summer and winter months are likely to increase by 1-2 ^{o}C. The full impact of the changes in precipitation will be explored in Chapter 7 (Met Office, 2020).

2.2.1.6 Survey areas

Figure 9. SA1 at Ring of Brodgar looking to the northeast, showing the main access path with the middle rested section between the white ropes (5m wide). White tapes indicate transects for MMS

At the Ring of Brodgar two survey areas were established; the first included the main access footpath and adjacent landscape (SA1) (Figure 6 and Figure 9); this is the path on which most of the visitors enter and exit the site. The path is approximately 30m wide, and, there is no hard engineering or constructed footpath in place, although there is the implementation of a rotational barrier in which the footpath is migrated across this area between April and October. The rotation barrier controls the direction and flow of visitors to the site, along with the grass being maintained from April to October. The second area (SA2) is a line of desire on the opposite side of the site (Figure 6 and Figure 10). The line of desire is located on the opposite side of the site from the main access path. The path is 0.5m wide and not frequently visited. These two paths receive vastly different types and numbers of visitor interactions yet have the same soil type and geology. This makes these two areas a good comparison to understand the impact that visitor pressures are having at Ring of Brodgar. SA1 had a survey on the 10th March 2020 using the 11cm and 30cm sensors, and on the 14th March 2020 with the 3cm, 11cm and 30cm sensors. The 3cm sensor was not used on the 10th March 2020 due to battery issues. SA2 had a survey on the 10th March 2020 and 14th March 2020 with the 3cm, 11cm and 30cm sensors.

Figure 10 SA2 Desire line located in the centre of the image with unmanaged vegetation on either side, looking southwest.

2.2.2 Rough Castle

2.2.2.1 Archaeology

The Antonine Wall is the northern most reach of the Roman Empire in Scotland. The Antonine Wall spans the width of central Scotland and was constructed around 142AD (Robertson, 1960). It was once a continuous turf wall and ditch with several forts and fortlets along its length (UNESCO, 2008). The Antonine Wall demonstrates the development of technical and cultural skills by the Romans in constructing turf and stone defences. The remains of the Antonine Wall are a snapshot of time and infrastructure brought by the Romans to Scotland. One of the best-preserved forts is Rough Castle, situated towards the eastern end of the Antonine Wall (Canmore ID: 46803). The fort, defensive ditches and internal layout, including the annex and bathhouse, are well preserved and documented and have improved our understanding of how the forts along the Antonine Wall were arranged.

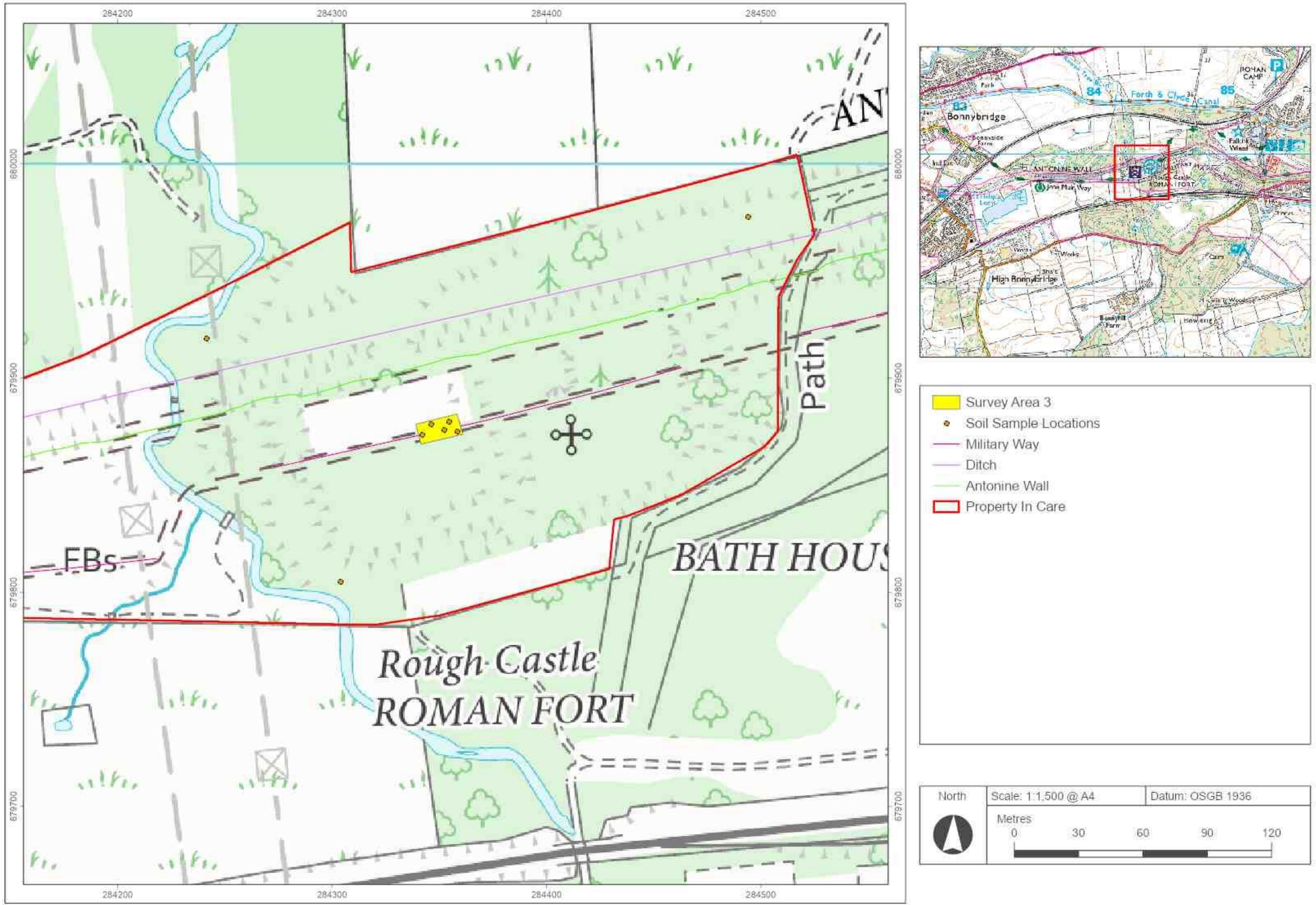

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Figure 11 Rough Castle PIC (outlined in red), the Antonine Wall and Ditch is denoted with the dashed lines in the north of the PIC. The hatched lines indicate the direction of the slope of defensive ditches. The Military Way is the double dashed line in the centre. SA3 is shown in Yellow on top of the Military Way. Location of the soil samples is shown by points.

2.2.2.2 Visitor pressures

Rough Castle forms part of the John Muir Way, a popular walking route through central Scotland. As Rough Castle is close to the town of Falkirk, the site is used as a recreational space and is popular with local walkers and dog walkers. This results in around 80,000 visitors to the site annually and receives visitor pressure throughout the year. Visitors can move through or across the site at their own time and pace, compared to Ring of Brodgar, where visitors are often time constrained. Rough Castle also has signboards placed throughout the site. These create areas of wear from visitors stopping at the signboards.

2.2.2.3 Geomorphological setting

The topography at Rough Castle is complex due to the remains of the Antonine Wall, Ditch and fort (Figure 11). In the north of the PIC is the Wall and Ditch; they are well preserved. In the western end, and centre for this study, of the PIC is the fort itself. The fort has been extensively excavated between 1902-03 and in 1932 (Robertson, 1960) (Canmore ID: 46803). Also, see Canmore, which gives a detailed understanding of the fort layout and the use of the buildings. To the east, south and west, there is a series of defensive ditches to protect the fort. The Military Way runs through the centre of the fort top and a bypass runs to the south of the fort. There are several turf mounds within the fort top to outline the location of buildings.

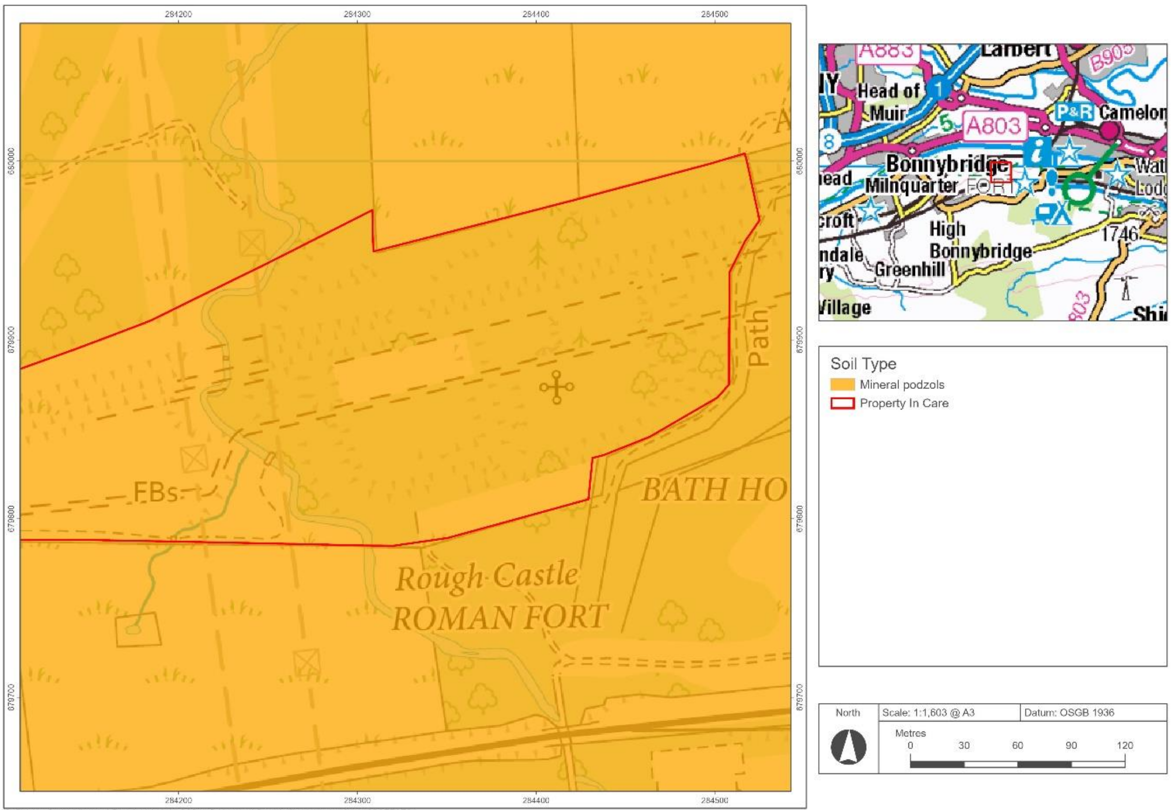


Figure 12 Soil type for Rough Castle is Mineral Podzol

2.2.2.4 Soil and geology

The geology at Rough Castle is complex and consists of two discrete geology types. The first is the passage formation, a sedimentary formation on the west of the site, and the second is the Scottish lower coal measure formation on the east. Rough Castle has three superficial deposits overlying the bedrock geology. These are a north-south seam of alluvium along the line to Rowan Tree burn, Devensian till to the east and west of Rowan Tree burn and a raised marine deposit in the north of the site. There are also two discrete areas of superficial sediment deposits: Raised Marine Deposits (Devensian) located to the north, and a Till (Devensian) south of the site (British Geological Survey, 2021). The soil at Rough Castle is a mineral podzol (The James Hutton Institute, 2021).

2.2.2.5 Climatological setting

The closest weather station to Rough Castle is the Stirling recording station (Met Office, 2019). The averages that follow have been taken from the 30-year period 1991-2020, to indicate the current climate for Rough Castle. Rough Castle generally receives 1,018mm per year of rainfall, with October to February being the wettest months. There is only one month, April, where there is rainfall recorded on less than 15 days of the month. May received the most sunshine (183.13 hours), with July recording the highest temperatures averaging 19^{o}C.

The projected climate change for Rough Castle by 2050 is a 10% increase in precipitation during the winter and summer months. The temperatures of both summer and winter months are likely to increase by 1-2 ^{o}C. The full impact of the changes in precipitation will be explored in Chapter 7 (Met Office, 2020).

2.2.2.6 Survey areas

Figure 13 SA3 at Rough Castle the main access line of desire is in the centre of the image between the trees, the link bridge is located on the left of the image. The white tapes mark the extent of the survey area.

One survey area (SA3) was established at Rough Castle, located within the fort and on top of the Military Way. The survey area encompasses one of the main footpaths through the site, two visitor interpretation panels and two footpaths that connect to the main footpath (Figure 11). The main footpath is 1m wide, although the exact widths of the two connecting footpaths could not be determined

2.2.3 St Kilda

2.2.3.1 Archaeology

St Kilda was the first World Heritage Site inscribed in Scotland and has a mix of natural and cultural heritage designations (UNESCO, 2005). St Kilda forms the most western archipelago in Scotland and demonstrates how people adapted and survived in harsh and challenging environments using traditional techniques which have now died out, mainly reliance on seabirds. The WHS hosts some of the best-preserved field systems and traditionally built structures of the Highlands (Canmore ID: 9661). The cultural landscape has remained relatively unchanged since its abandonment in 1930. St Kilda is currently maintained by the National Trust for Scotland through minimum interventions to maintain the landscape (UNESCO, 2005). The main island of St Kilda, Hirta, hosts the remains of the inhabited buildings, cemetery and main street (Figure 14). In addition, the bounding headwall of the Village Bay and approximately 1,260 cleits (stone storage huts) spread across the island. St Kilda will be used to denote general discussion around the archipelago, whereas Hirta will be used in direct discussion relating to the main island.

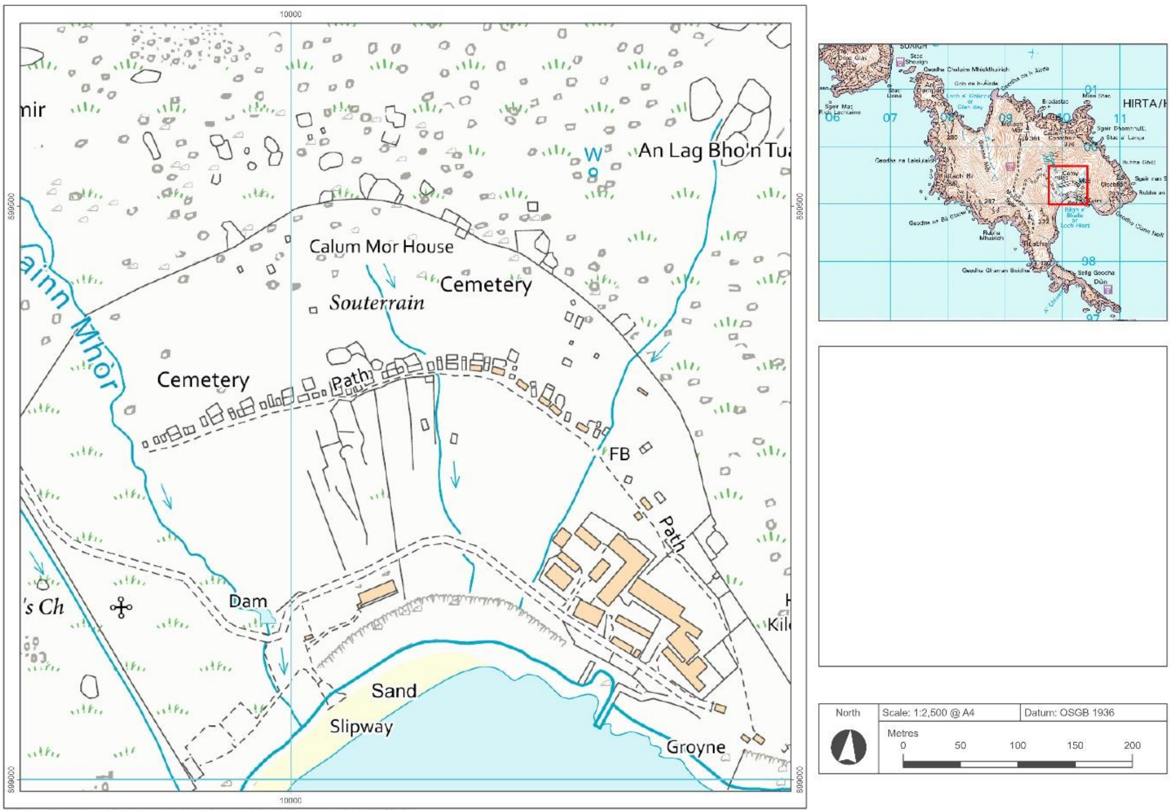


Figure 14 shows Village Bay on Hirta, St Kilda and the location of upstanding archaeology. The headwall is the solid back line surrounding the village.

2.2.3.2 Visitor pressures

St Kilda can only be accessed during the summer months when the island is staffed by National Trust for Scotland (NTS) and the day trip companies can operate. As a result, the number of visitors each year to St Kilda is limited and is relatively low for a WHS, with approximately 5,500 visitors. There are no formal path networks on St Kilda; however, there is a Military access road across Village Bay up to Mullach, along with the historic main street, which still forms the main access path to the buildings in Village Bay.

2.2.3.3 Geomorphological setting

St Kilda is an archipelago consisting of several islands; this study's focus will only be on Hirta, the largest and only inhabited island in the archipelago. The island’s highest point is Conachair at 430m, and its north face is 427m of sea cliffs (Figure 15). Village Bay is on the south of Conachair and contains the largest settlement remains on the island. This is where the main population of Hirta lived and worked. The dwelling, field structures and cleits are well preserved in Village Bay. Further settlement remains are located at Gleann Mor bay on the north-west coast. Village Bay and Gleann Mor are amongst the few areas where there is safe access to the sea. The rest of the island is framed by dramatic sea cliffs.

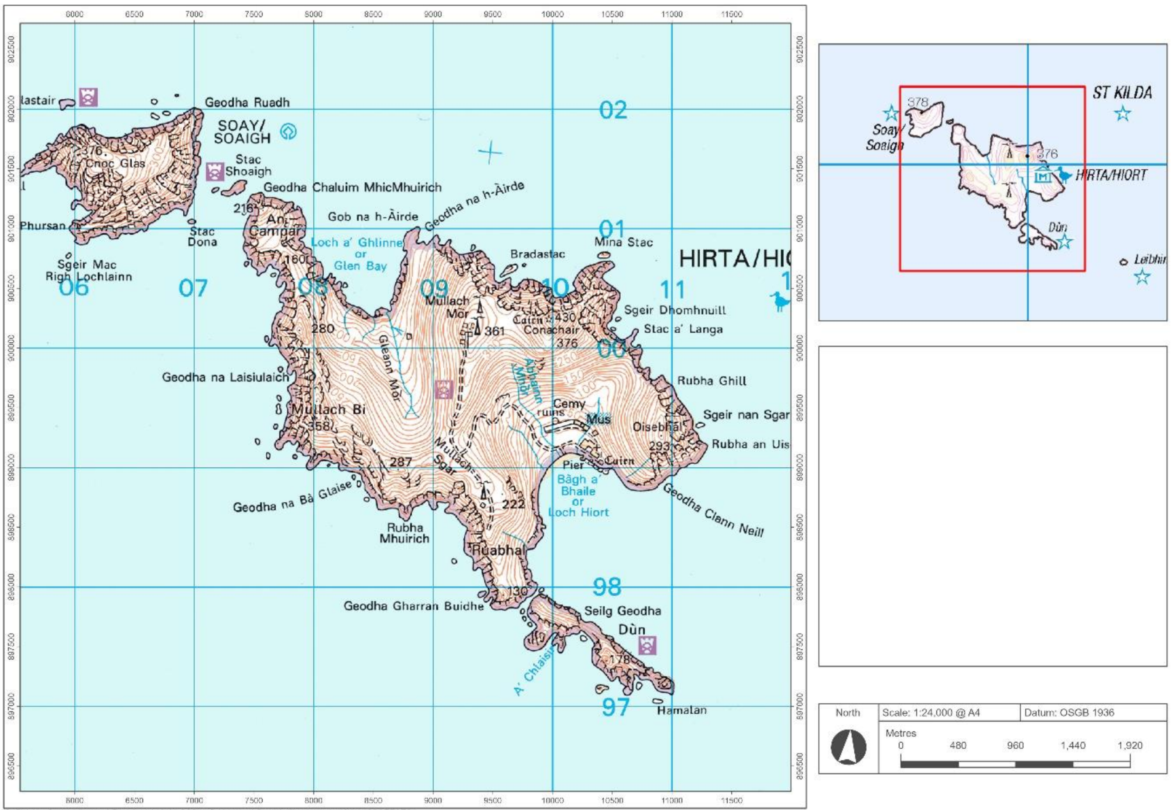


Figure 15 shows the topography of Hirta, with the highest point of Conachair.

2.2.3.4 Soil and geology

The geology of St Kilda is not recorded in the BGS national database (British Geological Survey, 2021), and the available soil data from The James Hutton Institute does not have a record of soils on St Kilda (The James Hutton Institute, 2021). However, the archipelago is composed of igneous formations (Meharg et al., 2006) and the soils of Village Bay soils are known to be plaggic in formation, having been artificially deepened through human activity (Donaldson et al., 2009). The geology of St Kilda is not recorded in the BGS national database (British Geological Survey, 2021)and the available soil data from The James Hutton Institute does not have a record of soils on St Kilda (The James Hutton Institute, 2021). However, the archipelago is composed of igneous formations (Meharg et al., 2006) and the soils of Village Bay are known to be plaggic in formation, having been artificially deepened through human activity (Donaldson et al., 2009).

2.2.3.5 Climatological setting- current climate and projected climate

The closest climate station to St Kilda is on South Uist, and these data have been used to infer the climatological setting of St Kilda. The averages have been taken from the 30-year period 1991-2020, to give an indication of the current climate in South Uist. In general, South Uist receives 1,202mm per year of rainfall with October to March 2020 being the wettest months where there is rainfall recorded on more than 20 days of the month. The driest months being April to July with less than 20 days receiving rainfall. July records the highest temperatures averaging at 16°C, there is no sunshine hours recorded for South Uist.

The projected changes in climate for South Uist by 2050 is a 30% increase in precipitation during the winter months with summer months receiving a 10% increase in rainfall. The temperatures of both summer and winter months are likely to increase by 1-2 °C. The full impact of the changes in precipitation will be explored in Chapter 7 (Met Office, 2020).

2.2.3.6 Survey areas

Due to covid restrictions, there was not physical survey carried out on St Kilda or soil samples taken. Hydrological modelling will be carried out on Hirta only with a particular focus on Village Bay and the interactions with upstanding archaeology.

Chapter 3. Methods and methodological development

This chapter will outline the methods and interpretation processes for MMS which is used in subsequent chapters. As both techniques, MMS and hydrological modelling, are experimental, this chapter will outline the methods undertaken to determine the best practice approach for this research.

3.1 Method for MMS Data Processing and Visualisation

In this section, the operation of the MMS will be outlined, and the complexities that visualising the data present will be outlined. Representation of the data collected by the MMS is challenging. We know that the sensors send out a ‘bubble’ of microwaves to determine a response for each reading. This ‘bubble’ encapsulates the shallower 'sensor’s depth within them (Figure 16). The volume of the ‘bubble’ produced is known when the technique is used on stone and hence the response can be calibrated (Orr et al., 2019). However, in a soil profile the response bubble volume is unknown, and there was not scope within this research to calibrate for any specific soil type due to the Covid-19 pandemic, let alone the two different types found on site at Ring of Brodgar and Rough Castle. The instrument uses different sensor heads for recording data from deeper depth, the deeper the sensor head used, the bigger the ‘bubble’ volume. Therefore, it is assumed that as the sensor's depth increases, it also captures the reading that from the previous sensor. Each depth sensor is a separate unit; therefore, the sensor readings are not consecutive. It is further known that the sensors are more sensitive to ‘moisture’ closer to the surface than at depth, despite the volume at depth being greater (Orr et al., 2019). Thus, with an increase in soil moisture the transmissibility of the sensors is increased. As the sensors operate in microwaves, the attenuation of the waves, can change in different mediums, in this case an increase in soil moisture could result in the waves traveling further, hence an increased response.

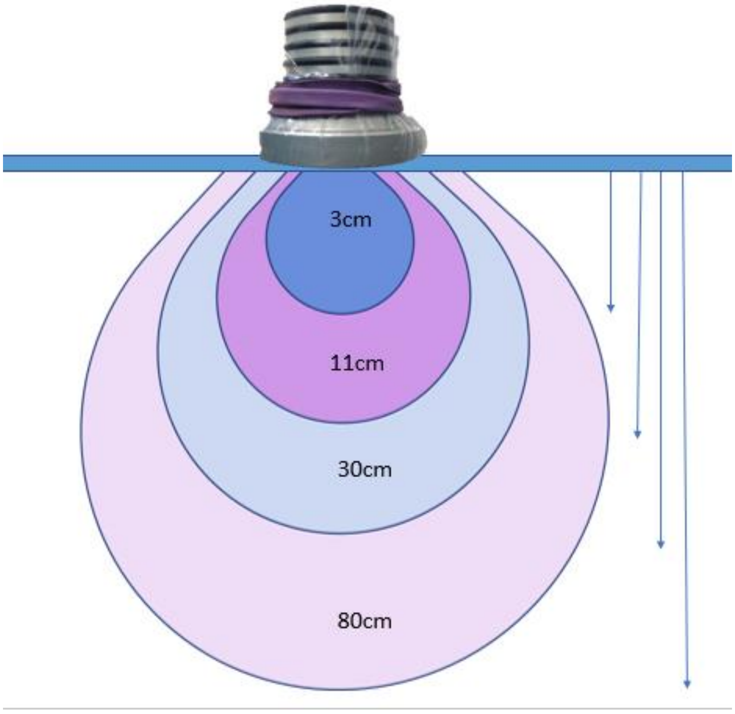


Figure 16 MMS sensor 'bubble' of microwaves for each sensor. Each bubble represents a different sensor head, the readings cannot be taken sequentially. Arrows indicate the perceived direction of the bubble and potential depths.

For this reason, these multiple methods have been trialled for the representation of the data. We looked at the Monte-Carlo method, which uses computational algorithms to predict a probability distribution of fluids, along with factors that require multiple degrees of freedom to interact. Due to the technique being a new application in soil and not having enough known control variables within the survey sites this method was not suitable at this time; however, with further investigatory work, this method may be possible. For the Monte Carlo method to be effective, soil properties, chemical makeup, pore size, and organic content represent some of the basic soil properties required to make this method suitable.

I further looked at a simpler proportion method, where each sensor is a proportion of the previous and subtracting that reading. Further to this, I trialled a basic method of subtracting the shallower sensor from the deeper one (30cm sensor-11cm sensor=30cm value). This basic method proved to be the most effective and user compatible for this study. From here on, the results of this subtraction method of data analysis will be referred to as ‘Processed data’. The Processed data will be used in Chapter 4. MMS field surveys for the applicability of using MMS for landscape scale monitoring of soil moisture. It is recognised that this method is not fully representative of what is happening with the sensors reading or the soil profile. However, until we can carry out further laboratory work to determine the actual influence of test parameters and soil conditions on the MMS response, this was the most effective method for use within this work.

Prior to the Covid-19 pandemic it was planned to carry out a laboratory experiment to determine what the MMS was detecting whether it was water filled pore space or volumetric % of soil moisture, and how soil type and composition could affect the MMS readings. This would have provided more robust parameters for understanding how to work with the data to gain a more accurate representative understanding of soil profiles. The laboratory-based experiments to understand the MMS response could not take place due to the Covid-19 Pandemic. This is an area of MMS research that would benefit from future work.

ArcMap was used to visualise the data, along with the interpolation tool of Inverse differential weighting (IDW) with a power of 1.5 and cell size of 0.8. Further methods were trialled through the interpretation section of ArcMap, such as Kriging and variation in cell size and power for IDW. However, upon comparison, IDW was identified as the most user-friendly and easiest to alter controlling factors, such as the power and cell size, for the interpretation of the MMS sensors. The specific power and cell size values were chosen as each point is one away from the other in the horizontal sampling plane, therefore, when interpreting the results, each point would be a discrete reading but have influence from points on either side. This also made vertical interpretation possible and meant a standard method could be used between the vertical and plan profiles. Further to the cell size, a variety of power options were tested on both the vertical and plan profiling. However, when powers higher or lower than 1.5 were used, they did not give an appropriate representation of the sensor outputs. Either the visual outputs were blocky, had disjointed connections between points, or gave the visual output a blanket smear of interpretation of the points. Choosing these specific cell sizes and powers this ensured that each reading was a separate entity in itself, but was influenced by the neighbouring data and was effective for the data viewed in plan. However, when this method was used for the vertical data, it was incompatible due to not having data present to 80cm in all profiles. For this, I duplicated the readings taken by the 30cm sensor at 80cm, carried out the IDW, as with the plan view, and then limited the viewing extent of the vertical profile to 30cm. It was found that this method was the most effective for visualising the data. The method outlined above will be used for displaying all of the MMS data throughout subsequent chapters (here, Chapter 4. MMS field surveys for the applicability of using MMS for landscape scale monitoring of soil moisture and Chapter 6- Exploring the connections between MMS and Hydrological Networks).

3.2 MMS Method- method development, field surveying, data processing and visualisation

MMS has four sensor heads; 3cm, 11cm, 30cm and 80cm (Figure 16 and Figure 17). These sensor heads are separate and therefore the readings recorded by each are not sequential, as a result each sensor was used once generating four separate surveys. In order to compare the sensors, the sensors will have to be placed in the same position on the soil surface. The position and the surface contact between the sensors and the soil surface is important when comparable readings are required. The sensor heads are connected to a handset that records the readings from each sensor head. The handset produces one output per reading, which is an average of the three pulse readings taken at each recording point.

Figure 17 MMS sensors and handset within storage box. 3cm, 11cm, 30cm and 80cm sensors oriented top to bottom of figure.

3.2.1 Laboratory testing of MMS Method

It has been established that MMS can be used on stone buildings to measure moisture content within walls (Orr et al., 2019). However, applying this technique to a soil profile is innovative and untested. Therefore, a laboratory trial was set up to establish if the MMS could be used on a soil profile. Within this laboratory study, I investigated the use of protection for the sensor head and if this impacted the sensor reading. Furthermore, I investigated whether the MMS can determine differences in soil moisture through the addition of water and the effects of compaction. Soil analysis was be carried out to determine the soil composition and the possible implication this could have on sensor response.

3.2.2 Methodology

The soil used for the laboratory experiment was a locally sourced topsoil. It was sieved through a 2mm sieve and oven dried for 12hrs at 80^{o}C. The soil was then placed in a single plastic container 40cm x 40cm x 40cm, which has predrilled holes in the base. A plastic tray was placed underneath to catch the excess water (Figure 18). All material and inorganics above 2mm were set aside for the first 6 stages (Table 4). At stage 7 they were re-incorporated into the profile through hand mixing.

The MMS sensor was used in the MIC setting. This setting allows for comparison between the sensors on an uncalibrated substrate. Calibrated settings that are available for special materials, such as stone and wood, if required. Protection of the sensor head was trialled with a plastic bag, a solid plastic plate and a bare sensor head.

Figure 18 Test soil profile, with 3cm sensor and handset

The moisture content of the soil profile was gradually increased (Table 4). The water was poured over the survey area using a watering can, and a seedling rose head to allow for even distribution. After a period, surveys using the MMS were carried out to allow the water to percolate the soil profile. Compaction of the soil profile (Table 4) was carried out by manually compressing the profile with a 2.5kg weight in a box of the same dimension as the soil profile. This was done to determine the difference in readings between a compacted soil profile, which is indicative of a footpath.

Table 4 Stages of experimental design for testing MMS on the soil profile

Stage 1	Stage 2/3/4/5	Stage 3/4/5	Stage 6	Stage 7
• Damp soil • MMS used to determine if a response can be determined	• Soil Dried • Sieved to 10mm • 2.5l Water added • Survey	• Water added at set intervals of 2.5l to reach field capacity • Survey	• Compaction • Survey	• Compacted soil • Inorganic material added • Water added • Survey

Table 5 Volume of water added to the soil profile and the length of time between water additions and surveying

	Stage 2	Stage 3	Stage 4	Stage 5	Stage 7
Volume of water added	2.5L	2.5L	5L	Field capacity	Field Capacity
Time between watering and survey	30 mins	30mins	4hours	24hours	24hours

At each stage, MMS was used in a grid survey pattern of 6cm by 5cm on the surface (Figure 18) and 5cm by 5cm on the side wall to determine the soil moisture. All sensors were used in a twofold process. Firstly, the MMS was used on the soil surface with a plastic sample bag over it, to prevent soil from sticking to the sensor; secondly, MMS was used on the side wall of the profile. This was done to determine if a solid plastic plate could be used instead of a bag to protect the sensor head and further to verify if water was infiltrating the profile, this survey pattern was 5cm by 5cm across the sidewall of the profile. Progressively MMS were subjected to soil profile testing through the incorporation of sieved inorganic materials at stage 7 into the homogenous profile, to test the variation or interference that inorganic material may have on the MMS sensors (Table 4).

3.2.3 Laboratory Results for trial use of MMS in a soil profile

3.2.3.1 Soil Analysis of the laboratory test profile

Five soil samples were taken and processed to determine their particle size distribution (Table 8) for the laboratory test profile. The particle size analysis indicated that the test profile is predominantly silt (61%). This would indicate that the profile has a texture of silt loam.

Table 6 Percentage of sand, silt and clay content of the test soil profile taken from five samples

Particle Size Content %						
Sample	1	2	3	4	5	Average
Clay	13.94	18.32	21	20.11	24.1	19.49
Silt	51.45	55.8	66.49	67.93	64.42	61.22
Sand	31.20872	21.54062	7.73102	7.18954	6.09461	14.76

3.2.3.2 MMS Response

The response from the MMS sensors is shown in Figure 19, which shows that, that as the soil profile's water content increases, the maximum response from the sensor increases. The 3cm sensor has several points (shown in red) where the sensor recorded a reduced reading compared to the surrounding point. It is important to note the scale of response for each sensor. The 3cm sensor had an overall narrower response across all water additions than the other sensors. Notably, all sensors indicated a higher response with the addition of water, with the exception of the 3cm sensor. In Figure 19, the 3cm sensor demonstrates that, despite the increase in water to the soil profile, the response from the sensor did not increase. This shows that the top 3cm of the soil had reached the maximum response from the sensor for the first addition of water. However, the 11cm and 30cm continued to show an increase in sensor response following each addition of water. Therefore, this would suggest that despite being influenced by moisture close to the surface, the 11cm and 30cm sensors continued to detect moisture from deeper within the profile.

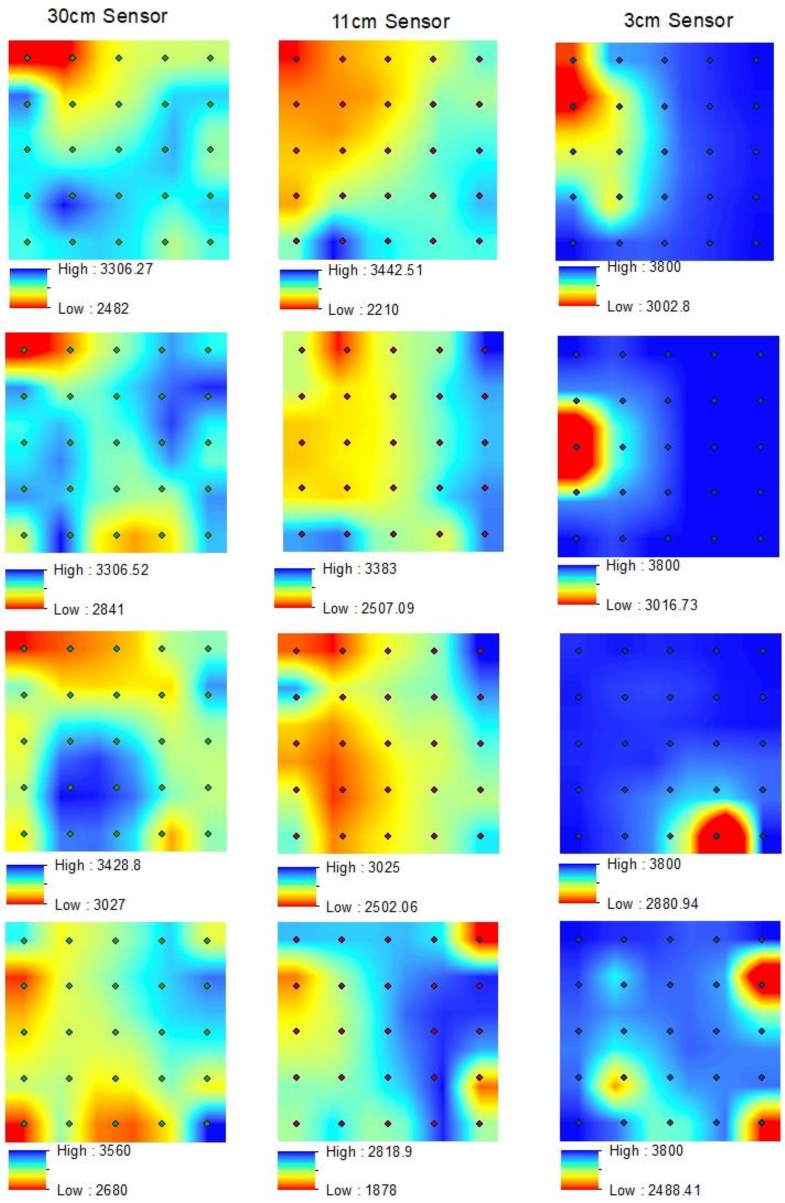


Figure 19 Plan Moisture readings with 30cm (left), 11cm (middle) and 3cm (right) sensor. The volume of water added increases from 2.5l (top), 5l (2nd row), 10l (3rd row) and field capacity (bottom). The blue indicates a high response from the sensor and the red a low response. Note the scale and range for each sensor change for each output.

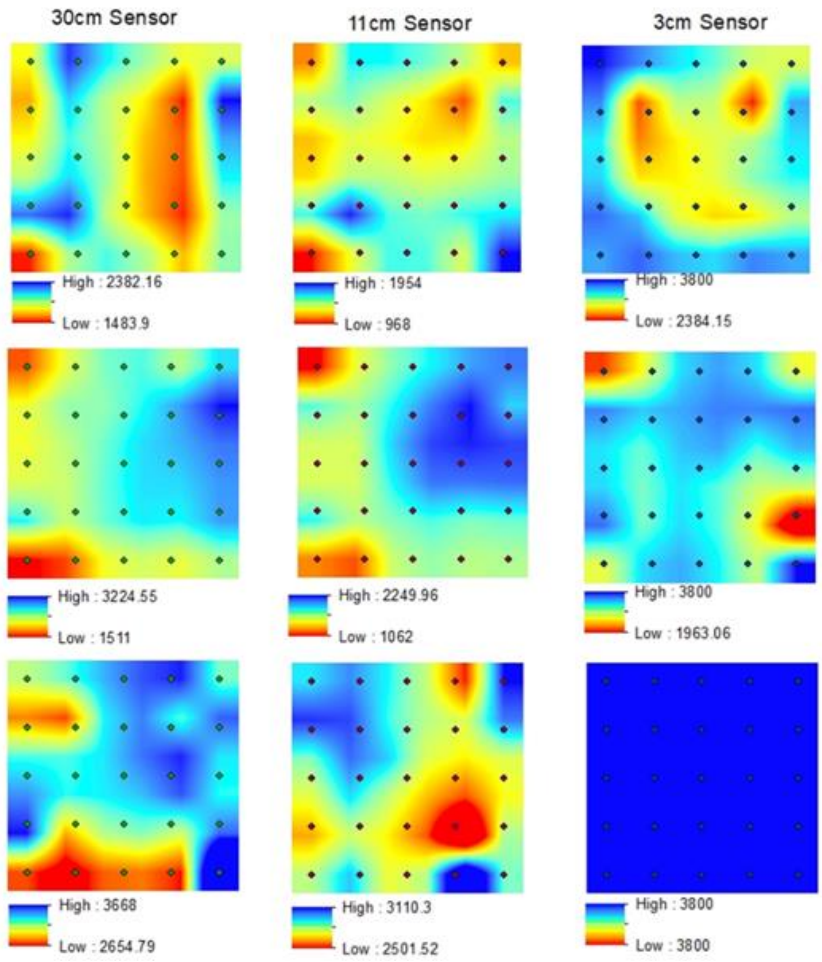


Figure 20 Plan Moisture reading with 30cm (left), 11cm (middle) and 3cm (right) sensor. The profiles with inorganic incorporated (top), field capacity (middle) and compacted (bottom). The blue indicates a high response from the sensor, and red a low response. Note the scale and range for each sensor changes for each output.

The incorporation of inorganics (Figure 20) affects the range of all sensors compared to the sieved profile, with the most pronounced effect on the 11cm sensor. The addition of water to reach field capacity increases sensor response from 11cm and 30cm and expands the range with a lower response of the 3cm sensor. Compaction of the profile results in the 3cm sensor giving a maximum response across the profile, with the 11cm and 30cm sensors having an overall increase in sensor response with a reduced range compared to that of an uncompacted profile.

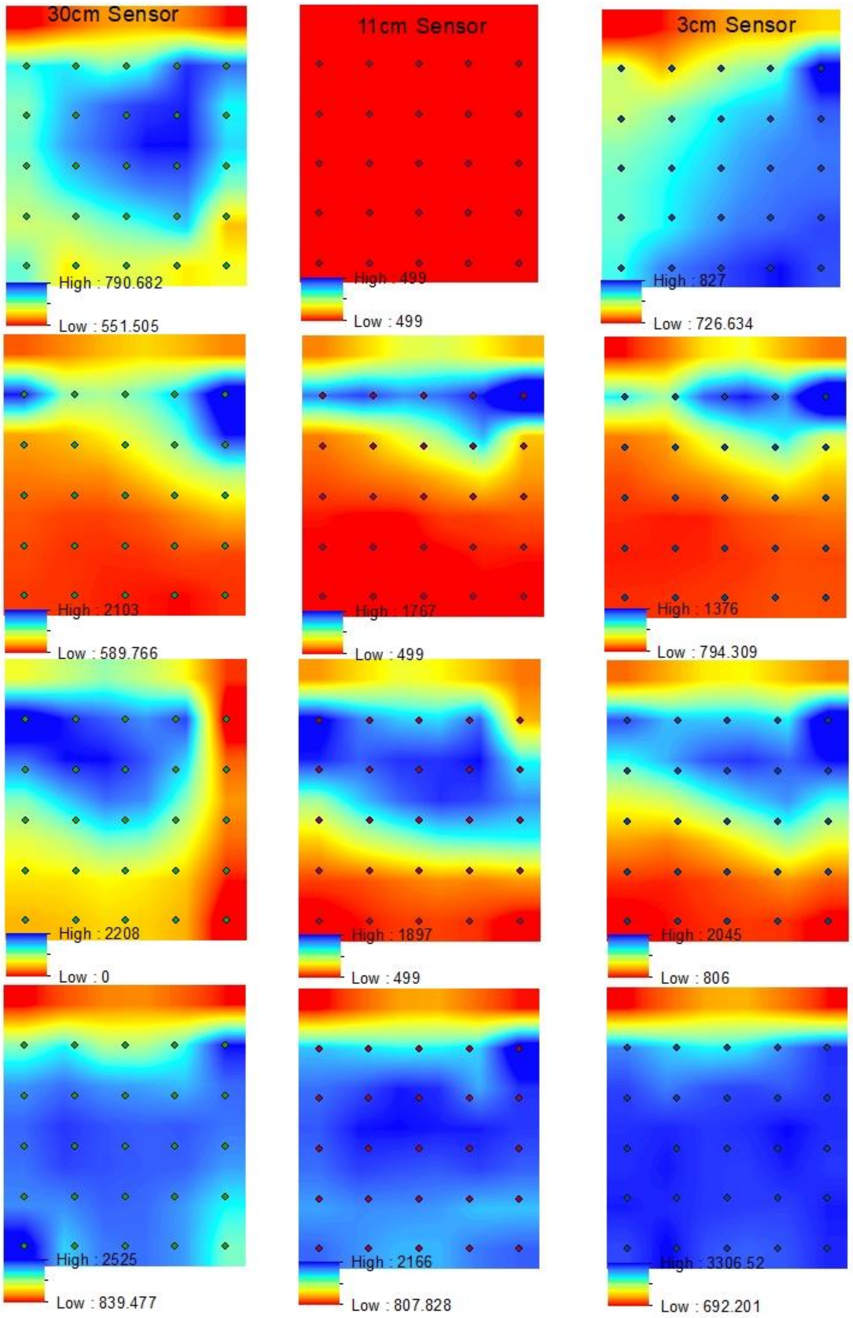


Figure 21 Vertical Moisture readings with 30cm (left), 11cm (middle) and 3cm (right) sensors through the sidewall of the profile. Moisture increases from dry (top), 2.5l (2nd row), 5l (3rd row) and 10l (bottom). The blue indicates a high response from the sensor and red a low response. Note the scale and range for each sensor change for each output.

Readings taken through the container's side wall demonstrate the infiltration of the water down through the profile (Figure 21). All sensors show an increase in response with the addition of water. All sensors also work when used against the side of the box.

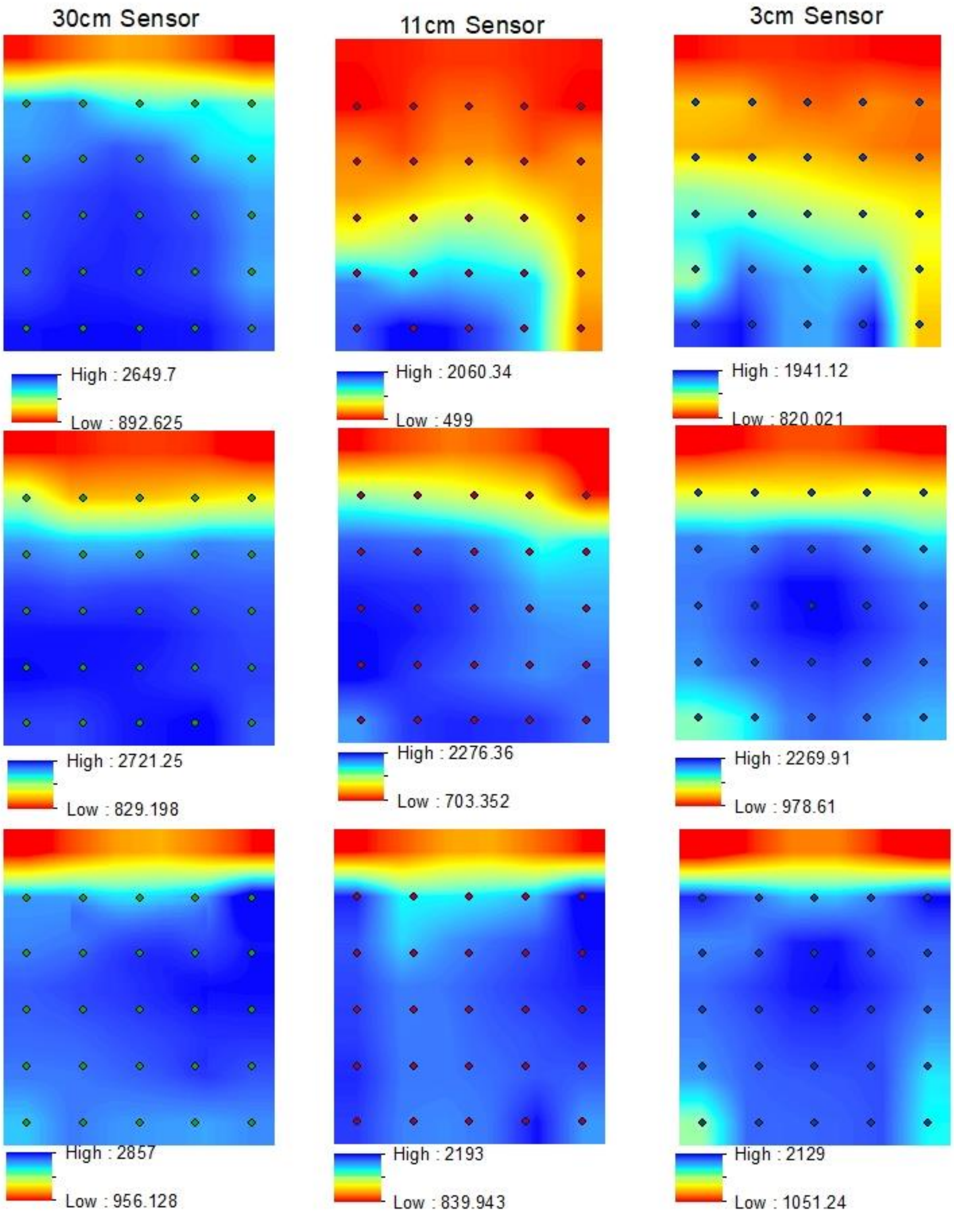


Figure 22 Vertical Moisture readings with 30cm (left), 11cm (middle) and 3cm (right) sensor through the sidewall of the profile. Reincorporation of inorganics (Top), profile at field capacity (middle) and compacted (bottom). The blue indicates a high response from the sensor, and red a low response. Note the scale and range for each sensor changes for each output.

Further, when the inorganics are added into the profile (Figure 22), there is a similar response through the side wall to that of the reading taken from the top of the profile (Figure 20). All sensors exhibit similar trends, with an increase in response and a reduction in range when the soil is compacted. However, all responses have a lower maximum response; this is most notable in the 3cm sensor.

3.2.4 MMS Laboratory test Discussion

3.2.4.1 Sensor head protection

The initial tests for sensor response were promising and indicated that the MMS could be used to determine the changes in moisture levels within the soil profile (Figure 19 and Figure 21). However, the initial test, not shown here, highlighted a few issues that needed to be considered when using wet soil sensors. Due to the sensitivity of the sensor heads, they need to remain clean and scratch-free. During the initial tests, it was found that the wetter the soil, the more likely it was to stick to the sensor head and thus scratch the sensor. Therefore, a method for protection for the sensor heads was trialled using a solid plastic plate and plastic sample bag. The sensor heads are affected by the relative permittivity of a substance (Doolittle et al., 2007, Algeo et al., 2016, Orr et al., 2019), therefore, trialling different protection methods is necessary. These options were chosen due to their ability to repel moisture and ease of use. The side wall of the soil profile box was used to simulate a plastic plate, and a plastic sample bag was placed over the sensor heads. Placing a bag over the sensor head proved to be an effective method for protecting all sensor heads, however, some consideration needs to be taken in relation to the surface tension of the plastic bag when attached. The effect of the surface tension of the bag affected the results recorded by the sensor. If the surface tension was low and did not provide sufficient contact with the soil surface, a low or abnormal reading was obtained (although this was only observational and not studied further). The plastic sample bag also must not contain perforations, again, this was observational, as when there were perforations present, the sensor recorded lower to null readings than when re-recorded with no perforation (not reported here).

The plastic sample bag was easy to clean and contained minimal soil accumulation between readings. The bag was wiped clean after every five responses; however, this did not appear to affect the sensor responses taken across the surface of the profile. There was no trend found for higher or lower responses between cleans. Therefore, the use of a bag to protect the sensor head is an effective way of obtaining moisture readings without damaging the sensors. However, the actual effect of the bag on the sensor response was not tested.

A solid plastic plate was also trialled to protect the sensor head. The side wall of the box was used as a substitute for a plastic plate on the sensor head. This allowed for testing of the protection of the sensor head whilst obtaining suitable moisture readings. The use of the plastic plate allowed for better surface contact and stability of the sensor when obtaining responses. In this trial, the use of the sidewall allowed for accurate identification of infiltration of the added water (Figure 21 and Figure 22). The plastic plate worked well with all sensors and proved to be a more successful protector of the sensor head than the plastic bag. The plastic plate also resulted in fewer anomalous readings throughout the laboratory testing than the plastic bag. The plastic plate further allowed for good surface contact, as a slight force could be used to maintain an even surface contact with the soil profile without damaging the sensor. This removes the issue of contact highlighted by the plastic sample bag as the plastic plate remained constant and had a good contact with the soil surface. Therefore, the plastic plate was chosen to protect the sensor heads when in the field.

3.2.4.2 Side wall results

The addition of water and the infiltration through the profile can be monitored effectively (Figure 21) through the side wall. With increasing volumes of water added to the profile there is an increased response from the sensor towards the base of the profile. All sensors respond similarly to each other, except for the 11cm sensor, when the soil is at its driest. The explanation behind this is unclear; the 11cm sensor gave the most variable results of all the sensors.

3.2.4.3 Incorporation of inorganics to soil profile

For the inorganic incorporated profile, the 30cm sensor produced a narrower range of readings compared to that of homogenous soil. The range of values that is recorded is still in line with the increasing volumes of water added and is expected, as the inorganics will have an effect on the range and attenuation of the MMS microwaves. This is in relation to the relative permeability of the properties which are incorporate in the soil profile. The similar response across all sensors used, would suggest the inclusion of inorganics into the profile will still give an accurate response along with the responses for both the plastic sample bag and the solid plastic plate are similar.

3.2.4.4 Compacted soil

The soil profile was compacted to simulate a footpath. Footpaths are well established to influence soil compaction (J. Gong, 2009) and establishing their impact is an aim within this research, establishing the ability for the sensors to still operate on footpaths is essential. Once the soil was compacted further readings were taken to distinguish if the compacted soils had an impact on the sensor response. The readings from the top of the profile indicate that there is an increase in response. Along with a reduction in range for which the response was recorded was much narrower than that of the saturated uncompacted profile, indicating that areas of compacted soil will give a narrower range of response than un-compacted soils. This was further found with measurements through the sidewall of the profile which exhibited the same narrower range of readings with higher maximums. However, this difference in range will not be able to be established accounted for in the field, it is important to note that there may be a difference in range when soil is compacted.

The difference in readings is important as it highlights the interaction between soil pore space and soil moisture. Through testing this methodology on a synthesized soil profile, it has been established that there is a complex interaction occurring between the number of inorganics within a profile and the compaction of the profile. Through being able to define this in the field, deciphering between compacted soil and soil with a high moisture content, will not be possible until repeat visits occur.

From the laboratory study the placement of the sensor is key for obtaining accurate readings. Further to this the interaction between soil water content and soil compaction is a complex matter and the two cannot be separated by using MMS. This is an important point to note; however the compacted soil presented an increase in sensor response. Therefore, this would suggest that in a heritage landscape, areas that have high compaction may be able to be detected by the sensor and therefore could indicate areas of visitor footfall.

3.2.5 Summary and implication of the use of MMS on a soil profile.

The MMS sensors are all affected by surface moisture. This study has highlighted that despite this effect the MMS have had an increase in response in line with the addition of water to the profile. With the addition of water, surface moisture increases first before the deeper soil. The sensors have accurately identified this. The 3cm sensor indicates that the surface moisture is high and the 30cm sensor would indicate that there is an increase in moisture throughout the profile with the 11cm sensor falling in the middle. This was consistent throughout all additions of water. The surface moisture influences the sensor but combined the sensors give an indication as to the influence and extent of the moisture.

The roughness of the soil will impact on how the sensors can be placed on the surface and the readings it will receive. Although this was not directly tested within this laboratory trial, the roughness of the surface had an impact on the sensor placement and contact with the surface. This is an important factor to consider when using this technique in the field. Unlike the test profile, use of the sensors in the field will have a degree of freedom to move the sensor around a sample point to maintain sufficient soil surface contact.

The only sensor that gave mixed results was that of the 11cm sensor. The reason for the different responses is unclear, but it gave the most varied results across all profiles and with both the plastic sample bag and the solid plastic plate. This experiment indicates that when using the 11cm sensor in the field, correct placement and surface contact will be essential for gaining accurate results.

3.2.6 Conclusion for using MMS on a soil profile-based laboratory testing

It is recognised that the test soil profile is not representative of those found within heritage landscapes. However due to the MMS never being tested on a soil profile, the laboratory test shows that the MMS can be used for determining soil moisture in a soil profile. The inclusion of inorganics and compaction generates a more realistic soil profile simulating a field surveying sensor response. The laboratory testing has determined the potential suitability of this equipment for use in heritage landscapes to determine patterns of soil moisture that could indicate visitor interaction on site.

From this initial study, it is suggested that the combination of 3cm, 11cm and 30cm sensors can be used within heritage landscapes. Surface roughness is an issue that will be present within the field but can be overcome with accurate and careful placement of the sensor. The 3cm sensor is affected most by the surface contact with and soil roughness along with moisture on the surface of the profile. The 11cm sensor, provides the most variable results of all the sensors. It is advised that care should be taken when placing the sensor on the soil surface in the field.

Overall, the MMS performed better than expected in a test laboratory setting. The ability of using the different sensors to establish response change at different depths has been successful. The use of a plastic plate for the protection of the sensor head proved to be effective and allows for consistent readings by all sensors. The ability to protect the sensors is vital for use during field surveying.

3.3 Field Surveying trial at Rough Castle

An in-field trial at Rough Castle, was carried out to determine the practicalities of the MMS sensors in the field.

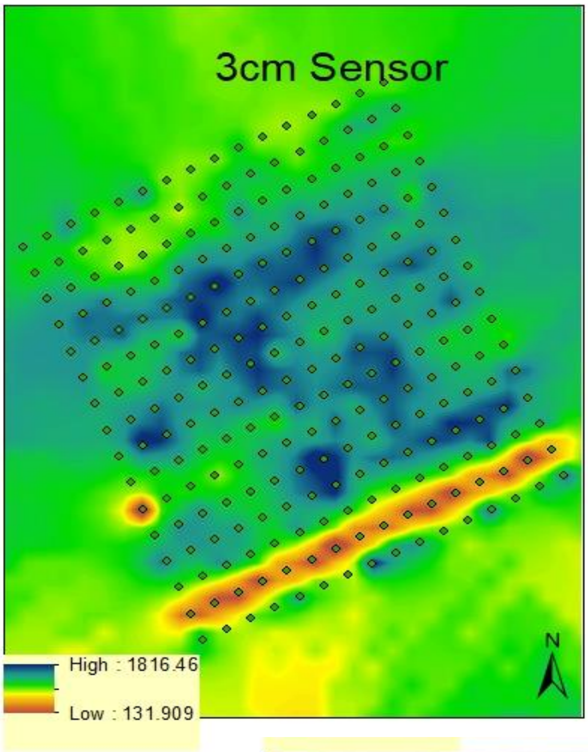
Figure 23 Sensor placed on the soil once moss had been removed, with base plate attached.

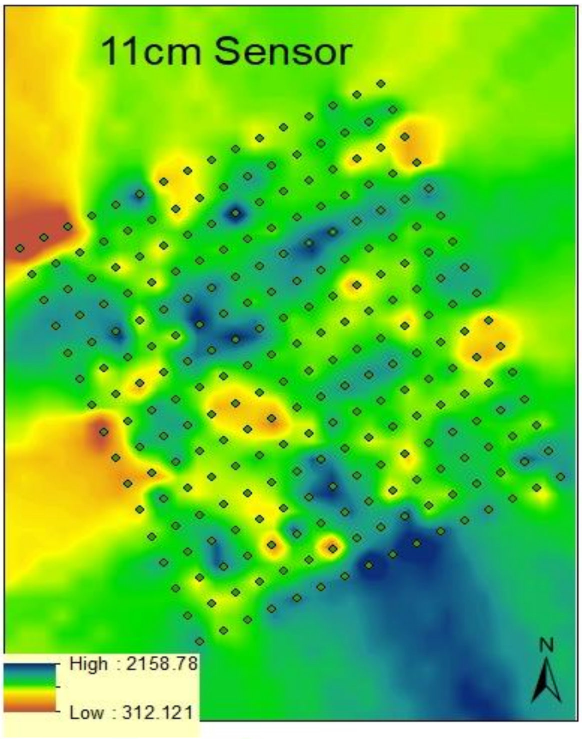
A 15m-by-15m grid was set up for sampling, with survey point spacing of 1m by 1m resulting in a total of 768 points for this area. Moss and grass cover had to be removed for good contact with the soil surface (Figure 23).

As identified in the laboratory, surface contact between the sensor and the soil surface is paramount for obtaining reliable readings and influence of grass and moss was not investigated. However, in the field, vegetation cover resulted in there being no readable response from the sensor. Therefore, the vegetation was peeled back to expose the soil and was replaced after sampling. The method of uncovering the soil from the moss was intensive but once carried out was time saving in subsequent sensors. Within the grass areas of the field trial if the grass was not long or dense it did not present a problem for surface contact with the sensor. However, if the grass was dry it was required to be removed prior to placing the sensor. This has highlighted the need to take into consideration the vegetation cover at the survey sites and has shown the possible need for removal of some vegetation for the sensors to be used appropriately.

The 3, 11 and 30cm sensors were tested in the field, with a plastic plate attached to each sensor. The plates were cleaned at the start of every row and at sample 8 within the row.

3.3.1 Field Trial Results and Discussion





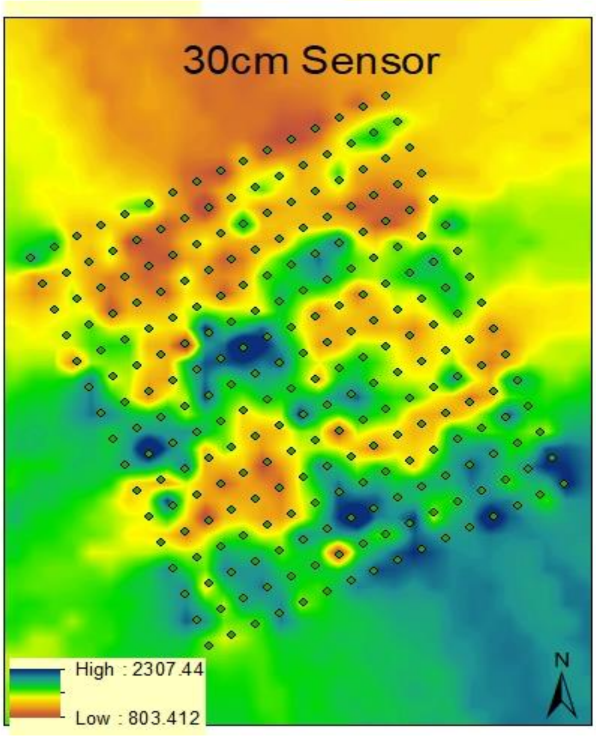


Figure 24 Moisture Map for 3cm, 11cm and 30cm sensor from the field trial at Rough Castle. The blue indicates a high response from the sensor, and red a low response. Note the scale and range for each sensor changes for each output.

The field trail has indicated that using a plastic base plate is essential for protecting the sensor head and maintaining good contact with the soil surface. The removal of vegetation and the plastic plate made the sensors a rapid and easy to use piece of technology. The root structures within the soil will have affected the readings that were taken, however due to the consistency of the sensor's response, the interference from the root mass can be presumed to be consistent and therefore when carrying out repeated experiments would not affect the readings further.

Within the field trial an attempt was made to manually georeference the points using a handheld GPS. The manual georeferencing was successful, however the GPS error resulted in points being inaccurately located and indicates the requirement to use DGPS for outlining the survey area and some points within. IDW interpolation in ArcMap, interpolates to a bounding rectangle dictated by an internal algorithm based on the georeferenced points. Therefore, the spread of data outside the marked points is due to the interpretation process and may not be an accurate interpretation of the soil properties in the adjacent landscape. This is important to remember for field surveys and interpretation of the data once georeferenced.

The final consideration is the weather. The MMS is sensitive to surface moisture and rainfall as there are several exposed electrical connectors between the sensor head and the handset. The cold will also affect the battery life of the handset and should be factored into surveys when being carried out in cold conditions.

3.3.2 Conclusion of the Field Trial at Rough Castle

Overall, the sensors performed well in the field trial and indicated their usefulness for establishing the difference in soil moisture, along with setting up and sample taking and timings. The field trial has also highlighted that the surveys can only be carried out in fair weather as the sensor equipment is not designed to deal with the rain or the cold. In addition, use of MMS for surveying of soil moisture in discrete areas of a landscape should be carried out along transects with a maximum spacing of 1m between points along a transect. All sensor heads should be protected through the use of a plastic plate and readings must be taken using the MIC setting to allow comparability between the sensors. The main limitation for using the MMS is that the sensors are not calibrated and cannot be used to measure direct soil moisture changes. This is due to every soil profile having a unique composition, making it difficult to establish calibration values. From the laboratory it is clear the MMS responds to changes in soil moisture, inorganic content and composition. Therefore, when using the MMS in the field the response reflects a combination of all three. Inorganics and composition are unlikely to change between surveys therefore when a sensor is used repeatedly on a site it could indicate the relationship between the soil profile and soil moisture.

3.4 Hydrological network modelling methodology

Hydrological modelling can be carried out using any topographic data. However, the resolution of the data can affect the detail and scale of the modelled hydrological networks. This section will explore the use of several data sets to provide a base understanding of the effects that difference in scale of topographic models can exert on hydrological network modelling.

DTM derived from Lidar data was proposed as a topographic model for determining hydrology networks within a heritage landscape. Heritage landscapes often have intricate features that require higher resolution topographic data to determine their location. However, not all heritage landscapes have been surveyed for fine scale topographic data. This therefore prompts the question as to what resolution is required for hydrological modelling within a heritage landscape. Three types of data-sets have been proposed for investigation in this project to determine the hydrological networks within heritage landscapes. The resolution of data is important for understanding the hydrological networks and upstanding archaeological interactions. Further to ascertaining what resolution of data can be used for accurate determination of the hydrological networks, is that of data availability. Two widely available data sets, 1m LiDAR from Scottish LiDAR and 5m Ordnance Survey DTM, as well as fine resolution 0.25m LiDAR from HES, will be used within this section. The data from HES was costly to obtain and was collected with the documentation of the historic assets as the primary focus.

When looking further into the widely available LiDAR data, it was found that some areas of Scotland were not covered by any LiDAR surveys. This was not only the case for the 1m data sets but for any LiDAR surveys that have been carried out in Scotland. There have been several surveys made available, with both 1m and 2m resolution, however they lack coverage for the sites within this study. This is unfortunate as it will not be able to establish if there is any suitability of the data sets between that of the 5m resolution and the 0.25m resolution. This does, however, further highlight that there is a lack of available data for heritage landscapes within Scotland that have not already been documented by high-resolution LiDAR.

3.4.1 Hydrological modelling method

The areas that are covered in Scotland and contained a site within this study (Rough Castle), were composed of raw point cloud data. This results in the data containing all features within an area, including trees and powerlines etc. that affects the overall topography, with specialist knowledge these features can be removed to leave a base topography. Furthermore, when using a data set that contains trees and powerlines, it affects the apparent base topography of the site and therefore alters the hydrological network mapping. Some sections of Scotland have digital terrain models (DTM) available, and these can be used to determine hydrological networks within a heritage landscape. However, the skillset required to extract additional features from the LiDAR data to generate a useable DTM, was felt to be out-with the scope of this study, as this is a skilled area of expertise. Therefore, open-source data that required pre-processing to remove features was excluded. This severely limited the data that was available but is more realistic for skillsets that are required for hydrological network determination in heritage landscapes.

Hydrological modelling was carried out in ArcGIS 10.8.1 using the in-built Spatial Analysis-Hydrology tool on an 5m topographic model and a 0.25m DTM derived from LiDAR. The LiDAR data was processed to produce a topographic model by the Digital Innovation Team at HES. The processing steps (named in ArcMap) are: Sink (shows where there are holes in the topographic model), Fill (fills in the holes identified in the topographic model), Flow Accumulation (determines where flows will accumulate based on topography), Flow Direction (determines the direction of flows based on topography), Stream Order (combines Flow Direction and Accumulation to generate stream orders), and Basins (determine the split of stream networks based on topography) were used to generate the hydrological networks for each topographic model. For each data set the same process was followed to generate a stream order network which shows the potential surface streams within the survey are and the split of these streams into a basin network.

3.4.2 Hydrological modelling resolution results

The difference in stream orders between the topographic models can be seen in Figure 25. The 5m DTM shows a lower number of stream networks than the 0.25m DTM, for both low and high order streams.

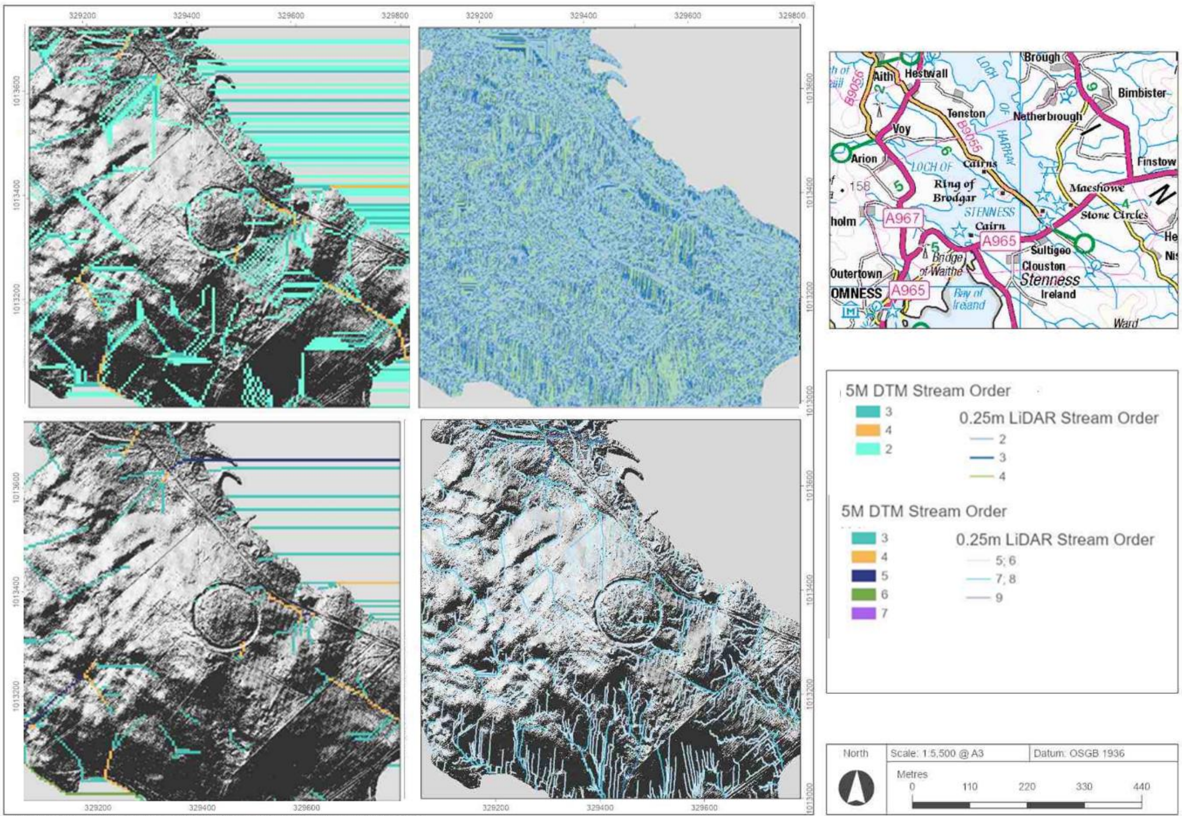


Figure 25 Left shows the 5m DTM Stream orders (Low top, High bottom) and 0.25m LiDAR Stream order on the right (Low top, High bottom).

Figure 26 shows the predicted drainage basins for each topographic model with the stream order over lain. The 5m DTM predicted fewer and more angular drainage basins, with the 0.25m DTM predicting more larger basins.

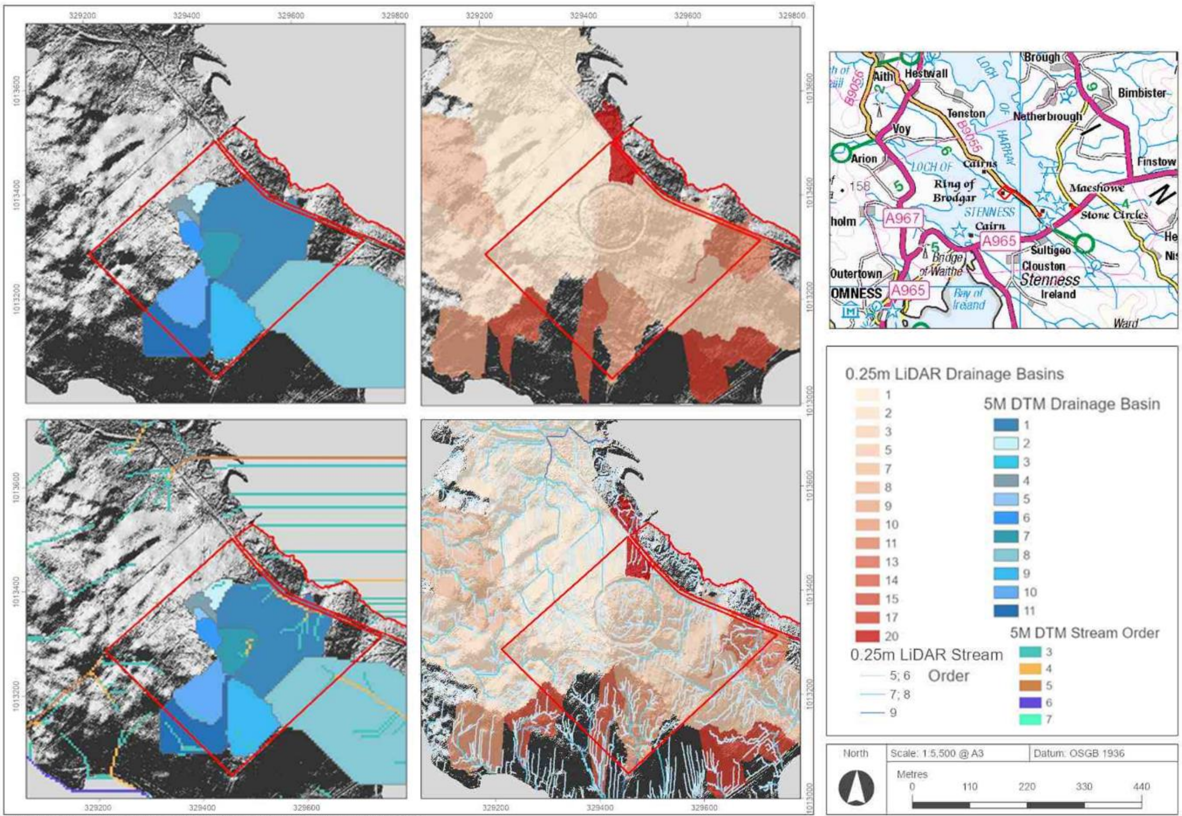


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Figure 26 Drainage basins (top) using 5M DTM, left, and 0.25m LiDAR, right, and the higher order stream networks overlain on the bottom.

3.4.3 Evaluation of the necessary data resolution for hydrological modelling

The 5m DTM data provides a course overview of the preferential flows. The impact that the lack of topographic resolution has on the hydrological flow determination is clearly seen in angular output of the preferential flow networks (Figure 25). There is a small number of higher order streams present across the landscape compared to the 0.25m DTM. Due to the low resolution of this data, it is not possible to determine accurately where these higher order flows would occur within the landscape and therefore it would not be possible to determine the full influence of hydrological networks on a heritage landscape. Further to this there is a lack of detection of any landscape features within the 5m DTM at Ring of Brodgar. Although the topography within this study site is not extreme (maximum height 16m, minimum height sea level), there are significant key features that have not been picked out by the higher order preferential flow networks- or subsequent lower flows- that are an essential part of the landscape, such as the ditch around the ring and the burial mounds across the site. Due to the lack of resolution within the 5m DTM these features have not been highlighted therefore their effect on the hydrology is unknown making this difficult to determine the extent of the hydrological networks. Thus, indicating that, at a low resolution, it would not be possible to determine the current and appropriate hydrological networks within a heritage landscape.

Further to this are the drainage basins (Figure 26); the effect of lack of resolution is demonstrated by their angular shape, and they are smaller in size compared to those of the 0.25 DTM. The area outlined by the basins is important for that of management practices within the heritage landscape. As the drainage basins' intended use is to form 'management areas', the 5m DTM does not pick up on the complexity of some of the basins; instead these areas are split into further drainage basins.

Comparing the 0.25m LiDAR (Figure 25) to the 5m DTM (Figure 25) shows that it produces a higher number of stream networks that are of a higher order, which indicates a higher number of stream connections within the landscape. The 0.25m DTM also highlights the complexities and connections of stream order networks that occur within a landscape and the influences of the adjacent landscape.

Furthermore, the finer scale data set identifies features within the landscape that form natural drainage areas, such as the ditch surrounding the ring (Figure 25) are not shown with in the 5m DTM (Figure 25). The finer resolution data is required to show all the hydrological interactions that occur within a heritage landscape.

When comparing between the two data sets it becomes clear that the 0.25m DTM allows for greater visibility of the effects that archaeological features have on the hydrological flow within the landscape. Along with this, due to the increase in resolution of the 0.25m DTM, basins are larger and demonstrate how different areas of the landscape interact with each other. Through comparing the two data sets it becomes evident that an increase in resolution of LiDAR data results in a better determination of hydrological networks and basins areas within the landscape.

Therefore, this research will use a 0.25m LiDAR derived topography for determining hydrological networks within heritage landscapes, which will be explored in Chapter 5. Hydrological modelling of WHS for determining hydrological networks to establish the effects of upstanding archaeology and visitor infrastructure in heritage landscapes.

Chapter 4. MMS field surveys for the applicability of using MMS for landscape scale monitoring of soil moisture

4.1 Introduction

Non-invasive monitoring of soil moisture within a heritage landscape is not a new and novel method for understanding the impacts that landscape features have on soil moisture, however the application of MMS for monitoring soil moisture is. Whilst soil moisture has been monitored in archaeological sites and landscapes before (Ferrara, 2015) it has not been used before to study the impact of visitor features on soil moisture. It is important to gain an understanding of the influence that the visitor features have, as soil moisture can affect the protection of above and below ground archaeology and the integrity of footpaths and site infrastructure. From the initial field trial, 3.3 Field Surveying trial at Rough Castle , it has been established that MMS can be used within a heritage landscape for determining changes in soil properties associated with visitor features (footpaths and signboards). The work being carried out within this study will establish a baseline for developing an understanding of the application of this technique within heritage landscapes.

This chapter has a two-fold purpose. The first is to investigate whether MMS can be used to determine the impact of key visitor features on soil moisture within a heritage landscape; in this case visitor features consisting of footpaths, lines of desire and signboards. The second is to establish if ambient soil moisture affects the ability of the sensors to detect these key visitor features. This was done through repeat surveys, one before and one after a rainfall event at Ring of Brodgar and a single survey at Rough Castle. Both survey areas at Ring of Brodgar are indicative of the types of footpaths, wide high intensity footfall and narrow low intensity footfall footpaths, that are found within our heritage landscapes. They will give an understanding of how different footpath use intensities affect the responses from the MMS sensors. Rough Castle survey area contains lines of desire, main access paths and signboards, all key visitor features within a heritage landscape, which will give an understanding of the influence of multiple visitor features.

It is important to note that, although in the laboratory experiment there was an increase in sensor response when water was added to the soil profile, there was also a reduction in sensor range when the profile was compacted. However, in the field these two factors cannot be studied separately. Therefore, it is assumed that the response of the MMS sensors is a composite of both soil moisture and a surface with higher density, such as compacted soil or stone. It is understood that this assumption will not be true for every environment or feature that we wish to monitor, and this chapter will specifically discuss footpaths for Ring of Brodgar and Rough Castle where these soil properties are a combined concern.

Due to the COVID-19 pandemic, there were fieldwork restrictions. This has resulted in two successful surveys at Ring of Brodgar and one at Rough Castle. Both of these sites offered an opportunity to test the use of MMS in different soil types, footpath types, and heritage landscapes.

4.1.1 Result of soil sampling and analysis for Ring of Brodgar (Survey Areas 1and 2) and Rough Castle (Survey Area 3)

Soil samples were taken with a soil auger to a depth of 20cm from five random locations within each survey area with three further background samples from across the Ring of Brodgar and Rough Castle study sites (Figure 6 and Figure 11) in line with SMC. The samples were visually split into horizons for each sample. At Rough Castle samples were only taken in the top 10cm from within Survey Area 3 and these were homogenised. All samples were visually assessed and bagged on site, then transported to the University of Stirling, where samples were dried in an oven at 80 ˚c for 24 hrs. Samples were sieved through a 2 mm sieve. Two cm of each sample was added to a 100 ml plastic bottle along with 2 ml of dispersant sodium hexametaphosphate (Calgon) and distilled water. Samples were agitated for 24 hours, and a LS 2000 Coulter Counter used to establish particle size distribution.

Table 7 shows the mean and standard deviations for all samples taken within the survey areas and background samples. The background soil samples for Ring of Brodgar have the greatest variation across all samples taken, with the background samples at Rough Castle having the least variation.

Soil samples taken from within Rough Castle SA3 (Table 7) were relatively shallow and this could account for the variation seen across the samples. The reason behind the shallow samples was the inability to penetrate to a depth greater than 10cm with a soil auger. Most samples were inhibited by stones.

Table 7 Mean and Standard deviation of soil particle size analysis for Ring of Brodgar (SA1 and 2), Rough Castle (SA3) and Background samples.

	Particle size									
Sample Fraction	Ring of Brodgar SA1		Ring of Brodgar SA2		Ring of Brodgar Background		Rough Castle SA3		Rough Castle Background	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
Clay	11.26	2.88	5.05	3.05	9.54	7.17	10.57	8.66	11.43	10.61
Silt	54.61	5.11	63.35	3.03	65.68	8.58	66.32	9.67	68.89	8.56
Sand	32.60	7.66	24.51	4.09	3.55	12.80	4.01	6.13	1.38	0.77

4.2 Ring of Brodgar

4.2.1 Ring of Brodgar Survey Area 1

Survey Area 1 (SA1) (Figure 6) is located within the PIC boundary of Ring of Brodgar and incorporates the main access path to the site. SA1 further takes in the rotating main access path system. The sections of the main access path are rotated throughout the summer months to rest worn areas. The rotating path was initially set up to 'aid soil recovery' but has subsequently been viewed as aiding 'grass recovery'. During the time of survey, the middle section of the access path was cordoned off to allow for resting and had been since late autumn (October 2019). SA1 covers an area of 30m by 15m to incorporate the main access footpath and adjacent landscape. This area was chosen due to:

1. The high number of visitors that use this path to enter and exit the site; up to 150,000 individuals per year (HES personal communication, 2021).
2. The width of the path, which at the time of survey reached up to 20m in places.

SA1 is located on a gentle slope to the northeast of the survey site. At the time of the survey there was a data logger at the entrance to the site which captures footfall for the main access path. Visually the area either side of the central path was 'muddy' and worn bare of grass.

The vegetation on the main access path was worn grass, with large patches of bare soil. The middle (rested) section of the path had the most consistent coverage of short grass, but this was also patchy in places. The adjacent landscape consisted of mainly long, dry, and dead grass, which formed tufted clumps. The difference in vegetation is important to note here as it could affect the response from the sensors and will affect the water holding capacity of the soil.

Figure 27 Photograph of SA1 looking north-north-east of the main access path, with loch of Harray. The rested section of the footpath is located between the two white ropes, which is elevated from the ground using three-pronged rope holders.

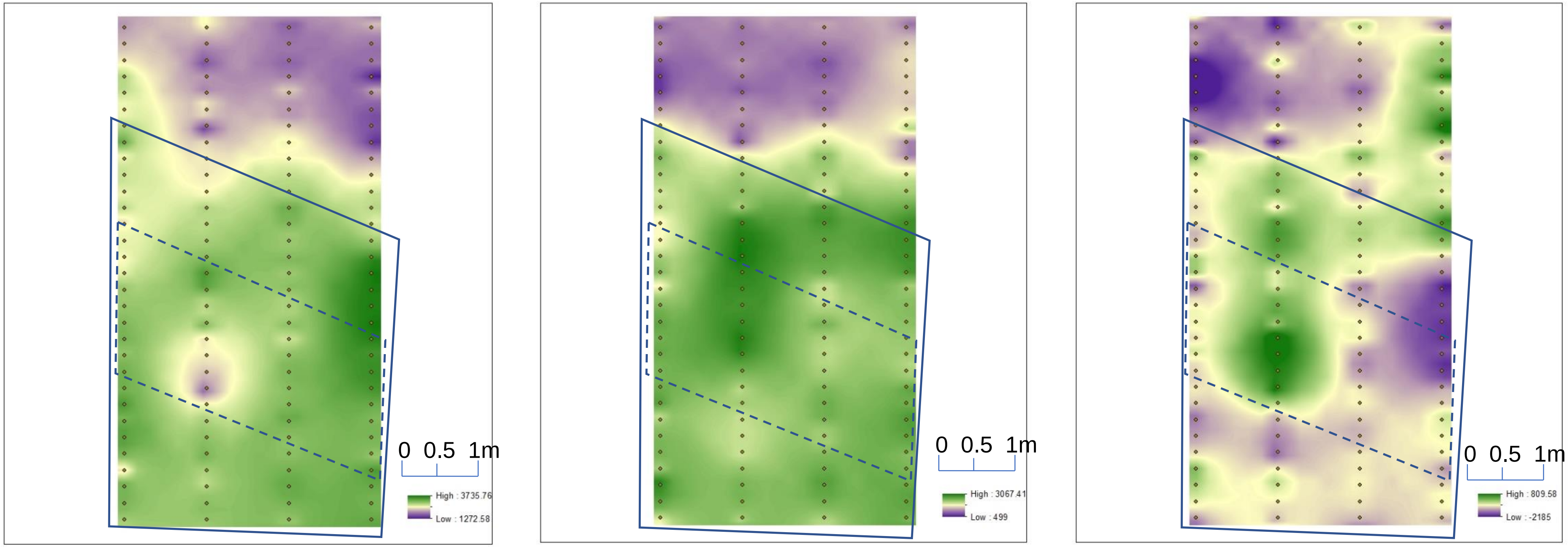
Due to the high number of visitors that the site receives each year, the main access path has become wide. As a result, the impact that visitors are having on the site has become more pronounced and interventions have been taken to try and control and restrict the impact of visitor access to the site, such as the rotating access barriers and geotextile paths outside the PIC. In discussions with the Works Manager and the District Architect for Ring of Brodgar, it was clear there had been interventions carried out on the main access footpath, however the extent and location of these interventions was not known.

It was anticipated that within SA1 a distinctive response from the sensor would be found on the main access path, reflecting changes in soil moisture and soil compaction, and the effects of the main access path (particularly on soil moisture) would extend into the adjacent landscape. To determine this, four survey transects of 30m in length and 5m apart were established, which incorporated the footpath and the adjacent immediate landscape. Two separate surveys were carried out, one on the 10th of March 2020 using the 11cm and 30cm sensor, and the second on the 14th of March 2020 using the 3cm, 11cm and 30cm sensors. As the sensors are sensitive to change in resistivity, surface water causes interference with the sensor’s responses and surveying could take place only when no standing surface water was present. In the four days prior to the first survey there was a total of 14.2mm of rainfall recorded at the Kirkwall weather station with one dry day, and in the three days between the surveys a further 14.4mm of rainfall and one dry day were recorded. The rainfall was obtained from daily totals, as a result the pattern of rainfall is unknown. SA1 was due to be surveyed every two days, however there was standing water in the survey area in the intervening period, which resulted in two surveys instead of four.

4.2.2 Ring of Brodgar SA1 Results

Figure 28 shows the raw data readings from the 11cm sensor and then the Processed data. Note the scale for each image is different and is relative to the range of values recorded by each sensor. The location of the footpath in SA1 is represented by a solid line, and the internal rested area by a dashed line. The raw data readings for the 11cm and 30cm sensors (Figure 28) follow a similar pattern and indicate that the main access path has a higher reading (indicated by the green) than the surrounding landscape (purple), and the boundary between the footpath and adjacent landscape is clearly defined. From the raw readings, it was expected that the response from both the 11cm and 30cm sensors would indicate an increase in response within the area of the footpath.

However, the processed data, (Figure 28) shows a slightly different interpretation of the sensor response, with there being one area of higher response within the rested footpath which continues above and to the right of the rested footpath. The Processed data (See 3.1 Method for MMS Data Processing and Visualisation for explanation) helps build a clearer understanding of the subsurface conditions. Within (Figure 28) the purple areas indicate that there was no further reading picked up by the 30cm sensor or that the reading the 30cm sensor recorded was a lower response than that of the 11cm sensor. The converse here are the green areas, where there is a higher reading recorded by the 30cm than the 11cm sensor.



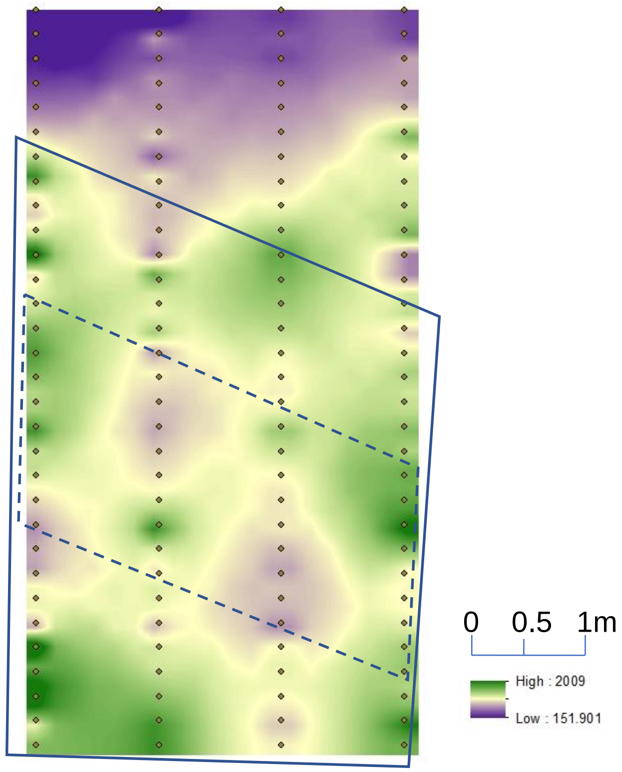
a) 10th March 2020 SA1 11cm Sensor data in Plan view.

b)10th March 2020 SA1 30cm Sensor data in Plan view.

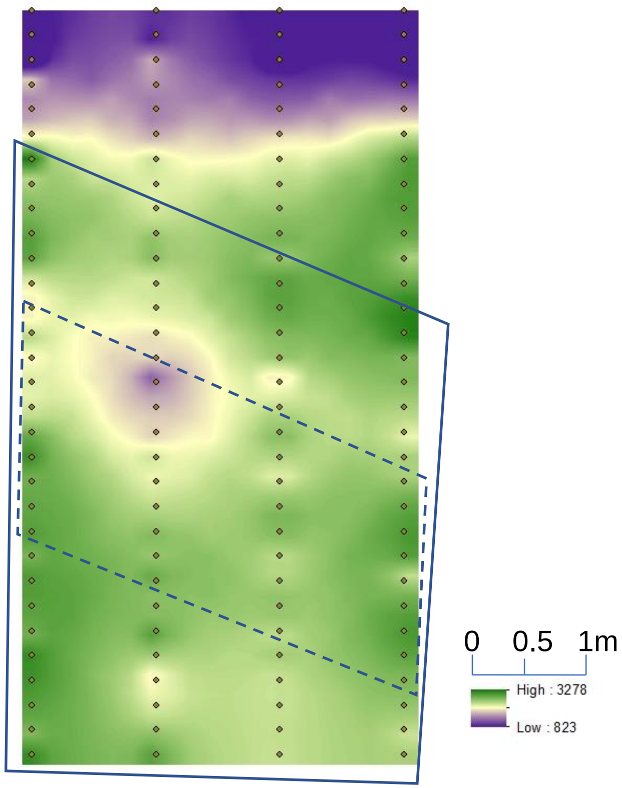
c) 10th March 2020 SA1 Processed 30cm data (30-11= Processed). The Processed data indicated the difference between the 11cm sensor (a) and the 30cm sensor (b).

Figure 28 Area that is used for the rotating footpath is outlined by the solid line, with the rested area outline by the dashed line. Each transect line is 30m long with sample points 1m apart and transects are 5m apart. T1 is on the left and is located upslope of T15 on the right. The slope of the hill dips from bottom to top of the image, and right to left. Green indicates a high sensor response with a purple indicating a low sensor response. Note the different scale for each sensor.

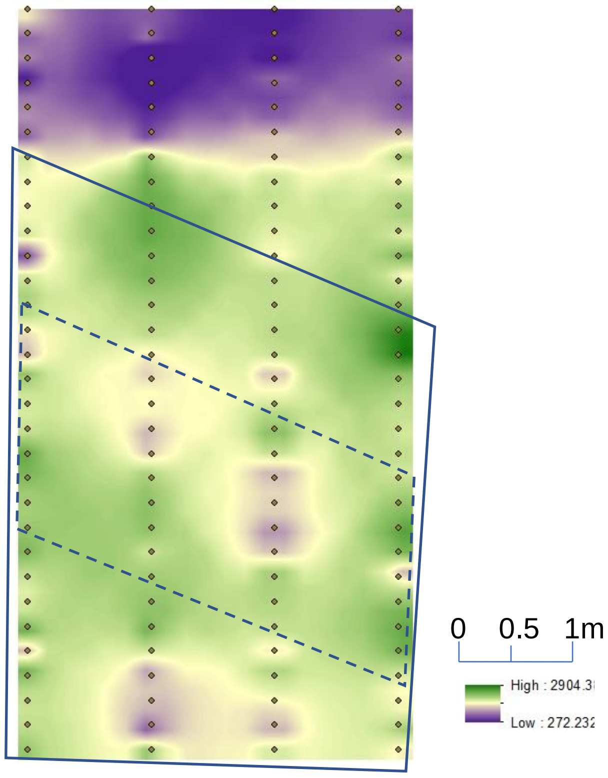
Figure 29 to Figure 30 show the results from the survey on the 14th March 2020. The 3cm sensor displays a similar pattern of results to that of 10th March 2020 11cm sensor (Figure 29). However, the Processed 11cm and 30cm results for the 14th March 2020 are different from the 10th March 2020. The Processed 11cm results show a high response from not only the main access path but also from the adjacent landscape (Figure 30). The Processed 30cm sensor indicates there is a much higher response from the sensor in the adjacent landscape than the footpath (Figure 30).



a) 14th March 2020 SA 1 3cm Sensor.

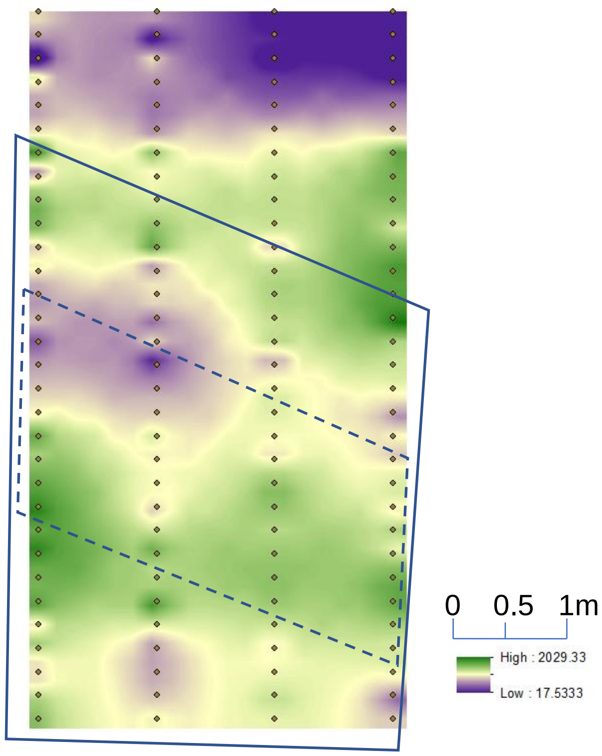


b) 14th March 2020 SA1 11cm Sensor.

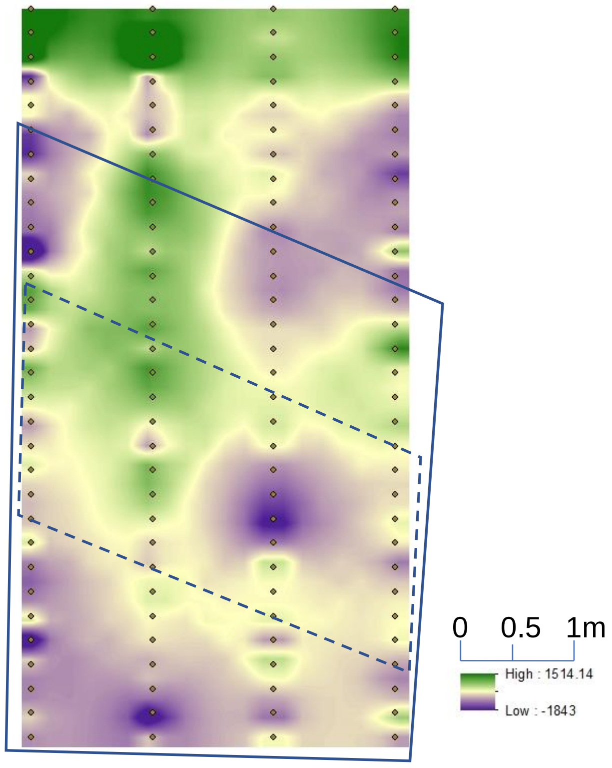


c) 14th March 2020 SA1 30cm Sensor.

Figure 29 Area that is used for the rotating footpath is outlined by the solid line, with the rested area outline by the dashed line. Each transect line is 30m long with sample points 1m apart and transects are 5m apart. T1 is on the left and is located upslope of T15 on the right. The slope of the hill dips from bottom to top of the image, and right to left. Green indicates a high sensor response with a purple indicating a low sensor response. Note the different scale for each sensor.



a) 14th March 2020 SA1 11cm Processed data (11-3= data).



b) 14th March 2020 SA1 30cm Processed data (30-11= data).

Figure 30 Area that is used for the rotating footpath is outlined by the solid line, with the rested area outline by the dashed line. Each transect line is 30m long with sample points 1m apart and transects are 5m apart. T1 is on the left and is located upslope of T15 on the right. The slope of the hill dips from bottom to top of the image, and right to left. Green indicates a high sensor response with a purple indicating a low sensor response. Note the different scale for each sensor.

The vertical profiles allow for interpretation of the results to aid understanding of the interactions at depth. Viewing the data as a vertical profile can establish different areas that have a higher response closer to the surface which affects both the sensors. When interpretating the vertical profiles, purple denotes a higher surface repose and green is a higher response at depth. The lesser response in the profile is in relation to shallower sensor (11cm) having a higher response than that of the deeper sensor (30cm), again note the variation in scales of the profiles. The profiles have been trimmed to display 0-30cm in depth and the points are presented at 11cm deep.

a) Vertical profile of Transect 1, for SA1 10th March 2020.

b) Vertical profile of T5 for SA1 10th March 2020.

c) Vertical Profile of T 10 for SA1 10th March 2020.

d) Vertical Profile of T15 for SA1 10th March 2020.

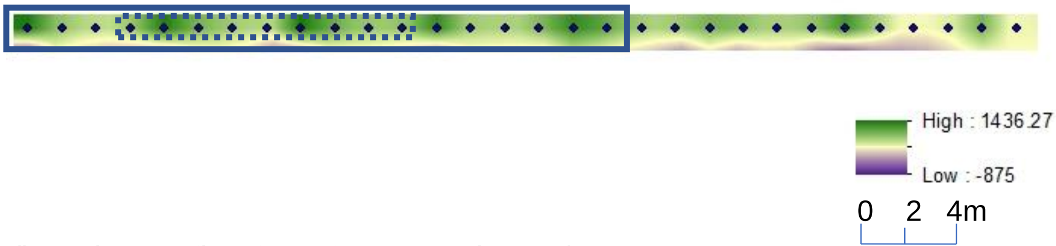
Figure 31 Vertical Profiles of the 3cm, Processed 11cm and Processed 30cm data. Sensor values are stacked, and the points indicate location of reading on the surface, displayed at 11cm depth. Area that is used for the rotating footpath is outlined by the solid line, with the rested area outline by the dashed line. Left is the highest elevation on the transect with right being the lowest elevation. Green indicates a high sensor response with a purple indicating a low sensor response. Note the change in range between each profile.

The vertical profiles demonstrate a higher response from the sensors closer to the surface than at depth for all transects (Figure 31). The vertical profiles also show a clear reduction in sensor response the further away from the main access footpath into the adjacent landscape.

a) Vertical Profile of T1 for SA1 14th March 2020.

b) Vertical Profile of T5 for SA1 14th March 2020.

c) Vertical Profile of T10 for SA 1 14th March 2020.



d) Vertical Profile of T15 for SA1 14th March 2020.

Figure 32 Vertical Profiles have been constructed from 3cm, Processed 11cm and Processed 30cm. Sensor values are stacked, and the points indicate location of reading on the surface, displayed at 11cm depth. Area that is used for the rotating footpath is outlined by the solid line, with the rested area outline by the dashed line. Left is the highest elevation on the transect with right being the lowest elevation. Green indicates a high sensor response with a purple indicating a low sensor response. Note the change in range between each profile.

The vertical profiles from the 14th March 2020 suggest that sensor response is similar between the main access path and the adjacent landscape (Figure 32). There is an overall reduction in response form the sensors across all transects, compared to the 10th March 2020.

4.2.3 Ring of Brodgar SA1 Discussion

The difference between the 11cm sensor and Processed 30cm readings (Figure 28) can begin to be used to establish the change in patterns of use intensity across SA1. For SA1 the footpath has a distinctive natural vegetation boundary (Figure 27) between the main access footpath and the adjacent grassland. When surveying the adjacent grassland, it became apparent that the dead grass present within this area was problematic for surveying. To prevent the dead and dry grass from becoming the controlling response factor it was removed from the surface to allow better contact between the soil and the sensor. Vegetation was also highlighted to affect the sensor response in the test survey (3.3 Field Surveying trial at Rough Castle) and therefore this was expected at Ring of Brodgar. Finding this effect again at SA1 emphasises the influence that the vegetation cover has on the ability to use the sensors in the field. The effect of the vegetation can be seen particularly in the 10th March 2020 survey using the 11cm sensor (Figure 28), through a lesser recorded response than that of the main access path. The contrast between the two areas highlights the influence that vegetation can have on the sensor response. However, vegetation was seen as a lesser influence on the 14th March 2020 survey (Figure 29), where the ‘boundary’ of the path appears to have moved into the surrounding landscape.

There could be two possible causes for the change in effect seen between the 10th March 2020 and 14th March 2020 surveys. The first is, once the vegetation was removed from the surface the contact between the sensor and the soil was good, and the sensor has no influence from the above ground vegetation. The sensors could still be affected by the below ground root structures associated with the vegetation and this is therefore causing the difference in sensor response. As the sensors are affected by the change in relative permeability of a substrate, change in root structures could also be affecting the sensor responses.

The second is the movement of water through the soil profile and downslope. The vegetation boundary is on the downhill side of the main access footpath and therefore the ‘change in boundary’ is a change in soil moisture through water infiltrating the soil profile and moving down slope. This highlights the requirement to better understand the external factors which can control the permittivity of a soil profile and their effect on the MMS. The increase in soil moisture and the vegetation composition are factors that need to be taken into consideration when understanding the sensor responses, particularly when carrying out repeat surveys.

From the 11cm sensor and 30cm sensor response (Figure 29), it cannot be established if the rested area is having an impact on the sensor response, however when the Processed data is used, the effect the rested area may be having on the sensor response is seen (Figure 28). This is shown through the increased reading from the 30cm sensor (green) within the rested area, compared to that of the 11cm sensor. Further to this however, the clear delineation of the main access footpath boundary that is captured in the raw data is no longer present. The 'loss' of the boundary between the footpath and the adjacent grassland in the Processed data indicates that there is an interaction happening at a depth greater than the raw sensor 30cm readings would suggest. Through understanding the differences between the 30 and 11cm sensor, the differences that occur at depth also become more apparent. Clearly the boundary between the main access footpath and adjacent grassland is more prominent in the top 11cm of the soil profile yet is still influencing the subsurface 11-30cm zone. This is due to the factors affecting the sensor response, soil moisture and compaction, having a greater influence on the sensors in the top 11cm of the profile.

In addition, the soil samples taken at SA1 and the adjacent landscape show a slight change in the particle composition of the soil samples (*Chapter 2. Site Selection and Research Design*). As a result, the responses that are recorded from the sensor could be interpreting the changes in soil composition towards the edge of the paths system and into the adjacent landscape (Figure 29 and Figure 30).

A similar trend of MMS response to the survey on the 10th March 2020 is seen for the survey carried out on 14th March 2020 for the boundary between the path and the adjacent land. The raw figures (Figure 29) of all three sensors (3cm, 11cm and 30cm) provide a clear distinction between the two areas. However, the boundary between the higher and lower responses from the sensor has 'moved' downhill and now presents as a straight line through the data sets rather than following the path boundary. This could be due to changes in environmental and soil conditions that were present at the time of survey.

However, when the raw sensor results are compared with that of the data, it can be established which sensors are being affected and at what depths. From this it can be established that the area adjacent to the path has a higher response from the Processed 30cm data than that of the 11cm data. Therefore, it can be deduced that the factors influencing the sensor are occurring at a depth deeper than the detection of the 11cm sensor, which is generating the higher response. This depth trend is further seen in part of the rested area and down slope along the second transect (T5), whereas the converse (higher response from the 3cm sensor) is seen in the 11cm data.

Further to this, it is interesting that the 11cm sensor picks up no further responses from the area adjacent to the main access footpath than that of the 3cm sensor (Figure 29). Thus, suggesting that the factors controlling the response of the sensor are contained within the top 3cm of the soil profile or that the factors affecting sensor response are too great in the top 3cm of the profile to be bypassed by the 11cm sensor. As a result, it is most likely that the sensors are detecting a change in soil moisture rather than any further external factors on the 14th March 2020 survey. This would suggest, the areas that are detected as having an increase between 10th March 2020 and 14th March 2020 are in fact the detection of changes in soil moisture.

From the analysis of both surveys of SA1, there is an interaction between the footpath and that of the adjacent downhill landscape. The lack of effect that the rested path is having on the sub-surface soil is particularly highlighted between the two surveys (10th and 14th March 2020). This is further shown in the vertical profiles of these four transects (Figure 32) where the top 11cm of the profile has the greatest response and as depth progresses the response from the sensor lessens. This reduction in response is due to the factors affecting the sensors being present in the top 11cm of the profile. Moving towards the edge of the path boundary and into the surrounding landscape, there is a lesser response from the 11cm sensor in this area along with a reduced response from the 30cm sensor. This would further highlight that the factors affecting the sensors are held with in the top 11cm of the profile.

The vertical profile for SA1 on 14th March 2020 presents differently to that of 10th March 2020 (Figure 32). Firstly, the range of responses from the MMS sensors is reduced compared to those of 10th March 2020. The cause of this is unknown, however there were three days of heavy rainfall between surveys. This could have resulted in a higher moisture retention in the surface of the soil which could have affected the sensor response. The second point to note is that the deeper sensors are affected at different locations across the transect resulting in patches of ‘no further response’. This does not mean that the sensor response was saturated, it is a measurement artefact of the processing used within this research. Finally, the sensor response from the 14th March 2020 in the boundary between the main access path and the surrounding landscape is not as well defined as the 10th March 2020 and has a lesser response. This highlights that understanding the ground conditions are imperative to obtaining a good survey at this location with the MMS.

The two surveys at SA1 highlight the importance of understanding the influence of soil moisture on the ability to gain an understanding of the influence of the footpaths and the extent into the surrounding landscape when using the MMS. Therefore, the ambient soil moisture can affect the ability to detect the location of footpaths at SA1. This addresses the second aim of this chapter, which is to establish if ambient soil moisture affects the ability of the sensors to detect these key visitor features.

4.2.2.1 Effects of soil moisture on sensor response at SA1

The only change between the surveys on the 10th and 14th March 2020 was precipitation, and therefore likely also a change in soil moisture. Thus, soil moisture is the most likely cause in the difference between the sensor responses. However, within this study it is not possible to determine if the sensor was detecting the changes in soil composition or other factors linked to soil composition, soil moisture and density. In order to determine the extent that soil composition is a factor influencing the sensor response further experimental work would have to be carried out. This would include investigating the influences of depth of horizon changes, porosity, water filled porosity, soil texture, organic matter and metal concentrations.

With repeat surveys it could be possible to build up a clearer understanding of the soil moisture in relation to the main access path and the adjacent landscape as well as the relationship between the two. However, the change in response between the two surveys indicates that this technique could be used to determine the changes in soil moisture within a heritage landscape.

It is important to note that through an increase in soil moisture, the depth and area of the microwave bubble from the MMS can increase due to there being a higher conductive/ response medium. Without being able to verify this, it is assumed that the depth to which the MMS is detecting is the same for each survey, as the rainfall prior to and between surveys was similar. Therefore, when comparing between 10th and 14th March 2020, the changes in sensor response is directly related to changes in soil moisture. This is also due to there being low footfall on the site at this time of the year. This assumption suggests there is a greater change in soil moisture at depth (Figure 30) and on the downhill side of survey area. The soil moisture ‘boundary’ that was presumed to be created by changes in vegetation, has now ‘moved’ downhill (Figure 28 and Figure 30), therefore indicating the change that was detected on day one was that of changes in soil moisture rather than that of direct vegetation change. This is an important location within the survey at SA1, as although it was assumed that, on the 10th March 2020, the vegetation was controlling the influence on the sensor’s response, carrying out a second survey shows that soil moisture is controlling the response from the sensor in this survey location.

As highlighted in the literature, footpaths can have an effect on soil moisture up to 15m either side of them (J. Gong, 2009). Here at SA1 this could be what is seen, with the changes in sensor response, between the main access footpath and adjacent landscape. Although the sensor response is lesser for the adjacent landscape than the main access footpath, the changes in sensor response with increased soil moisture, would suggest that the footpath is having an effect on the adjacent landscape. Within this study this is the only footpath of this size and use intensity therefore establishing how far into the adjacent landscape the footpath is influencing is difficult to determine, especially when the 14th March 2020 survey (Figure 31) does not present the same results for the vertical profile as the 10th March 2020 survey (Figure 32).

In addition to soil moisture, soil recovery also needs to be better understood in the context of a heritage landscape. Within SA1 the resting/use cycle of the footpath was designed to aid soil recovery. The path is split into three sections with each area being rested for a 2-week period. Soil recovery takes place on the decadal scale when all elements of soil degradation are removed (Obour et al., 2017, Alaoui et al., 2018, Alaoui and Diserens, 2018), in this case compaction effects. The soil will take at least 10 years to revert to a structure where no compaction can be seen. The resting process being carried out on the main access path within SA1 does not allow sufficient time for this to occur. This is clearly seen in Figure 28 and Figure 29, where there is no discernible difference between the rested area and the remainder of the main access footpath.

The difference in readings between each sensor head for SA1 highlights the impact that the entrance footpath is having at the Ring of Brodgar (Figure 28). Although the interaction between the factors that control the sensor response are complex, it would be expected that the sensor responses would be different between these two areas. Therefore, it could be concluded that the resting of the footpath is solely allowing for aesthetic recovery of the grass, rather than the recovery of the soil beneath. Thus, a fundamental shift in the perception and understanding of soil recovery is needed to aid the protection of heritage landscape, especially at sites where we see large numbers of visitors each year and in relation to rainfall patterns and use intensity.

4.2.4 Ring of Brodgar Survey Area 2

The second survey area (SA2) at Ring of Brodgar covers a line of desire (Figure 33). This area does not form part of the managed path system on site and receives a low visitor footfall. This path is narrow, yet well-defined, and cuts across the slope of the site.

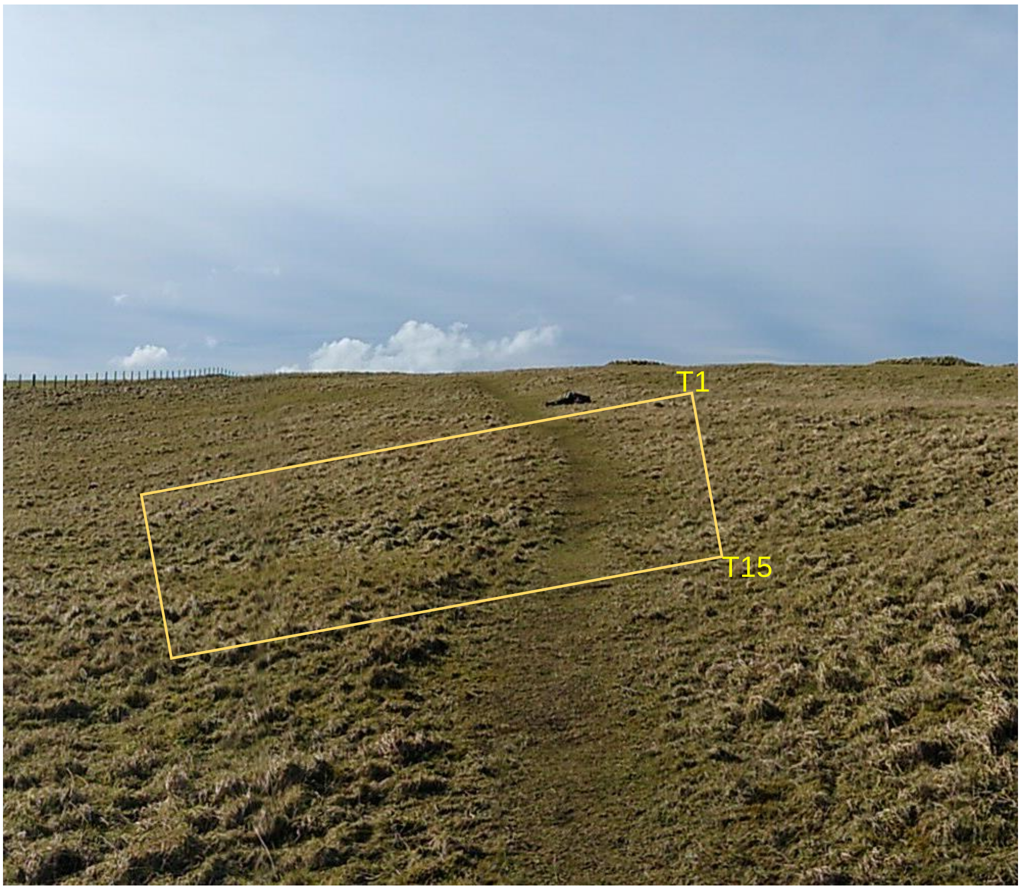


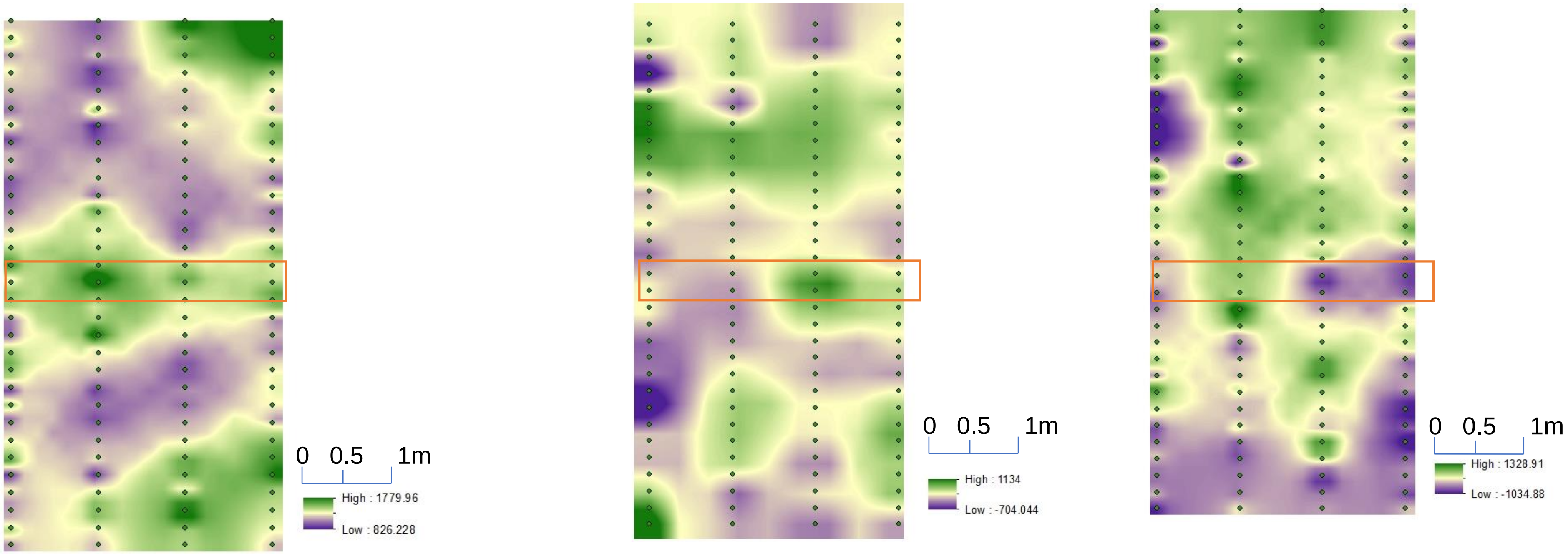
Figure 33 Photo of SA2 looking west, showing the defined line of desire, with an approximate outline of the survey area, highlighted in yellow.

Two surveys were carried out at SA2, on the 10th March 2020 and 14th March 2020. Only two surveys were carried out, due to heavy rainfall occurring in the intervening days. Although there was no standing water on site, rainfall prevented use of the equipment due to exposed connections between the sensor and the handset. When carrying out this survey, placement of the sensor was carefully considered, as the area was covered by tufted dry and new growth grass. Removal of the dried grass was carried out at each survey point to ensure adequate soil surface contact for the sensors.

For the surveys that were carried out at SA2, only the Processed data have been presented here. In SA2 it was thought that the footpath would not be detectable and its affect into the adjacent landscape would be not determinable. This is due to the narrow width of the path, which could result in the path either not being located on a sensor survey point or the lack of width resulting in the effect of the path being undiscernible.

4.2.5 Ring of Brodgar SA2 MMS Results

The results for Ring of Brodgar will first show the plan view of the MMS data and then the vertical transects for 0m, 5m, 10m and 15m within SA2.

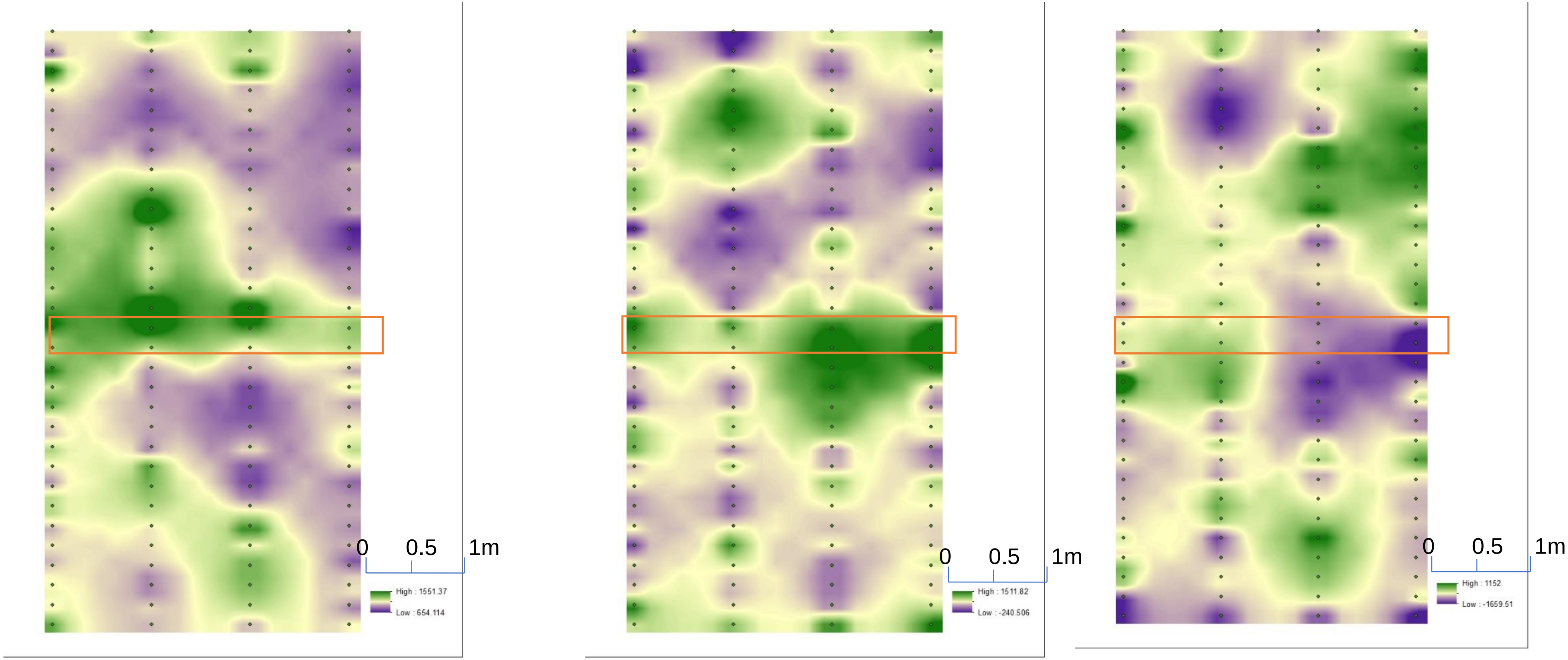


a) 10th March 2020 SA2 3cm Sensor.

b) 10th March 2020 SA2 Processed 11cm Sensor.

c) 10th March 2020 SA2 Processed 30cm Sensor.

Figure 34 Area that is used for the footpath is outlined by the solid line. Each transect line is 30m long with sample points 1m apart and transects are 5m apart. T0 is on the right and is located upslope of T15 on the left. The slope of the hill dips from top to bottom of the image, and right to left. Green indicates a high sensor response with a purple indicating a low sensor response. Note the different scale for each sensor.



a) 14th March 2020 SA2 3cm Sensor.

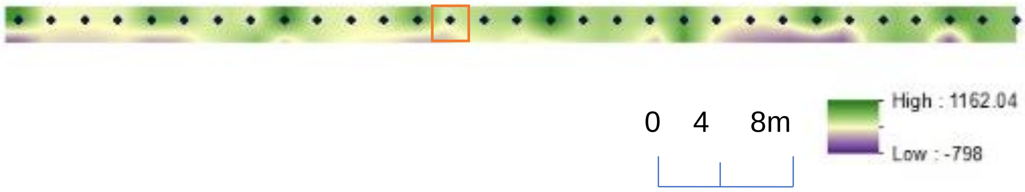
b) 14th March 2020 SA2 Processed 11cm Sensor.

c) 14th March 2020 SA2 Processed 30cm Sensor.

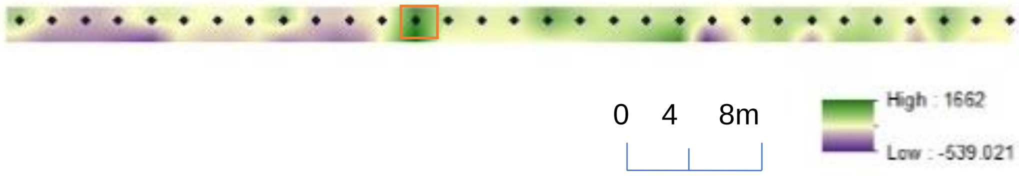
Figure 35 14th March 2020 SA2 that is used for the footpath is outlined by the solid line. Each transect line is 30m long with sample points 1m apart and transects are 5m apart. T0 is on the right and is located upslope of T15 on the left. The slope of the hill dips from top to bottom of the image, and right to left. Green indicates a high sensor response with a purple indicating a low sensor response. Note the different scale for each sensor.

The response from the 3cm sensor indicated three areas of increased response: the top right, bottom right and middle of the survey area (Figure 34). The 11cm sensor shows a sporadic increase in response across the survey area. There is an increase in response along the top of the survey area and the left half of the footpath, along with three points in the lower half of Survey Area 2 for the 11cm sensor (Figure 34). The 30cm sensor has a general increase in sensor response across the top half of the survey area, with a general reduction in response downslope of the footpath (Figure 34).

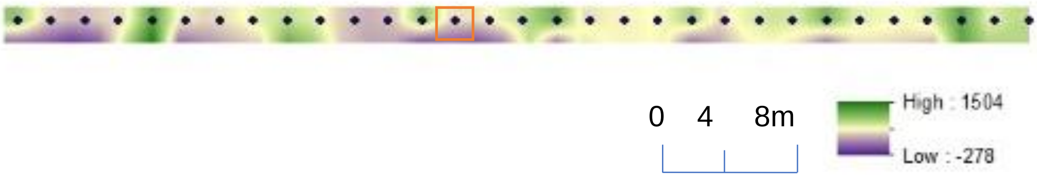
For the survey on the 14th March 2020 the 3cm sensor has an elevated reading across the middle of the survey area and on the right-hand side (Figure 35). The Processed 11cm sensor data shows an increase in response across the centre of the transect with one area of increased sensor response in the top half of the survey area (Figure 35), as well as increased readings at the bottom of the survey area. Overall, for the Processed 11cm sensor the readings show a lesser response than those of the 3cm sensor. The Processed 30cm sensor data reveals three distinct areas of increased sensor response, the first is at the bottom of the survey area, similar to 3cm sensor, the next is on the left side of the survey area and the final one is on the top right of the survey area (Figure 35). The areas that showed an increase in sensor response from the 11cm sensor, show a lesser response in the 30cm sensor data.



a) 10th March 2020 SA2 T0.



b) 10th March 2020 SA2 T5.



c) 10th March 2020 SA2 T10.

d) 10th March 2020 SA2 T15.

Figure 36 3cm, Processed 11cm and Processed 30cm data is used to generate the vertical profile form survey on 10th March 2020 at SA2. Sensor values are stacked, and the points indicate location of reading on the surface, displayed at 11cm depth. Area of the footpath is outlined by the solid line. Right is the highest elevation on the transect with left being the lowest elevation. Green indicates a high sensor response with a purple indicating a low sensor response. Note the change in range between each profile.

The vertical transects for the 10th March 2020 show a more complex interaction of sensor response than the plan views (Figure 31). There is a general trend across all the transects for the right side having an overall higher reading than the left. This could be linked to the topography of the site with the left being up hill and the right downhill. Note the location of the footpath is not easily seen in the vertical transect for 10th March 2020, however all transects show an increase in sensor response in the footpath's location.

The vertical transects for the 14th March 2020 indicate a general increase in sensor response across all transects (Figure 32) compared to the 10th March 2020. The 30cm sensor appears to have a lesser response at similar points across all transects to the survey on the 10th March 2020. The location of the footpath has a slight increase in response in Transect 0 (Figure 32) but a reduced response for the rest of the transects.

4.2.6 Ring of Brodgar SA2 Discussion

4.2.6.1 Plan view sensor response

The line of desire in SA2 at Ring of Brodgar is clear within the MMS data. The results from 10th March 2020 show that the footpath forms a distinct sensor response. The 3cm sensor (Figure 34) clearly shows a higher response in the area within and around the footpath but also for other sections within the survey area, this is further highlighted by the survey 14th March 2020 (Figure 35). The response from the 11cm sensor data (Figure 34) on 10th March 2020 indicates that within the footpath there is an increase in response on the right side of the footpath and a reduction in response on the left of the survey area. The inverse of this is true for the 30cm sensor (Figure 34) on 10th March 2020. Whereas 14th March 2020 indicates a continuous higher response across the area of the footpath (Figure 35) for the 11cm sensor, than the 10th March 2020. The 30cm sensor on the 14th March 2020 has a similar response to the 10th March 2020 survey (Figure 35). This then raised the question of why the 30cm sensor detects an increase in response compared to that of the 3cm and 11cm sensors.

Further to this there are several areas that have a higher response from all three sensors indicating that the factors affecting the sensor response (soil moisture, porosity and density) are increasing with depth. This could suggest there is only one factor at play when determining the response from the sensors. Additionally, it is interesting that the increase in response is occurring on both sides of the line of desire (Figure 34). This could indicate that the footpath in this section although picked out well within the 3cm sensor response, does not have a significant influence at depth. The increased response both above and below the footpath at 11cm and 30cm depth ranges (Figure 34), could indicate that there is a hydrological connection beneath the footpath to allow for an exchange of soil moisture to occur that is unimpeded by the presence of the footpath. The subsurface connections are speculative and cannot be fully understood without further monitoring and understanding of the soil profiles in this location. However, the lack of further detection by the 11cm and 30cm sensors would suggest more complex interactions are happening around the footpath.

When using the sensors within a laboratory setting it was found that the response of the sensor was linked to the volume of water that was added to the profile. In addition to this, compaction also had an impact on the response of the sensors, through a reduction in the range of response received. However, in the field it was not possible to test these variables independently. Thus, when interpretating the results from the sensors, it is assumed both these factors are influencing the sensor response. Presenting the results in the plan view has helped interpretation of the points at which there is an increase or decrease in sensor response compared to that of the previous sensor. This in turn has allowed the identification of areas which either have compaction or an increase in soil moisture within the sensor range. As both soil moisture and compaction are an interrelated response from the MMS, it has been assumed that they are mutually exclusive within this research.

The sensor responses were reduced on the 14th March 2020 survey compared to the 10th March 2020 survey; this is shown in the maximum and minimum responses for each sensor. As the 14th March 2020 survey was carried out after a rainfall event, the sensor responses were predicted to increase, not decrease. A possible explanation for this is that there was a change in dielectric properties on the soil. This could explain the reduction in range of the sensor responses; as moisture content increases the relative permittivity of the soil increases. Through an increase in relative permeability due to the increase in water content of the soil, this could result in the microwaves traveling further through the soil. This could result in a lower sensor response due to the dispersion of the microwaves.

4.2.6.2 Ring of Brodgar SA2 Vertical Transects

The vertical transects for SA2 show the narrow impact of line of desire. The ability to distinguish the difference between the line of desire and that of the surrounding landscape is highlighted in the vertical transects (Figure 32 and Figure 36). In every transect for 14th

March 2020, the line of desire has a higher response than that of 10th March 2020, however the line of desire is not markedly different from that of the surrounding landscape. Thus, making it difficult to identify its location within the landscape. Being able to view the transects vertically, instead of plan view, aids in the understanding of the impact that the line of desire has on the adjacent landscape. Although the line of desire is visible on the ground (Figure 33) and the plan view of the data distinguishes the potential location of the line of desire (Figure 34), the vertical transects show the full impact that the line of desire is having on the landscape. Unlike the main access path in SA1, the line of desire SA2 has minimal impact on the adjacent landscape which is shown through the vertical transects.

4.2.6.3 MMS Method application and use within at SA2 and in a Heritage Landscape

Viewing the sensor response in more than one format allows for a better understanding of the impact that a footpath can have on soil properties, which in turn can influence the landscape surrounding the footpaths. In plan view, the line of desire appears to have an influence on the adjacent landscape (Figure 34). Whereas in the vertical profile, the footpath is almost unrecognisable from the sensor response, showing that the footpath is having a narrow lateral impact on the landscape. Being able to view the sensor responses in both formats allows for a fuller understanding of how the footpath interacts with the landscape. The most noticeable difference between 10th March 2020 and 14th March 2020 is along Transect 15 (Figure 28 and Figure 35). Within this transect there is a decrease in range of response from all sensors between the two surveys that has produced the most marked visible change in the data. However, this indicates the importance of scales and relationships between surveys.

Within this study scaled data has not been used due to the range of values from the sensors and the processing of the data. The sensor response has a maximum response of >3000 and a minimum of 499. When basic processing was carried out some values could reach – negative 2000. This resulted in a large range in the data (-2000 to +3000). Therefore, when carrying out IDW processing some of the complexities of the data was lost. Using scaled data is important when comparing across different surveys, but if the range of the scale impairs the interpretation of the data a comparison is not possible. As a result, using scaled data is not conducive to understanding of the sensor responses.

Further to the use of scale data, is the connection between the topography and the MMS response. For all transects in SA2, left is located higher up the slope with the right at the bottom (Figure 34 and Figure 35). Generally, for SA2, the sensor response would indicate that the uphill section of the transect has a lower sensor response for both surveys than the downhill side of the transect, indicating that the downhill slope from the line of desire is wetter, and the uphill side is drier. This interpretation is an oversimplification of a general trend seen within the transects. There is variability of sensor response within each transect. The sensor response is similar over both 10th and 14th March 2020 surveys which would suggest, potentially, that the topography is controlling the sensor response. As the footpath in SA2 is difficult to distinguish within the MMS data, it is assumed that the sensor response is related to the soil moisture in this location.

Within SA1 and SA2 it has been possible to identify several locations that need further consideration when monitoring the footpaths for changes in subsurface soil structure, density, and porosity. Through having increased soil compaction, it can impede soil moisture infiltration and therefore cause long-term problems with standing water on site. At Ring of Brodgar, this could result in footpaths becoming wider and having a greater influence over the heritage landscape. This could result in the footpaths having a wider impact on the upstanding and buried archaeology. If unregulated, these footpaths could continue to impact the soil structure, density, and porosity which in turn will have a greater impact on the heritage landscape.

Further research is required to understand the full potential impact of the footpaths within the heritage landscape at Ring of Brodgar. However, this work has provided a baseline understanding of their influence within the landscape.

4.3 Rough Castle

The survey area at Rough Castle is on a footpath that does not manage visitor flow or footfall but is maintained through grass cutting. The path is located along the line of the Military Way which runs through the fort top. Rough Castle is used as a recreation site and is a popular dog walking area, with multiple access points, averaging around 80,000 visitors annually. This survey location is SA3.

Figure 37 gives an overview of the site and the key features that are the focus of this study. The survey area, highlighted in red (1) and the main footpath (3), the link bridge line of desire which crosses the ditch (4). Line of desire (2) was not noticed during our initial site visit (28th February 2020) and was not visible at the time of survey, however at a second site visit on 1st October 2021 the line of desire could clearly be seen on site. The development and location of the lines of desires and footpaths across this landscape is essential for determining the impact that they could have on the MMS readings.

Figure 37 showing the approximate locations of the main footpaths that are included in the survey area on site and the survey area. 1 is the area that is included in the survey, 2 is a new line of desire that has occurred between the first visit on 28th February 2020 and 1st October 2020, 3 is the main footpath and 4 is a line of desire that crosses the ditch on site known as the link bridge.

Surveying at SA3 was relatively straight forward due to the short grass on site and lack of other vegetation in the survey area. The surveyed area is 22m long by 8m wide, the width is controlled by the geographical constraints of the fort top and the presence of other buried archaeological features that were seen as confounding for this survey and avoided. The survey was conducted using transects spaced 1m apart, each point on the figures below indicated a survey point also 1m apart. Transects were carried out on the 8m axis generating 22 transects with 8 survey points in each.

4.3.1 Rough Castle SA3 Results

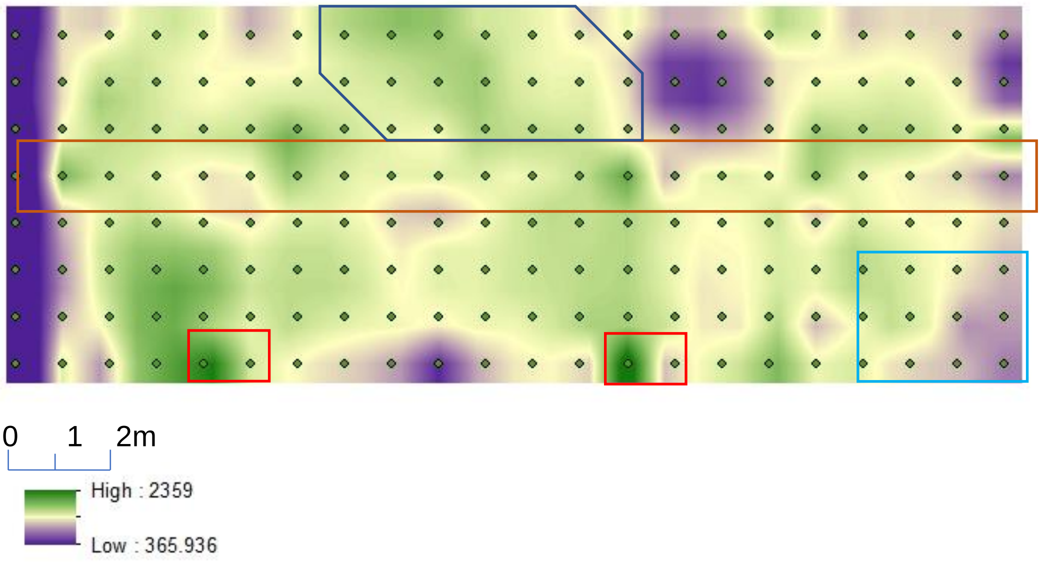
In the field at Rough Castle there is no visible definition of a path, path boundary or the interface between the two which is picked out in the MMS data in Figure 38 . As a result, this presents a slightly different opportunity for understanding the application of MMS in a heritage landscape.

The plan results contain only the Processed data, as highlighted at Ring of Brodgar the Processed data gives a clearer interpretation of the interactions between the MMS response and soil properties. All transects are annotated with the locations of key features. Transect 22 on the left and 1 on the right, signboards are at the base of the image highlighted in red and the joining path and ditch at the top highlighted in blue, with the main footpath running through the middle highlighted in orange, the area highlighted in light blue is a line of desire that has become prominent between 28th February and 1st October 2020.

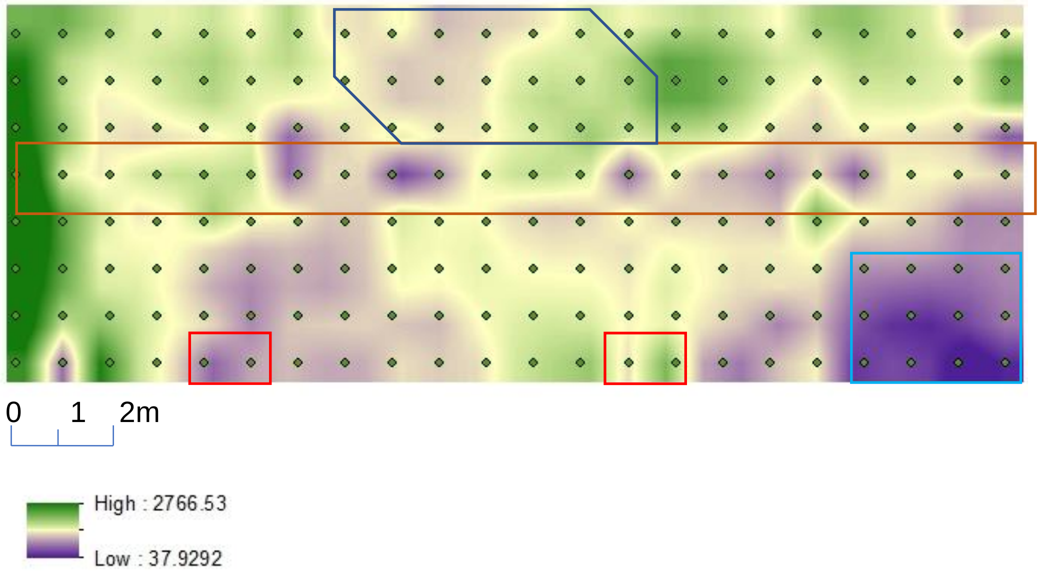
There is an increase in the 3cm sensor response at the location of the signboards (Figure 38) and an elevated sensor response in most of the survey area compared to areas around the signboards. The low reading on the left is due to a sensor error resulting in a missing transect. The footpath has an overall elevated response but is not discernible from the rest of the survey area. There is one distinct low reading to the right of the link bridge path. In the location of the new line of desire (2) there is a mixed response from the sensor.

The Processed 11cm sensor data has a lower response in the area of the left signboard and an increased response for the right one (Figure 38). Across the survey there is a mixed response from the sensor with some areas having a higher response than the 3cm sensor. The elevated reading on the left is due to processing and the missing transect from the 3cm sensor. The footpath has an overall reduced sensor response. The link bridge has a half lower response, half increased response. The line of desire had a reduced response.

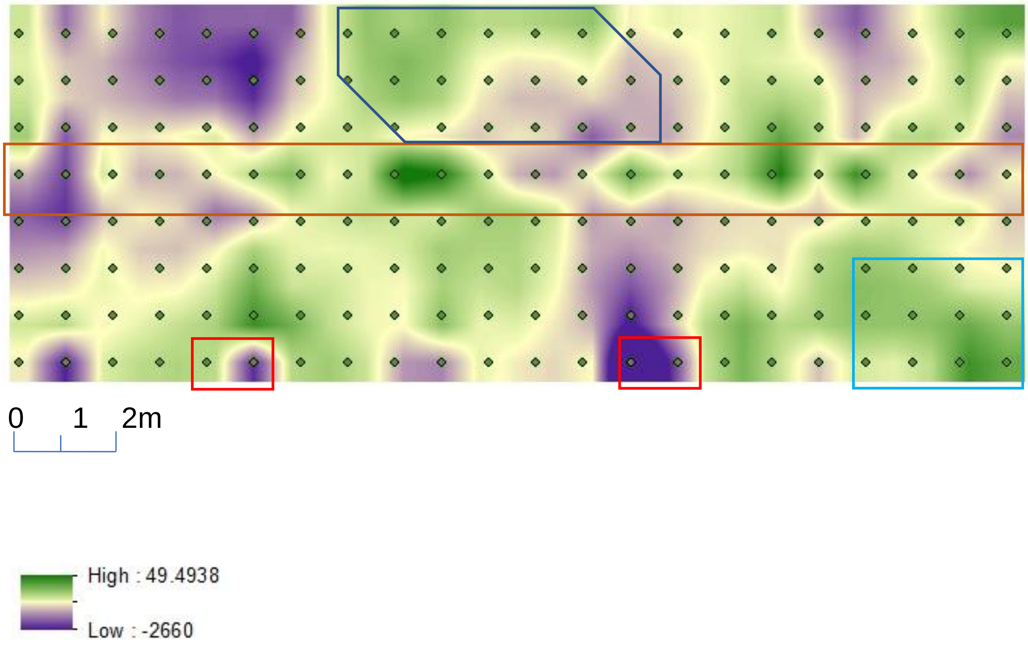
The 30cm sensor (Figure 38) has a reduced response for the right signboard and a mixed response for the left one. Overall, across the survey area there is a varied response from the sensor. The main footpath area has a general increase in response from the 11cm sensor, however the response is not that different to the rest of the survey area. The link bridge path has a divided response with an area of increased and area of lesser sensor response from the 30cm sensor and is the opposite to what was recorded by the 11cm sensor. The responses from the 11cm and 30cm sensors are a mirror of each other. The line of desire has an increase in response compared to the 11cm sensor data.



a) Raw 3cm Sensor



b) Processed 11cm Sensor

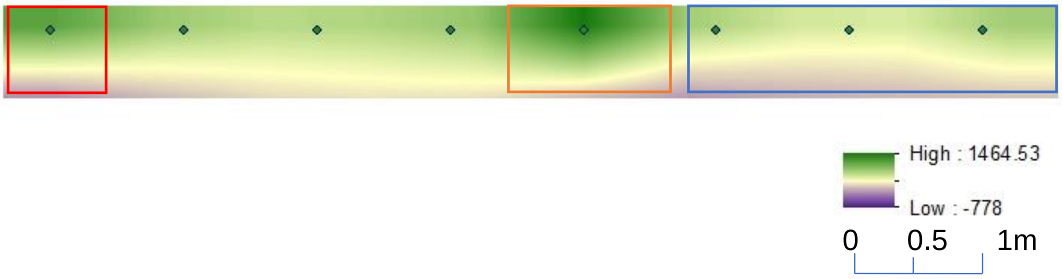


c) Processed 30 cm Sensor

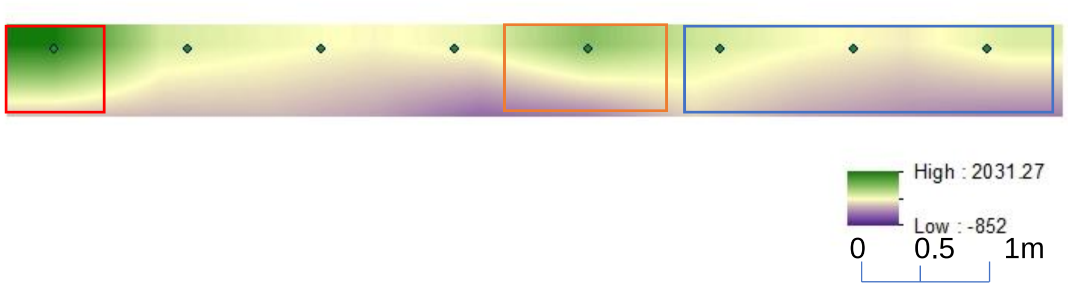
Figure 38 SA3 Signboards are highlighted in red at the bottom of the image and the diffuse footpath to the link bridge at the top is highlighted in dark blue, with the main footpath running through the middle highlighted in orange. The area highlighted in light blue, on the right, is a line of desire which became visible between February and October 2020. Green indicates a high sensor response with a purple indicating a low sensor response. Note the changes in scale for each sensor.

Three transects (Figure 39) were chosen to further interrogate for SA3 and the full set of transects is shown in Figure 40. The layout of the three transects is point 1 on the left and 8 on the right, the signboards are highlighted in red (none are present with in these transect, but all are located between signboards with varying distances). In the middle is the location of the footpath highlighted in orange and the right is the line of desire to link bridge highlighted in blue.

Transect 12 is located between the two signboards (Figure 39a) and has an elevated reading in the location of the signboard, along with an increase in reading in the location of the main footpath. The link bridge path location has an elevated response near the surface and a reduced response at depth. Transect 18 is located to the left of the left signboard (Figure 39b). There is a high reading on the left of the transect where the signboard is located. The main footpath location has a slight elevated reading, with the link bridge line of desire having the lowest response. There is a reduced response at depth along the transect. Transect 21 is located on the left of the survey area and is located before the signboards (Figure 39c). There is an increased sensor response along the transect, with high sensor responses on the left and where the main footpath is located. There is an elevated reading between the left of the survey area and main footpath. The link bridge line of desire has an elevated reading.



a) SA3 Transect 12.



b) SA3 Transect 18.

c) SA3 Transect 21.

Figure 39 SA3 Vertical Transects. Signboards are highlighted in red on the left and the diffuse footpath to the link bridge is highlighted in dark blue on the right, with the main footpath running through the middle highlighted in orange. Green indicates a high sensor response with a purple indicating a low sensor response. Note the changes in range for each profile.

All transects are shown in Figure 40 which shows an increased response in all transects where the main footpath is located. An increased response in the location of the signboards, as well as elevated readings before, between and after the signboards, shows the impact that visitors are having on not only the area directly in front of but around the signboards.

Along with a slight increase in sensor response this indicates the impact that visitor footpath choice is having on the sub-surface in relation to soil properties in the area associated with the link bridge.

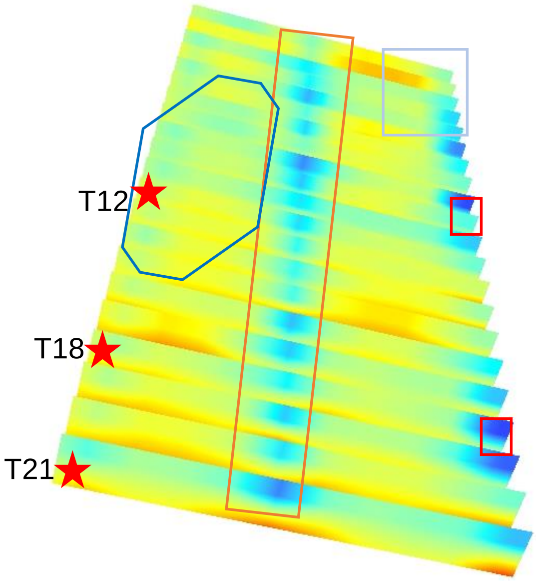


Figure 40 shows all transects form SA3, with T21 at the front with T1 at the back. Signboards are highlighted in red on the right of the image and the diffuse footpath to the link bridge at the top is highlighted in dark blue, with the main footpath running through the middle highlighted in orange. The area highlighted in light blue, on the right, is a line of desire which became visible between February and October 2020. Blue indicates a high sensor response with red indicating a low sensor response. The red stars indicate the vertical transects in Figure 39.

4.3.2 Rough Castle SA3 Discussion.

4.3.2.1 Rough Castle SA3 Plan View Discussion

Interpretation of the MMS data has been challenging and one of these challenges is the display of missing data. This can be seen in Figure 38 , where the solid colour on the left of the transect is due to a sensor error, not a low response as is the case with the other readings across SA3. When the 11cm sensor response is processed in , it appears that the sensor response has increased, however this is not the case, the readings are presented as higher due to there not being a 3cm sensor reading. Although the final transects in Figure 38 a and b are inaccurate, it highlights one of the artefacts that can be incurred when processing data and trying to profile the sensor responses.

Through processing this data there has been some issues and difficulties when trying to establish the ‘best’ format to process and display the data and these two figures (Figure 38 a and b) highlight this well. In contrast Figure 38c,Figure 38c displays the data on the left, in line with what is expected from the Processed data, with points of higher and lower response (Figure 38). Through viewing the data in plan view at SA3, the issues with only viewing the data in one plane can be clearly seen. The effects of missing data and the artefacts of processing the data can also be seen in Transect 22. Further work is required to better understand the influence that the data processing is having on the interpretation and presentation of sensor responses.

However, there are several interesting points that can be picked out in the plan view. One of these is the footpath that runs directly through the middle of the survey area. In Figure 38a there is no obvious difference between the areas highlighted as the main footpath and that of the survey area. However, in Figure 38c, there is a reduction in response from the processed 30cm sensor for distinct parts of the main footpath which makes it difficult to differentiate from the rest of the survey area without knowing the exact location of the main footpath. The reason for the reduced response in this location could be indicative of changes in soil compaction that influence the sensor response. Nevertheless, this does not explain why the response is variable across the main footpath. Furthermore, in Figure 38c, there is an increase in response from the 30cm sensor compared to that of the 11cm sensor. This clearly shows the footpath through the survey area, and it becomes a distinct feature within the survey area with the 30cm sensor. The increase in sensor response at this point has again an unknown cause but is in the location of the main footpath.

A possible reason for the variability in response, is that the survey area is located on top of the old Roman road. It is known that the road is relatively well intact in this location and is present below the survey area. What is not known is the depth of at which the road is located below the survey area surface. If the depth is variable, this could explain the difference in sensor response, particularly the reduced response of the 30cm sensor. Along with this is the culverts that run alongside the Roman road (Robertson, 1960) which could be affecting the sub-surface hydrology, and we could be seeing this in the MMS response. As the stone of the Roman road is a different density to the soil profile, it will absorb more of the sensors microwaves thus indicating a lower response. With further surveys it could be possible to determine if the variable response is due to the changes in subsurface structure or variation within the soil profile.

An area of further interest is the line of desire at bottom right of the survey area (highlighted in light blue). The line of desire presents as uninteresting when surveyed with the 3cm sensor (Figure 38a), however, the Processed 11cm sensor shows a marked reduction in response (Figure 38b). The reduction in response would indicate that there was no further reading picked up in this location by the 11cm sensor than the 3cm sensor. This would suggest that factors affecting the sensors' response is held within the top 3cm of the profile. In Figure 38c, however, there is an increased response from the 30cm sensor, which suggests indicates there are further factors affecting the sensor at depth.

The area in the bottom right of SA3 presents as a complex to understand and determine the results of the sensor outputs at this point. When a second field visit (1st October 2020) was carried out on site, the line of desire was visible on the ground and was well established. During the first field visit this was not visible on site, and it is unclear as to the intensity and periodicity of use of the line of desire. What is further unknown is if the survey carried out on 28th February 2020 was detecting the effects of this line of desire with low intensity use, or if this was a natural anomaly within the results. If the cause is the line of desire, this indicates the negative impact that informal routes through the site are having on the subsurface soil.

A similar response is seen, though to a lesser extent, in the area where the line of desire from the link bridge joins the footpath in the survey area. These two low intensity diffuse footpaths help us to understand the variability in sensor response across the survey area. Without site knowledge, the link bridge line of desire appears as a general variation within the sensor responses. Therefore, knowing the response from the sensors is related to a specific use on site can aid in understanding of why there is certain responses are recorded. It further indicates that the variation in the sensor responses is highly influenced by footfall. This makes the survey area difficult to interpret and establish the full effects of one individual footpath on site when there are other influencing factors also occurring on the site. The low intensity footfall between the main footpath and the link bridge and the line of desire entering the survey area would suggest that footfall is having more of an impact on the subsurface than is presently realised.

Further to the footpath at SA3, there are the two signboards located along the base of the survey area. When carrying out the transects they were placed on either side of the signboard locations as the area directly in front of each board contained worn bare earth. In Figure 38a, both signboards have an increased response from one transect and a slightly reduced response on the second transect. The increased response is notably higher than that of the surrounding sensor responses, especially for the signboard located on the right. These two areas of distinctly higher responses from the sensors indicate an area of interest on site and warrant further investigation. The 11cm sensor results are variable (Figure 38c) and would not indicate the signboard as an area of interest. Further to this, the responses from the 30cm sensor (Figure 38c) would suggest that there is a reduction in response from the sensor and therefore suggest a change in subsurface composition at these locations. However, given the readings around the signboards it would also not indicate any further interest in these locations. At this point vertical interpretation of the results is essential to determine the impact that the footpath and signboards are having on the site at Rough Castle.

4.3.2.2 Rough Castle SA3 Vertical Transect Discussion

In transect 18 (Figure 39b) the location of the signboard can be detected by an overall higher response from all sensors. Across the range of sensors this is the highest response detected throughout the transects and clearly indicates a point of interest in this location. However, the rest of the transect has relatively low response compared to this area, including the main footpath. Site observations and the MMS readings suggest that within this transect there is more diffuse trampling occurring. This ties in with site layout as this location is close to the link bridge for visitors crossing across the ditch, along with being the first signboard that visitors divert to. This transect shows that despite the footpath being obvious and well walked the signboards and links to other footpaths need to be considered when looking at the location and interaction of a footpath and the surrounding features.

Transect 12 (Figure 39a) is located between two signboards, however there is an elevated response from the sensor on the right, which occurs between the signboards. This is intriguing as this is similar for all transects located between the signboards. From the increased response it would suggest that there is a change in the subsurface soil matrix. It is presumed that the increased readings of the sampling points between the signboards is due to visitors walking directly between the two signboards. The main footpath is clearly visible in Transect 12 and the reduction in sensor response occurs at a relatively constant depth of between 20 and 30cm, until just after the footpath. The reason for this change in sensor response could be due to the data interpretation method (IDW) used and the processing of the data. However, this is also the area of the diffuse trampling to the link bridge, and this could account for the changes in sensor response.

Finally, transect 21 (Figure 39c) shows the full extent and impact that diffuse trampling has on the sensor readings. The main footpath is clearly visible in the middle of the survey area. Along with an increase in response in the area of the ‘signboard’ location. There is no signboard located on this transect. However, similar to Transect 12, this is the area leading up to and away from the signboard, which further highlights the importance of considering the impact that placement and connections of signboards have to the subsurface soil and archaeological matrix. The elevated sensor readings show that the effects of diffuse trampling can be seen across the transect. This would indicate that despite diffuse trampling having minimal visual impact there could be a much greater impact happening in the subsurface soil. Overall, the reduction in response at the base of all transects could be that higher responses in shallower sensor readings mean the 30cm results have an overall lower response. However, due to consistency of occurrence at the base of the profile, this would suggest that there is a change in subsurface structure. Given the underlying archaeology at this location is stone, it could be considered that the sensor is picking up the change from soil to stone. Due to stone having a different resistivity and pore size and water holding capacity, all these factors would result in there being a reduction in response from the sensor and possibly indicating the changes and presence of an archaeological feature within the profile.

The variation of the lesser sensor response is not always consistent within each transect, so it is difficult to determine how accurate the interpretation of the change in sensor response is for archaeological features. However, as this technique is experimental and this is the only buried archaeological feature that is being studied within this research, the fact that the sensor records a consistently lower reading by the 30cm sensor would further indicate the change in profile structure between 11cm and 30 cm. This is further backed up by infield soil sampling, where when using a Dutch auger to sample the soil within this survey area, the profile was shallow and samples were difficult to obtain. The maximum depth samples were taken from was 20cm within the survey area, this was due to being unable to use the auger as it came in to contact with stones. There were several attempts to take deeper samples within this area, in line with the SMC, but this was not possible. From the field soil sample observations, the MMS survey and visualisation, it can be assumed that the lesser response determined from the 30cm sensor, is due to the Military Way that the survey was carried out over.

4.3.2.3 Rough Castle SA3 General Discussion

Despite the soil samples for SA3 having a higher clay content (>18%) than was thought advisable (Doolittle et al., 2007) for use of the MMS, it does not appear to affect the sensor response. This is encouraging for the use of MMS in areas where a higher clay content of a soil are recorded. The variations in sensor response, within SA3, are thought to be in relation to the inorganics not the clay content of the soil. The clay content varied throughout the survey area, however the lack of consistent low sensor reading at one location would suggest the sensors were not affected by the clay content of the soil, but were affected by the inorganic materials found at varying depths. This relates to the impact that inorganics were having on the ability to take soil samples. This is encouraging for the results seen from the MMS, as the lower reading are related to the inorganics rather than the clay composition of the soil.

The ability to detect a change in the subsurface is essential for monitoring the impact that modern site use is having on the archaeological structures in relation to the soil profiles. It can be seen from Transect 12 and 21 where the higher response of the main footpath does not have an impact on the 30cm sensor and remains at a constant level beneath the footpath- not dropping or rising as in Transect 18. This would indicate that although the footpath is having a narrow influence on the landscape, it could be having an impact on the top layers of the subsurface matrix.

Viewing the data in a vertical format highlights the impact that footpaths are having on the survey area. This highlights the necessity to view data in more than one plane, as in plan view it was not possible to see the full impact of the signboards, footpaths, and diffuse trampling was having on the survey area. It also highlights the need of developing a robust method for viewing the data in more than one format to aid site understanding and visualisation. Through being able to view the data in both vertical and plan view, a greater understanding can begin to develop as to the impact that key visitor features are having on the soil profile.

4.4 The implications and considerations for footpaths and diffuse trampling

One key point that has been established between all survey areas is the footpaths are having an impact on their immediate environment, and this extends into the surrounding landscape. The impact is seen through the changes in MMS response, which is associated with soil properties and soil moisture.

The wider the footpath the more noticeable the impact, regardless of footfall. The impact of wider footpaths on the sensor response can be seen extending into the adjacent landscape. Larger footfall results in a clearer definition for where a footpath boundary occurs, and the impact of wide, high use footpaths is seen out into the surrounding landscape.

In this study, only earth-based footpaths were studied, and their effects into the surrounding landscape could be seen but not be fully established due to rainfall and vegetation. As the sensors are untested for use within heritage landscapes, there is further work to be carried out on the effects of soil type and different vegetation. Anecdotally, the contrasting vegetation at each site played a role in the ability to gain good surface contact between the sensor and the soil. The influence of vegetation varied across each survey area;, dried or dense long grass and moss had the most noticeable effect on sensor response.

However, it is clear that an earth-based footpath is having a high impact on the subsurface within immediate area of use but also into the adjacent landscape. This could potentially have a consequential impact in the future as a result of climate change. As rainfall increases across sites, footpaths could become waterlogged for longer periods, as was seen during field work at Ring of Brodgar. Some of the implications of changes in rainfall will be explored in Chapter 7. Climate Change: Precipitation and its Hydrological Implications for Heritage LandscapesChapter 7. Climate Change: Precipitation and its Hydrological Implications for . This will result in visitors moving around these waterlogged areas and out into the adjacent landscape. Thus, spreading the effects of the footpaths into a wider area, which could result in unknown damage occurring to buried or upstanding archaeology.

From this study, it would be suggested that with widening of footpaths, there is an increase impact of soil properties in the adjacent landscape. This coupled with visitors finding alternative ways around a site, lines of desire, are having a localised impact directly beneath them but possibly not into the adjacent landscape. These new lines of desire could have a greater impact on a heritage landscape and affecting the sub-surface archaeology. Therefore, determining the routes across a heritage landscape that are essential and implementing a solution which would prevent widening of footpaths and the development of lines of desire, would be beneficial for the preservation of a cultural landscape both for upstanding and buried archaeological features.

Diffuse trampling across sites (Link bridge in SA3 Figure 38) is having a much wider impact on the landscape and soil moisture and compaction (sensor response) than can be understood in this study and could become more of a concern as footpaths widen. As seen at the main access footpath in SA1 the path has reached over 15m wide, through visitors spreading out on the access and return to the site. Although this footpath sees a high number of visitor footfall, it gives an example of the diffuse trampling that is seen at SA3 may develop as soils become wetter and visitors changes paths to avoid the wet areas. This then becomes an issue for footpaths as they could become so wide that their impact is seen across more of the landscape. This in turn then becomes an issue for soil moisture infiltration and could result in unknown damage to archaeological features. Although there was only one area of diffuse trampling identified in this study, the impact of it can be clearly seen in the response from the sensors. This gives a clear indication of the impact that this type of footfall across a site can have.

The areas around and between the signboards is impacting the subsurface, soil structure, through visitor footfall. The visible impact of the area in front of the signboards clearly shows the impact visitor footfall is having. Within this study the impact on the area between the signboards is more substantial than first thought. The impact that visitors have moving between signboards is noticeable in the sensor response but not in the above ground vegetation. Therefore, it would be suggested that placement and maintenance of signboards, should not only be of the area immediately in front of the signboards but to either side and the journey between them.

In order to maintain the integrity and minimise the impact that footfall is having on a heritage landscape, the placement of signboards will play an important role, particularly if they are placed on, or close to, archaeological features. Through knowing the location of signboards and the journeys between them are having an impact on the sub-surface, developing infrastructure around and between signboards will become essential in in a climate change future. The impact may be small and not visible currently, but with changes in rainfall regimes, the impact that signboards have may become more prevalent. Further work is needed to be able to understand the extent of the impact that signboards are having on a heritage landscape, however this study has developed a base understanding that signboards are having a greater effect on the sub surface than originally thought.

Through developing a base understanding that signboards, footpaths, line of desire and the areas in between are having an impact on the sub-surface of a landscape, it is then possible to develop an understanding of how their locations can be managed to maintain and protect archaeological features in a heritage landscape in a climate changed future.

We need not only to consider the protection of upstanding and buried archaeology but how people are using the site. From footpaths, to signboards, to lines of desire, these are all having an effect on heritage landscapes and their impact will only become more apparent with changes in climate, which will be explored within Chapter 7. Climate Change: Precipitation and its Hydrological Implications for Heritage Landscapes

4.5 Application of MMS and Future work

The MMS sensors worked well in laboratory setting. When applied in the field, MMS performed well given the limitations and novelty of application. Although the exact basis of response from the sensors could not be established fully within the research, it has highlighted the ability to use MMS within a heritage landscape.

Further consideration needs to be given of time of day, surveyors, and environmental conditions such as temperature, rain, heavy dew, frost, and ice. When surveying at Ring of Brodgar the battery life of the MMS controller in the chilling wind was around 4 hours. This resulted in the handset having to be charged each day, which limited the time in the field.

Ground conditions played a larger role in the ability to carry out a survey than originally anticipated. Heavy dew and frost impacted the ability to survey with the sensors, due to surface moisture from the dew and the frost affecting the soils' dielectric properties.

Vegetation cover also affected the sensor response. This highlights the requirement to better understand the external factors which can control the permittivity of a soil profile and their effect on the MMS. The increase in soil moisture and the vegetation composition are factors that need to be taken into consideration when understanding the sensor responses, particularly when carrying out repeat surveys. Further work is required to understand the full extent to which different ground conditions influence sensor's responses.

Additionally, as all survey areas contained visitor access paths, being able to access them at a time of day without clashing with visitors took planning and organisation. Rough Castle is a busy dog walking area and has people walking through the survey area. Although this did not affect the use of the sensors or the readings recorded on the day, it can present an issue in stopping surveys and movement of set up if required. At Ring of Brodgar, the paths were quiet, due to surveying in March 2020, which resulted minimal visitors when surveying. However, if surveys were to be carried out in busier and peak visiting season then timing and durations of surveys would need careful planning.

In addition to this there needs to be further soil profile analysis carried out to determine some of the external influences of the MMS. This should include recording changes in soil horizons, boundaries between organic and inorganic layers, locations, and depth of archaeological features, along with characterisation of, at a minimum, soil composition, density, texture, structure and porosity. All these factors would help to give a better understanding of the different factors that can influence the MMS and allow for a more accurate interpretation of the sensor responses.

Having established the applicability of this technique for key visitor features, the next steps are for applying this technique to using in for monitor soil moisture around buried and upstanding archaeology. Through using MMS to determine changes in soil moisture around buried archaeology, this would allow for monitoring of potential changes to the understanding and changes in potential the state preservation. Additionally monitoring around upstanding archaeology would allow for further understanding of how upstanding archaeology influences soil moisture movement. St Kilda would provide a good test site for the applicability of MMS for this approach.

Through only using one experimental method, it is difficult to determine if the full influence of response is in relation to soil moisture or other sub surface interactions. Compared to the techniques outlined in Table 1 Summary of commonly used on ground methods for monitoring soil moisture, MMS is quick and easily accessible way to determine the influence of key visitor features on soil properties in a heritage landscape. MMS is also non-invasive and repeatable over the same area. GPR can also be used in non-invasively and its use for soil moisture determination is growing. However, it is costly to purchase and algorithms are still in development. EMI is equally costly to purchase, and algorithms require development, making it unsuitable in the short term and without a specialist for determining soil moisture. Therefore, to gain a rapid assessment of key visitor features and their impact on soil properties, MMS is more suitable. TDR and NMM both require access holes to be accessible within a landscape, however once established these locations can be visited repeatedly, or permanent monitoring from these locations can occur. In the long term either of these options may be more suitable for soil moisture monitoring within a heritage landscape. The ability to set up access holes and have repeat or constant monitoring could be beneficial for gaining real time data on the effects precipitation and visitor pressures are having on soil properties. TDR and NMM could also reveal real time fluctuations in soil moisture and response to precipitation, which would better inform heritage practitioners of potential soil moisture fluctuations in relation to archaeology.

Overall, the MMS worked well within a heritage landscape and for surveying key visitor features within the landscape. Careful consideration should be taken when wishing to scale up this technique and for long term monitoring within a heritage landscape.

Chapter 5. Hydrological modelling of WHS for determining hydrological networks to establish the effects of upstanding archaeology and visitor infrastructure in heritage landscapes.

5.1 Introduction

There is currently limited understanding of the diverse, complex, and intricate small-scale surface hydrological networks within heritage landscapes. To understand these hydrological networks, fine scale topographic LiDAR data from three World Heritage Sites (Ring of Brodgar, St Kilda and Rough Castle) will be used. LiDAR surveys are widely used within the heritage sector for site documentation and produce highly accurate fine resolution topographic data (Cowley, 2011, Wulder et al., 2012). LiDAR surveys are often carried out at a scale of less than 0.5m and it is anticipated that the fine scale nature of these surveys will enhance understanding of site micro-hydrological networks. The purpose of this chapter is to demonstrate how DSM and DTMs derived from LiDAR can be used to determine hydrological networks within WHS, which will give a robust foundation for site conservation where water and its influence need careful management.

This work will form the base understanding of the hydrological networks of Ring of Brodgar, St Kilda and Rough Castle to aid planning of response of site management to predicted climate change (Discussed in Chapter 7. Climate Change: Precipitation and its Hydrological Implications for Heritage Landscapes). The management of heritage landscapes needs to consider the impacts of changes in rainfall intensity and therefore understanding the current hydrological networks within a heritage landscape is vital to enable appropriate measures to be put in place without causing detriment to the heritage landscape. Through understanding all parts of a hydrological network, forward planning can be carried out to ensure that the heritage landscapes we are protecting are not damaged by changes in hydrological and precipitation events.

To ascertain if hydrological modelling can be applied in different landscapes, the Ring of Brodgar WHS is an exemplar of hydrological networks in a stream-less landscape, with the additional aspect of natural visitor footpath influences. Hirta, St Kilda WHS is an exemplar of built archaeological structures and their potential influence of hydrological flows together with the influence of historical land management practices on current hydrological network. Rough Castle is a non-physically bound area exemplar for determining hydrological networks together with the effect of earth structures and buried archaeological features on hydrological networks. Collectively these three exemplars can be used to demonstrate a new and novel approach to small scale hydrological modelling for heritage landscapes.

5.2 Hydrological Modelling Methodological Summary

Based on the trials of topographic scale in*3.4 Hydrological network modelling method*, using a fine scale DEM allows for the best possible accuracy in determining the potential hydrological networks within a discrete topographical area at Ring of Brodgar. A standard hydrological modelling procedure is used to determine the stream order (hydrological networks) and basins of each landscape (3.4.1 Hydrological modelling method). Basins are defined and overlain on the stream network to give a clear delineation for each stream network.

5.3 Hydrological Modelling Results and Discussion

5.3.1 Hydrological Modelling Ring of Brodgar

Ring of Brodgar presents a novel application of establishing hydrological networks in a stream-less landscape. The purpose is to establish if the hydrological flow networks by which water can move across a site can be determined in stream-less heritage landscapes. Previous attempts to determine preferential flow networks in areas with low topographic relief have had variable results suggesting that in some cases it can be done successfully (Amatya et al., 2013, Poppenga and Worstell, 2013).

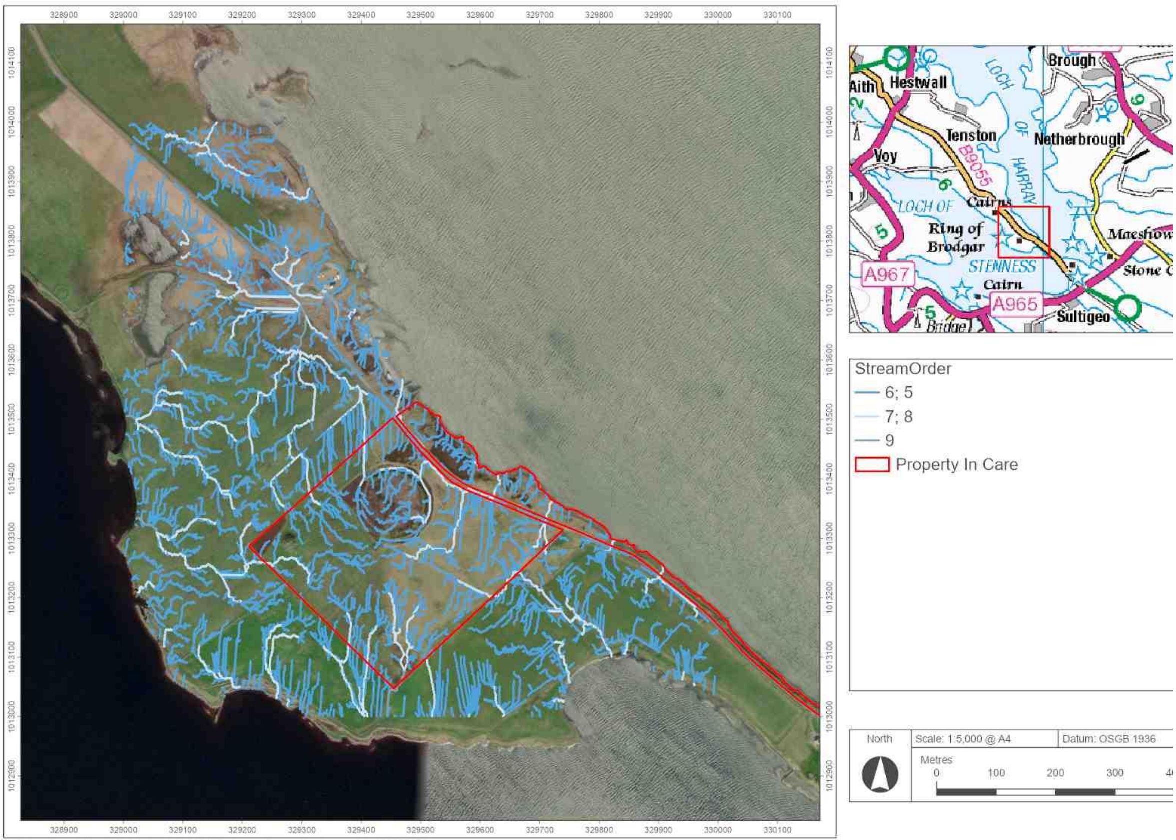


Figure 41 Higher order (5-9) Preferential flow networks at Ring of Brodgar. Note the straight edge to the north-west and south is due to the edge of the LiDAR data.

Figure 41 shows the complex nature of the preferential surface flows at Ring of Brodgar. Visually there appears to be lots of complex surface interactions between all preferential flows on site. Such as, the interactions between the preferential surface flows and the ring and ditch, influence of burial mounds and the road. Within the preferential flow network there is a flow that runs in a straight line, which is located north of the PIC boundary. This runs along a fence line within the landscape. From this baseline study it is unclear whether the straight line is generated due to the fence line or has been caused by a data processing error; in landscapes of low topography, when determining hydrological networks, straight lines can often be a result of the hydrological determination and topography, rather than a feature in the landscape (Amatya et al., 2013, Poppenga and Worstell, 2013). Despite there being fence lines occurring on all sides of the PIC and in the surrounding agricultural fields, only one is seen to influence the preferential flows. This would suggest that the straight-line flow appears to be a real flow path and demonstrates the potential impact that a fence line can have on the preferential flows within a landscape.

To visually simplify the stream network, drainage basins have been outlined (Figure 42). This splits each stream network into a clearly defined area that allows for clearer understanding of the site hydrology. Within the PIC boundary there are ten drainage basins, but it is the largest drainage basins that require greater understanding as they contain a higher number of preferential flows and physically altering these basins could have a greater influence over site hydrology. This is a simplistic and one-dimensional approach of looking purely at basin size and complexity of hydrological networks, there is however, the need to take into account the archaeological sensitivity of each basin points across the site. As this is baseline work, being able to understand drainage basins and their hydrological networks is a good starting point.

The origin for basin delineation occurs to the WSW of the Ring of Brodgar itself. From this point five basins originate due to cairns, which are a distinct topographic feature within this landscape and have a controlling influence on the shedding of water and therefore the creation of distinct drainage basins. Further cairns to the south also create a distinctive shedding of water in multiple directions to generate further basins. Due to the gentle topographic nature of the Ring of Brodgar these cairns provide a high point in an otherwise low relief landscape and are therefore pivotal when understanding the hydrodynamics of the site. Though both sets of cairns have an influence in the generation of drainage basins, it would indicate that they are a controlling factor when understanding the determination of hydrological networks within this landscape.

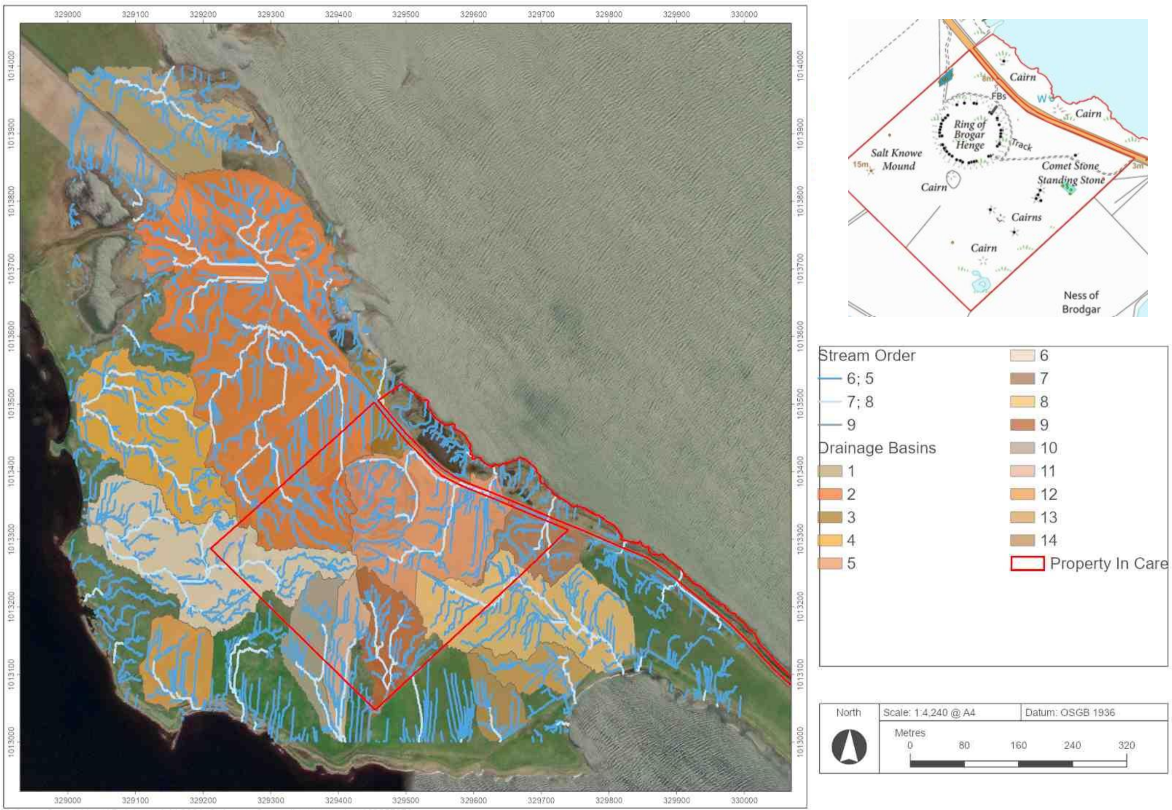


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Figure 42 Combined basin and surface preferential flow, showing clear delineation of the different boundaries. Basin labels do not relate to size.

Further to the cairns, the ditch surrounding the Ring of Brodgar is clearly defined by the hydrology networks (Figure 43). The ditch was expected to have the largest impact on the hydrological networks at the Ring of Brodgar. The ditch has a large effect on the direction of flow from the inner ring (Figure 41). Through using the basin delineation, it is possible to determine the influence of drainage and topographic control that the inner ring and ditch has on the drainage at Ring of Brodgar.

Using drainage basins as potential management areas, it is possible to explore the potential impact of hydrological networks in further discrete areas. Focusing on the drainage basin which incorporates the Ring of Brodgar itself (Figure 43) the prominent effect that the ditch has on the preferential surface flow and the area that is draining into the ditch, indicates that any conservation measures taken throughout the inner ring will affect the directional drainage into the ditch. Alteration of the ditch drainage network could be key to dealing with the surface flow in this area. Most of the inner ring flows to a single point at the ENE on the ditch (Figure 43). Through using the basins as 'management areas' for the PIC, this may help to highlight how works carried out in one section of the basin may affect another area. This can be seen at the exit point of the preferential flow network from the ditch. This is a key location in the management of the site for controlling the drainage of the inner ring and ditch, if alterations are made to this area and the topography of this section is altered, it could be detrimental to the drainage of the ditch and inner ring. Therefore, understanding where the preferential flows originate can be vital for protecting heritage landscapes. Understanding how preferential flows and drainage basins interact with archaeological features could provide a greater understanding of the hydrological influence of a heritage landscape.

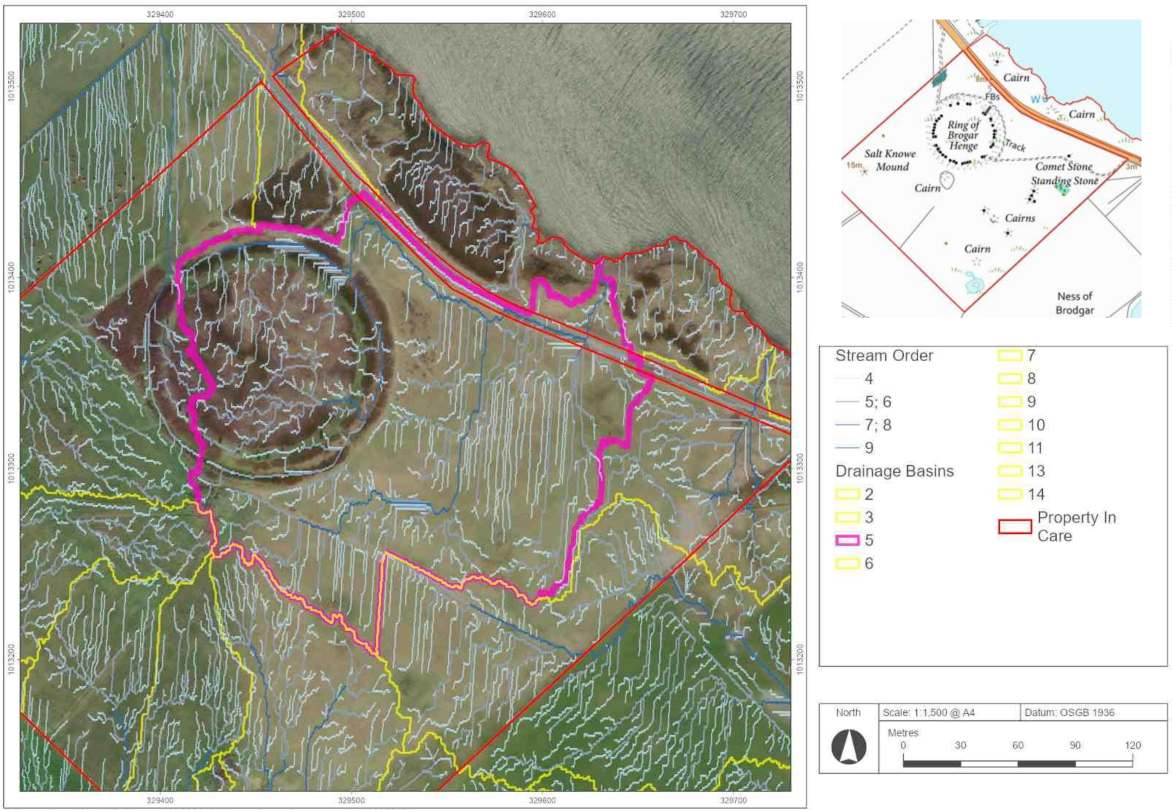

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Figure 43 The basin highlighted in pink incorporates the ring, main footpaths for the inner and outer ring, and the footpath to the comet stone and site exit. Refer to Figure 6 for path locations.

In addition to the key archaeological features within a heritage landscape, it is important to understand the influence of visitors on the site. The largest basin on site contains two key visitor interaction points on site, the carpark, and the main entrance pathway. From Figure 44, it is possible to determine the influences that these key visitor features have on surface preferential flow. The main access path and preferential surface flow (Figure 44).Figure 44

Largest basin within the survey area incorporates the main footpath, entrance to site and carpark. Entrance path outside PIC has a geotechnical surface with a preferential flow alongside (Yellow oval). Orange oval highlights the bare earth path with a preferential surface flow delineating its western extent. Figure 44 shows a distinct interaction between the bare earth path inside the PIC and a geotechnical path outside the PIC. The preferential surface flow runs alongside the main access path, which is a geotechnical surface, consisting of plastic geo-grids. The geo-grids allow visitor access to the site in all conditions and provides a wide walking surface. The geo-grids are out with the PIC boundary and come to an abrupt stop at the PIC boundary edge. There is a preferential flow order of 6-7 that runs alongside the geotechnical path. The preferential flow increases in stream order and alters course at the beginning of this geotechnical path. Therefore, it can be assumed that the geotechnical path is affecting the preferential surface flows within this heritage landscape.

The influence the bare earth path, inside the PIC (highlighted in Orange), has on the preferential flows can be seen as a straight line in Figure 44. The preferential flow that runs alongside the main access path originates to the south of the path, and it flows along the edge of the bare earth path. As the path is wide, up to 15m at this point, it would appear that the preferential flow is flowing along the boundary between the path and adjacent landscape. Where the bare earth path and the geotechnical path meet, the preferential flows do not join, this could be due to the width of the bare earth path being much greater than that of the geotechnical path, or that the geotechnical path has slightly altered the micro-topography and therefore has in turn affected the preferential flow network surrounding it. This is an important finding as it highlights the importance of knowing the influence that paths systems have on site hydrology.

The second key visitor feature is the car park, which affects the overall surface flow of the surrounding landscape. The carpark is clearly outlined in the preferential flow maps, indicating that the carpark drains to the edges and into the surrounding wetland to the south, between the carpark and the road. Although the carpark is not an archaeological feature within this landscape, it has a clear influence on the preferential flow network of this area and is vital for allowing visitors to access the site. In addition, the largest preferential flow order (8-9) flows past the carpark to the freshwater loch. Although not shown in the LiDAR topography, there is a boardwalk running from the carpark to the road and site access gate, across the 8-9 Order preferential flow. As the boardwalk is an above ground feature, it was presumed that it would be included in the topographic model. Therefore, it was assumed to impede the preferential flow, due to the topographic model considering this is ground level, however this is not the case. In the pre-processing of the data the boardwalk has been removed creating and accurate ground elevation model. Further research in to whether the exclusion of the boardwalk has not affected the hydrological flows is required, but not possible within the scope of this work. Through understanding the size of the area that drains to this point, through the drainage basin outline, this highlights the importance of using the raised boardwalk to ensure the preferential flow can continue beneath the boardwalk without flow without interruption. The boardwalk not only allows access to the site but also continual drainage and minimal disturbance to the wetland.

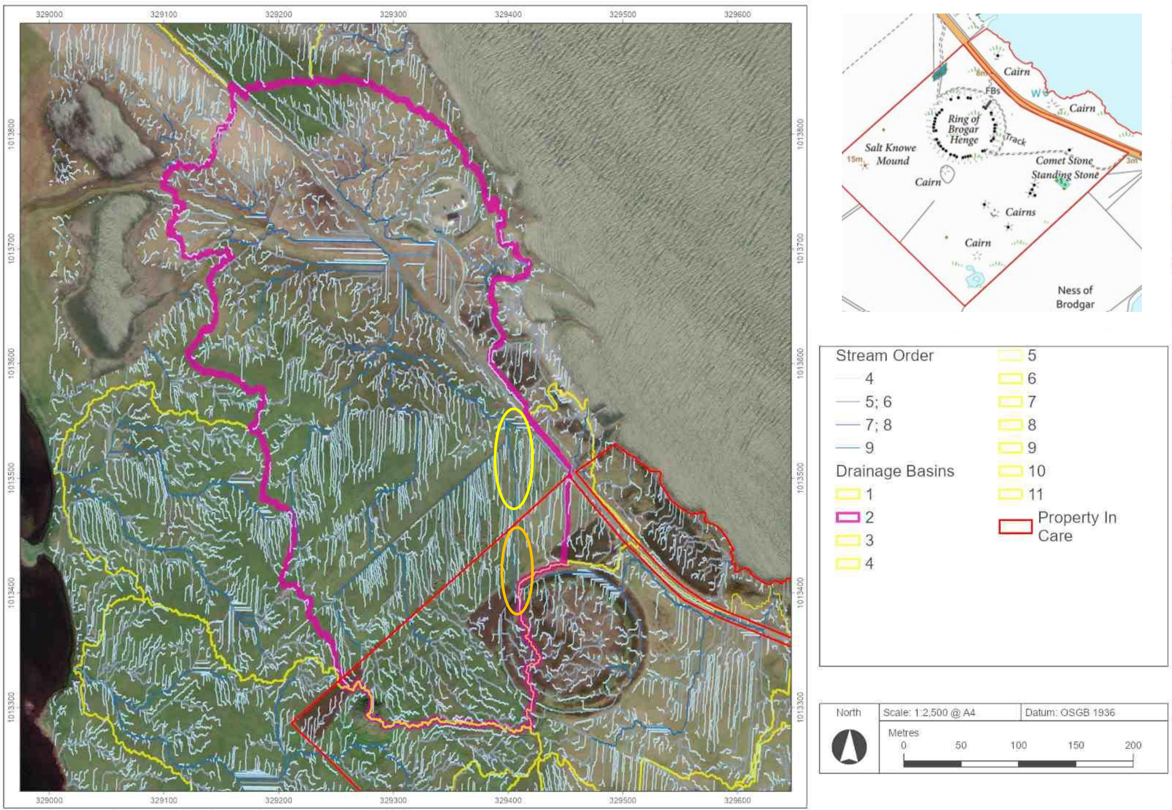

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Figure 44 Largest basin within the survey area incorporates the main footpath, entrance to site and carpark. Entrance path outside PIC has a geotechnical surface with a preferential flow alongside (Yellow oval). Orange oval highlights the bare earth path with a preferential surface flow delineating its western extent.

In addition to the main access path, there are several footpaths visible from the satellite base map image of the site. The variation in use of the footpaths is not determined by the base image yet the influence of preferential surface flow for specific paths can be clearly determined. The main path that runs round the outer ring correlates with the preferential surface flow around the bare earth path, particularly on the SW of the ring (Figure 43). The outer ring path continues round the full ring however the effect on the preferential surface flow is only seen on the SW side of the ring. This could be due to a change in topography as the SW is elevated compared to the rest of the outer ring path. In addition, there is a footpath in this location which could be affecting the preferential surface flow. The interaction between the topography, footpaths and hydrology is a complex one and this location highlights this interaction. From this baseline study alone, it is not possible to determine what the main controlling factors of the preferential surface flow are, as the relationship between footpath, hydrological network and topography is complex. However, for Ring of Brodgar it could be suggested that footpath use intensity is having an effect on controlling the hydrological networks.

The inner ring footpath is also clearly defined by surface flow for the north and east areas of the inner ring (Figure 43), further highlighting the influence that the on-site footpaths have on surface flow due to intense and concentrated use. The main entrance footpath and inner ring footpath have heavy use by visitors to the site compared to some of the other paths around the site (Figure 43). Based on the definition of the preferential flows at these locations it could be suggested that visitor interactions with a site can affect surface flow.

At Ring of Brodgar there are two paths visible from satellite imagery that appear to have no effect on the preferential flows. They the path to Salt Knowe on the west (Figure 44) and to the Comet Stone on the east (Figure 43). At several points along these paths the preferential flow is perpendicular to the direction of the footpath. The path to the Comet Stone, receives a lesser footfall volume than that the main entrance path, the inner and outer ring paths, however the path is visually well defined. This indicates that regardless of the visual impact that these paths have from aerial photographs, it is the intensity of their use that has the biggest impact on preferential surface flow across a heritage landscape. The path out to Salt Knowe is also well defined and receives management through grass cutting in the summer months. This could be why visually it appears distinctive yet has little influence on the preferential surface flows. From looking at two lesser walked paths (Salt Knowe and Comet Stone) and two high footpath paths (outer ring and main access path) shows the difference in influence that footfall intensity can have on surface hydrology. It further highlights the complex interactions with footfall, topography and hydrology that occur in heritage landscapes.

5.3.1.2 Management implication for Ring of Brodgar

The non-invasive determination of preferential surface flow has allowed the identification of archaeological and visitor influences which are clearly affecting preferential surface flow networks. For use in a scheduled monument or sensitive areas this method of determining preferential surface flows before carrying out management works could prove to be vital for minimising the interference with the archaeology and maximising the effectiveness of the drainage systems. This could change the way maintenance and preservation works are carried out within a heritage landscape.

The number of preferential flow basins within the scheduled area at Ring of Brodgar is indicative of the complexity of the landscape. By creating preferential flow basins, it has split the PIC down into smaller management parcels within the landscape. The creation of these basins allows for a more direct and comprehensive approach for understanding the implications that this will have on site. This method also allows for understanding of the wider landscape influences that may be caused as a result from modifications made with in a PIC.

Further to this is the requirement to better understand the effects of built visitor infrastructures, such as the board walk and geotextile of the main access paths and how these affect surface hydrological networks. In addition to this, understanding how and why certain natural footpaths are potentially affecting surface flow needs further investigation but could prove to be vital in the management of hydrological networks at Ring of Brodgar.

Ring of Brodgar has focused on two of the larger drainage basins that contain archaeological features and contain visitor footpaths to the Ring of Brodgar. Through being able to hydrologically model it is possible to highlight areas that conservation management could be focused on in relation to water management and visitor access to Ring of Brodgar. The two drainage basins and their associated preferential flow highlighted here, indicate the complex interactions that occur between site visitors, access management and the protection and conservation of archaeology.

5.3.2 Hydrological Modelling Hirta, St Kilda

Hirta has many upstanding archaeological structures that are unique to the island and form an integral part of its identity. Through using a DSM, it may be possible to see the effect that archaeological features have on preferential surface flows. For Hirta, the influence of footpaths will not be investigated, due to the footpaths following the historical path networks that form part of the upstanding archaeology. Therefore, understanding how the upstanding archaeology interacts with the hydrological networks has the potential to aid in their conservation. Of all the sites studied, Hirta presents as the most complex, both in stream networks and drainage basins.

The stream network for Hirta is complex and appears to be split into two distinct stream networks, with smaller streams around the edges (Figure 45). Within these two visually distinct stream areas, there is a complex make up of streams. The smaller streams around the edge of Hirta will not be looked at further within this research, as these complex steams are out- with the scope of this study. However, it is important to note the number of them and the effects that changes in rainfall regimes (Chapter 7. Climate Change: Precipitation and its Hydrological Implications for Heritage LandscapesChapter 7. Climate Change: Precipitation and its Hydrological Implications for) may have on their prominence within the landscape. Therefore, defining the drainage basins for Hirta is imperative to gain a better understanding of where the streams originate from and their areas of influence.

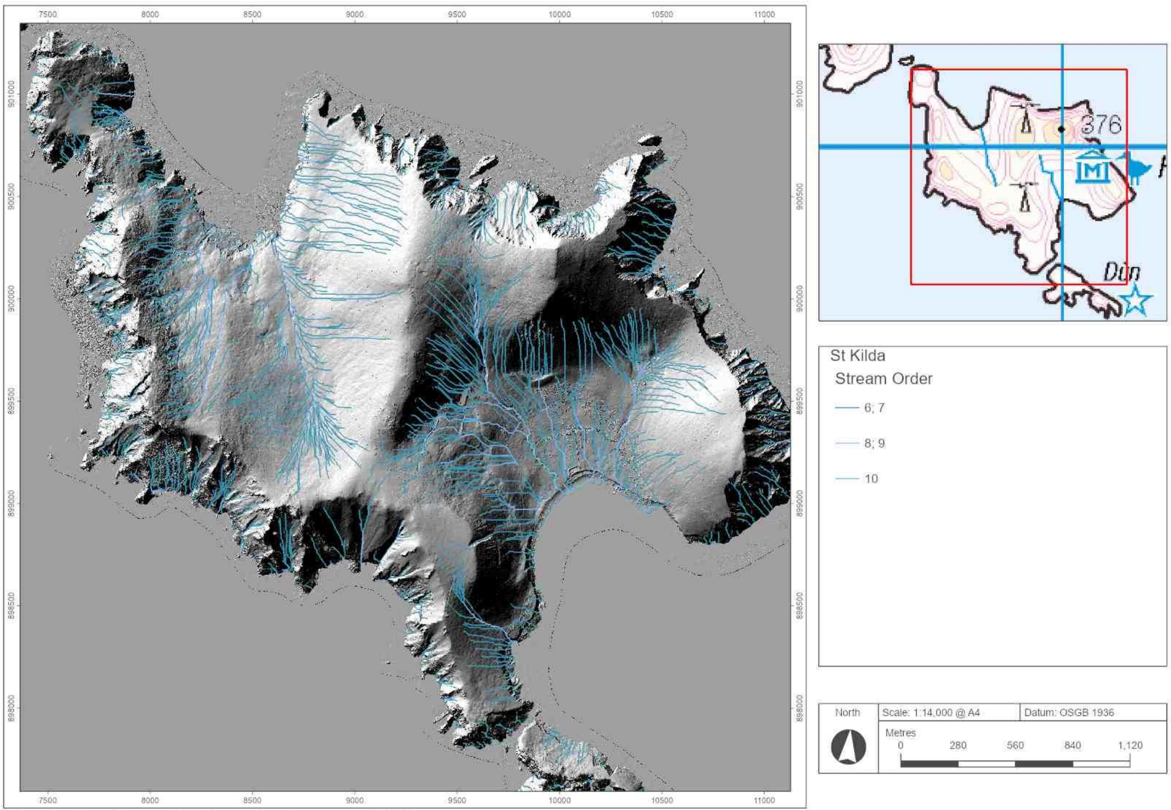

Figure 45 indicates the higher order hydrological networks for Hirta, St Kilda clearly showing the delineation of networks across the highest point of the island, Conachir.

The drainage basins on Hirta vary in size and shape. For Hirta the smaller basins are located around the edges and are a result of extremes in topography, such as cliffs or steep hillsides (Figure 46) and have been removed to aid interpretation. Through carrying out drainage basin delineation, the two distinct stream networks appear as five drainage basins. There are four drainage basins that encompass Village Bay on Hirta (Nos 1-4), and the rest of the discussion will focus on this area. These four basins originate from the highest point, Conachir, on Hirta. This makes understanding the origin of the basin clear. However, as the drainage basins are hoped to aid management of the site and provide targeted areas for intervention and preservation works, having Village Bay split in to four sections, could make conservation challenging. The smaller basins could be a challenge when implementing management techniques and the protection of the upstanding archaeology in Village Bay (Figure 46) due to the potential isolation of interventions or occurring in the wrong basin. However, for the rest of this study Village Bay will be viewed as one management area, with two permanent streams and four drainage basins.

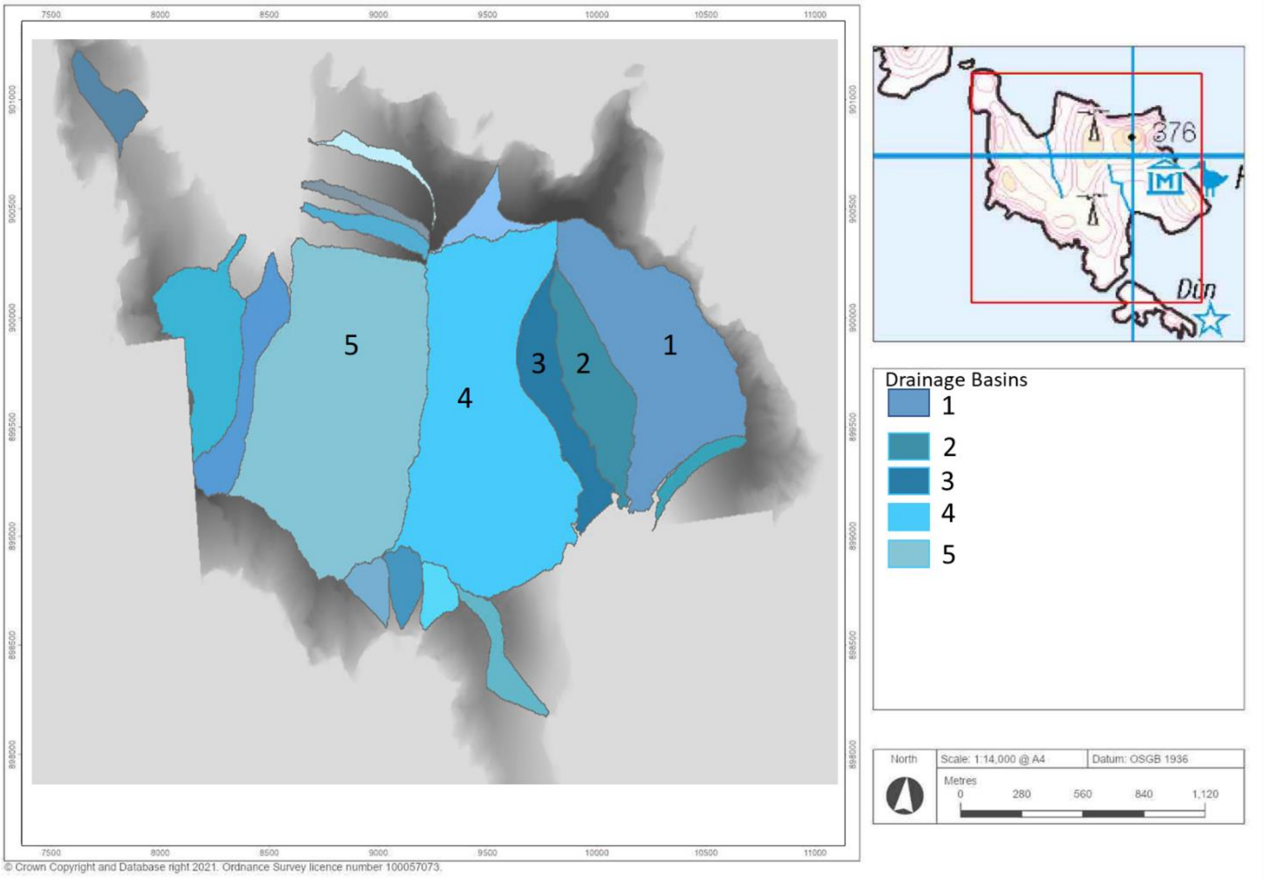

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Figure 46 depicts the main basins present on Hirta, St Kilda, with Village Bay consisting of four main basins. Basins are numbered for interpretation only.

The effect upstanding archaeology has on the hydrological networks is clearly shown in Figure 47. Some of the houses - either roofed or unroofed - influence the hydrological flow of both the higher and lower order hydrological flows (Figure 47 and Figure 48). Their influence can be seen by the distinctive angular changes in the flow patterns around the houses and along the main street (Figure 47). This is caused by the upstanding archaeological features being orientated perpendicular to the topography and indicates that the buildings have potential to alter the natural flow of the water. These locations also highlight key areas of site management concern, as with heavy rainfall events this could see the accumulation of water at these points leading to an increased effect of rainfall and surface water around the upstanding archaeology. Additionally, when water flows change direction abruptly there is potential for water pooling and sediment deposition or erosion to take place. Through identifying the locations of change in direction of hydrological flows it allows for monitoring and on-site investigations to take place to determine the current hydrological impact at these locations. This work has identified these points as areas of interest (concern) that should be monitored to establish the full impact that the change in direction of hydrological flows is having. In addition, as these locations are preferential flows, their influence will only possibly be seen in heavy rainfall events or after prolonged periods of rainfall.

Furthermore, the baseline mapping of stream orders and identifying possible risk points, along with generating the full stream network, allows for an understanding of where the water is coming from to reach these locations. Thus, resulting in a greater understanding of where the streams originate, the confluences and where possible upstream and downstream remedial action could be carried out. Knowing where an area of concern is and where remedial work is to take place, understanding how this work will affect the downstream section of the hydrological network is also important. Changing, altering, or diverging streams could lead to an area not receiving enough water or too much, which could have a significant impact on the preservation of buried archaeology and the stability of upstanding archaeology (Historic England, 2016). The practicalities and the impact of remedial works is not considered further here, but the stream order networks allow for a visual understanding of where some problems may occur and how the hydrological flows are connected with the wider landscape.

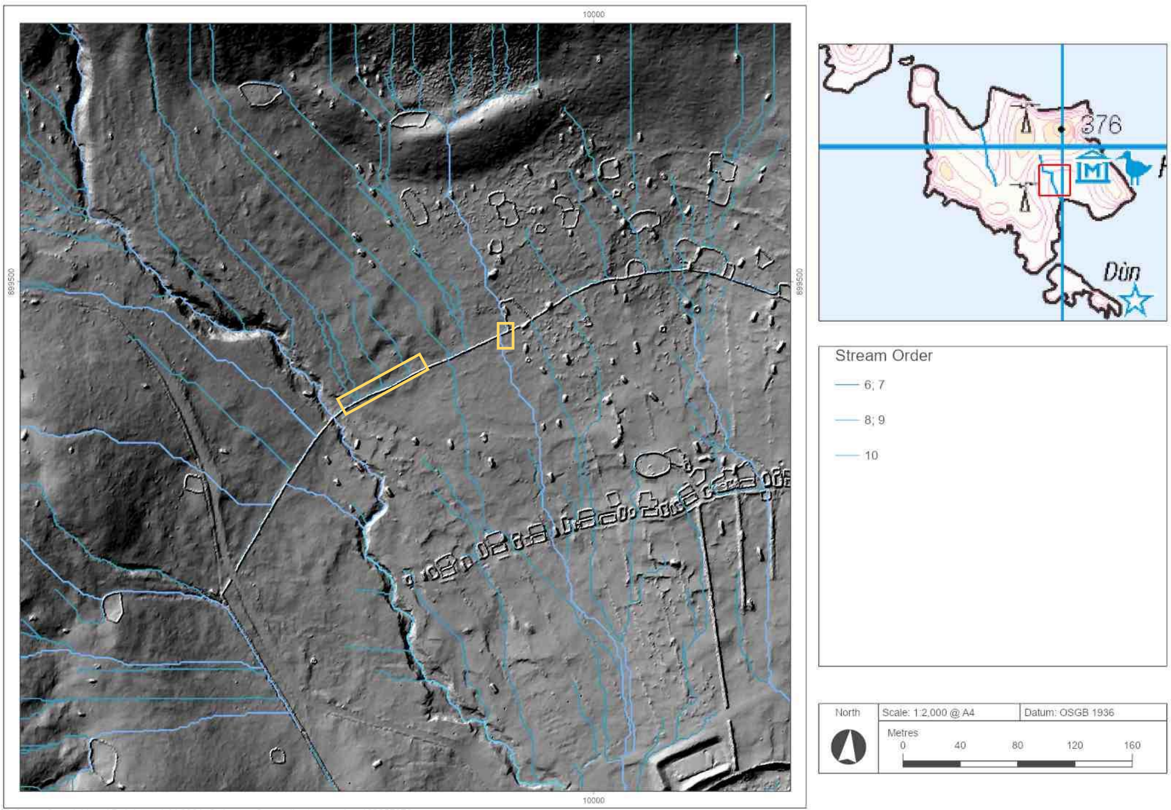

Figure 47 Higher order Preferential flows demonstrating the effect of the upstanding archaeology has on altering the preferential flow paths. Yellow boxes indicate areas of interest discussed in text.

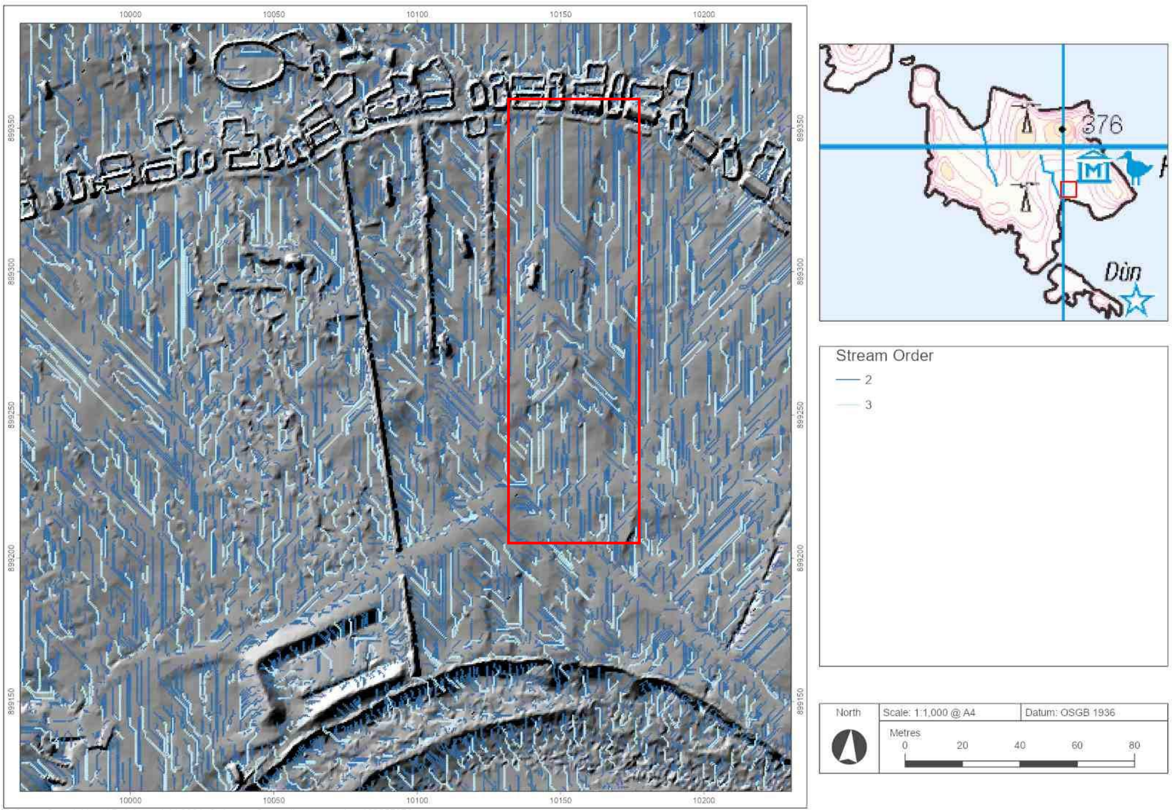

Figure 48 Lower order Preferential flow networks around upstanding archaeology and along historical field boundaries. The box highlights one agricultural field boundary, others can be identified to the left and right of the box. The influence of the lower order Preferential flow networks can be seen flowing into the boundary between two fields.

Additionally, the lower order flows highlight the influence of the upstanding archaeological structures on site (Figure 48), than the higher order streams. Lower order flows may not be obvious on the surface as hydrological flow networks and may be seen after extreme rainfall events or if the soil is saturated. However, the low order hydrological networks can highlight archaeological landscape use features, such as historic field boundaries, which play a vital role in moving water through a landscape (Zhang et al., 2021, Chen et al., 2022). The importance of identifying and understanding these flows could aid in the protection of the historic field boundaries and the heritage landscape.

Through using fine scale LiDAR data, it is possible to pick out archaeological features and the effects that they have on hydrology, which are not normally seen with coarse topographic data (Figure 48). One of these features is the culturally managed soils on Hirta. It has been recognised that the field systems were having a controlling influence on the water management around Village Bay, and anecdotally it has been indicated that in recent years the influence of the field systems is starting to change. As this data set is from 2011, it would indicate at this point in time that the culturally managed soils are having an influence on the hydrological networks within Village Bay. The effects of the culturally managed soils' field boundaries have on the hydrology can be seen in the lower order preferential flow networks (Figure 48). The lower order preferential flows have distinctive splits between each culturally managed field boundary (highlighted in Figure 48), indicating an influence of the micro-topography of the culturally managed soils on the hydrology. In Figure 49, the higher order networks do not show the boundary between each field system, further highlighting the use of lower order flows for understanding the micro-hydrology of a heritage landscape. Therefore, using fine-scale LiDAR topographic data and hydrological modelling, could help monitor the changes that are happening to cultural soils overtime and the potential effect of climate change.

The influence of culturally managed soils on hydrological flows is a crucial one for sites around the world, either for culturally active or in a managed state of preservation. Being able to understand the influence that historical management has on cultural soils, hydrological modelling becomes a tool for monitoring cultural soils and hydrological flows. It also historically shows how instrumental the management of field systems were for the management of water flow through a landscape. The management of the hydrological flows and the continual maintenance of the changing landscape was something intrinsically linked to the livelihoods of those based on Hirta. However, since the evacuation (1930) the lack of upkeep of these historical management practices could have led to a decline in the hydrological management across the site and the effects of which are little understood.

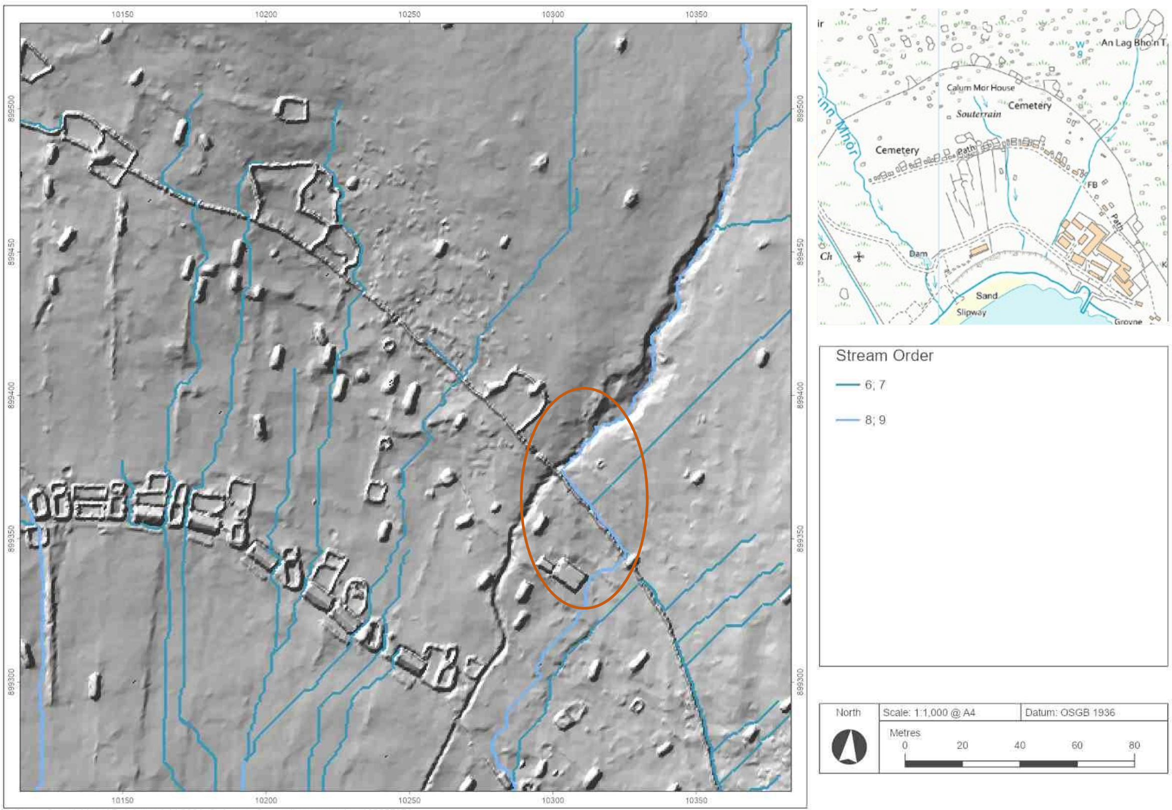

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Figure 49 Highlights interventions to maintain stream flow under the headwall. The modelled Preferential flow does not follow topography due to interventions taking palace under the LiDAR surface.

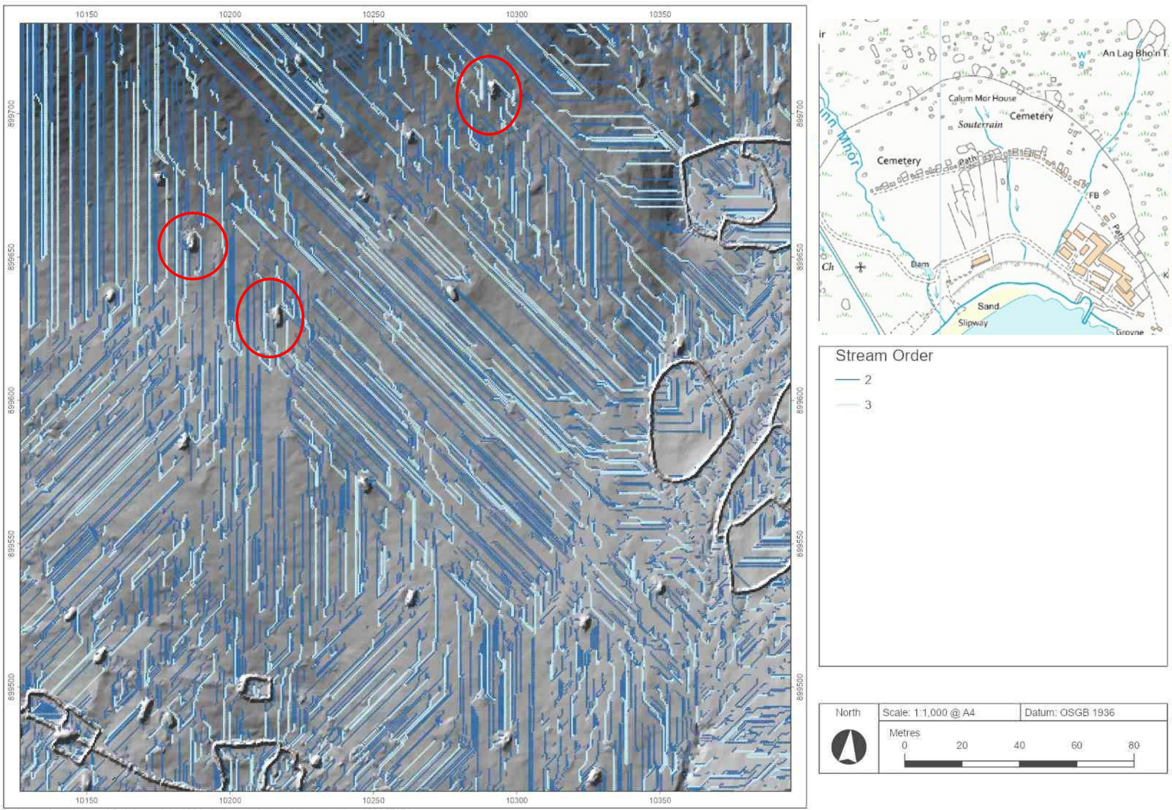

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Figure 50 Cleits are found throughout Hirta, and the red circles indicated three and their effect on the lower order preferential flows. In the centre of each circle is a cleit with the lower order flows diverging on the uphill and converging on the downhill side of each cleit.

In addition to using the lower order stream networks to understand the legacy of agricultural practices, the same technique can be used to determine the influence of the cleits located throughout Village Bay (Figure 50). Cleits are numerous across Hirta and do not appear to have an influence on the higher order stream networks due to being located above the village, however using the lower order flows it can be clearly seen that they influence the micro surface flows around them. Selected cleits are highlighted by the red circles in Figure 50.Although the alteration of flow is not as dramatic as some of the buildings in Village Bay, the cleits do have a large effect on the micro hydrology. Above each cleits the surface flows separate to flow around each structure, and then converge back to the cleits further down slope of cleit. The influence of one cleits is not substantial but due to the number of cleits (approximately 1,260) on Hirta their overall effect on altering the micro hydrology of Hirta is substantial. Due to their influence on the micro-hydrology, the cleits could be more susceptible to changes in precipitation due to climate change, the full effect of this will be explored in Chapter 7. Climate Change: Precipitation and its Hydrological Implications for Heritage Landscapes. However, the micro hydrology diverts around the cleit relatively close to the uphill side. In the event of heavy rainfall, the flows may not be able to divert around the cleit, leading to cleits having water inundation. Through understanding the impact that the cleits have on the micro hydrology of Hirta it can then become possible to understand how changes in rainfall regimes will affect the cleits individually and as a collective.

One of the issues with using LiDAR data is that it cannot take into account subsurface features, such as subsurface drains (Figure 49 highlighted in orange). This is seen within a section of the headwall on the east of Village Bay through the predicted divergence of the natural stream. When the stream reaches the headwall, it turns 90° to the east and flows along the headwall and then down to the right of where it is naturally located in the landscape. The alteration of the stream's natural pathway at this point would indicate that there is a possible management practice in place, or there was something on the surface preventing the bridging of the headwall being seen. As this work is a baseline study understanding that there can be anomalies within the hydrological modelling is important. Overlaying, overlaying the hydrological data on the topographic models allows for these anomalies to be visually identified; they and can then assessed though a ground truthing survey.

Alteration or modification of the modelled hydrological networks to take into account modern works, such as the influence of the canalised stream in Figure 49, has not been carried out with this study. Through being able to find features, such as ditches under walls, which generate inaccuracies in the hydrological network, this can be built on for site understanding and management practices. Through identifying the areas on Hirta that generate anomalies within the hydrological network we can then apply this knowledge to other sites where similar results are seen. This approach requires a good site understanding to determine where these anomalies could occur, and the approach is especially important for rural and inaccessible sites that cannot be visited easily or frequently to validate the predicted hydrological networks. Hirta has been a good pilot for the use of a DSM and highlighting anomalies. Hirta was not visited at any point during this research and so the understanding of the anomalies within the hydrological network have come from discussions with an onsite ranger. Although determining the hydrological networks for remote locations is possible with fine scale topographic data, having onsite knowledge is essential for an accurate site understanding (Personal communication, S. Bain 2021).

5.3.2.1 Management outputs for Hirta, St Kilda

One of the key outputs shown in this hydrological study is the ability to split heritage landscapes down into management parcels (Zhou et al., 2021). Hirta has one large drainage basin that encompasses the northwest of the island, and four within Village Bay. The concept of being able to break down heritage landscapes into drainage basins is to allow for independent areas of management to be created. However, within Village Bay the four basins that make up the area may not be particularly practical in terms of on-the- ground management. Figure 46 shows that four basins all originate at a similar point and discharge into the sea at the south of Village Bay. Due to the origin and discharge points and the complex upstanding archaeology within these drainage basins, it may be more practical to look at them as one area from an overall management point of view.

Large drainage basins, however, could create more of an issue with looking at the wider scale implication of management interventions. The size of the basins in Village Bay is one of the largest within this study. Although these basins capture all the archaeological features contained within Village Bay, understanding how interventions may impact different areas will be harder to do. The ability to view and manage all of the bay as one integrated site and management parcel could be a benefit as an intervention can be easier to understand in relation to the full site instead of in isolation when using smaller basins. Alternatively, treating the basins individual entities could allow for interventions to be trialled in separate areas or within one basin before being implemented across Hirta. Further consideration is required by those managing Hirta, as to the most practical way to use the drainage basins.

Hirta further highlights the importance of not using a ‘one method fits all’ model for hydrological management of a site. Drainage basins outline key hydrological units, but they may not always be the best option when looking at heritage landscape management. Management decision may be better informed by a particular scale, but this is dependent on specific characteristics of a site. Therefore, being able to define drainage basins and use them as a tool to aid heritage landscape management is essential.

5.3.3 Hydrological Modelling Rough Castle

Rough Castle presents a very different case for use of LiDAR data to determine hydrological flows within a heritage landscape, than that of Ring of Brodgar and Hirta. One of the issues at Rough Castle is the lack of surrounding fine resolution topographic data. Ring of Brodgar and Hirta both have very distinctive geographical boundaries, which also include the highest point in the geographically bound landscape and were included in the LiDAR survey. By contrast, Whereas Rough Castle does not, it is not topographically distinct from the surrounding landscape, which could make the interpretation of the hydrological modelling challenging. For Rough Castle there will be a particular focus on the fort and surrounding defensive ditches.

The DSM for Rough Castle not only differs in the lack of topographical bounding but is elongated compared to the other two sites within this study. The elongated nature of the DSM runs in line with the topography, therefore does not contain any topographic data above the elevation of Rough Castle fort top. However, Rough Castle is not the highest point in the surrounding landscape. Nonetheless, within this study the fort top is the highest elevation due to the narrow swath of DSM. This generates an artificial narrow landscape surrounding the PIC. The area that is included in the DSM will allow for the connections from the immediate surrounding landscape and the PIC to be established.

As with St Kilda and Ring of Brodgar, drainage basin mapping was carried out for the site (Figure 51). For Rough Castle there are only four drainage basins present. The low number of drainage basins was unexpected due to the complex topography of Rough Castle due to the Antonine Wall, Ditch and defensive ditches. It was also presumed that the narrow swath of LiDAR data would have affected the number and size of the drainage basins, however this was not the case. The extent of the DSM can be seen in the west of Figure 51 , where there are no drainage basins shown. This may have affected the size and extent of the drainage basins and the stream network. However, as the focus is on the PIC and Rough Castle fort this should not affect the stream networks.

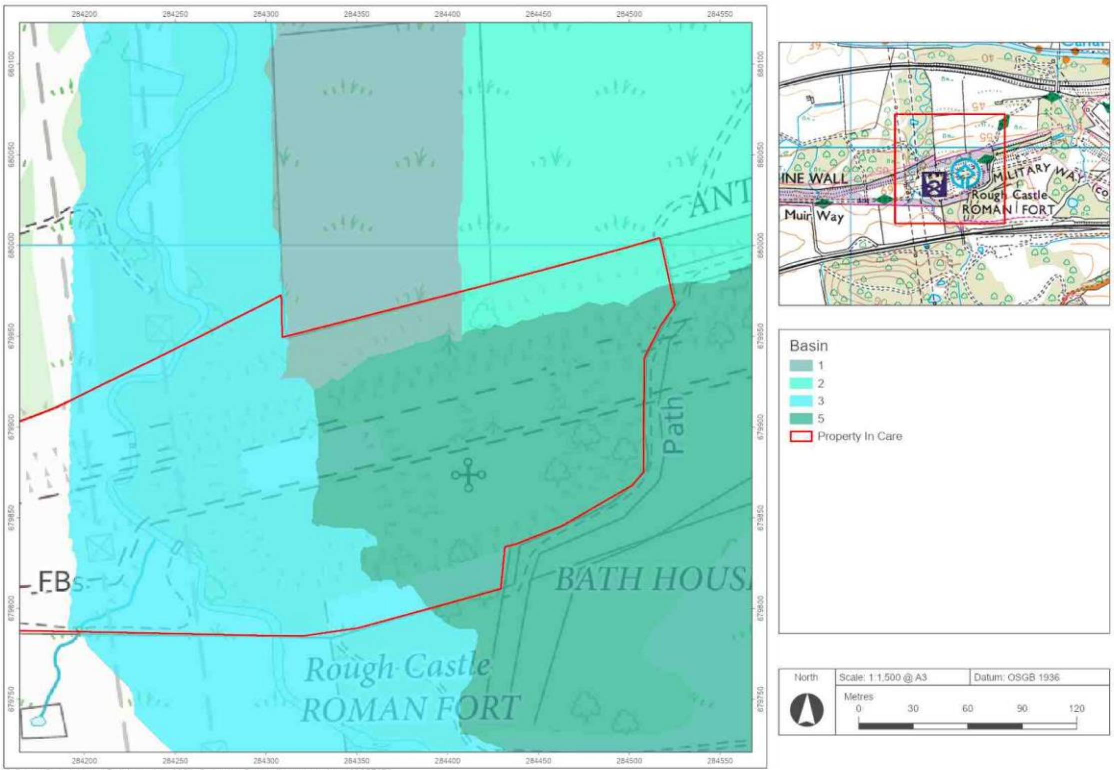

Figure 51 Basin map for Rough Castle, PIC highlighted in red. Lack of basins on the west is a result of the LiDAR extent.

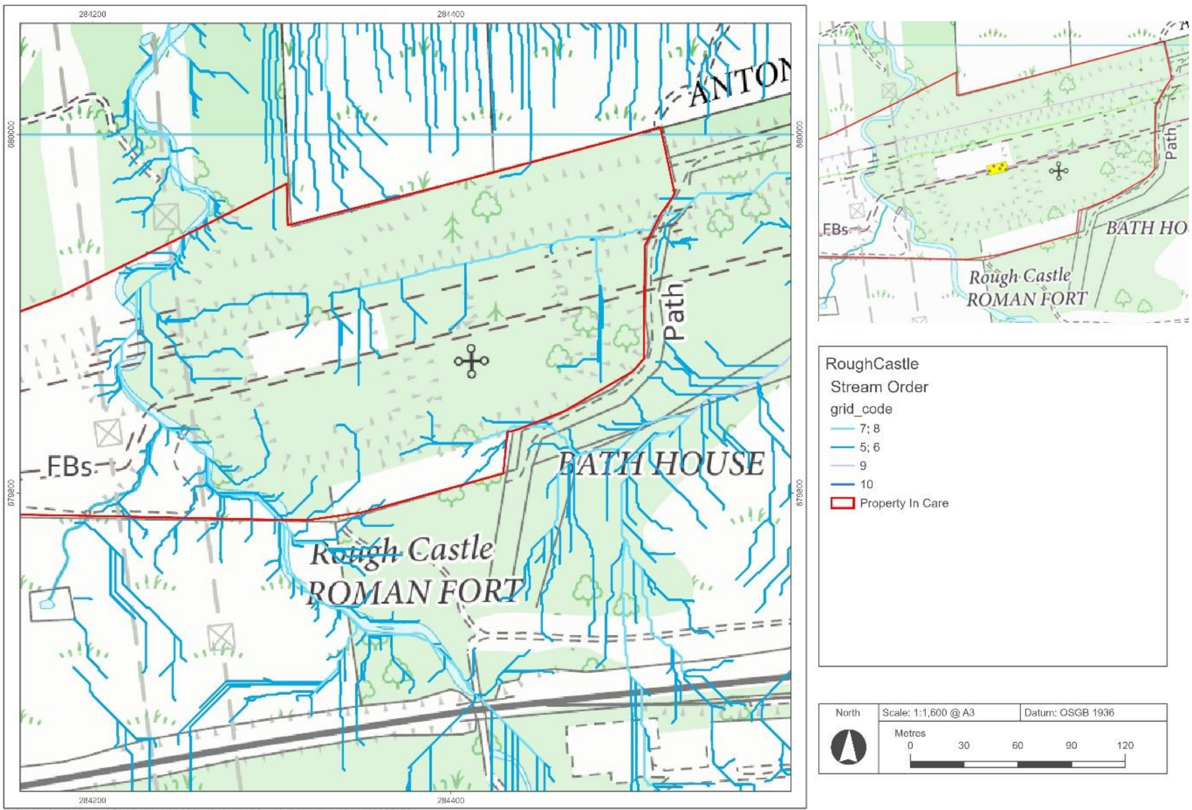

Figure 52 Hydrological model flow networks (6-10) overlain on the OS map Note the modelling predicts the location of the on-site stream.

Focusing on the area delineated in Figure 52, it is possible to determine some of the influences that the archaeological features have on the hydrological networks for Rough Castle (Figure 53). Within this area a focus will be on the visible stream network, the ditches and mounds surrounding the fort top and the turf outlines of the buildings within the fort.

The permanent stream is identified in the hydrological modelling (Figure 53). This is good and slightly surprising, as although it sits in a topographical low point, it was expected that this would not be possible due to the lack of upstream topography. It is however reassuring that the hydrological modelling is representative of the hydrological networks that are visibly present at Rough Castle.

Based on the assumption that the hydrological modelling is an accurate representation of the surface hydrological networks on site, the effect that the archaeological features have on the hydrology can be understood. Figure 53 shows the full extent of the archaeological features at Rough Castle and their effect on the hydrological networks as well as the impact that other features within the landscape have. For this the railway line, south of the site, is picked out through the straight-line flow of the hydrological network. Also, there is the breaking of the stream network at the railway line, this is a similar result to Hirta, where there had been sub-surface works carried out to maintain the flow of water that were not detected by the LiDAR. The scale of the railway line alteration is much larger than that on Hirta, but through the modelling it is possible to determine an apparent break in flow due to a sub-surface intervention. Through being able to determine the influence at the two different scales, industrial infrastructure (railway line) and canalising under a headwall (Hirta), shows the different impacts that alterations on hydrological networks will have on heritage landscapes.

In addition to the railway line, there are also several fence lines around the site that are picked up in the hydrological modelling. This is a similar effect to that seen at Ring of Brodgar. Again, not all fence lines are picked out especially to the south of the site, however on the north side there are several that have been depicted (Figure 53).

Being able to pick out fence lines that could be impacting or controlling hydrology in specific locations can alert site managers to these locations and monitor or alter them to control the hydrological networks on sites.

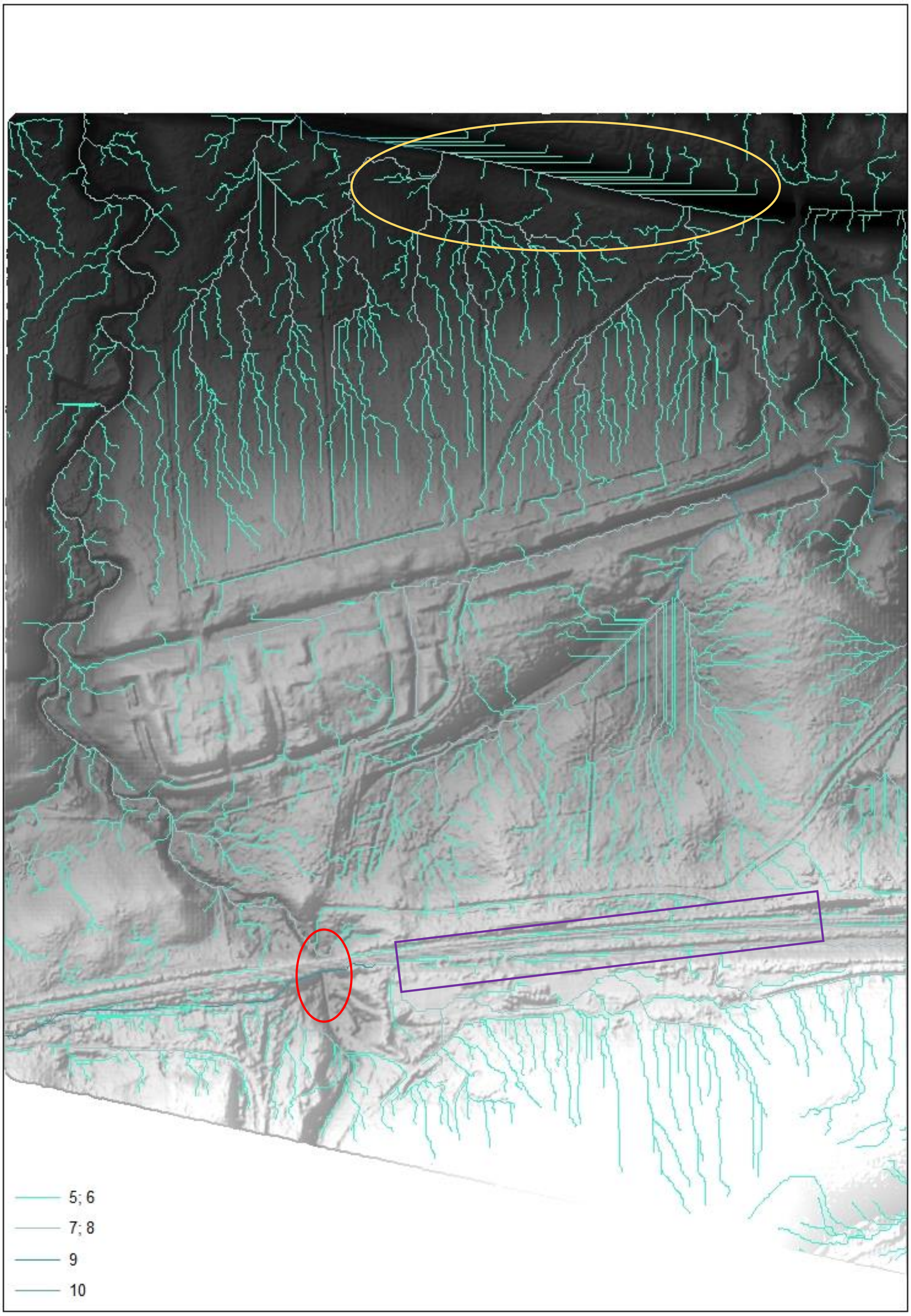
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Figure 53 Higher stream order flows at Rough Castle fort. Red circle shows the break in the onsite stream, due to the railway. Purple box, highlighting the railway line. Yellow circle showing straight lines, caused by another railway line.

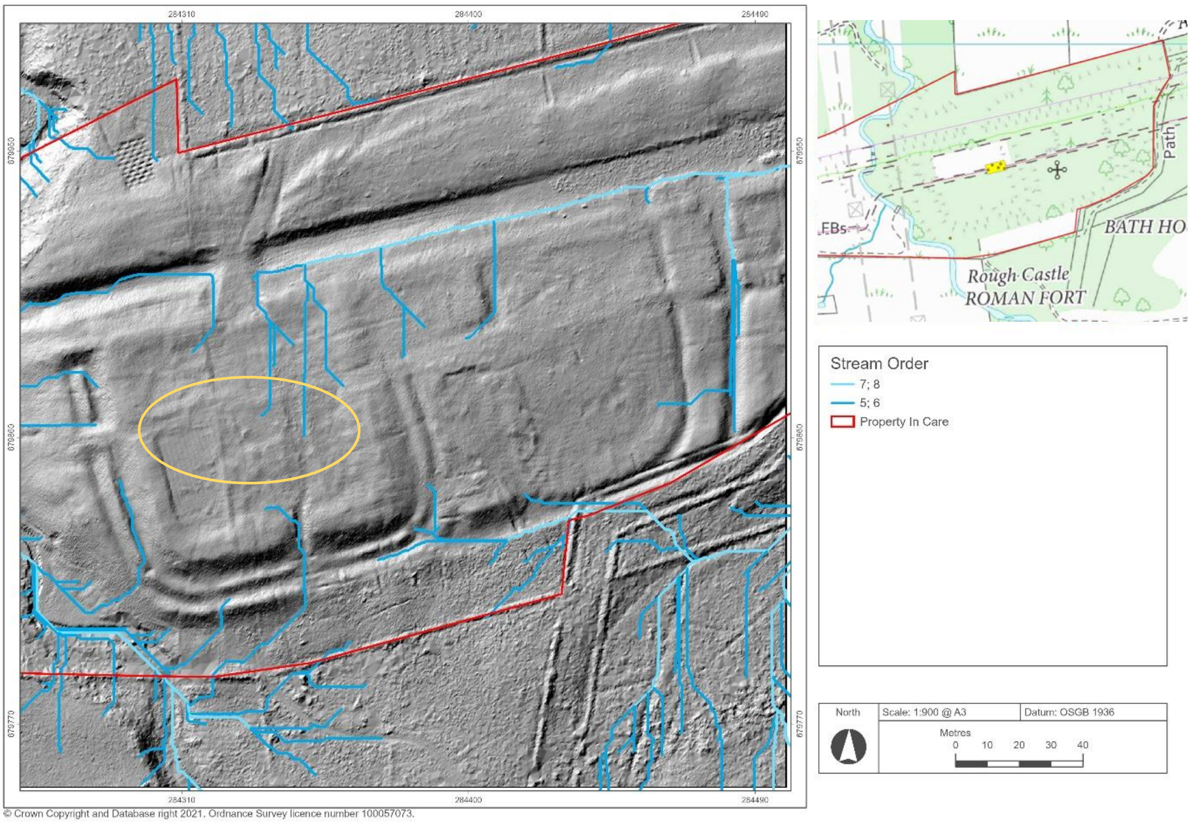

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Figure 54 Zoomed in section of the fort top with Higher order steam flows, note the depiction of the onsite stream on the left. The yellow circle highlights the splitting of streams around the link bridge.

One issue with the hydrological data that was encountered was the straight lines found in specific places across the heritage landscape (Figure 53, Figure 54 and Figure 55). These straight lines are occurring at topographic low points within the landscape, for example in Figure 54 and Figure 55 the bottom of the Ditch. It is known from the literature that there is often difficulty when using topographic data sets with extended topographic lows or extremes in topography (Amatya et al., 2013, Poppenga and Worstell, 2013). Either could be the cause of the effects seen in the hydrology networks in these locations. Focusing on the Ditch, there is a definite change in topography between the Ditch and the Wall, which could explain why there is an anomaly within the hydrological modelling. However, the area at the bottom of the ditch appears as one elevation, this is due to there being standing water present, which could have resulted in the straight lines at the intersection between the Wall and standing water in the Ditch. As this was the only site to have standing water, the influence that standing water has on hydrological modelling was not explored further. Furthermore, being able to highlight anomalies within the hydrological modelling can aid in directing site managers to a location that there may be impeded hydrological flows around a heritage landscape, which need further investigation on site and monitoring.

As with the canalised streams on Hirta, there has been no further investigation into altering or remediating the low topography straight lines within this research. As this is a baseline study, being able to develop this technique and identify areas that generate hydrological network anomalies is just as important as identifying where the hydrological networks occur on site.

Lastly at Rough Castle fort top, the effects of the archaeological features on the preferential flow part of the hydrological network can be understood. The Ditch and defensive ditches are one of the biggest controlling and influencing factors of the hydrological networks at Rough Castle (Figure 54). They often have standing water in them after heavy or prolonged rainfall events. As can be seen from the hydrological network maps these features provide key parts to the drainage network. The hydrological flows in the defensive ditches on the east connect to further hydrological flow to the south to form a large preferential flow. However, there are areas where there are ‘barriers’ created by archaeological features, such as the Military Way, through which the preferential flows do not flow; an example can be seen on the east of Figure 54. Gaining an understanding of how these features control the hydrological networks on site makes it possible to understand the influence that changes in rainfall patterns may have on these locations (explored more in Chapter 7. Climate Change: Precipitation and its Hydrological Implications for Heritage Landscapes).

The features originally designed to hold and/or move water, such as the defensive ditches, are still active at Rough Castle. This is important as it indicates that these features are key for helping to manage water on the site. These features may hold a greater importance in a climate- changed future where there may be more water moving across and beneath the site. Identifying these areas as still being key hydrological features means it becomes increasingly important to maintain these areas and allow them to function as intended to help preserve the site.

Through determining the location of preferential flows and how they interact with archaeological features, it becomes possible to establish areas that may need interventions to aid in the protection of the archaeological features. This is particularly seen in the defensive ditches that surround the east of site, where preferential flow networks flow into the ditches between the mounds but have no exit points. Through identifying this as an area where the hydrological network does not have an exit point into the wider landscape or stream network, makes this an area of concern for site managers. These locations will develop an accumulation of water due to areas of the site draining into them, creating a potential waterlogged area onsite that could experience wetting and drying cycles depending on precipitation. As a result, this could be detrimental to the onsite archaeology (Historic England, 2016). Having identified the defensive ditches as areas of concern it allows for further management discussion and identification of solutions to allow connections to be made or re-established in the hydrological network.

The main 'buildings' on the fort top have two distinct preferential flows (Figure 54 highlighted in Yellow) that drain into the Ditch on either side of the link bridge. This section contains several archaeological features that come in to contact with a key drainage section of the site and would form an important area for site management in terms of protection of the archaeology. With increasing rainfall and the potential for standing water on site it highlights the need to understand the hydrological networks of Rough Castle.

The lower- order flows at Rough Castle (Figure 55) do not add any further interpretation of the hydrological networks on- site, but they do highlight the complexity of potential water flows across the landscape and the influence of archaeological features.

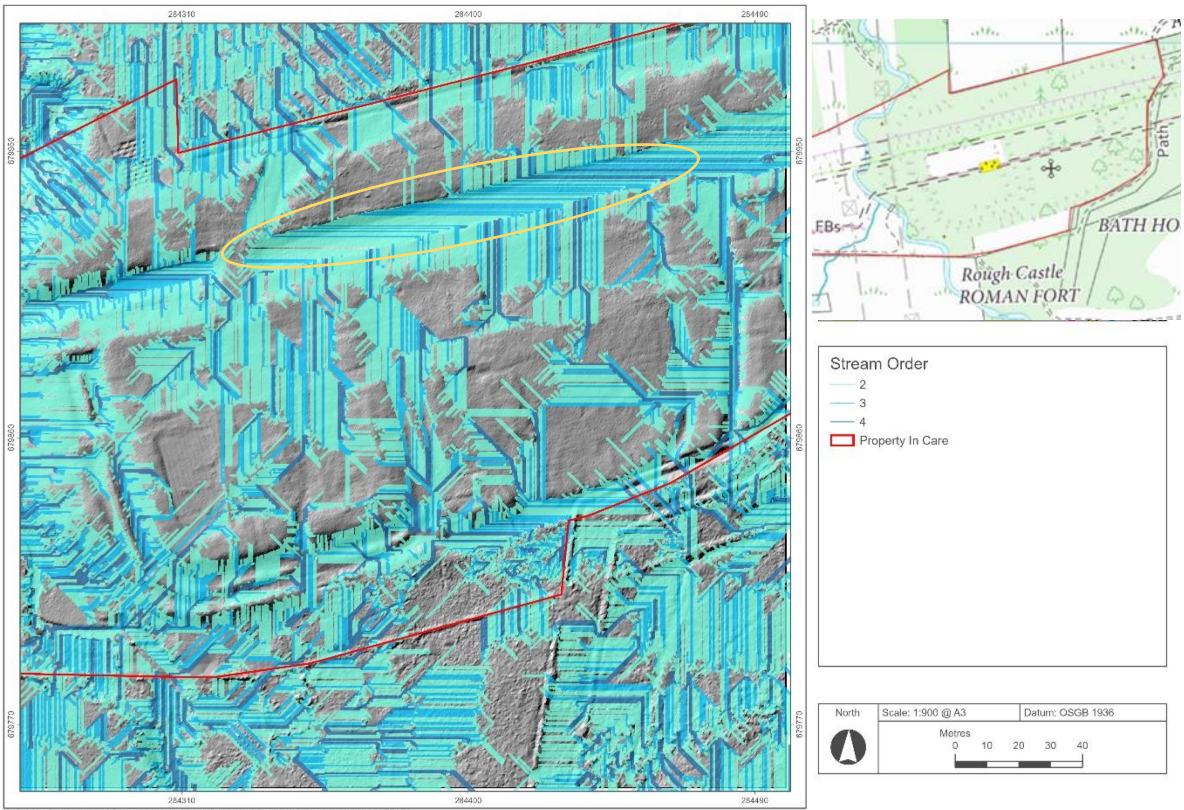

Figure 55 Lower order stream flows for Rough Castle fort top, note the straight lines for area of low topography highlighted in yellow due to there being standing water in the Ditch at time of survey.

The landscape around Rough Castle has had a long history of occupation. Understanding of occupational influence on hydrological influences is outside the scope of this study (explored briefly with Hirta), but it is an important factor to consider when exploring hydrological modelling in heritage landscapes. There has been limited work carried out in the area surrounding Rough Castle despite the extensive excavations on the fort itself (Mate et al., 1995), but it was not considered further within this research. Exploring how past land use practices are shown in current hydrological modelling, and the influence they still have, would make an interesting follow-on study. It would also be interesting to determine if hydrological mapping could be used to identify some of these features or monitor their change over time in the area surrounding Rough Castle.

Flow accumulation is part of the hydrological modelling that is carried out to determine the hydrological networks on site. For Ring of Brodgar and Hirta, it did not add any further understanding to the hydrological networks presented on site. However due to the complexity of the lower order stream networks at Rough Castle the flow accumulation added an understanding of where the hydrological networks could accumulate on site (Figure 56).

The interpretation for flow accumulation is that the areas shown in red indicate a likely area for an ephemeral stream to occur. In a manner this is a simpler stream network map as this is used within the modelling to generate the stream networks. At Rough Castle the flow accumulation model helps to simplify the complex flows across the fort top and in the surrounding archaeological features. Through using the flow accumulation, it is possible to determine the areas in the ditches surrounding the top that could see an accumulation of water before a stream or preferential flow is established. This is particularly useful on the fort top, where flow accumulation shows in more detail where water accumulation may occur. The flow accumulation gives more detail than the higher order stream network (Figure 54) and simplifies the lower order stream networks (Figure 55). Thus, generating a point in the middle that aids in site understanding for hydrological flows, but for Rough Castle on only the fort top and ditches. However, in the areas surrounding Rough Castle fort top, the flow accumulation does not aid in the understanding of the stream networks. This would suggest that flow accumulation maps can be used to understand areas where flows are likely to occur in complex heritage landscapes to aid in site hydrological understanding.

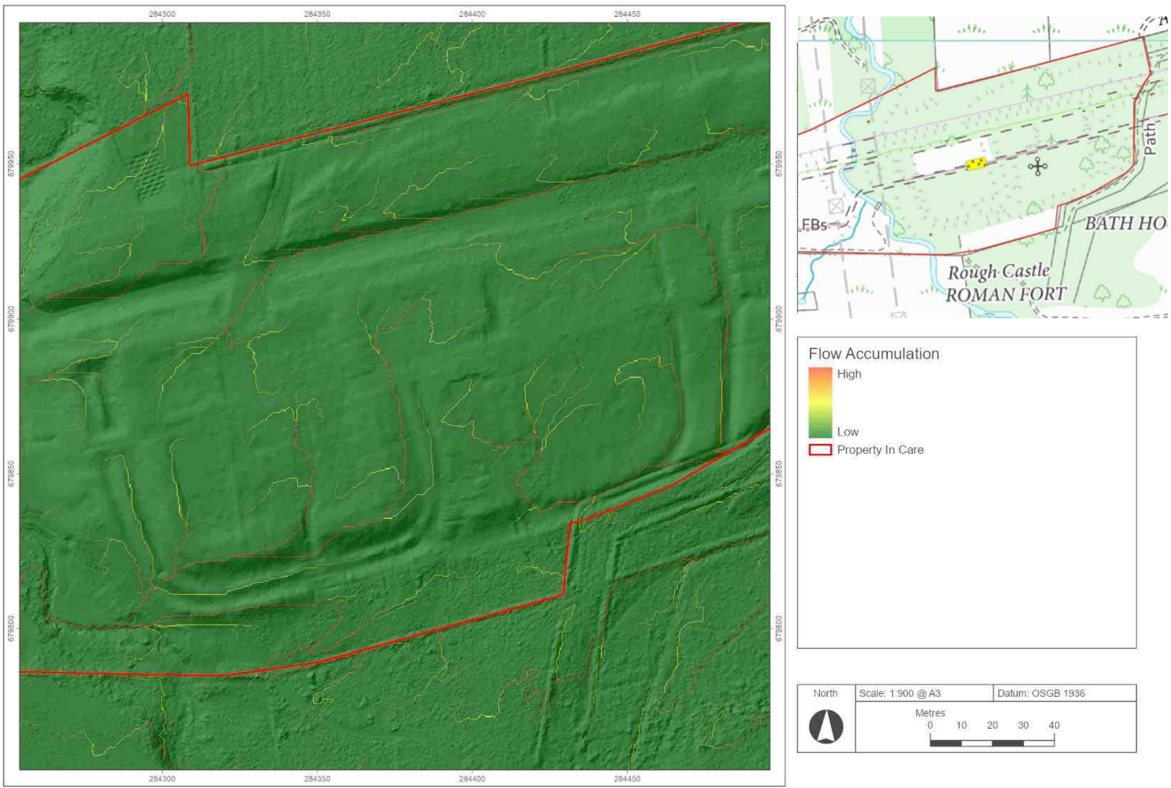

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Figure 56 Flow accumulation for Rough Castle. Red indicates a high accumulation and green low accumulation.

By developing a baseline understanding of the capabilities for hydrological modelling in a non-geographically bound heritage landscape, it is possible to determine the hydrological influence of archaeological features. From this it is possible to determine the key locations on site which require further investigation or monitoring to determine what effect the hydrological network is potentially having on these locations. Furthermore, this also gives heritage practitioners the potential ability to monitor these locations in the light of changes in precipitation on site (Discussed more in Chapter 7).

5.3.3.1 Management outputs for Rough Castle

At Rough Castle there are four distinct drainage basins found across the fort top. Unlike the other sites within this study the drainage basins feel like an oversimplification of the hydrological networks across the fort top. Rough Castle has complex hydrological interactions that require further investigations on site, particularly around the defensive ditches to the east of the site. In addition, the hydrological modelling shows where the larger preferential flow networks originate and flow across the site (Figure 54). This aids in the understanding of where the water on the fort top is being moved to and where the water will end up. Although this is mainly looking at preferential flow networks, it is imperative to understand the impact that altering or preventing them from flowing across site could have on the site hydrology but also the preservation of buried archaeological features (Historic England, 2016). As these are only preferential surface flows, they will be having a direct impact on the surface moisture and therefore the preservation of buried archaeology.

The hydrological networks highlight points of connection to the wider landscape at Rough Castle. These connections are imperative to understand as they could impact the site hydrology. Being able to establish entry and exit points of hydrological networks across the site can allow for careful monitoring and maintenance of these locations across the PIC.

Rough Castle highlights an important factor when using LiDAR data for remote understanding of heritage landscape and that the adjacent landscape of the site needs to be include the nearest highest elevation point. This would allow for a better understanding of the connections between the surrounding and heritage landscapes.

Finally, the hydrological mapping at Rough Castle also shows how the archaeological features control hydrological flows around the fort top and defensive ditches, and how maintaining them could aid site drainage. Determining where some of the key drainage points are on site could allow for maintenance of these locations to aid in water transport around the site. At Rough Castle the ditch is one of these key features, being able to use key archaeological features for an intended purpose is not only testament to how well they function but also an effective way to maintain drainage networks without adding infrastructure to a site.

5.3.4 Similarities and anomalies found between study sites

The use of digital models derived from LiDAR for hydrological modelling allows for a foundation in the understanding of hydrological networks that occur across heritage landscapes. Hydrological flow networks and the influences on water movement vary greatly between each heritage landscape within this study. Through examining three very different heritage landscapes it has been established that it is possible to use digital models to investigate the hydrological networks present within these landscapes. Although each site examined produced contrasting results, and they are very different sites in terms of topography, heritage and geography, the method for hydrological modelling is effective for each site. This demonstrates the suitability of this technique for use in other heritage landscapes where fine-scale LiDAR data is available.

It should be noted that this study is establishing a baseline for the use of digital models derived from LiDAR for hydrological modelling within a heritage landscape, therefore further research is required to understand some of the anomalies highlighted (straight lines, modern interventions etc.). Further work is also required to include the standing stones at Ring of Brodgar to understand the preferential flow in a stream less-landscape and the influence of the standing stones. This is essential as when considering the wider impacts of this research in relation to climate change and archaeological preservation, the standing stones are an integral part of the landscape.

On Hirta the predicted higher order preferential flows are physically present on site and the hydrological networks that flow into them are well defined due to the geographical isolation of an island and having distinctive bounding edges. This demonstrates a suitability of using LiDAR data to determine preferential flow networks of sites in remote locations with existing stream networks.

Hirta further demonstrated the ability to determine the influence of upstanding archaeology and the legacy influence of historical agricultural activities. This further highlights the suitability of this technique to establish the points of influence on hydrological networks, whether that be the hydrological interactions with monuments or the impact of past land use activities, which are not visible, but still influence the hydrology. Understanding the invisible effects that past activities are having on the current hydrological network is essential for understanding how hydrology may change over time within a heritage landscape. Although this was not investigated further within this research, it could be possible to monitor change in hydrology based on the past activities of the landscape and the maintenance of these activities. Through highlighting the possibility to monitor the changes in hydrological networks as a proxy for historical land activities, this then becomes a way of monitoring the deterioration and influence that past practices have on a landscape.

Digital models derived from LiDAR can be used to examine the impact that modern day interventions are having on heritage landscapes. This is particularly seen at Ring of Brodgar and the impact that the entrance footpath has on the hydrological network, through the hydrological network running alongside the footpaths (Figure 44); in Hirta this is shown in the headwall, where the flow does not follow the stream outline (Figure 47); at Rough Castle the effect of fence lines and railway lines (Figure 53). These points may seem minor in the face of the full landscape; however, they have large impact of the understanding of the hydrological networks on a heritage site. Being able to identify modern interventions and the impact that they have on the hydrological networks, can allow for better management of them on site to either aid or remediate the impact that they are having on the heritage landscape. Furthermore, in relation to hydrological modelling they also highlight the areas that need further work to be able to understand the full impact modern interventions are having on hydrological networks and develop a method of incorporating them into the digital models for sites.

Additionally, the impact that modern land use is having on the hydrological networks can also be seen using LiDAR data, particularly that of fence lines (Figure 44 and Figure 53). Although it has been found that fence lines have an impact of the hydrology of agricultural landscape, it was not expected to be found in this research. The fact that the influence of fence lines was found within two study sites and the prominence that some of the fence lines have on the hydrological networks, highlights the need for them to be included when determining hydrological networks of heritage landscapes. In addition to this, it highlights how connected a heritage landscape is with the adjacent land uses, indicating that although we can look at these heritage sites in isolation, they are connected to a much wider landscape that has multiple different land uses, all of which can affect the hydrological networks.

The use of fine scale LiDAR data has made it possible to determine key management areas within a heritage landscape through the creation of basins and appropriate stream order networks. Through the creation of drainage basins, it can allow for site-based interventions to the hydrological network to be developed within the appropriate areas of the site. This will also allow heritage practitioners to understand the influence that some works may have on the wider landscape surrounding the site and inform heritage practitioners of the current hydrological patterns and determine appropriate climate adaptation measures.

5.3.5 Technical issues occurred within the datasets

Further to the site-specific outcomes, there is further consideration required when using LiDAR data for hydrological modelling in a heritage landscape. There are three key factors to consider when using fine scale LiDAR data prior to that of hydrological modelling. The first is that of georeferenced data. For Rough Castle and Hirta, neither raw data set was georeferenced. It requires considerable time, but it is possible to manually geo-reference the data sets to a base map. This is only required if you wish to overlay photographic imagery or base maps to the outputs. It is imperative that georeferencing happens at the beginning of processing and not at the end, as all individual processes of the hydrological modelling would have to be done manually. This will create errors and distort each layer individually. Having a clear understanding of the required output from the hydrological modelling is essential before you start.

Secondly is that of the joining of LiDAR tiles. For Ring of Brodgar there were no issues in the joining of the LiDAR tiles, however for St Kilda and Rough Castle technical difficulty was encountered. There are two reasons for this; firstly, the number of LiDAR tiles that was required for St Kilda and Rough Castle was much greater than that of Ring of Brodgar. This could have caused some of the issues that were experienced when trying to join the LiDAR tiles. The other is that there was a lack of software and hardware processing power. Either of these could be a reason for preventing the data sets from joining to create a DSM or DTM. In order to overcome these issues, discussions with the LiDAR data provider can prevent any joining issues occurring.

This brings us to the third factor to consider- receiving a site DSM or DTM that has been generated from LiDAR data. After the difficulties experienced with the LiDAR data sets, there was an exploration of the data sets with the Digital Innovation and Learning team at HES. Through this it was established that a smoothed version of a DSM, although the data set is visually more appealing, was not suitable for use in determining hydrological networks. Through being able to have a dialogue to determine the most suitable version of a DSM for Rough Castle, it was possible to trial a few options to see what worked. This highlighted the necessity for specifying what type of data set you are asking for when wishing to use it to determine hydrological regimes with a heritage landscape.

These three factors - georeferencing, joining LiDAR tiles and smoothing of data sets - were an unexpected obstacle when evaluating hydrological modelling within a heritage landscape. However, there is now a much greater appreciation for the complexity of using LiDAR data and its applicability.

5.4 Conclusion for using LiDAR data for small scale hydrological modelling within archaeological landscapes.

Using the LiDAR data, it is possible to create an understanding of the current site hydrological networks. LiDAR data can allow for a representation of the current hydrological networks and give an indication of areas of hydrological interest. Through gaining a base understanding it is possible to provide information to allow site management planning to undertake interventions for climate adaptation. This can result in sites being appropriately prepared for these changes instead of retrospectively fixing the effects that an increase in precipitation may have. An adoption of innovative site hydrological modelling and monitoring techniques into current site management practices is essential for determining the site hydrological stability and conservation of archaeology within a heritage landscape and archaeology.

Through using fine scale topographical data, it has become apparent that by applying hydrological modelling it is possible to determine the influence different archaeological features have on the hydrological networks. Fine-scale topographic data allows for an understanding of the influence of upstanding archaeologically on the hydrological networks of a site, and highlights the areas in which flows occur and their connected pathways.

Overall using fine-scale topographic data has allowed for small- and large-scale interactions of hydrological networks to be established for three different WHS. This method is an effective way for heritage managers to determine key areas of a hydrological network across a site to understand the hydrology of a heritage landscape. Through this research I have generated a novel approach for understanding the surface hydrology of heritage landscapes that can be used widely within the heritage sector.

Chapter 6- Exploring the connections between MMS and Hydrological Networks

6.1 Introduction

Understanding the surface hydrology of a heritage landscape can help aid conservation practices, along with knowing the impact that different visitor features are having on the subsurface. Building an understanding of how these two data sets relate to each other, can show the different scales of the MMS surveys and hydrological mapping, which can be combined to provide a greater understanding of the interaction between the surface and subsurface hydrological connections. This chapter will look at the process of combining these two data sets, and explore the issues and challenges that this brings, along with the benefits of combining hydrological modelling and MMS data.

6.2 MMS and Hydrological Modelling Results

6.2.1 MMS and Hydrological Modelling Ring of Brodgar

Figure 57 to Figure 60 shows the combined MMS outputs for the raw 11cm and processed 30cm data, together with potential streams identified by the hydrological modelling The stream orders have been split to aid interpretation; the lower orders of 2-4 on the left with the higher orders of 5-10 on the right. Through combining the data sets it was hoped to demonstrate the connection between the lower order flows of the hydrological modelling and the MMS data. Through using different depths of MMS sensors and the hydrological modelling it was hoped to determine if there was a potential depth correlation between the two data sets. Figure 57 and Figure 58 show no correlation between the hydrological networks and MMS survey. This is the same for Figure 59 and Figure 60.

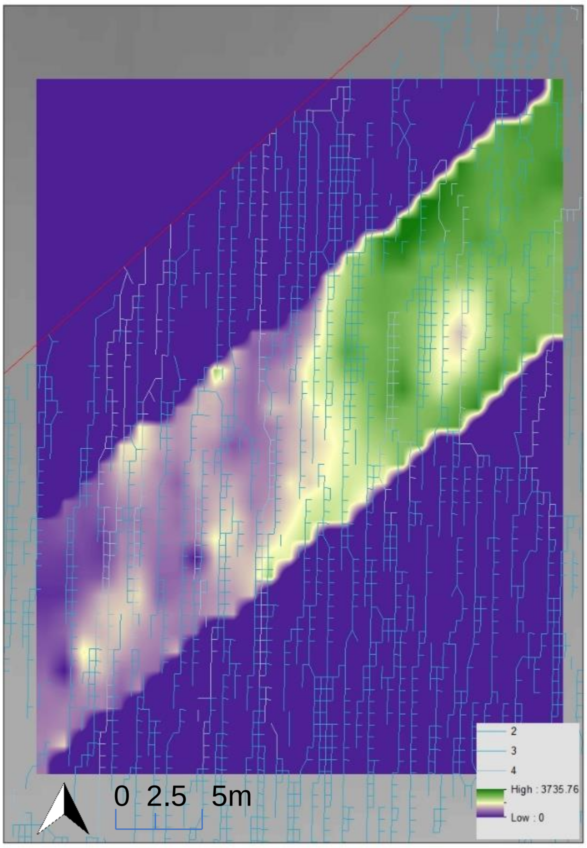

Figure 57 Combined MMS 11cm Sensor data and low preferential flow networks at Ring of Brodgar SA1. MMS 11cm Sensor (green indicates high sensor response with purple indicating low). Preferential flow networks 2 to 4 are denoted by the angular blue lines. PIC boundary is indicated in red.

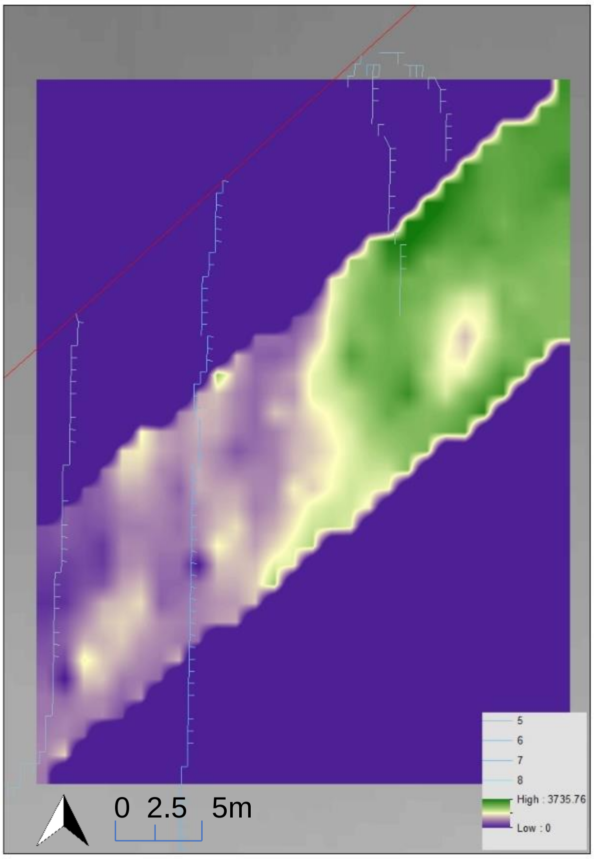

Figure 58 Combined MMS 11cm Sensor data and high preferential flow networks at Ring of Brodgar SA1. MMS 11cm Sensor (green indicates high sensor response with purple indicating low). Preferential flow networks 5 to 8 are denoted by the angular blue lines. PIC boundary is indicated in red.

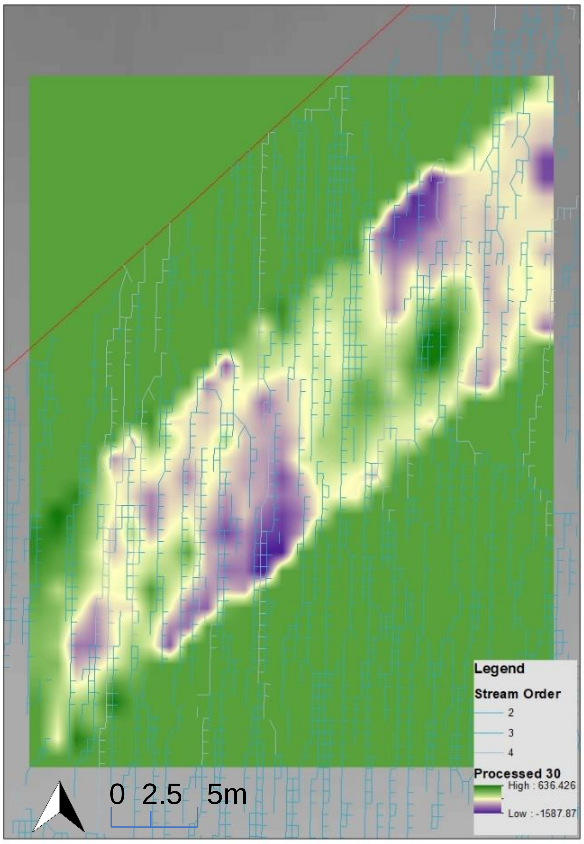

Figure 59 Combined MMS Processed 30 cm Sensor data and low preferential flow networks at Ring of Brodgar SA1. MMS Processed 30 cm Sensor (green indicates high sensor response with purple indicating low). Preferential flow networks 2 to 4 are denoted by the angular blue lines. PIC boundary is indicated in red.

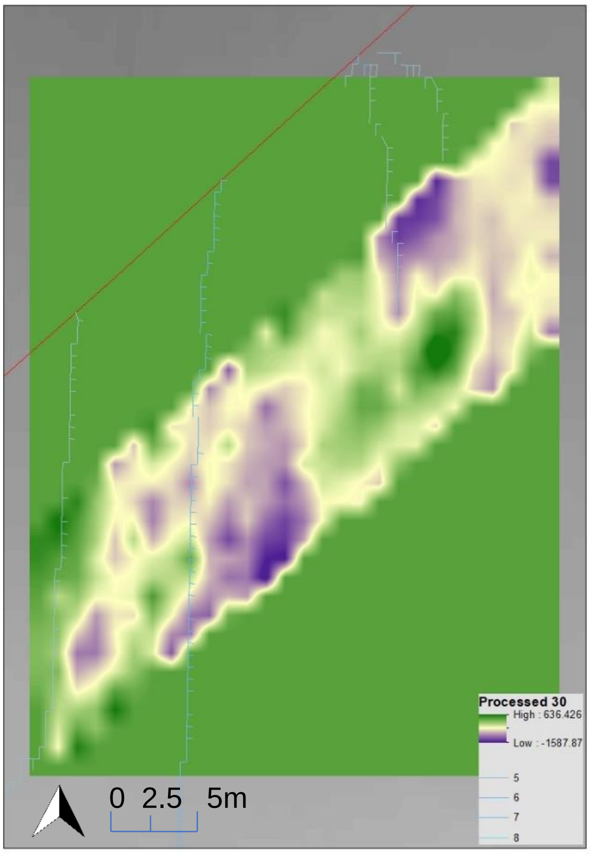

Figure 60 Combined MMS Processed 30 cm Sensor data and high preferential flow networks at Ring of Brodgar SA1. MMS Processed 30 cm Sensor (green indicates high sensor response with purple indicating low). Preferential flow networks 5 to 8 are denoted by the angular blue lines. PIC boundary is indicated in red.

Figure 61 and Figure 62 show the flow accumulation overlain on the MMS data. The red colour indicates lower flow accumulation with blue indicating high flow accumulation. Within Figure 61 and Figure 62 there is only low flow accumulation. For both Figure 61 and Figure 62 there is no correlation between the MMS and flow accumulation.

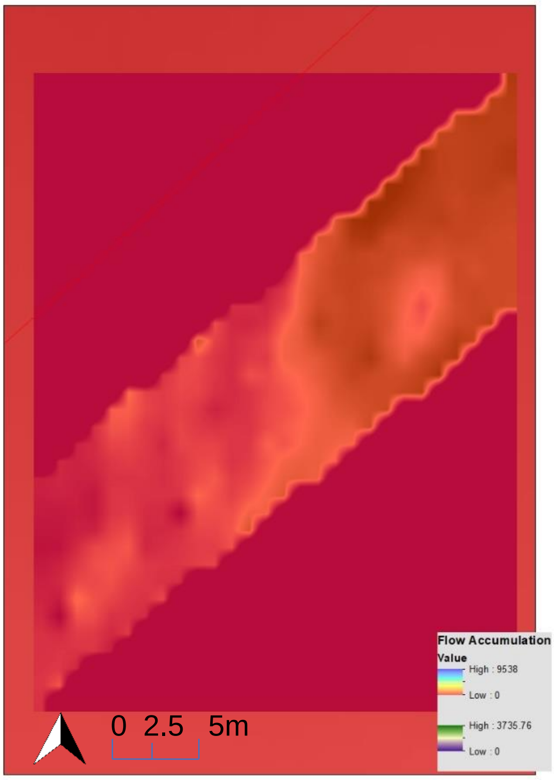

Figure 61 Combined MMS 11cm Sensor data and Flow Accumulation at Ring of Brodgar SA1. MMS 11cm Sensor (green indicates high sensor response with purple indicating low). Red indicated low flow accumulation, with blue indicating high flow accumulation. PIC boundary is indicated in red. There is only low flow accumulation displayed in this figure.

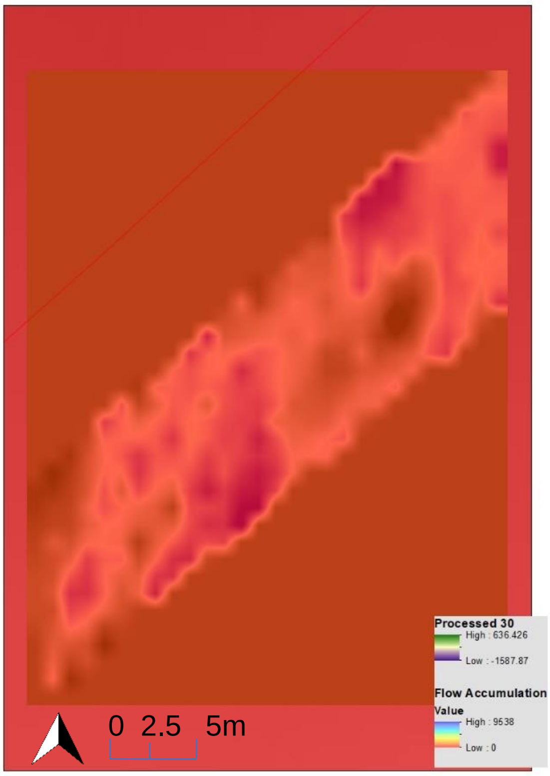

Figure 62 Combined MMS Processed 30 cm Sensor data and Flow Accumulation at Ring of Brodgar SA1. MMS 11cm Sensor (green indicates high sensor response with purple indicating low). Red indicated low flow accumulation, with blue indicating high flow accumulation. PIC boundary is indicated in red. There is only low flow accumulation displayed in this figure.

6.2.2 MMS and Hydrological Modelling Rough Castle

Figure 63 to Figure 68 shows the combined MMS outputs for the raw 3cm data and the Processed 11cm and 30cm data., together with potential streams identified by the hydrological modelling. The stream orders have been split in two to aid interpretation, the lower orders of 2-4 on the left with the higher orders of 5-10 on the right. Similar to Ring of Brodgar there is no correlation between any of the MMS sensors and hydrological model networks.

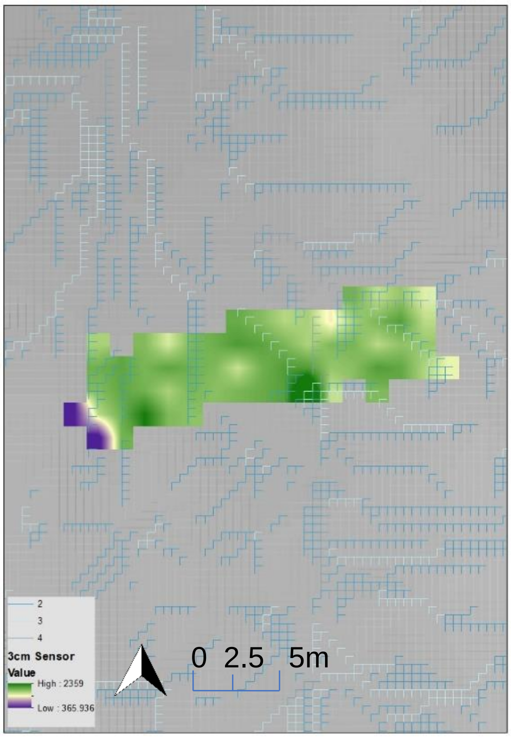

Figure 63 Combined MMS 3cm Sensor data and low preferential flow networks at Rough Castle SA3. MMS 3cm Sensor (green indicates high sensor response with purple indicating low). Preferential flow networks 2 to 4 are denoted by the angular blue lines. Angular edge of the MMS is due to the rectification process.

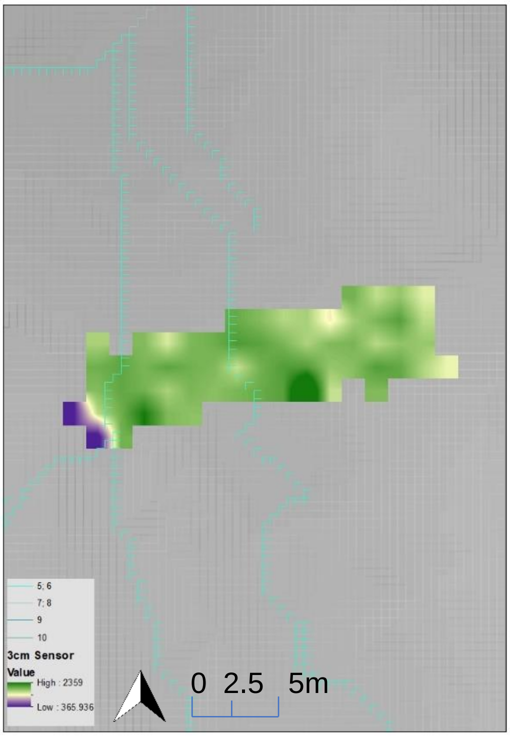

Figure 64 Combined MMS 3cm Sensor data and high preferential flow networks at Rough Castle SA3. MMS 3cm Sensor (green indicates high sensor response with purple indicating low). Preferential flow networks 5 to 10 are denoted by the angular blue lines. Angular edge of the MMS is due to the rectification process.

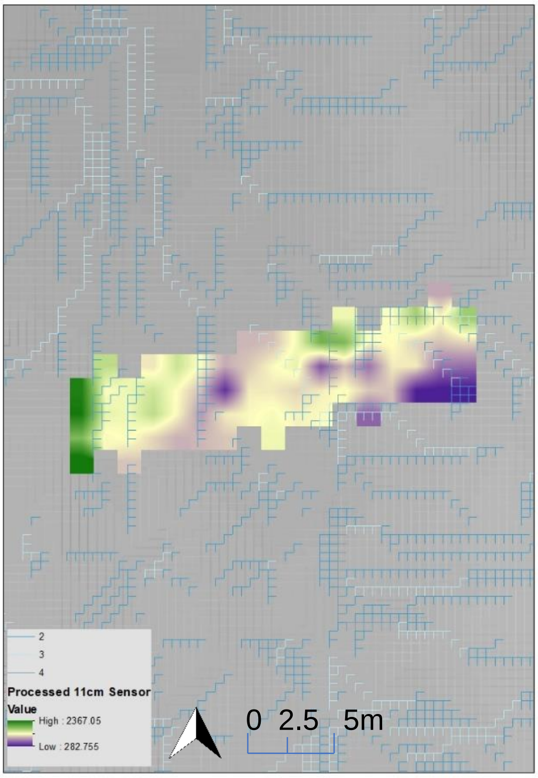

Figure 65 Combined MMS Processed 11cm Sensor data and low preferential flow networks at Rough Castle SA3. MMS Processed 11cm Sensor (green indicates high sensor response with purple indicating low). Preferential flow networks 2 to 4 are denoted by the angular blue lines. Angular edge of the MMS is due to the rectification process.

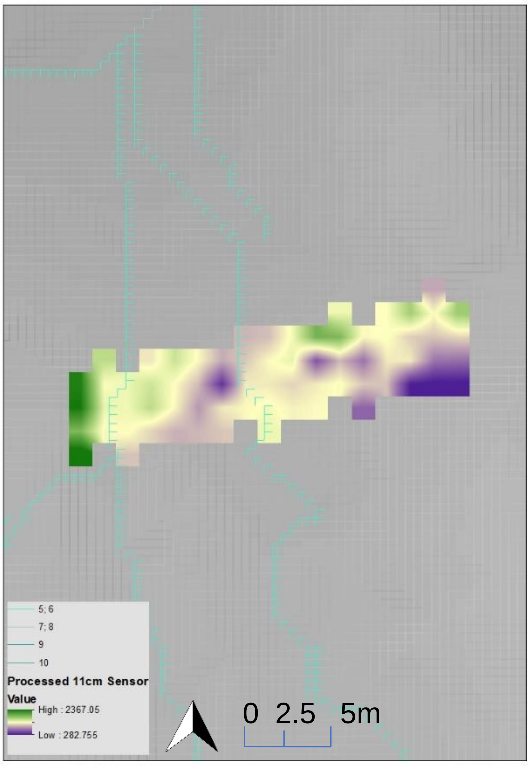

Figure 66 Combined MMS Processed 11cm Sensor data and high preferential flow networks at Rough Castle SA3. MMS Processed 11cm Sensor (green indicates high sensor response with purple indicating low). Preferential flow networks 5 to 10 are denoted by the angular blue lines. Angular edge of the MMS is due to the rectification process.

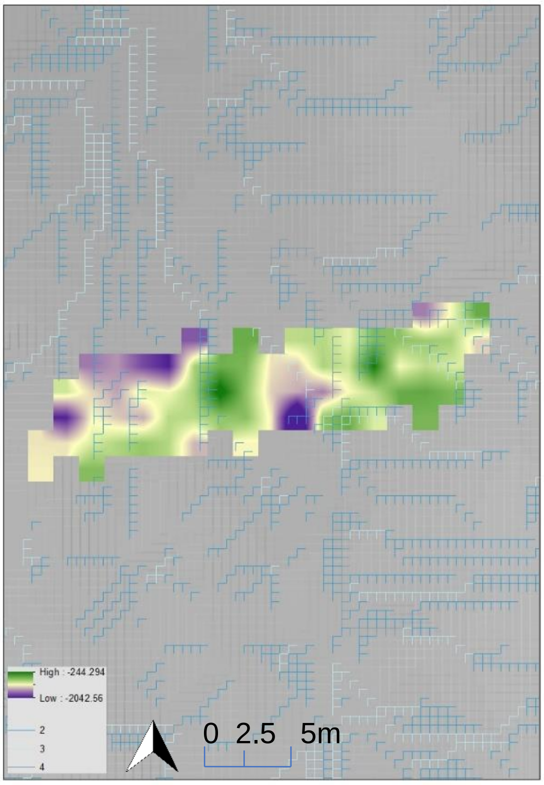

Figure 67 Combined MMS Processed 30cm Sensor data and low preferential flow networks at Rough Castle SA3. MMS Processed 30cm Sensor (green indicates high sensor response with purple indicating low). Preferential flow networks 2 to 4 are denoted by the angular blue lines. Angular edge of the MMS is due to the rectification process.

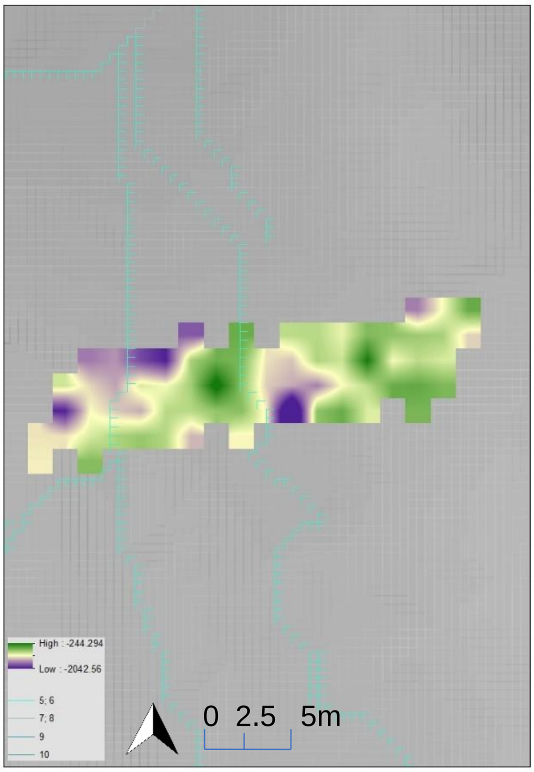

Figure 68 Combined MMS Processed 30cm Sensor data and high preferential flow networks at Rough Castle SA3. MMS Processed 30cm Sensor (green indicates high sensor response with purple indicating low). Preferential flow networks 5 to 10 are denoted by the angular blue lines. Angular edge of the MMS is due to the rectification process.

Flow accumulation has been overlain on to the MMS outputs in Figure 69 to Figure 71. For each image the flow accumulation scale is the same. The blue areas indicate low flow accumulation with the red areas indicating higher flow accumulation. Theses flows also indicate the location of stream orders 2 and 3 for this area at Rough Castle. Through using flow accumulation, it was expected that a connection between the MMS and Hydrological modelled networks could be established. As there are only lower order flows at Rough Castle SA3, flow accumulation was anticipated to give a clearer understanding of the connection between the two data sets.

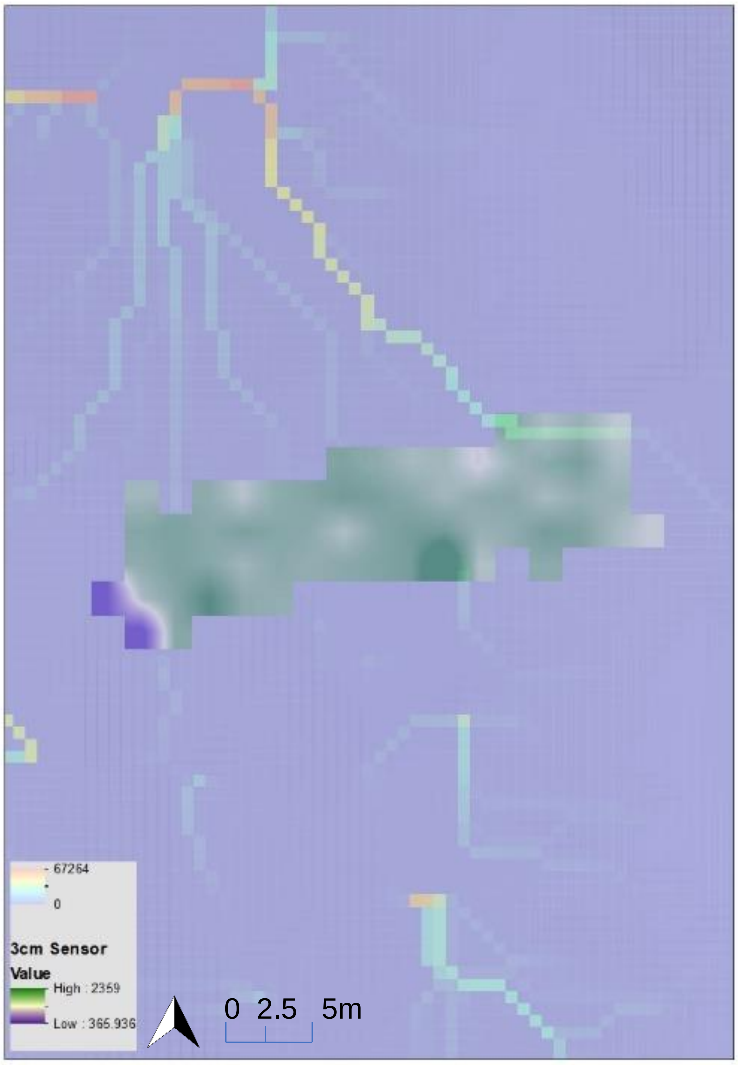

Figure 69 Flow Accumulation and 3cm sensor data Combined MMS 3cm Sensor data and flow accumulation at Rough Castle SA3. MMS 3cm Sensor (green indicates high sensor response with purple indicating low). Red indicates high flow accumulation, with blue indicating low flow accumulation. Angular edge of the MMS is due to the rectification process.

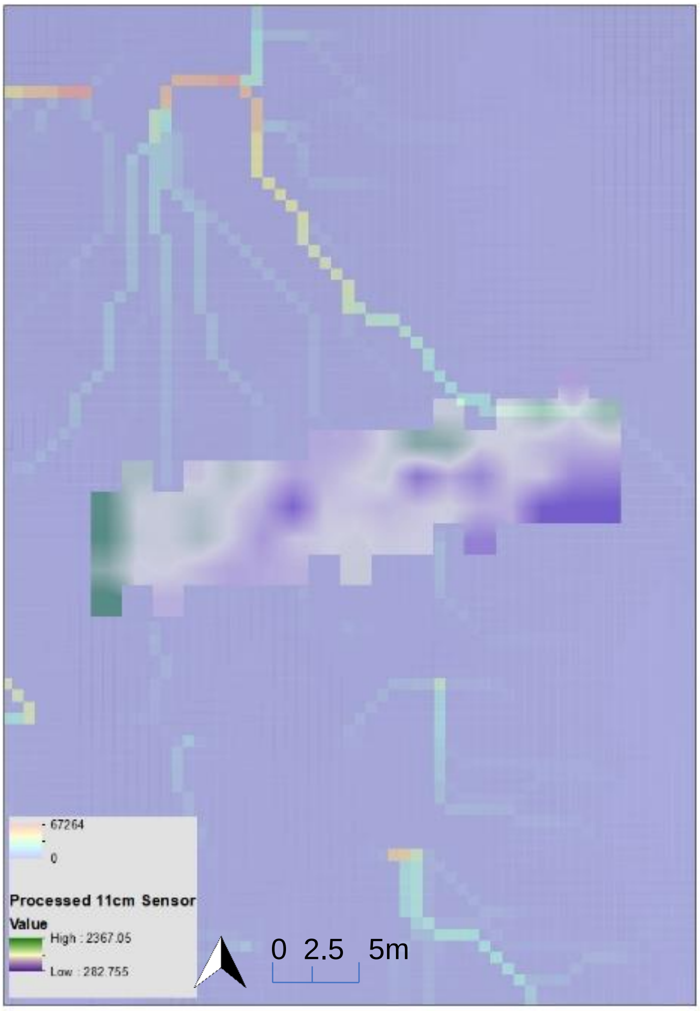

Figure 70 Flow Accumulation and 3cm sensor data Combined MMS Processed 11cm Sensor data and flow accumulation at Rough Castle SA3. MMS Processed 11cm Sensor (green indicates high sensor response with purple indicating low). Red indicates high flow accumulation, with blue indicating low flow accumulation. Angular edge of the MMS is due to the rectification process.

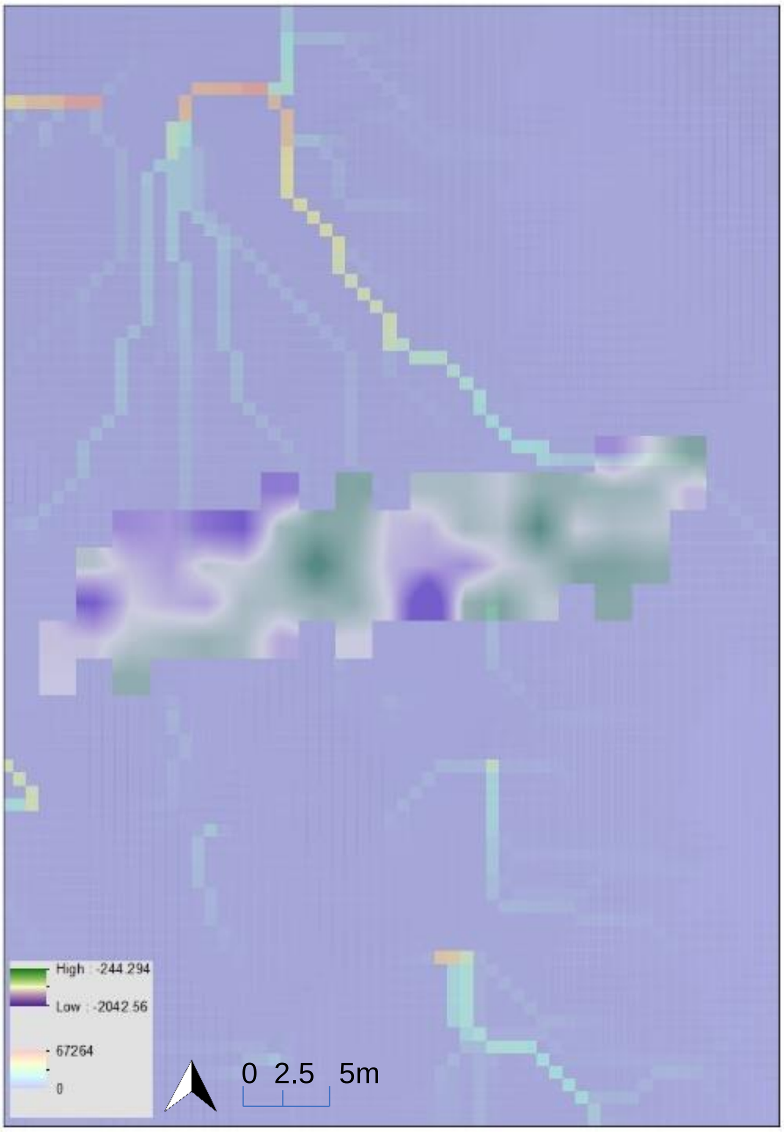

Figure 71 Flow Accumulation and 3cm sensor data Combined MMS Processed 30cm Sensor data and flow accumulation at Rough Castle SA3. MMS Processed 30cm Sensor (green indicates high sensor response with purple indicating low). Red indicates high flow accumulation, with blue indicating low flow accumulation. Angular edge of the MMS is due to the rectification process.

6.3 MMS and Hydrological Modelling Discussion

The discussion for this chapter is split in to two distinct sections. The first section will address the issues encountered with combining the datasets and methods for overcoming these issues, the second section will discuss the outputs and the interpretations that can be made.

6.3.1 Issues encountered with combining data sets and how to overcome them

Each site had its own complication in combining the two data sets. The first common issue encountered is the due to the georeferencing of the data sets. In the generation of the hydrology maps, this is purely topographically driven and therefore, does not need to be georeferenced to generate the hydrological networks. Likewise with the MMS data georeferencing is not needed to generate these maps as permanent survey grids can be set up. Therefore, there is no specific georeferencing held for either data set. To combine these two data sets, manual georeferencing was carried out on the MMS data set, called Rectifying in ArcGIS. This can generate unknown inaccuracies in the placement of the rectified datasets.

In order to accurately use the combined MMS and hydrological mapping there needs to be georeferencing built into the collection of the data sets. Using spatial data sets requires accurate georeferencing of both data sets to ensure compatibility. Georeferencing a LiDAR data set is possible and can be done through rectifying in ArcGIS using defined topographic features within a landscape. Additionally, geo-referencing of MMS data in the field is possible using DGPS. This would have allowed for accurate mapping of the MMS data on to the LiDAR data sets and in turn the hydrological modelling. However, it was not possible to carry out a DGPS survey of either site during fieldwork. Combing the data sets has highlighted the necessity for carrying out an accurate georeferencing of the MMS surveys.

Further to the inbuilt georeferencing of the data sets, is the process of rectifying in ArcGIS. This was carried out to situate the MMS layers on to the hydrology maps. Firstly, the orientation of the MMS data sets had to be corrected before situating the MMS data within the landscape. For Ring of Brodgar it was relatively straightforward, and achieved by of rotating the data- set 90^0 counter- clockwise. However, for Rough Castle this resulted in flipping the dataset 180^0 on the end-to-end axis and then 180^0 on the horizontal axis, then rectifying the data set into the correct position. The reorientation of the MMS data sets can be incorporated in the rectifying process and is easily done, however knowing the correct orientation of the MMS data set is essential for this. The MMS these datasets were ‘eyeballed’ in to position on top of the base LiDAR topography maps using small scale features within the landscape. Nevertheless, being able to locate both MMS data and the hydrological flows on site georeferencing is essential.

Additionally for this research, the scale of the data being rectified is 20m long by 8m wide on a relatively flat area of Rough Castle fort top. Due to the small dimensions and lack of distinct topographic changes rectifying the data set was challenging. Besides the difficulties of rectifying the data sets, the different scales of the two data sets makes comparison challenging. The hydrological dataset, although it has a 0.5m topographic resolution, is designed to be understood at a landscape scale. Combining it with MMS in discrete, minimal variation topography areas, demonstrated the size disparity between the two data sets, especially at Rough Castle. In order to fully understand the MMS and hydrological connections, the hydrological dataset has had to be zoomed in on. This has resulted in L-shaped pixels of the hydrological networks and presents as a disjointed network. However, being able to zoom in and have the ability to determine the interactions at the small scale could be invaluable for heritage landscapes, especially those with upstanding archaeology or known problem areas.

At Ring of Brodgar the MMS maps are slightly larger at 15m by 30m, this did not make the rectifying any easier as the landscape at SA1 is relatively featureless, in terms of distinct topographic features. For the MMS data the solid colour (purple) around the 11cm sensor data and the 30cm (green) data is present due to the rectifying process (Figure 57 to Figure 60). As with the rectifying process at Rough Castle the MMS data sets have become pixelated along the long axes. ArcMap has then filled in the remaining area to generate a solid rectangle for Ring of Brodgar. Again, with Ring of Brodgar the stream networks are presented as an L-shape due to differences in overall scale of the data sets.

As this study is trialling the combination of the hydrology and MMS datasets, the process for combing them has been used as an educational and problem consideration and solving process rather than for accurate site interpretations. It has shown that despite the limitations of the datasets with some further considerations during the data collection, such as environmental conditions and suitability of survey location, and input phase, these two datasets could work effectively together to give a better understanding of an area within a heritage landscape.

6.3.2 MMS and Stream Orders and Flow Accumulation interpretations

Both Ring of Brodgar and Rough Castle MMS data sets were taken in areas of low topographic relief, but on key footpaths within the landscape. When combining the MMS with the hydrology, due to the lack of varied topography in these locations it makes the combined MMS and hydrology datasets difficult to interpret. However, this has shown that if used in a different topographic setting the method for combining data sets and linking to topographic changes and MMS responses would be possible. The links topography connections are shown in the high number of low stream order streams present at both Ring of Brodgar (Figure 57) and Rough Castle (Figure 63), indicating very slight topographic changes. Which is in contrast with the higher order streams where there are only three or four present (Figure

58 and Figure 66). Due to the high number of lower order streams at both sites, being able to find a direct connection between them and the MMS data is challenging. This has highlighted that if georeferencing issues were resolved, then the connections between the stream networks and the MMS would be more apparent and easier to establish. The inverse is also true for the higher order streams;, due to the narrowness of the MMS surveys it is difficult to tell if there is a connection between the higher order streams and the MMS survey.

The lack of visible connections could also be down to the interpolation method, especially at Ring of Brodgar as the transects are 5m apart with interpolation being 0.8m. A solution to this would be to carry out wider MMS surveys that would incorporate a longer section of a stream network, along with transects which are closer together. This would help to gain an understanding of the hydrological interactions between MMS responses on footpaths and the hydrological mapping. Through having carried out the hydrological mapping post MMS survey this highlights how useful it would have been to carry out the hydrological mapping first to ensure that MMS could have been targeted to capture the possible hydrological connections.

Flow accumulation is generated as part of the stream network generation process and highlights the locations where accumulation is likely to occur. Within this research, I have mainly been looking at the larger scale and direct interactions of the stream network with the heritage landscape. However, when looking at the smaller scale of the MMS, flow accumulation may prove to be more helpful in establishing connection between then MMS and hydrological data. This shows that there is variation in the flow accumulation across the site, but not within the MMS survey area. Therefore, before carrying out an MMS survey, understanding the possible hydrological networks that are present would be beneficial for understanding the connections between the above and below ground.

For Ring of Brodgar using flow accumulation is not an option and does not help understanding of the connections between the MMS and hydrological networks (Figure 61 and Figure 62). The lack of variation in the flow accumulation for Ring of Brodgar could be due to the lack of topographic variation within the site and connectivity between the hydrological flows. The flow accumulation could, however, indicate that there would be an increase in MMS response due to the lack of flow accumulation on the main access path, which could result in an increase in soil moisture due to there being minimal flow pathways present. This is in contrast with the stream networks that show a high number of lower-level streams, which would indicate that there is possible movement of surface water in this location. This therefore highlights the possibility of using both flow accumulation and stream network to determine an interaction between the MMS and hydrological networks. Overall, for Ring of Brodgar it is difficult to infer the connections between the MMS and hydrological networks present on site.

However, for Rough Castle the flow accumulation could be used to determine possible connections between the hydrological networks and the MMS (Figure 69 to Figure 71). Even though it is not possible to determine a direct relationship between the MMS and the flow accumulation it is possible to see how useful it could be. Figure 69 to Figure 71 highlight the possibility of using flow accumulation to understand the responses from the MMS. Within Figure 69 it is possible to determine the connections between MMS and flow accumulation, as the higher responses from the MMS could be linked with the higher areas of flow accumulation. Using the plan view data, it is presumed that the 3cm MMS data would have the most direct connections to the flow accumulation. This is due to the flow accumulation being derived as a direct result of the topography and the 3cm sensor, which is affected by the surface moisture, having a possible close connection. As a result, the flow accumulation at Rough Castle gives an indication to the areas in which the MMS response could be higher or lower and give a reason for such responses.

Additionally, where the flow accumulation shows a constant colour, this would suggest that there could be no variation in the MMS. If there is a change in MMS response, this could indicate that there is something happening in the near subsurface, signalling a more complex interaction occurring than solely relating to moisture movement. This is a very simplistic approach to the combining of MMS and flow accumulation, but if this combined technique was to be used in a heritage landscape that has an unknown subsurface structure, then the combined technique could provide some would be able to give an indication as to the reasoning for some of the MMS responses.

Arguably, flow accumulation is a more appropriate output to use in conjunction with MMS and soil moisture mapping in general, as it will indicate areas where there could be higher responses from the MMS due to water accumulation. Through using a combination of flow accumulation and stream network it is possible to build a greater understanding of the hydrological connections between the surface and sub surface hydrological connections. There needs to be further work carried out to understand the connections between using MMS response and flow accumulation and stream networks. However, through the exploration by a combination of combining the datasets it has shown the possibility of using them to determine hydrological connections and provides an additional possible reasoning as to why some responses may be recorded by the MMS.

6.4 Further work for combining MMS and Hydrological Modelling

In addition to the plan data, being able to determine the interaction between the hydrological data and the vertical profiles of the MMS would be invaluable. Further research is recommended for the ability to 3D rectify the MMS transects, as being able to integrate the above- and below- ground predicted hydrology connections could prove to be essential when monitoring sites in light of changing precipitation patterns. As discussed in *Chapter 4. MMS field surveys for the* applicability of using MMS for landscape scale monitoring of soil moisture , the vertical profiles give a clearer understanding of the interactions throughout a profile and the connections that can be made between each depth of sensor reading. Thus, being able to combine the vertical profiles and the hydrological data would provide a better understanding of the connections between the two data sets. This could also give an indication as to the depth at which the hydrological flows are seen within a profile, or if they are not seen at all. Through being able to view the data sets in a vertical manner, it could aid further site understanding and development of management practices within heritage landscapes.

6.5 Wider heritage context for combining MMS and Hydrological Modelling.

Within the wider heritage sector this technique could be used for developing a greater understanding of the above- and below- ground hydrological connections. Through being able to match up the responses of the MMS with a stream order or flow accumulation map, could aid in the understanding of why some MMS readings are increased without the presence of changes in sub-surface structure or archaeology. Conversely this could also be used to explain the presence of change in subsurface structure and the possible presence of an archaeological feature if there is no correlation to the flow accumulation or stream order networks. Understandably and as previously outlined in *Chapter 4. MMS field surveys for the* applicability of using MMS for landscape scale monitoring of soil moisture , the MMS technique is not suitable for use over a large area, but the fundamentals of this technique have shown that it is possible to determine connections between the surface and subsurface using these techniques.

This technique could also be used to determine the pathways for water to reach an area and with further work modelling the volume of surface water passing a location under known precipitation is possible. This could then be paired with the MMS and used to determine the sub-surface interactions that are occurring under specific conditions. This would in turn allow for better monitoring and understanding of the interactions between surface and sub-surface hydrology. For heritage landscapes this could be monitoring of a known buried archaeological feature for the changes in hydrological interactions that occur. In this case knowing when and how much water is interacting with the buried archaeology could lead to an increase in understanding of the state of preservation.

Further to the direct flow and hydrological mapping is that of erosional mapping. Within this research this is theoretical, however with more advance modelling and combining this with field techniques such as Cs-137 mapping (Varley et al., 2020) to determine the location of accumulation and erosion of soil, this could be a good method for establishing erosion and accumulation in a non-destructive manner in heritage landscapes. It is acknowledged that the Cs-137 mapping requires further work to be useful at erosional for mapping, and it can only be used in specific circumstances. However, as this technique has been carried out in a heritage landscape and highlights the possibility of using it in conjunction with other modelling to determine erosional and accumulation routes within a heritage landscape context. This could be coupled with the hydrological modelling to determine source locations and accumulation areas within a heritage landscape.

6.6 Conclusion of MMS and Hydrological Modelling

If the issues are addressed in terms of georeferencing both the Lidar and MMS datasets, then combining the hydrological mapping and MMS would be an effective way to understand the above- and below- ground hydrological connections. Through combining the data sets it is possible to see the advantage that using combined MMS and hydrological modelling could bring to the heritage sector. Through using flow accumulation instead of stream networks, it may be possible to gain a better understanding of the link between the surface and subsurface. In landscapes where flow accumulation is not varied, like Ring of Brodgar, lower order stream networks could provide the detail required to determine these connections.

Overall, with the appropriate georeferencing of the MMS and hydrological modelling, this technique could be useful for exploring the interactions of the above- and below- ground hydrological interactions within heritage landscapes.

Chapter 7. Climate Change: Precipitation and its Hydrological Implications for Heritage Landscapes

7.1 Introduction

Climate change is threatening our heritage landscapes and immediate action is needed to preserve them for future generations, as the likely effects on our heritage landscapes remain poorly understood as recently highlighted by ICOMOS (Day et al., 2020).

Through this research I have established two different methods: one for determining soil moisture within a heritage landscape and the second for determining hydrological networks. . Based on our understanding of these techniques, the impacts that may occur as a result of changes in precipitation regimes and the potential implications for heritage landscapes can be inferred. This chapter aims to highlight how a fundamental understanding, which has been developed for landscape hydrology, can be used to infer the implications of changes in precipitation as a result of climate change on our heritage landscapes. From this, it is possible to equip heritage practitioners with increased site knowledge of hydrological networks and influences to help sites adapt and become more resilient to cope with the changes in precipitation.

In the CCRA and HONO Climate Vulnerability Index the high emissions (RCP8.5) scenario was used for the predictions of impacts to Scotland's historic environment, therefore, to maintain continuity the same RCP scenarios have been chosen for determining the predictions of changes in precipitation pattern (Historic Environment Scotland, 2017, Day et al., 2020). Under this scenario, Scotland will experience warmer, wetter, winters with more intense rainfall events in both summer and winter (Met Office, 2019, Day et al., 2020) and a more pronounced increase in summer temperatures. This study focuses on predicted changes in precipitation; other factors of climate change, such as temperature, will be considered within this chapter. However, the changes in climate will also bring about changes in secondary factors, such as ecological shifts and soil moisture variation, which will be influenced by the main climate change factors, which could pose a much larger threat to our sites (McCarty, 2001, Walther et al., 2002).

An increase in precipitation could result in prolonged soil wetness and therefore more susceptible to compaction and smearing. As soil wetness increases soils can reach Atterberg's limit of plasticity where they can become more susceptible to compaction and smearing (Brown, 2017). This is particularly important for heritage landscapes as visitor footpaths and lines of desire can cause an increase in compaction, which will result in a potential reduction in soil moisture and could become detrimental to buried archaeology (Cassar and Pender, 2005, Nir et al., 2022). Through an increase in soil wetness this could lead to an increase in effects to access and poaching (Brown, 2017) of common routes through sites, particularly that of main access paths in heritage landscapes. With changes in precipitation the number of days where soil profiles reach their Atterberg's limit is set to increase and for this reason determining appropriate management options and solutions is essential for monitoring and protecting heritage landscapes. Changes in soil wetness could further prove to have other consequential effects on archaeology, both upstanding and buried, such as prolonged water logging and increased wetting and drying (Douterelo et al., 2009).

Changes in rainfall could also cause changes in soil erodibility (Brady and Weil, 2008). Within heritage landscapes this could be detrimental to sites. Soils are a finite resource that is susceptible to degradation and erosion due to mismanagement and climate change (Lichtfouse et al., 2009). The sites focused on in this study all have substantial areas of soil surrounding them or are composed of soils, therefore understanding how changes in precipitation will affect the hydrological networks across and through soils, and in turn soil erosion, is essential for maintaining WHS integrity and Outstanding Universal Value (OUVs). As soil is the main component of primary paths and archaeological protection in heritage landscapes, maintaining the integrity and stability of the soil is essential (Polykretis et al., 2021). Soil recovery and accumulation takes place on a centennial time scale and depletion occurs at a decadal rate for this reason it is imperative that we determine the hydrological networks that can lead to soil erosion and manage these systems accordingly to minimise the depletion (Cuca and Agapiou, 2017, The Food and Agriculture Organization of the United Nations, 2019). Erosion and loss of soil from our heritage landscapes needs to be limited to ensure that they remain protected and viable managed landscapes. Understanding the hydrological networks in heritage landscape gives an understanding as to the potential mechanisms by which soil could be lost.

7.2 Climate Data

This chapter uses the UKCP18 data sets based on the RCP 8.5 emissions scenario, with the 1980-2000 base line and generated at a 2.2km resolution for each site using absolute and anomaly values- the change in precipitation in mm/per day. These criteria have been used to remain in line with HES's current climate impact predictions and research (Historic Environment Scotland, 2017). These criteria have also been selected to predict the worst-case scenarios for sites, as through adapting sites for the worst case we can apply long term site adaptations. As this research is providing a baseline for each site, having an overall understanding of the monthly changes in precipitation, along with the anomaly values, will provide a perspective on how changes in precipitation may affect heritage landscapes. This will allow site managers to gain an understanding of the potential impacts that changes in precipitation will have on soil moisture within a heritage landscape. Precipitation is being used a direct proxy for the potential changes in soil moisture; increase in precipitation ≈ increase in soil moisture, and a decrease in precipitation ≈ a decrease in soil moisture.

Understanding the overall potential impact of changes in precipitation is important before gaining a further understanding of one-off intense precipitation events, as this research is establishing a baseline. The main findings from this chapter will form the basis to inform discussions around other factors concerning climate change, including frequency and intensity of precipitation.

For each two decadal period of change the average rainfall (plotted in solid colours) and then a fitted trend line (dotted line) was calculated, to provide an overall potential change in precipitation patterns (Figure 72, Figure 75 and Figure 78). For the anomaly data only the period 2061-2080 was used (Figure 73, Figure 76 and Figure 79). The annual % change is plotted, with a 20-year average plotted in red, to give a general trend of changes in precipitation.

7.2.1 Ring of Brodgar

Understanding the predicted changes in precipitation is essential to ensure that the hydrological management of the Ring of Brodgar can adapt. Figure 72 shows the predicted changes in annual precipitation at Ring of Brodgar. 1980-2000 is used as a base line (red) with 2021-2040 (yellow) showing the changes in precipitation that are currently being experienced and finally 2061-2080 (green) indicating the changes that are expected. The 2061-2080 precipitation data shows a likely increase in precipitation in November to March and drier summer months from April to October. The grey lines are the annual predicted precipitation changes. The change in precipitation distribution is most noticeable in the 2061-2080 period.

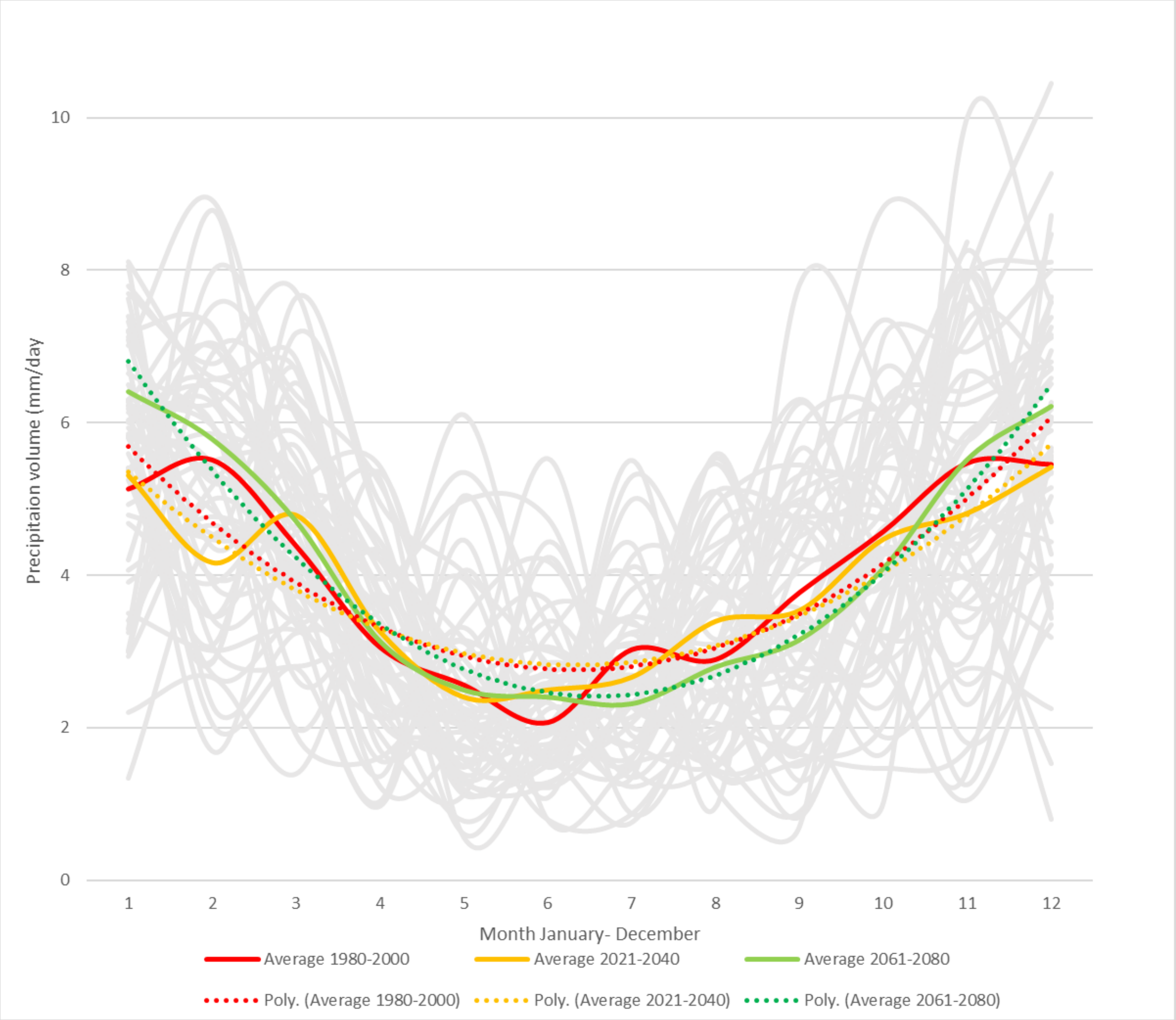

Figure 72 Precipitation rate (mm/day) for three two decadal periods based on RCP 8.5 for Ring of Brodgar. Red solid average precipitation 1980-2000, Red dotted is the trend of precipitation between 1980-2000, Yellow solid average precipitation for 2021-2040, yellow dotted trend of precipitation between 2021-2040, Green solid average precipitation for 2060-2080, green dotted trend of precipitation between 2060-2080.

The extremes in precipitation are the times at which impacts of changes in precipitation will likely be greatest within a heritage landscape (Pendergrass et al., 2015). Predicted precipitation anomaly rate for Ring of Brodgar is shown in Figure 73, which shows a percentage change in precipitation for 2061-2080 against the baseline period of 1980-2000. Overall, there is a percentage increase in rainfall in November to May and a decrease in percentage precipitation in June-October. This is a general trend and there is a high degree of variability within this. The anomaly values are a percentage of which change is expected to occur, the variance in the response for this period can range from a >160% increase to a <50% decrease in predicted precipitation.

The increase in some months to over 100% more precipitation could be detrimental to heritage landscapes. This could cause localised flooding and runoff over a site, along with soil saturation. The same goes for the reduction in rainfall which could cause the soil to become hygroscopic and cracks could appear. The changes in precipitation could lead to the soil at Ring of Brodgar reaching soil saturation more frequently, particularly between November and May, but with the possibility of temporally localised extremes throughout the year affecting soil moisture which may increase saturation and hygroscopic cycles.

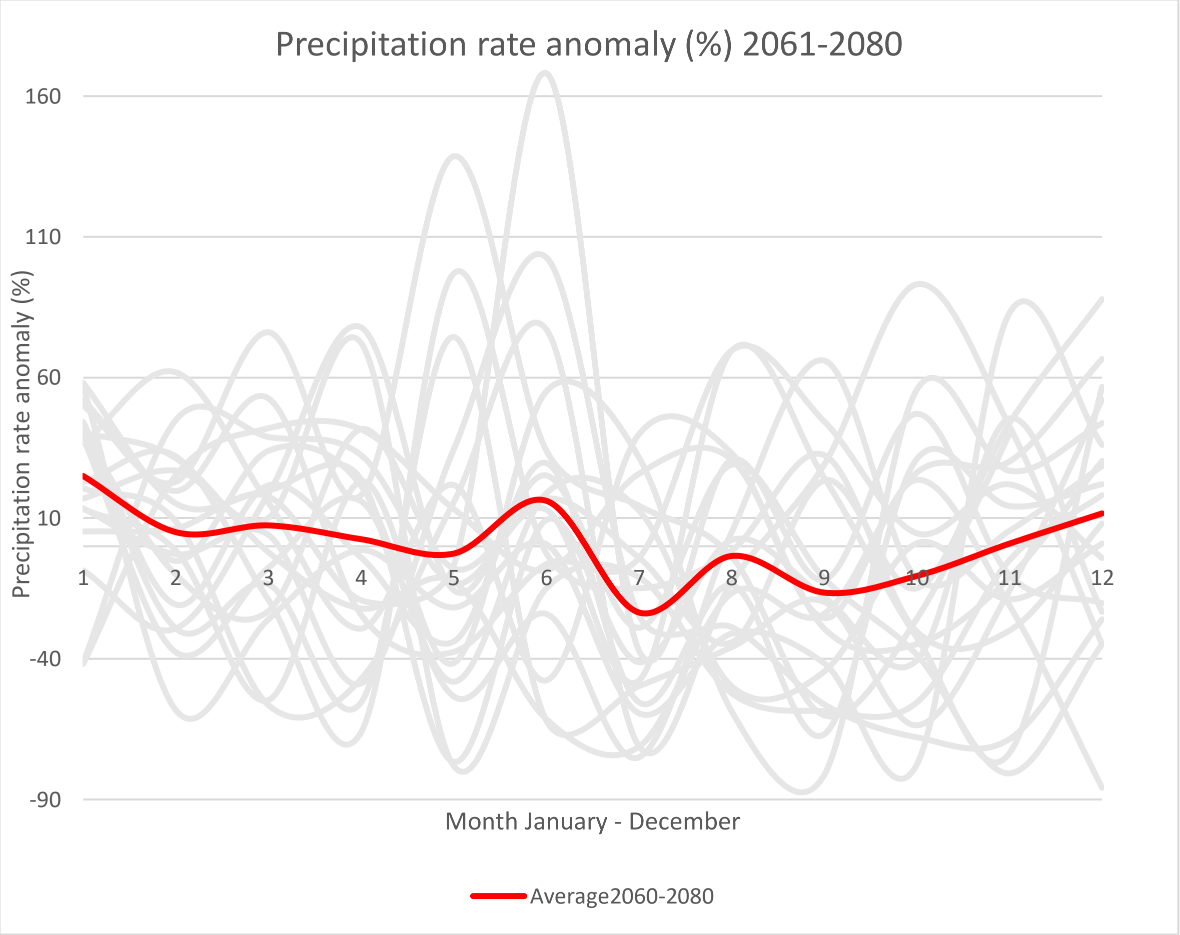

Figure 73 Precipitation rate anomaly (%) 2061-2080 against a 1980-2000 baseline, for RCP8.5. This is the change in precipitation against the base line of 1980-2000.The red line indicates the predicted average precipitation % increase from 2061-2080. Grey lines are the predicted individual year % anomaly.

As most of the paths are soil based at Ring of Brodgar, an increase in soil moisture could lead to an increase in compaction and smearing of the soils and result in soils reaching their saturation limit more frequently. It could also lead to an increase in poaching and widening of footpaths as visitors avoid the wetter areas (Ballantyne and Pickering, 2015). This would increase the area of the landscape that is impacted by the footpaths. The potential widening and poaching of the footpath will result in larger areas of soil becoming compacted and smearing to occur (Explored in 4.4 The implications and considerations for footpaths and diffuse trampling). This will result in degradation of the soil and in turn, may affect the integrity of the heritage landscape (Polykretis et al., 2021) . Path widening, and soil degradation could visibly affect upstanding archaeology through increased waterlogging around their bases due to soil compaction and smearing. The widening of footpaths and the impact that this is currently having on a heritage landscape was seen at Ring of Brodgar in SA1 (4.2.3 Ring of Brodgar SA1 Discussion). Footpath widening is having unknown impacts on the buried archaeology, through the increase or decrease in soil moisture as a result of soil compaction and smearing from widened paths (Agapiou et al., 2020). Therefore, combining the hydrological networks, with predictions of changes in precipitation and site management is essential for understanding the implication of changes in precipitation on heritage landscapes.

The work presented in *Chapter 5. Hydrological modelling of WHS for determining hydrological networks* highlights the hydrological networks around the site. Establishing the main hydrological networks across the site can suggest the probable impact that changes in precipitation may have. It is expected that with the changes in rainfall and seasonality the hydrological networks will become more pronounced on site. Currently, there are no visible surface flow networks present at Ring of Brodgar; however, with the predicted changes in precipitation, this may not be the case for long. The changes in volume of precipitation could cause the hydrological networks to become more pronounced within the landscape. This presents itself as a management problem that could be detrimental issue to the upstanding archaeology (Cassar and Pender, 2005). If hydrological flows widen or erode part of a heritage landscape, they could expose buried archaeology or erode earth features, such as the ditch surrounding the Ring of Brodgar.

Maintaining visitor access is essential for many heritage landscapes, therefore if hydrological networks are changing and affecting the stability of the soil then this could prevent sites from being safe to access or require the installation of permanent path structures (Whinam et al., 2003).

Within the context of heritage landscapes and preferential flow networks, a focus has been on the interactions around confluences. Confluences are known to have scouring and depositional environments (Smith et al., 2011). For heritage landscapes, scouring (removal of sediment) could expose or damage upstanding or buried archaeology and thus damage the integrity of the landscape. Therefore, gaining an understanding of where these locations occur and the impact that they may have on a heritage landscape is imperative.

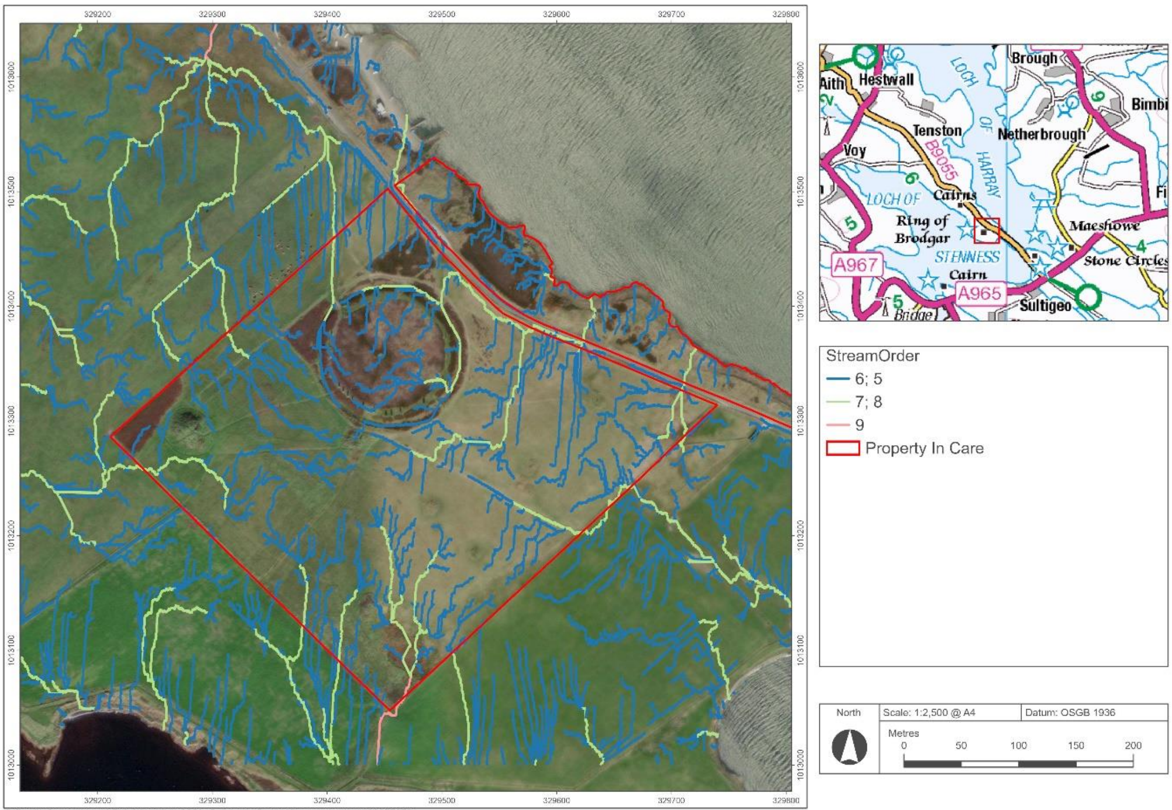

Figure 74 Three locations at Ring of Brodgar which may become more at risk due to changes in precipitation based on the hydrological flow maps. Orange- main footpath yellow confluence of streams at NNE of the ditch and red circle- confluence of streams prior to exiting. Yellow circle confluence of flows exiting the ditch.

There are several key areas at Ring of Brodgar, which have been identified as needing further consideration in relation to access and footpaths in a climate changed future. The first is associated with the main access footpath (indicated in orange in Figure 74). The main access footpath to the site has one prominent hydrological network that runs alongside and has multiple smaller hydrological networks that flow into it. For this reason, during times of increased rainfall this area could become susceptible to increased surface water and flooding, along with the possible development of an ephemeral stream. This could lead to an increase in the widening of the main access path, as visitors avoid the wetter areas and, if a stream develops, walk around the stream. The widening of the footpath would in turn affect the soil structure, resulting in wider effects of compaction being seen. Along with soil smearing and effects on soil moisture. Therefore, understanding where the hydrological networks could occur (or potentially develop) allows for heritage managers to have a better understanding of the potential impacts that may occur as a result of increased precipitation.

Due to the numerous smaller hydrological networks that feed the preferential flow beside the main access path and the number of confluences that are present this could lead to increased erosion of the main footpath, which could result in an in-increase sediment transport around the site and alter the top layer of the soil within the site. The erosion and deposition of soil around the site, might not necessarily be detrimental to the site, however it could lead to the accumulation of sediments in different locations around the site. The accumulation of sediment could lead to changes in soil composition and result in changes in soil moisture. The changes in soil moisture could affect the underlying archaeology, through either increasing or decreasing soil moisture. Further work and understanding are required on sediment movement and the effects on soil moisture within heritage landscapes (Historic England, 2016).

One management suggestion to prevent further erosion or damage from the current hydrological networks and visitor footfall, could be the installation of a hard footpath system along with suitable drainage and interventions to prevent erosion, which manage the increase in water flow across this area of the site whilst always maintaining access. Currently there is a managed natural path with a movable barrier. Ring of Brodgar sees a high number of visitors to the site each year and the main access path experiences visitors walking in and out of the site. The movable barrier does not allow for soil recovery or prevent soil erosion. As demonstrated in 4.2.1 Ring of Brodgar Survey Area 1.

Soil recovery is a decadal process, therefore compaction and soil loss could prove to be damaging for a heritage landscape. As footpaths are currently natural surfaces, the erosion of them could result in deeply worn areas for access or wide footpaths. As seen in Chapter 4 this is having an impact not only on the soil directly beneath the paths but also into the area immediately surrounding the footpaths. The full extent of which we do not fully understand yet. However, what Chapter 4 highlights is that the wide main access footpath is having a much wider landscape impact than that of a narrow footpath. In relation to managing the main access footpath of Ring of Brodgar in a climate changed future, installing a hard engineered and defined path system, such as boardwalk, stone paving or geotextile, and associated drains could be an option for the site (Fukubayashi et al., 2016, Jeon, 2016). This could constrain the extent to which the landscape experiences surface and subsurface impact from visitor footfall. This, coupled with an integrated drainage system, would help to manage the hydrology in this location (Wimpey and Marion, 2010, Cazzuffi et al., 2016, Zornberg, 2017, Alam et al., 2018).

Drainage surrounding an engineered footpath require careful consideration. If water is removed to quickly from a heritage landscape through artificial drainage, it is possible to cause flooding elsewhere, and in turn cause drying of the surrounding soils (Historic England, 2016). Changes in soil moisture can affect the preservation of archaeology (Cassar and Pender, 2005). Through installing a drainage system that allows water to be removed from access paths but still have the ability to infiltrate into the surrounding soil, may be the most appropriate for a heritage landscape. There is current research on the effects of altering soil moisture around buried archaeology and maintaining soil moisture is important for their preservation (Cassar and Pender, 2005), however further work is still required to understand the impact that different types of footpaths have on soil moisture.

An alternative to the hard path with drainage could be a shift in the location of the footpath around the site. This could prevent any hard or invasive engineering occurring on site and if the path location was substantially moved and for a prolonged period (decade) this could help aid soil recovery. As a result, this would be a fully natural solution and the hydrological networks would not need to be contained within engineered drains and access could be maintained. However, this is caveated with the observation that the soil at Ring of Brodgar is brown earth and the soils have a high soil moisture content; this may result in widening of footpaths (Lance et al., 1989). Therefore, the issues of wet and widening footpaths could be equally apparent in another location and thus the problem has been moved from one area to another. Brown earths can have a higher moisture and organic content than other soils. As a result, they are also more susceptible to the impacts surrounding visitor access (Holden, 2005). Additionally, due to the prevalence of the preferential flows, a suitable alternative location is difficult to distinguish. Therefore, careful planning and consideration is required to ensure access can be maintained for Ring of Brodgar.

The second area that is proposed to need further intervention is that of the confluence of the hydrological flows in the ditch (highlighted in yellow in Figure 74). This area is the confluence of hydrological networks from both sides of the ditch, and is the exit drainage point for all of the inner ring and could be sensitive to changes in precipitation. This location has the potential to move a large volume of water across the site and is in a very delicate location as the water leaves the ditch. This area requires further investigation to establish the level of water accumulation and flow in this location. When carrying out observations during onsite visits, this location was wet due to the footpath around the outer ring passing this point. In order to maintain this hydrological network, there needs to be an intervention or remediation work carried out in this location. As highlighted above, the confluence areas of streams are highly sensitive to change (Todd-Burley et al., 2021). Therefore, with the predicted changes to increased precipitation during winter months, and in June, erosion in this area could become more pronounced and sensitive to the changes in rainfall regimes.

An intervention on the outer ring path would be needed to prevent the widening of the confluence through erosion and deposition and to maintain the integrity of the ditch at this location. At locations like this where a large catchment area is draining through a key archaeological feature, having an intervention that is visible or contained may become essential. As the water leaves the ditch, it may damage and erode the surface, showing that the location is already presenting as a key management point. Ensuring a drainage system is installed, maintained and present, or altering the location or height of the footpath, could help minimise further intervention to the site, along with maintaining the structure and integrity of this key archaeological feature.

The third area of interest for Ring of Brodgar is the area indicated by the red circle (Figure 74). This area is where there is a confluence of preferential flows and the point at which a hydrological network leaves the site to a main road and freshwater loch. The point at which a hydrological network leaves a site needs to be properly managed and maintained by both the site owner and the neighbouring landowners to ensure the hydrological network’s integrity is maintained. If the connections to the neighbouring landscape are not maintained, this could result in flooding within the PIC and could cause potential waterlogging of soil. The area is highlighted for two purposes; the standing water, and the point of exit from the site. These two factors are crucial for maintaining access and the integrity of the site.

Hydrological modelling has highlighted that there are several confluences relatively close together at this location (highlighted in red), thus making this area more susceptible to localised flooding. A factor affecting this point is the loch on the other side of the road, if the loch levels change this may prevent drainage from the site, however this is speculative. As this is out-with the PIC, managing the drainage around this location is complex. With changes in climate, rising sea levels and changes in precipitation regimes, this location may become more vulnerable to the predicted changes in precipitation, and thus create the possibility that this location could become flooded with standing water. In order to prevent standing water, we need to build a better understanding of where the water is coming from and the time it takes to reach this point along with the integrity of the drainage systems that are in place to allow the water to leave the site. This could be done through modelling of the established hydrological networks. Along with in site monitoring of water through observations. Once these factors have been established then it will be possible to make a more robust plan and recommendations for this location on site. Overall, proper maintenance of installed drainage systems, through cleaning and flushing, along with monitoring of the standing water on site is essential in the short term to help maintain this area of the site.

Further to the physical interventions (harden footpaths and drainage) an increase in visitor education about the site and the methods being used to protect the site, could be beneficial. Through understanding the increase in volume of precipitation that would be present at Ring of Brodgar and demonstrating how interventions are being applied now for future conditions, this could help to build understanding and create changes in behaviours to the benefit of the site. By understanding that there could be a 60% or higher increase in rainfall by 2080 and implementing measures now, we can help sites adapt and respond better to the changes in precipitation events that they will experience in the future. Through creating a prepared and climate adapted landscape, monitoring, management, and protection of heritage landscapes becomes easier. Through installing climate adapted solutions, could further result in a cost-benefit for site. Adapting sites could reduce the number of on-site interventions. Through knowing where the hydrological networks are on site it becomes possible to maintain or alter them from source to end point.

For Ring of Brodgar, and other sites that are geographically self-defined, water network maintenance will encompass all the site and minimal additional landowner connections to reach the termination point of these hydrological networks. This could result in a fully connected flow network that is well maintained and benefits a site. This is compared to landscapes where there are multiple connections between a site and the surrounding landscape where the connections may not be well maintained and as a result could be detrimental to a site. Through creating hydrological networks that are ‘future enabled’ it can help to prevent erosion from across the site, as precipitation events and intensities increase. Through enabling these hydrological networks across the site and appropriate management, not only are we preventing damage to the site but allowing the sites to be preserved for future generations.

The same consideration also needs to be taken in to account for the predicted reduction in summer precipitation. The seasonal reduction in precipitation could lead to the drying of soils and therefore have a large effect on heritage landscapes. Drying of soils is complex and is interlinked with temperature changes as well as the periodicity of rainfall amongst other factors (Brady and Weil, 2008). During intense rainfall events, dry soils exert repellency and therefore increase overland flow and reduce infiltration (de Jonge et al., 1999, Battany and Grismer, 2000).

Soil repellency is where dry soils appear to repel water, thus making them drier (Doerr et al., 2000, Jordán et al., 2013). This can increase the surface flow during rainfall events that occur on dry soils. This can also lead to an increase in soil erosion, but also increase the erosion by rain splash, and that of wind (Doerr et al., 2000). Through the increase in intensity of rainfall events, particularly in the drier months, this will increase the potential for erosion by rain splash (Doer et al 2000) as well as enhance overland flow in heritage landscapes. Precipitation on dry soils can be damaging because of the increased soil repellency and therefore reduced infiltration, which could be detrimental to upstanding and buried archaeology. The drying of soils could also lead to soil shrinkage and destabilisation of upstanding archaeological monuments due to their foundations becoming unstable (Pritchard et al., 2014). This reduction in precipitation leading to a drying in soils along with an increase in intense precipitation events could be detrimental to heritage landscapes as we know them. These effects, although secondary, are a very real threat to heritage landscapes.

Therefore, managing sites to allow for effective containment of hydrological networks during intense events is essential. It is important that these methods do not remove the water too quickly from sites as this will have a detrimental impact on the heritage landscapes. Drainage solutions are not about the quickest way to remove water from a landscape, but to allow infiltration to occur. For this reason, there needs to be a balance between effective removal of water and infiltration within a heritage landscape. This may be essential in areas surrounding upstanding archaeology. As these changes will have a negative impact on the soil structure and therefore affect the long-term infiltration, water holding capacity and integrity of a soil profile around a footpath.

We further need to consider the integrity of the heritage assets that reside within the landscapes we are protecting. Although the hydrology work presented in the earlier chapters did not highlight the standing stones as having a particular influence or being influenced by the hydrological networks it is essential to maintain their integrity and structure and understand how they interact with water movement. Through the changes in wetting and drying of soils it could lead to an increase in the destabilisation of the stone structure (McCaughie et al., 2020). The wetting and drying cycles could lead to an increase in rock-cement dissolution and lead to structural destabilisation in the stone structure. This in turn leads to the degradation of the monuments. The shrinkage of soil away from the base of upstanding archaeological structures could be catastrophic, through leading to structural collapse. Further investigations into the possible effects of soil shrinkage and upstanding archaeological structures are not considered in this study. However, as a theoretical concept and in drier months this is an essential to consider the impact and determine how this could affect not only the upstanding archaeology but also buried archaeology (de Beer and Matthiesen, 2008). Therefore, this could be catastrophic to some sites. Thus, when installing or considering drainage and footpath options around upstanding archaeology is essential to consider the soil moisture implications.

There is additionally the effect of the changes in precipitation on buried archaeology. The soils at Ring of Brodgar are brown earths and can be more susceptible to the changes in moisture regimes due to their organic content (Holden, 2005). The drying of these soils and the effects on the integrity of the underlying archaeology, such as increased decay and loss of organic artefacts could be damaging to buried archaeology (Douterelo et al., 2009).Through finding the effective balance between water removal, water retention and landscape management it will become possible to create a more sustainable and climate enabled landscape. There is not one solution for a site, and this is highlighted well at Ring of Brodgar, there is more to consider than just the access footpaths and visible archaeology.

7.2.2 Rough Castle

The predicted change in precipitation for Rough Castle has a marked increase in precipitation during the winter months by the period 2061-2080 (Figure 75), with a decrease in rainfall during the summer months. This change is in line with the rest of central Scotland. The changes in precipitation could result in an increase in soil moisture during the winter months, which could result in the site becoming wetter and, from the hydrology modelling, it is possible to identify areas that could be at a risk from an increase in precipitation.

The main areas of concern for Rough Castle are the higher order preferential flow networks. These higher order flow networks could result in increased erosion across the site, which could have negative effects on the Outstanding Universal Value. For Rough Castle this is the Ditch, Wall and Rampart, along with the surrounding defensive ditches, and the potential impact that changes in soil moisture, as a result of changes in precipitation, will have. As Rough Castle, and the Antonine Wall, consists of turf-built Wall and Ramparts, these could become more susceptible to changes in soil moisture as a result of the increase in precipitation. Although the Wall and Rampart were not studied within this research, the effects of precipitation on soil moisture play a vital role in the preservation or archaeological features above and below the surface (de Beer and Matthiesen, 2008).

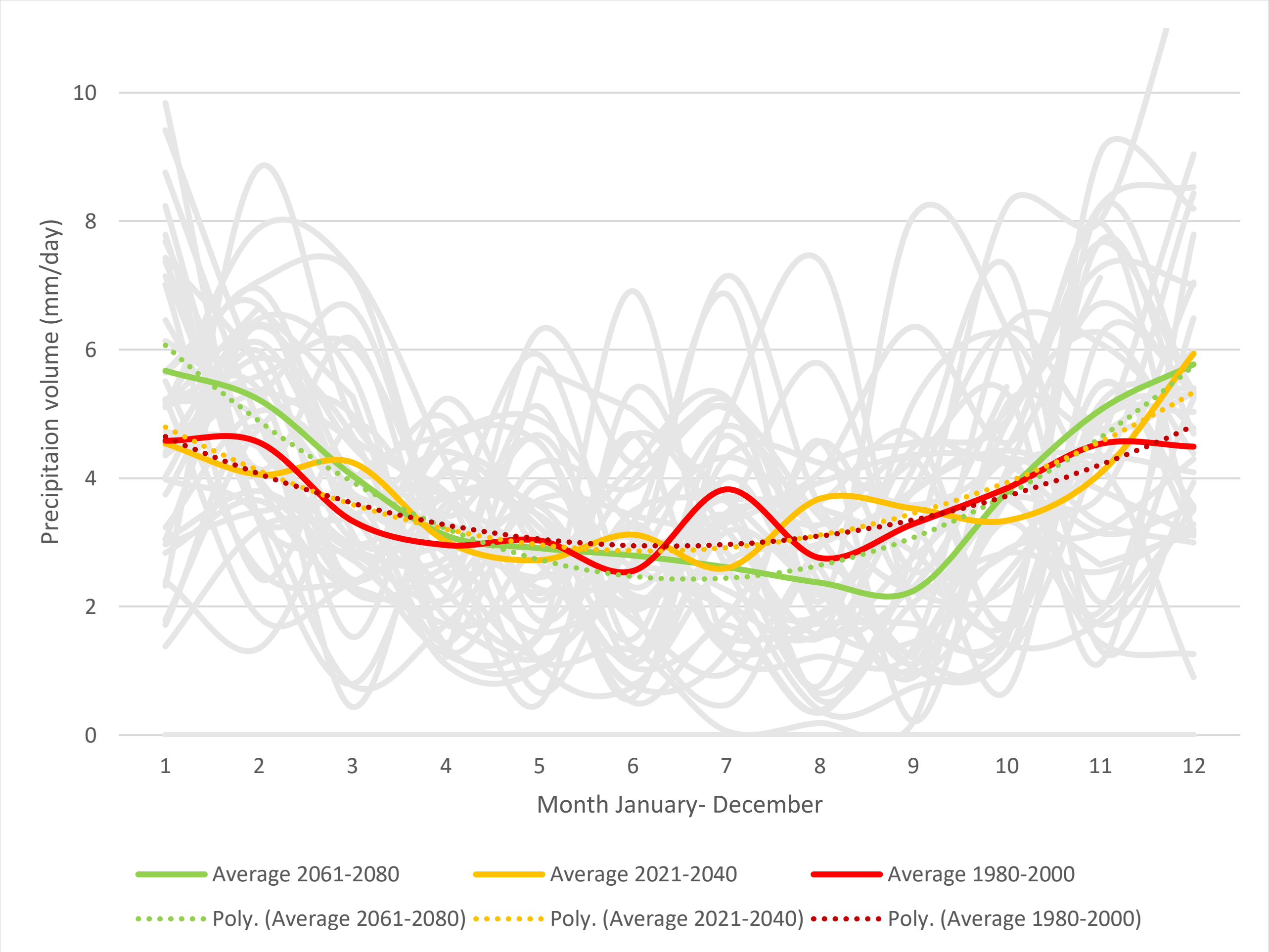

Figure 75 Precipitation rate (mm/day) for three two decadal periods based on RCP 8.5 for Rough Castle. Red solid average precipitation 1980-2000, Red dotted trend of precipitation from 1980-2000, Yellow solid average precipitation for 2021-2040, yellow dotted trend of precipitation 2021-2040, green solid average precipitation for 2060-2080, green dotted trend of precipitation from 2060-2080.

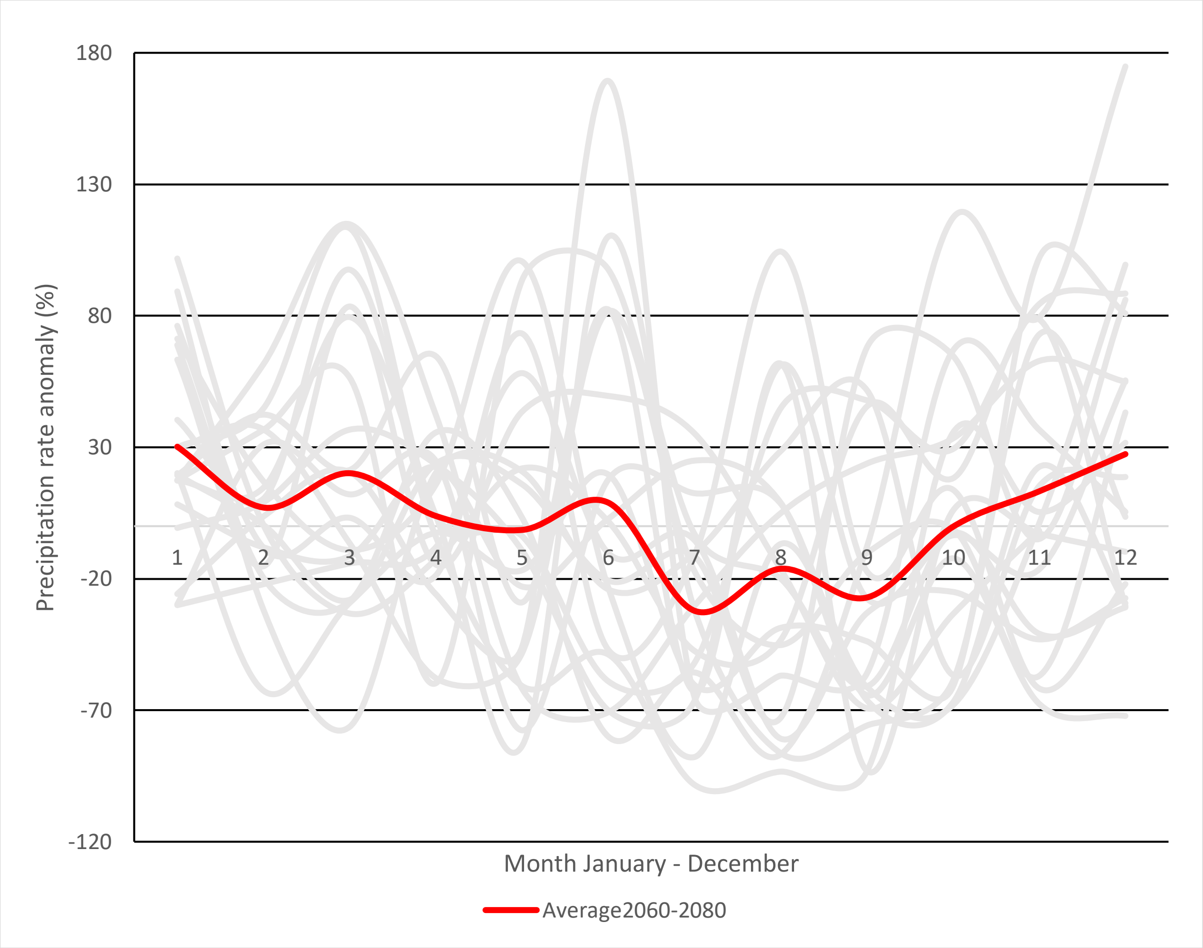

Figure 76 Precipitation rate anomaly (%) 2061-2080 against a 1980-2000 baseline, for RCP8.5. This is the change in precipitation against the base line of 1980-2000. Red line indicates the predicted average precipitation % increase from 2061-2080. Grey lines are the predicted individual year % anomaly.

The anomaly values for Rough Castle show that the change in predicted rainfall pattern is variable. The summer months are getting drier with the winter months getting wetter. This could pose a threat to Rough Castle as the site is earth based. Two areas have been identified through the use of the hydrology mapping (Figure 77): the defensive ditches to the east and the Wall and Ditch on the north of the fort top, which may be at risk from changes in precipitation.

During site visits there were areas of standing water at various points across the site, but noticeably in the east defensive ditch (Figure 77 highlighted in green). An increase in precipitation could result in these areas becoming waterlogged for longer periods of time (Figure 77 green circle) and at different times of the year, for example during intense summer rainfall events. Determining how rainfall patterns relate to the presence of standing water on site is needed to establish the impact that changes in precipitation will have on these areas. Further work needs to be carried out to understand the hydrological networks that feed and drain these areas of standing water and how these areas affect the archaeology of the site.

The second area of interest is where the flows from the fort top flow down into the Ditch on either side of the link bridge (Figure 77 highlighted in yellow). This has been highlighted as an area of interest due to the potential impact that changes in precipitation may have on the hydrological networks in this location. The Antonine Wall is turf and therefore changes in precipitation will affect the soil moisture and soil integrity, but also can be more susceptible to erosion where there are hydrological flows. With the predicted increase in rainfall this could see an increase in the volume of water flowing in the hydrological networks, which could result in an increase in erosion. This could be detrimental to the integrity and structure of the Antonine Wall. The hydrological flows may not be currently visible on the Antonine Wall. However, continued monitoring of these locations is required to understand the current state of the hydrological networks and to identify any potential threat to the Antonine Wall as a result of increased precipitation.

An understanding of hydrological networks, coupled with the seasonal and inter-annual variability of precipitation, can help site managers to prepare for the changes in inter-annual rainfall patterns, not only at Rough Castle, but for all heritage landscapes. Preparing sites to deal with the changes in precipitation is challenging, especially as the difference interannually and annually is becoming more variable. Site adaptation is not a one-method-fits-all practice but a constant evolution of practices to help preserve our heritage landscapes.

The summer months are predicted to become drier, which could pose a threat to Rough Castle through the drying of the soil and turf features. A reduction of precipitation in the summer could be detrimental to Rough Castle as this would result in a reduction in soil moisture. This could lead to drier soils and soil repellancy, resulting in increased overland flow and erosion. As the Wall and surrounding features are constructed of turf this could lead to an increase in erosion of the outer structure.

A similar impact surrounding footpaths may also be seen at Rough Castle as Ring of Brodgar, through path widening, soil smearing and compaction of soils. However, at Rough Castle this will directly affect the archaeology and may affect their integrity. The widening of footpaths will cause more of the site to experience compaction and in wet soil lead to soil smearing and degradation of the soil structure in these locations. The widening of footpaths will in turn affect the buried archaeology at Rough Castle as well as upstanding archaeology of the Wall and Ramparts and ditches. In turn, this will be having an unknown impact on the archaeology until the changes in soil moisture surrounding archaeology can be better understood.

The reduction in precipitation and changes in soil moisture may cause vegetation changes within the site. Rough Castle has open managed grassland and mature trees. Changes in precipitation patterns could lead to a shift in the vegetation present on site. In addition to the vegetation change is that of the drying of archaeological features on site (Historic England, 2016). The impact of changes in soil moisture and the impact on archaeology can only be speculated within this study, but the changes in rainfall could affect the hydrological networks. This could be a widening or deepening of some stream networks thus increase in erosion during intense rainfall events or an increase in overland flow during these events.

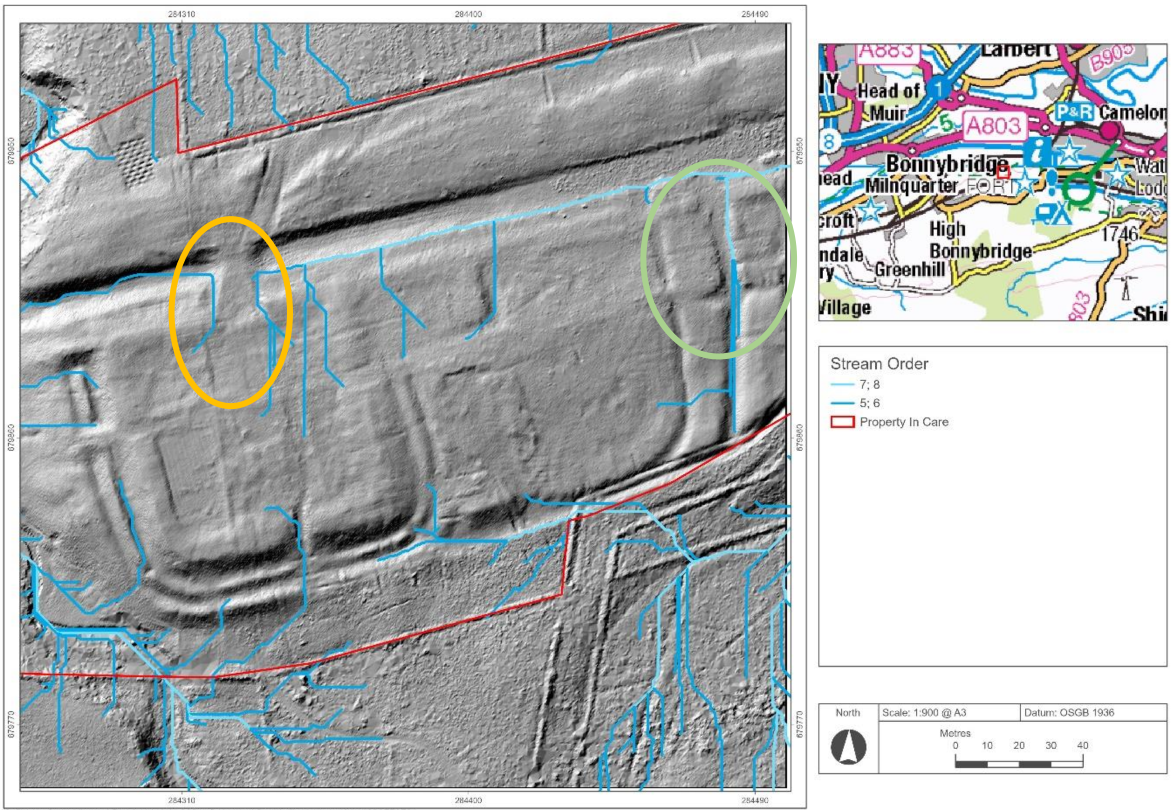

Figure 77 Rough Castle higher order stream networks yellow circle highlighting an area on the Fort top into the ditch. Green circle highlighting an area of flow through boundary ditches and blocked by the Roman road.

Further to the surface hydrological changes and vegetation shift, is the impact that changes in soil moisture may have on buried archaeology. Although neither vegetation shifts nor buried archaeology have been investigated directly in this study, they are both important and should be considered within heritage landscapes. Through identifying the hydrological networks and the areas of flow accumulation at Rough Castle it is possible to determine the areas where soil moisture may increase and which may be more at risk from erosion (Historic England, 2016). Within this study there are no solutions for the maintaining of soil moisture, the MMS monitoring carried out (Chapter 4. MMS field surveys for the applicability of using MMS for landscape scale monitoring of soil moisture) begins to enable soil moisture monitoring. Through carrying out repeat surveys on areas that are more at risk of extreme changes, this will allow for changes in soil moisture to be detected and then possible to implement a solution to help stabilise the soil moisture.

7.2.3 Hirta, St Kilda

As with Ring of Brodgar and Rough Castle the same UKCP18 predictions of RCP 8.5 emissions scenario (Figure 78) have been used for St Kilda. When plotting the predicted monthly rainfall for each year there appears to be a large change predicted for some years' (greylines) rainfall. From grouping the data in to three two decadal periods it can be established that there is not a large, predicted change in overall annual volume of rainfall for St Kilda. However, the wetter months (September to February) of the year are predicted to get wetter between 2021-2040 and wetter again from 2061-2080 (Figure 78). This further highlights the current trends of increase in rainfall during winter months. From 1980- 2000 and 2021-2040 the summer months predicted rainfall remains relatively similar with little change in total monthly volume received, however between 2061-2080, there is a marked decline in the volume of rainfall during the summer months (July and August).

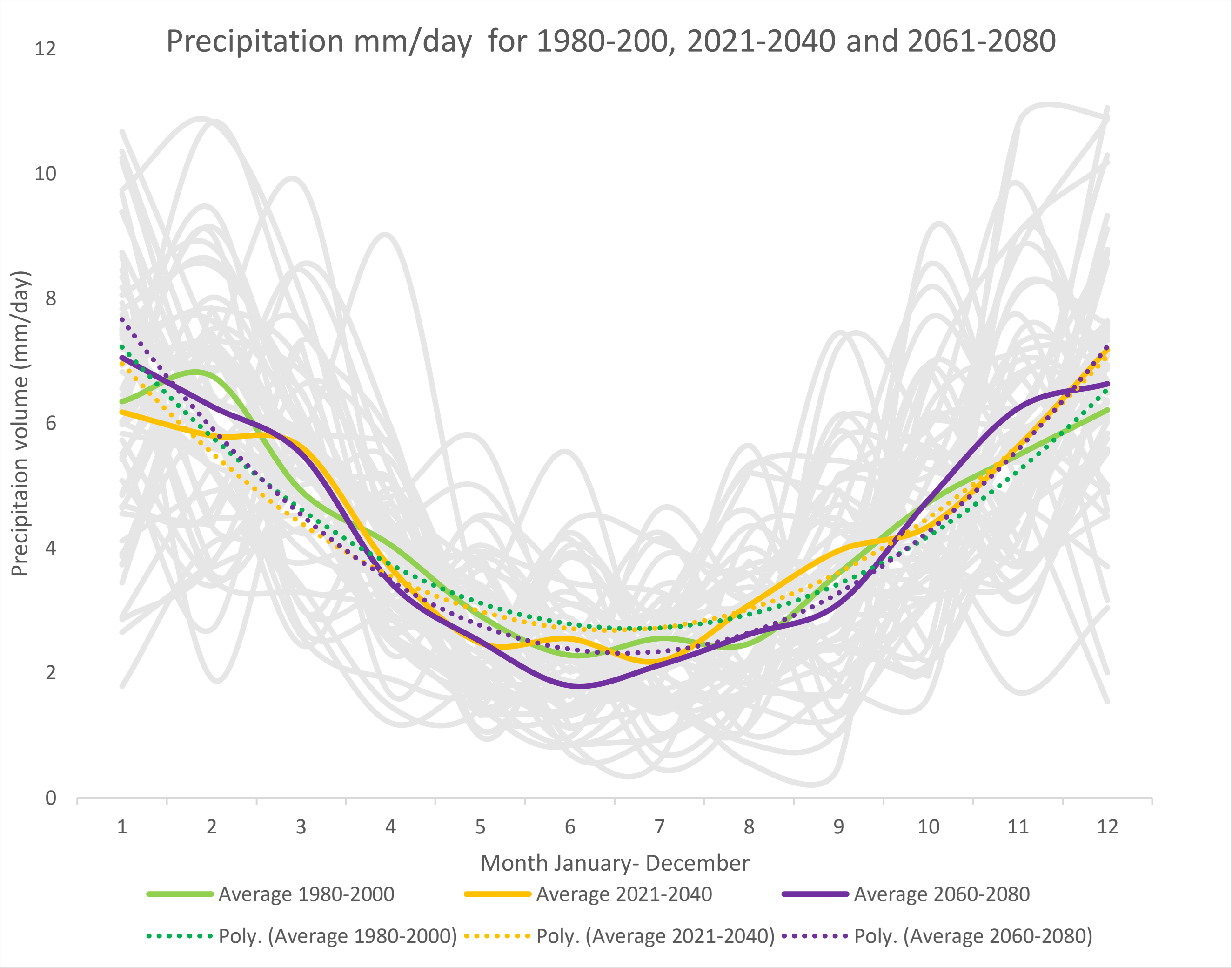

Figure 78 Precipitation rate (mm/day) for three two decadal periods based on RCP 8.5 for Hirta, St Kilda. Red solid average predicted precipitation 1980-2000, Red dotted trend of predicted precipitation from 1980-2000, Yellow solid average precipitation for 2021-2040, yellow dotted trend of predicted precipitation 2021-2040, green solid average predicted precipitation for 2060-2080, green dotted trend of predicted precipitation from 2060-2080

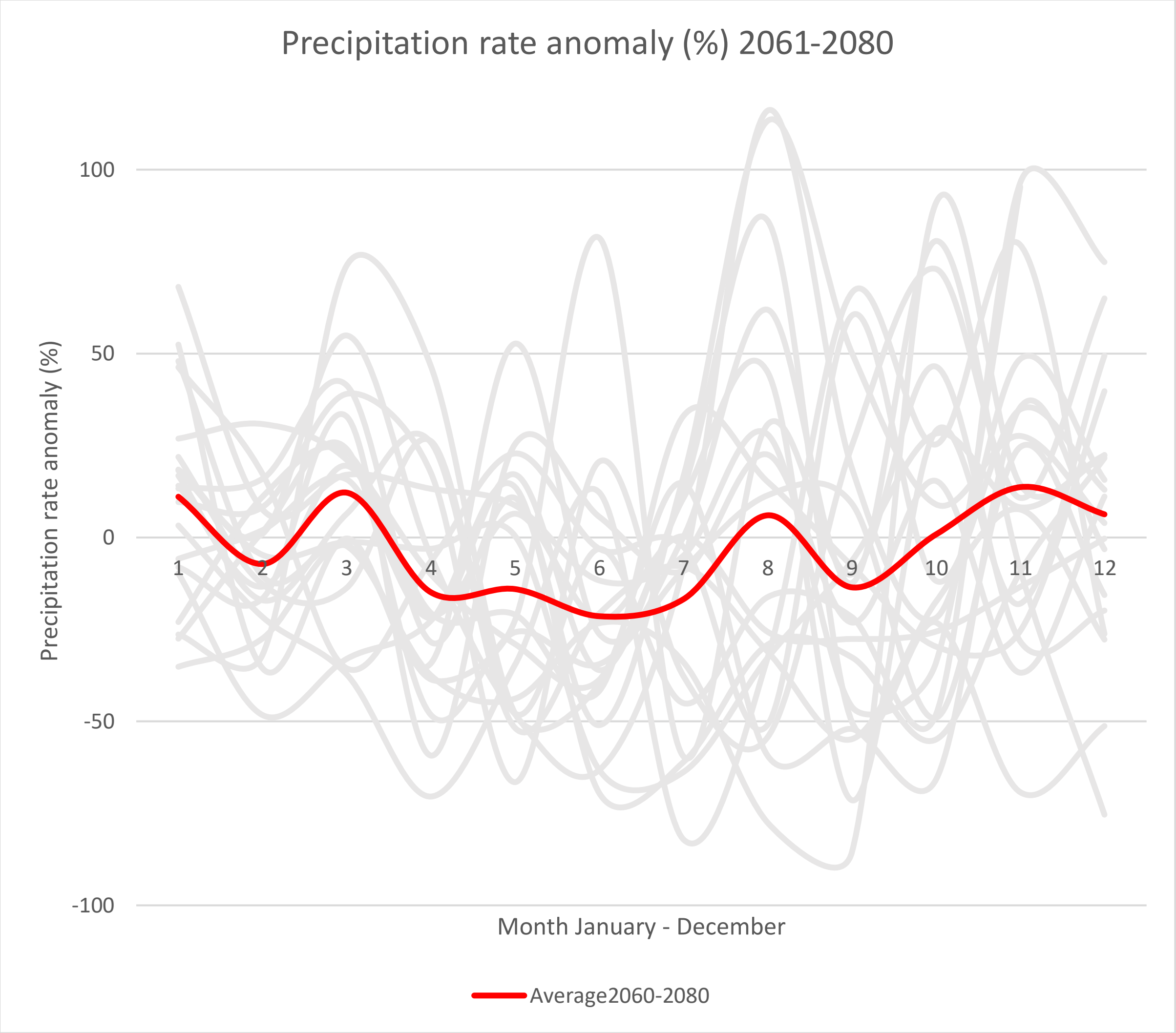

Figure 79 Precipitation rate anomaly (%) 2061-2080 against a 1980-2000 baseline, for RCP8.5. This is the change in precipitation against the base line of 1980-2000 for Hirta, St Kilda. Red line indicates the predicted average precipitation % increase from 2061-2080. Grey lines are the predicted individual year % anomaly.

Compared to Ring of Brodgar and Rough Castle, the change in monthly precipitation patterns for St Kilda is markedly different in the 2061-2080 period than 1980-2000. It is distinctly drier (months May- July) (Figure 79) by 2061-2080, with an increase in precipitation in winter (months October - January). The months immediately preceding the higher rainfall months are predicted to be drier (months February and September). In terms of heritage landscape management this could present a difficult precipitation pattern to manage. The marked drier months (February and April- July) will result in a decrease in soil moisture, with an increase in rainfall immediately after this period it could make the site more susceptible to erosion and degradation during the wetter months (March and August). Drier soils are more susceptible to erosion and this could result in greater soil loss across Hirta, which in turn will result in a potential degradation of the landscape and enhanced hydrological channels (Marzen et al., 2017).

Within this section, a focus is placed on hydrological network directional change that is related to upstanding archaeology and the possible impact that could be caused as a result of the predicted changes in precipitation. Changes in flow direction within hydrological networks can generate depositional or erosional environments (Todd-Burley et al., 2021). Therefore, identifying these areas within a heritage landscape could allow for an understanding of the potential effect of increased precipitation. With the predicted increase in precipitation, the directional change of the hydrological flows around the upstanding archaeology may become more pronounced, especially in intense rainfall events following drier periods. Through knowing where these points occur and the impact that they could have on specific features, it is then possible to make alterations and plans to help protect the upstanding archaeology. Identifying a point that could become a potential threat to a monument, intervention can either be made at the point of potential threat or further upstream. Through working upstream from the point of potential threat, alterations can be made within the landscape that help to minimise a possible threat to the upstanding archaeology.

The decrease in predicted rainfall during the summer months could become a particular area of interest and concern for heritage landscapes. It is predicted that there will be an increase in intensity in rainfall during summer months (Met Office, 2020). The increase in intense rainfall could present a major concern for all heritage landscapes, not just St Kilda. Due to the lack of overall rainfall in summer months this will cause the soil to become drier and have a moisture deficit. As a result, during intense rainfall events in summer months, soil repellency could exert a considerable influence on the capacity of the soil for infiltration, but will also affect the overland flow and erosion through rain splash (Dekker et al., 2005).

For St Kilda, the predicted changes in rainfall could mean that there will likely be increased erosion at points where the preferential flows have directional changes due to upstanding archaeology, this is particularly seen around the houses in Village Bay (Figure 80). This could increase erosion of established hydrological networks resulting in adverse effects on the upstanding archaeology. This could be more defined for areas surrounding the upstanding archaeology where the flow directional changes are most pronounced. The overall increase in precipitation will begin to exacerbate the visible effects of these flows. The increase in intensity of rainfall events will likely accelerate the impact that these hydrological networks are having on the landscape, through erosion of hydrological channels.

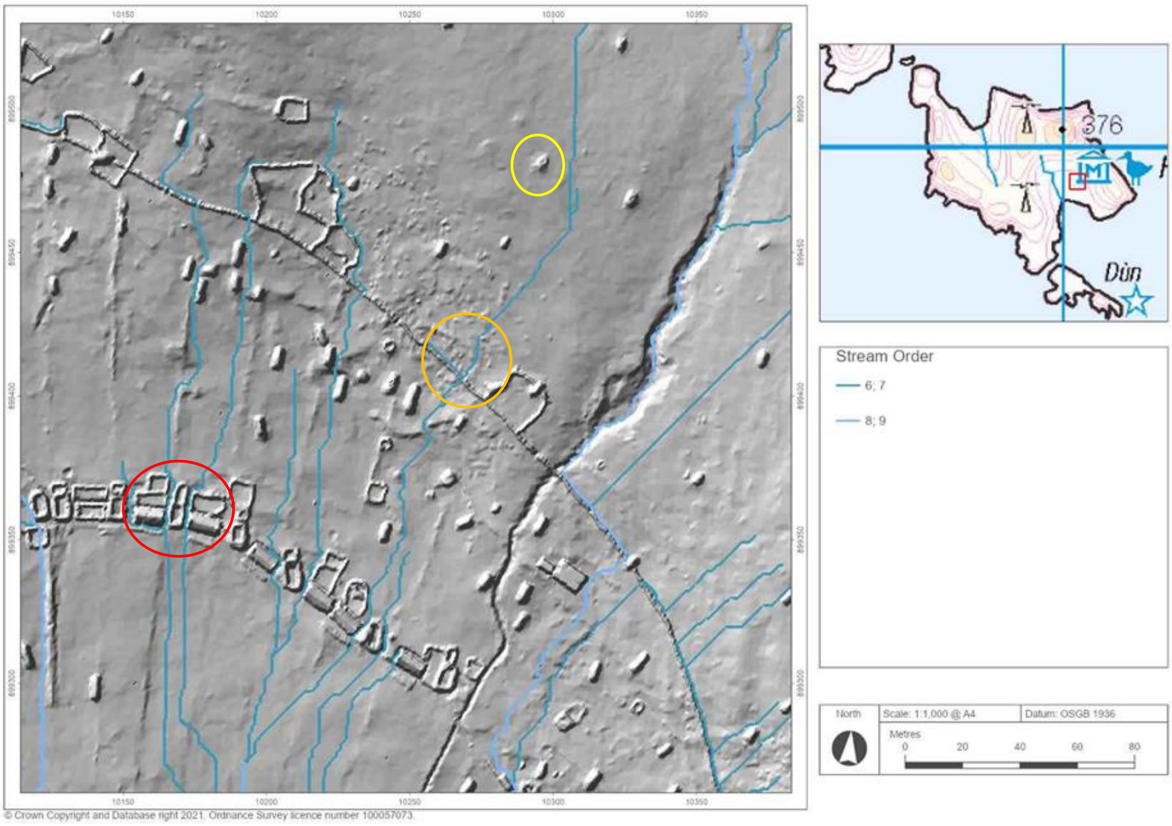

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Figure 80 Three locations on St Kilda that could be at risk due to changes in climate. The red circle highlights changes in flow direction around buildings along the main street, the yellow circle is indicating the cleits that are found throughout St Kilda and the orange shows the change in direction and confluences around the headwall.

The red circle (Figure 80) highlights one specific direction of flow change, however the same change in direction around upstanding archaeology can be seen along the main street. These locations are key for continuing to manage the integrity of the buildings and longevity of the site. As changes in direction of flow can create erosional environments the areas around the upstanding archaeology could become unstable due to the erosion of soil from around them.

During drier weather, soil moisture reduces and thus making the soil more friable and susceptible to erosion, which means when rainfall events occur soils are even more susceptible to erosion during these rainfall events (Brady and Weil, 2008). Although the erosion of soil will likely be seen on all study sites, it may have a more acute effect on the upstanding archaeology of St Kilda, as a result of overland flow due to the topography and the plaggic soils (Brady and Weil, 2008). This is particularly important with the predicted changes in precipitation for St Kilda being four months of less rainfall that are followed by one month of increased rainfall (Figure 79). This could see a change in the way the hydrological networks respond on St Kilda, such as widening and deepening of existing hydrological networks, and visibility increasing of ephemeral streams. In order to help protect the upstanding archaeology of St Kilda it is important to establish the current influence of the changes in flow direction locations and the impact that they are having on the integrity of the upstanding archaeology. From this it is then possible to plan the most effective methods to help protect the upstanding archaeology. With the predicted changes in precipitation a hard intervention for managing water flow around upstanding archaeology could be a possible solution to their long-term conservation. This could come in the form of direct intervention through the installation of a drainage infrastructure around the upstanding archaeology or interventions further upstream to divert some channels to prevent water from reaching the upstanding archaeology.

The cleits highlighted in yellow (Figure 80) could become a concern in relation to changes in precipitation regimes. Through using fine scale hydrology maps in 5.3.2 Hydrological Modelling Hirta, St Kilda, it is possible to identify that hydrological flow networks diverge around the cleits on the uphill side. With an increase in predicted precipitation, and intensity, which could lead to water inundation of the cleits, due to a potential increase in overland flow due to soil repellancy. Becoming inundated with water could be detrimental to their structural integrity and lead to partial or total collapse due to the hydrological flows either undermining them or eroding soil from the internal structure.

The cleits form an integral part of the landscape and heritage of St Kilda and it is imperative to understand effective ways at maintaining their integrity. In order to help protect them from the prospect of structural deterioration, flooding and standing water within them, several intervention options should be examined, all of which need to be properly considered to maintain the structural integrity of the cleits. Using the hydrological modelling and onsite monitoring of the current hydrological networks around the cleits is essential to be able to establish those that are most at risk from water inundation. In order to protect these structures, it could be recommended to implement soft interventions to help divert water around them and establish new hydrological networks across the island around the cleits. This could be through making new channels to divert the flow or increasing channel volume around the cleits to prevent the water from reaching them. Or purposefully making turf embankments above the cleits to force the water away from them. It is recognised that this may not be possible due to the number of the cleits, however identifying those most at risk now, is essential for maintaining their integrity of future generations.

Highlighted in orange is one of the changes in direction and confluences of hydrological networks at the headwall (Figure 80). This one occurrence has been highlighted, but there are several locations along the head wall where a change in direction occurs. The changes in direction and confluences of the hydrological networks against the headwall could be detrimental to its integrity and stability, through water inundation or soil erosion. Through identifying where these locations are along the headwall it may be possible to put in place interventions to help maintain the structure of the wall but not alter the surface water courses. As these water courses may already be established maintaining their current location would prevent downstream hydrological changes. Through carrying out a field survey of the wall, in combination with the hydrological survey, it may be possible to identify where these changes in direction occur and their current state of impact and therefore determine the level of climate adaptations that will need to include forward engineering. It would therefore be possible to put interventions in in place, such as a stone-lined surface drains, under the head wall. Or harder interventions of implementing an under-surface drainage system to move the above ground hydrological networks from these locations. Either of the options, or others, need to be considered with the integrity of the headwall and downstream hydrological capacity and archaeological structures in mind, along with the locations of the hydrological networks is essential. Due to the number of the confluences along the headwall it is imperative that we establish their current impact and implement appropriate solutions to manage the hydrological networks whilst maintaining the integrity of the head wall. Thus, in doing so, we have prepared these locations to deal with the predicted changes in precipitation.

The cultural agricultural soils in Village Bay could be more susceptible to deterioration during intense precipitation events. Within this specific example, cultural soil is referring to the area that was used for crop growing on the south of the main street. The effects discussed for the field systems are purely theoretical, however anecdotally, there has been changes in the hydrological regimes on St Kilda in recent years, such a small-scale flooding and changes in overland hydrological flows (Personal communication, S. Bain 2021). These small-scale changes, such as water accumulation, or saturated ground where there wasn’t before, indicate that potentially the agricultural practices were having a controlling factor on the direction of the hydrological flows.

As indicated, confluences are potentially one of the biggest hydrological threats to St Kilda’s archaeology and thus to these field systems (Todd-Burley et al., 2021). When determining the hydrological networks for this area of St Kilda, there are micro-flow confluences within the traditional field systems. Unfortunately, there is little intervention that can be done at this stage to maintain them, short of recreating the farming practices that occurred on St Kilda.

This would inevitably change the current landscape and lose the current field systems that can be identified.

As the topographic data is from 2011, there could already be changes in the micro topography of the landscape caused by changes in the climate. If this is the case, then there has never been a more critical time to establish the current hydrological networks within the heritage landscapes. This will allow for better site understanding and planning on how to manage changes in precipitation patterns. Through knowing and identifying the field systems, they could become a key location to help monitor the impact change climate is having on this type of field /natural system. Therefore, hydrological modelling could be used to monitor the farming legacies within heritage landscapes and the impact that changes in precipitation are having on the surface hydrological flows, along with the impact the change in precipitation is having on traditional farming systems and the rate of loss that is occurring in the natural systems.

For St Kilda, decadal repeat topographic survey and hydrological modelling would provide an opportunity to monitor the changes in the micro-hydrological networks associated with past farming practices. Particularly the increase or decrease in presence of lower order hydrological networks, which would suggest a change in the micro-topography. This could be a result of a change in surface topography but also the effects of changes in precipitation regimes resulting in some hydrological networks becoming more pronounced.

The hydrology mapping is a visual way to identifying areas that could become at risk and the hydrological networks through which water will reach these areas. Although hydrology mapping for St Kilda was not all accurate for some locations, due to previous interventions that could not be picked up on the LiDAR data, hydrological modelling gives a good base starting point for identifying the areas at risk. With climate change one of the biggest threats to our heritage landscapes, being able to develop a means for identifying areas that could be at risk, is an essential step forward for equipping site managers and practitioners with a tool set moving forward for the protection of all heritage landscapes, not only WHS.

Climate change could have considerable effects for St Kilda. However, to help build landscape resilience and have the best ability to deal with the changes in precipitation we can use the hydrology mapping to establish where and how overland flow resulting from changed patterns of precipitation can move through the landscape. The base hydrology map helps us to understand the locations which may become more pronounced due to an increase in rainfall, such as the higher order preferential flows. We can also establish where these flows originate from and how they connect throughout the landscape. Through using these maps and our knowledge of precipitation changes due to climate change we can begin to establish the possible effects that this will have on the landscape.

7.3 Further Management Implications to Consider within the Wider Heritage Sector.

Using the predicted changes in rainfall and the hydrological mapping of heritage landscape it enables management planning for climate adaptations. By identifying the threats from predicted changes in precipitation, heritage practitioners can then begin to determine the impacts that this will have on a heritage landscape site and then begin to build on this understanding to generate adaptive plans to ensure that sites are here for generations to come (Sesana et al., 2018). Through identifying the hydrological networks by which precipitation can flow across a heritage landscape coupled with the predicted changes in precipitation this can be used to establish the impacts that our sites could be facing as a result of climate change. Combining the work that I have carried out with MMS, hydrological mapping and climate modelling of precipitation data, building a wider landscape focused approach to managing heritage landscapes is possible.

As seen at Rough Castle (Survey Area 3) and Ring of Brodgar (Survey Area 1), diffuse trampling of a footpath has a much wider impact on a heritage landscape that that of a constrained narrow footpath (Survey Area 2 and Survey Area 3). Further seen at Ring of Brodgar was the widening of footpaths by visitors to avoid wetter areas. This may become more evident on sites in coming years as precipitation increases, areas on site will become wetter, causing visitors to move around them, thus resulting in a wider footpath and therefore having a wider impact on heritage landscapes. Through installing designated footpaths and managing their drainage and surface integrity, through a site and to key locations, such as signboards, it may become possible to help minimise the compounded factors of an increase in precipitation and visitor footfall. Through implementing designated footpaths, it becomes possible to help sites deal with the changes in precipitation patterns and the impact that this may have on the sub-surface soil structure.

Additionally, from the work carried out this study has shown that signboards have more of an impact on the subsurface than originally anticipated; the increase in precipitation, making soil profiles wetter, this could lead to a greater soil hydrological impact seen around the location of signboards. The location of signboards needs to be carefully considered. The influence of the signboard locations is similar to the footpath at Rough Castle; this is significant as their below ground influence extends further into the landscape than expected.

The effect that the signboards had is significant and highlights the importance of building signboard locations, patterns of soil moisture and hydrological flows, into site design and planning. In order to help maintain a heritage landscape, signboards should be positioned with relevant infrastructure in place surrounding them. This could be a range of infrastructures from a stone lined pathway, a geo-textile or hidden hard engineering around the signboards. This could potentially aid in the preservation of buried archaeology through prevention of soil compaction and smearing, all of which affect soil moisture and therefore, potentially, archaeological preservation (Historic England, 2016).

This study is primarily focusing on the direct hydrological networks across a heritage landscape and it is important to consider the landscape as a whole and the changes that could occur as a result of climate change and the impacts that this will have on heritage landscapes. As this study has highlighted the above ground hydrological networks for water movement across the site could be changing. Managing, leaving, or altering these hydrological networks will have an effect soil on moisture across the site. Soil moisture is having an unknown impact on the preservation and deterioration of below ground archaeology (Cassar and Pender, 2005). Soils are predicted to reach field capacity for more days of the year by 2050 (Brown, 2017) than currently. This means that heritage landscapes are likely to see an increase in soil moisture and surface flows. Due to the poorly understood impact that this will have on archaeology it is important to manage these landscapes to maintain their hydrological function. Excessive deep drainage may be best for lowering the number of days those sites reach field capacity (Brown, 2017) but this could be detrimental to the preservation of below ground archaeology. The reverse is also true, if no drainage is put in place, then sites will reach field capacity quicker and could result in a rapid deterioration of key buried archaeological features (Historic England, 2016).

Visitor interactions with sites can affect soil structural properties across a site. This not only has a visual impact but also has an environmental one. Widening of footpaths/ lines of desire reduces the areas of natural habitat across sites. Wetter soils are more susceptible to compaction, smearing and degradation. If soils reach their field capacity more often, the impact that visitors may have on sites may become more pronounced. Through increased compaction and smearing, this will affect the structure of the soil and may result in a decrease in porosity and infiltration capacity. This will increase surface runoff of water and in turn increase erosion of a site. Managing visitor footpaths is essential for maintaining the integrity of soil properties across a heritage landscape (Brandolini et al., 2018). This in turn will prevent further damage to the habitats adjacent to the footpaths and has the potential to prevent damage to buried archaeology. Further work is also required on the impact that having footpaths adjacent to upstanding archaeology is having on moisture movement between the soil and upstanding archaeology.

Along with all the environmental factors that climate change is having on our sites there is also an economic one (Day et al., 2020). With an increase in precipitation leading to an increase in soil wetness with no mitigation, will lead to sites being closed due to unsafe footpath access and/or further damage to sites occurring if they are not closed. At sites where there are natural footpaths this effect will be more acutely felt. Developing designed access routes may not be the best aesthetically but for the integrity of the site and maintaining the protection the archaeological features this may be necessary. Peak visitor numbers occur during summer months, when sites are likely to have drier soils. However, as frequency and intensity of precipitation events are also due to increase during these months, this could lead to an increase in soil degradation. If visitors access a site immediately after a precipitation event, this could lead to smearing and compaction occurring in the soil. If standing water occurs, it could lead to widening of footpaths, thus exacerbating the impacts of compaction across a heritage landscape. The effects of footpaths can be seen in the soil moisture up to 15m away from the footpath (J. Gong, 2009). MMS and Hydrological modelling, along with climate predictions have made it possible to determine the effects that footpaths are having on the landscape. Given the proximity of some footpaths to above ground archaeological features, it could be inferred that the archaeological features are being impacted by footpaths. Therefore, considering a footpath intervention in the form of designed infrastructure may be needed in certain locations to help maintain the PICs significance and OUVs, to prevent the degradation of archaeological features that could be caused by an increase in precipitation and footpath use.

Managing visitor interactions and site visit expectations in a climate changed future is essential. Through using a more holistic approach to how visitors interact with sites and how these sites are managed is essential to maintain their integrity (Weber et al., 2019). Combining heritage landscapes with nature-based solutions can not only enhance the visual aspects of the sites it can provide a real-world application to help sites adapt to the changes in climate. Using nature-based solutions within the landscapes to help protect heritage features form an increase in precipitation could create a more robust site. Although careful consideration on the solutions will be required to ensure further or future damage is not exerted on heritage landscapes.

Determining the impacts of changing precipitation regimes on heritage landscapes and implementing the best possible practices to ensure that sites are future climate enabled which will ensure their protection for future generations. One of the key factors highlighted here is that although precipitation change will directly affect the hydrological networks, there is the secondary impact from visitors and footpaths that could be equally detrimental. Further work is required to understand the current hydrological interactions between above ground hydrology and belowground archaeological preservation. This research has provided a starting point for understanding the hydrological networks and the potential impacts of these networks in changing precipitation patterns. However, a greater understanding is required on the effects of changing precipitation patterns and heritage landscapes for soil hydrological interactions and heritage preservation. From this research establishing changing precipitation regimes, impacts of footpaths and mitigation measures is essential for maintaining the integrity of heritage landscapes.

7.4 Recommendations

In the face of climate change, doing nothing on sites may lead to increased erosion, destabilisation of structures and overall site degradation. For this reason, there are some key recommendations that can be made in relation to the sites studied.

At Ring of Brodgar, designed interventions are needed to maintain visitor access, the rotation of the access path is not sufficient to maintain adequate access and drainage systems need to be installed around the site in areas where higher preferential flows are predicted to occur. The hydrological modelling highlights the impact that the main access footpath is having on the hydrological network, with a high order flow occurring alongside the footpath. This, coupled with the MMS data, would indicate that the footpath, left unchecked, will continue to have an impact on the soil properties. Therefore, it is recommended that a designed intervention for the footpath is installed, along with appropriate drainage. The grass pathways are wide and bare of grass in places; with climate change, these paths will only get wider and barer. Bare earth is more susceptible to erosion and with increased rainfall, the soil has the potential for increased erosion. This will in turn lead to a reduction in protection of the buried and upstanding archaeology. In addition, drainage needs to be of an acceptable depth and gauge to deal with the predicted changes in precipitation.

Rough Castle requires interventions to be carried out on the footpath system and the connection between the footpaths themselves and signboards, as seen through the MMS data. Installing an intervention in front of signboards may help to preserve the areas in front of them but also direct footfall to one specific location. In addition, the impact of diffuse trampling needs to be addressed and a solution on which intervention needs to be investigated further. However, a geo-textile may be a good intervention to help minimise the impact that footfall is currently having on site. In addition to the footpaths, seen in the hydrological modelling is the drainage of the ditches surrounding the fort top. This could come in the form of using the ditches to transport water and connecting them up to allow for drainage to prevent standing water occurring on site.

St Kilda's recommended approach is focused on the hydrological networks and the key locations where it interacts with upstanding archaeology. Through implementing effective drainage across the landscape and diverting it around upstanding archaeology it may be possible to maintain the integrity of the upstanding archaeology (Agapiou et al., 2020, Polykretis et al., 2021). Further understanding is required on the effects that upstanding archaeology has on the hydrological flows and the impact his is having downstream, especially along the main street on Hirta. Intervention upstream could be beneficial for managing the flows further downstream. St Kilda's stream network may lead this to being an ideal candidate for the alteration of stream networks with in a distinctive topographic landscape.

8. Conclusion

Heritage landscapes are complex and at threat from climate change. The aims explored throughout this thesis has shown that it is possible to use novel and new application of methods to understand the hydrological interactions which occur in a heritage landscape, and the possible effects of changes in precipitation.

Overall, the novel application of the MMS provided insights to the below surface impact that different visitor footpaths are having on our heritage landscapes. MMS provided a base understanding of the influences that high use footpaths have on soil moisture at Ring of Brodgar and the extent into the surrounding landscape that influence reached. At Rough Castle the MMS showed the impact of diffuse trampling had on the soil along with the importance of connections between footpaths and signboards. Despite the limitations of this technique, it has proven to be successful in providing a baseline understanding of the impact that footpaths are having on heritage landscapes.

Hydrological modelling provided an insight to the overland flow at all three sites. The main challenges with the hydrological modelling within this research was lack of topographic variation at Ring of Brodgar and constraint of topography for Rough Castle, and the effects of upstanding archaeology on St Kilda. Overall, this technique provided an insight into the current hydrological networks within the three study sites and provided a good understanding of the different influences present at each site. This technique worked well within this study and can be readily applied to other heritage landscapes to gain an understanding of the surface hydrological interactions.

Combining the MMS and the hydrological modelling proved to be challenging due to the scale of the datasets and lack of georeferencing. This can be overcome in future surveys and could prove to be beneficial for connecting the above and below ground hydrological interactions within a heritage landscape. This could not only be benefitable for use in understanding the impacts of soil moisture from footpaths but also that of buried archaeology.

Through hydrological mapping and MMS survey of visitor footpaths it has been possible to identify areas that could potentially be at risk from changes in precipitation by 2080. It has also provided a means for identifying areas that could become more susceptible to changes in precipitation. This study has highlighted the effects of just one factor of climate change may have on sites. Through combining site knowledge and hydrological modelling along with precipitation changes, it becomes possible to take a targeted approach to heritage landscape conservation.

Heritage landscapes comprising of a landscape record are landscapes of the past, present, and future. Their management cannot remain stagnant as these sites themselves are dynamic and changing. The future aspect is one of the most important with regards to climate change. Our heritage sites vary in age and have experienced aspects of climate change more than we ever will in our individual lives. As a result, heritage landscapes have seen a huge environmental changes. The sites will adapt themselves and nature will take its course. However, if we wish to maintain these sites for future generation, we need to act now to begin interventions to help these sites to remain intact. Intervention, development, and installation of key visitor access features at sites, is essential for maintaining access to our heritage landscapes for future generations. Therefore, the hydrological modelling and MMS monitoring that has been developed and applied within this research can be applied to heritage landscapes to aid site knowledge and understanding to ensure preservation for future generations.

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