Quantifying the Impact of Rural Land Management on Soil Hydrology and Catchment Response

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Abstract

This thesis investigates several types of rural land management and the relationship with soil hydrology, local runoff and catchment response. There has been a clustering of extreme events over the last few decades which has encouraged debate amongst hydrologists that the frequency and magnitude of hydrological extremes are increasing. Land management changes are thought to have caused modifications to the hydrological cycle by altering the partitioning of rainfall into runoff. In England, farming is dominated by pastoral agriculture, with 40% of land cover classified as either improved or semi-natural grassland according to the Land Cover Map 2007. National-wide change to farming practices since the Second World War are thought to be responsible for high levels of soil compaction, longer slope lengths, increased runoff velocities and greater potential for connectivity, which may be responsible for an increase in flood risk at the catchment scale. However, there is a lack of physical evidence to support these theories.

This thesis uses the case study of the River Skell catchment (120km^2) as a test catchment to examine the impact of soil compaction and the presence of hedgerows on soil hydrology. Firstly, field experiments were conducted in multiple fields to determine the heterogeneity of natural soil characteristics and the level of soil compaction under a variety of land-management types and at different periods of the hydrological year. The results showed no correlation between sites with a high potential for compaction and sites that experienced high levels of compaction, using the factors assumed to show compaction in this study.

The results did highlight statistically significant differences in levels of soil compaction between heavily compacted areas where animals congregate and tractors move down tramlines and less-trafficked, open areas of the field. Feeding troughs and field gates where animals congregate were identified as having the highest levels of soil compaction in comparison to the open areas of fields. The results showed that the least compacted sites and most compacted sites showed no change in level of compaction following a period with no trafficking.

Secondly, a hedgerow was intensively monitored for a period of eighteen months to capture information on soil-vegetation-atmosphere interactions. Results show that the hedgerow structure improved the soil properties by increasing the organic matter content and saturated hydraulic conductivity and reducing the bulk density. The structure altered the spatial rainfall distribution by reducing the quantity of rain falling on the leeward side of the hedgerow up to at least one metre away from it. The structure changed the surface water balance by partitioning rainfall into throughfall and stemflow and intercepting a large portion of rainfall on its leaves. The structure also altered the subsurface water balance by modifying soil moisture levels on the leeward side of the hedgerow up to three metres away from it.

Acknowledgements

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List of Contents

Chapter 6 – Quantifying the Impact of Hedgerows on Soil Hydrology………235

List of Figures

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

List of Tables

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Appendix 1

Appendix 2

List of Equations

Chapter 2

Chapter 3

Chapter 5

Chapter 6

Chapter 1 - Introduction

1.1 Introduction

This thesis investigates several types of rural land management and their relationship with soil hydrology, local runoff and the implications for catchment response. It provides new insights and evidence into the role that land management can play in slowing and storing rainfall locally and creating disconnections in flow paths to reduce downstream flood risk.

Flooding is a global problem and in England 2.5 million people are at risk of fluvial flooding (Environmental Agency, 2013). In the winter of 2015/2016 three major winter storms caused flooding of 16,000 properties and insured losses totalling £1.3 billion (Environmental Audit Committee, 2016). There have been a clustering of extreme events over recent decades which has encouraged hydrological debate that the frequency and magnitude of hydrological extremes are increasing (Hannaford and Marsh, 2008; Kendon et al., 2013). There are two main theories to explain these hydrological observations.

The first theory is that changes seen in land management have caused modifications to the hydrological cycle by altering the partitioning of rainfall into runoff. This is thought to have changed the hydrological connectivity within catchments and increased the conveyance of water downstream (Lane et al., 2007; Marshall et al., 2013; McIntyre and Marshall, 2010; Milledge et al., 2012; Pattison and Lane, 2012). However the impact of land management on hydrology is significantly under researched (Deasy et al., 2014) and the link between land management and catchment-scale flooding is still unknown (O’Connell et al., 2004). The second theory is that climate change has caused alterations to regional weather patterns and the distribution of rainfall which are believed to have affected the sequencing and magnitude of extreme events (Huntington, 2006; IPCC, 2013).

Since the start of the 21st century there has been increased attention on the use of rural landscapes to store and slow down the movement of water. The WWF report (Avis and Royo Gelabert, 2002) discussed integrated catchment management solutions and the role of wetlands for ‘natural flood control’. The report provided evidence of European projects that had successfully altered the flood plain to reduce flood peaks. Harris et al., 2004 identified three land management practices with the potential to mitigate against flooding including soil surface and structural protection, changes in flow connectivity and the retention and storage of water on the land.

The ‘Making Space for Water’ report (DEFRA, 2005) outlined how a future strategy would include working with natural processes. Then, after the 2007 floods in England, the Pitt Review (Pitt, 2008) acknowledged that ‘flood risk cannot be managed by simply building ever bigger hard defences’. The report identified that ‘softer approaches’ were more sustainable in managing flood risk and this led to the establishment of Catchment Flood Management Plans, to achieve greater working with natural processes (Environmental Agency, 2013). The Flood and Water Management Act (2010) helped to clarify sustainable management of flood risk through ‘maintaining or restoring natural processes’.

Since then Natural flood management (NFM) has become a well-used phrase covering a wide range of flood risk interventions. The Parliamentary Office of Science and Technology (Houses of Parliament, 2011) released a note on NFM defining it as ‘the alteration, restoration or use of landscape features’ which included land and soil management, runoff vegetation planting, attenuation features, river channel control structures and re-meandering/re-cutting of banks to reduce flood peaks and change flood timings. The note stated that ‘for NFM to become a standard part of managing flood risk, evidence is required to inform its development and deployment’ (Houses of Parliament, 2011).

Following this DEFRA funded three multi-objective demonstration projects to assess the impact of land-use management on flood risk including the ‘From Source to Sea project’, Holnicote Estate (National Trust, 2015), the ‘Slowing the Flow project’, Pickering Beck (Nisbet et al., 2011) and the ‘Making Space for Water project’, Kinder Scout (Pilkington et al., 2012). These projects provided the first data sets linking land management and runoff response at the small scale. In 2017, the Environment Agency published the Working with Natural Processes (WWNP) evidence base (Environment Agency, 2017a) to help flood and coastal risk managers understand, justify, develop and implement WWNP schemes to reduce flood risk. It will also provide new evidence regarding the impact of NFM schemes at the field, hillslope and catchment scale.

1.2 Philosophical Approach

There is a need to understand the link between land management and historic floods so that land management changes can be assessed in terms of future flooding and flood risk management (Ewen et al., 2013). However, the links are complex (Pattison and Lane, 2012) and there is a great deal of variability in time and space. This includes anthropogenic variability caused by land management and natural variability in seasonal weather patterns.

Hydrological processes such as soil moisture and interception vary over small spatial scales. At the farm scale the layout of fields and modern farming practices affects the ability of the soil to preserve existing flow pathways, retain rainfall and transport runoff through the soil (Wilkinson et al., 2013). Intensive farming practices such as winter tillage, when the soil is saturated and overstocking of fields, has caused soil compaction (Drewry and Paton, 2000), weakly structured soils with no vegetation cover and infiltration excess runoff (O’Connell et al., 2007). The removal of field boundaries has increased field size and slope lengths (Posthumus et al., 2008) and the system of field ditches and tractor wheelings has funnelled overland flow and allowed it to be conveyed quickly to the watercourse (Moussa et al., 2002).

Sub-field scale variability is not currently represented in hydrological models and yet the hydrological response of hillslopes has been shown to be strongly sensitivity to the quality and grid resolution of the data used (Lane et al., 2003). Coarse spatial grid resolution in catchment-scale models typically fails to integrate the significant effects of field heterogeneity on runoff generation and overland flow (Hutton et al., 2014). Therefore, there is a need for better field data for use in physically based models (Pattison and Lane, 2012), because the representation of fine scale variability gives significantly better prediction of fluvial flood inundation (Yu and Lane, 2011).

(Lukey et al., 2000) showed the importance of using real world observations to parameterise a physically based distributed model and to understand complex hydrological processes. The majority of field studies investigating the impacts of land management change on flood generation have shown that there is potential to use good land management practices such as animal exclusion and tree planting to reduce runoff volumes and improve infiltration rates (Marshall et al., 2013). Nonetheless there is still a lack of long-term monitoring sites in the UK and therefore a lack of field and laboratory data available for the parameterisation of physically-based distributed models (De Roo et al., 2001).

1.3 Thesis Aim and Objectives

The main aim of this thesis is ‘To determine the impacts of rural land management on local soil hydrology. This aim will be achieved by answering the following objectives.

1) To develop a holistic methodology to study the process-based relationship between soil compaction and soil hydrology.

Soil compaction is the compression of the soil by an external force such as the weight of an animal or a piece of machinery (Graves et al., 2015). Compaction is known to affect soil hydrology due to the creation of surface caps and plough pans in the top ten-thirty centimetres of agricultural soils (Horn et al., 1995; Jones, 2013). The process-based relationship between compaction and soil hydrology can be quantified by collecting information about the site. Firstly, site specific soil characteristics provide information on the natural soil features including soil texture and organic matter content which show the ease of water transport through the topsoil. Secondly, the level of soil compaction can be assessed by collecting information about the soil strength, structure and drainage potential.

There are numerous approaches that can be implemented to collect data including visual assessment in the field, tests in the field and the collection of field samples and subsequent laboratory tests. This research will use both of the above approaches to develop a complete methodology to provide physical data that can be used to assess the soil hydrology in the study catchment. This is important because the characteristics of the soil can be determined individually and then they can be assessed together to define relationships.

2) To assess the problem of complexity in the relationship between soil compaction and soil hydrology at different agricultural sites.

The relationship between soil compaction and soil hydrology at all scales is complex due to multiple interactions of its individual components (Pattison and Lane, 2012). In the context of flood risk, increasing stock numbers and densities have been correlated with changing risk. However, this does not imply causation unless it is supported by process-based observations. Overgrazing has been linked to soil compaction, reduced biomass, root depths and earthworm populations which lead to increased runoff and erosion. Hoof impacts have been linked to bank poaching, erosion and scour. The impacts of these processes include sediment loss, channel instability and widening, siltation and aggradation which have multiple impacts on flood frequency, channel management and habitat loss.

There is also likely to be a significant amount of complexity in compaction levels within fields (intra-variability) and between fields (inter-variability), due to multiple controlling factors, including positioning of gateways, feeders, drinking troughs, location of tramlines, the type of farm management, the intensity of farming, type of stock, hoof area and type of stock movement. This will be investigated by asking how does soil compaction fluctuate in space and time and what are the mechanisms that drive these spatial and temporal patterns of change. Inter and intra-field variability has not yet been studied together and this will be one of the first process studies to compare the level of variability in soil strength, soil structure and water movement between arable, cattle, horse and sheep fields.

In horse paddocks the problem of compaction has been mentioned in grey literature (Dyring, 1990; Kent Downs AONB, 2011; O’Brien and Wren, 2005; van den Berg et al., 2015) but, there are very few academic studies that have quantified the presence or degree of compaction. This will be one of the first studies to investigate soil compaction and soil hydrology in horse paddocks.

3) To develop a conceptual model to assess how the presence of a hedgerow modifies the hydrological cycle locally.

Man-made field boundaries including linear woody features (hedgerows, windbreaks, and shelterbelts) are common rural features in many countries around the world. The number of fields and the field density (the number of fields per km^2) has decreased since the 1890's throughout England due to the removal of field boundaries. The removal of hedgerows creates larger fields which encourage the propagation of runoff, due to longer flow pathways. This can lead to increased runoff velocities and greater soil erosion (Evans and Nortcliff, 1978; Barr and Gillespie, 2000). However, the impact that individual hedgerows may have in terms of storing water, slowing the flow, breaking up flow paths is largely unknown, due to a lack of monitoring data.

This research will use existing literature regarding soil hydrology to create the first conceptual model of hedgerow hydrology. This will be done by asking the question 'how do hydrological processes vary around a hedgerow in space and time' and 'what are the mechanisms that drive these spatial and temporal patterns of change'. The model will focus on the local soil-hedgerow-atmosphere interactions, firstly the hedgerow characteristics, secondly the surface water balance and thirdly the root zone balance.

4) To test and revise the conceptual model through a long-term monitoring programme of the holistic hydrological cycle and assessment of soil-hedgerow-atmosphere interactions.

This will be investigated by asking the question 'how does hedgerow modify local hydrological processes'. The initial conceptual model created in Objective three will be tested using hydrological data collected at a field site. A novel, long-term monitoring programme combined with field and laboratory experiments will be used to assess the three areas of the conceptual model to provide an assessment of the soil-hedgerow-atmosphere continuum. Field experiments were successfully used at Pontbren to monitor hydrological processes, including rainfall, throughfall, stemflow and soil moisture levels, at multiple depths and locations in the hillslope and at tree shelter belts. This data was then used to condition fine resolution physical models of the site (Jackson et al., 2008). Field experiments were also used to monitor rainfall, throughfall and stemflow at hedgerows in Swindon (Herbst et al., 2008, 2007, 2006). This data was used to parametrise the Gash analytical model to determine rates of interception.

This research will build on the above work by providing comparable and new data sets on the soil hydrology around a hawthorn hedgerow in Northern England. The field data will be analysed using statistical techniques to quantify the main hydrological processes and then all the data sets will be analysed together to gain an insight into the water balance around the hedgerow. Finally, the outputs will be used to revise the original conceptual model developed in Objective three.

5) To make recommendations about the impact that soil and hedgerow management can play in soil hydrology and catchment response and the role that this data can play for use in:

a) Natural Flood Management implementation schemes

This research will make recommendations to land managers on the spatial and temporal variability associated with soil strength, structure and drainage under different types of farm management and around intra-field features. Based on the conclusions, it will include ways to improve overall soil quality. This may include changes to arable farming practices, the timing of ploughing and sowing crops and the use of different types of machinery. It may include changes to pastoral framing practices, changes to stocking densities, the length and timing of the grazing period, the type of grazing, changes to the positioning of field gateways, feeders and shelters.

This research will make recommendations on the potential impacts of hedgerows and woody linear features on the surface and subsurface water balance. This may include changes to the number and density of these features within the landscape, their position and aspect and the maintenance of these structures.

b) Future numerical modelling studies

This will be investigated by asking the question 'what are the implications of this field data for catchment-scale flood risk'. Effective land management measures have been shown to significantly reduce runoff at the plot and field scales (CIRIA, 2013) however, there is no conclusive evidence that the impact of farm scale land management schemes can reduce flood risk at the catchment scale (Blanc et al., 2012). This is related to the lack of long-term monitoring data and lack of catchment wide land management programs in the UK. This limits realistic modelling and the ability to upscale the impacts of land management schemes on river flows at the catchment scale.

Upscaling the impacts of sub-field features to the catchment-scale is complicated by the complexity of catchment systems. Catchments are unique and at the field scale the effects of sub-field features are spatially and temporally variable depending on topography, soil characteristics and the individual rainfall events (Beven, 2000). At larger scales these effects become diffuse due to the cumulative impact of other land management and climatic signals (Blöschl et al., 2007). This does not mean that there is no influence on flows just that it is not discernible (Blöschl et al., 2007; Fiener et al., 2011; Wheater and Evans, 2009).

The spatial location and extent of land management features, their effect on the local river reach and the relative flow timings from the sub-field areas, disturbances caused by travel time in the reach (hydrodynamic dispersion) and the shape of the river network (geomorphological dispersion) adds to the complexity (Pattison et al., 2014; Rinaldo et al., 1991). This research will make recommendations on how sub-field scale features may be incorporated into physically based distributed hydrological models to determine if land management schemes can have an influence on peak river flows and timings.

1.4 Study Catchment

This section will provide a brief introduction to the Yorkshire Ouse catchment (Section 1.4.1) and then a more detailed summary of the Skell catchment (Section 1.4.2). The Skell catchment is one of the River Ouse sub-catchments and has been selected as the main study catchment. All field sites are located within the Skell catchment.

1.4.1 Yorkshire Ouse Catchment

The Ouse catchment is located in Yorkshire, northeast England and covers an area of 4,847km^2. It is made up of five main rivers systems the Rivers Nidd, Swale, Ure and Wharfe and Foss (Environment Agency, 2010) (Figure 1.1). The catchment is home to 606,000 people and includes the cities of York (206,900) and Ripon (16,430) and the towns of Harrogate (75,260), Northallerton (18,890), Knaresborough (15,300), Wetherby (11,155) and Thirsk (9,460) (North Yorkshire County Council, 2016) .

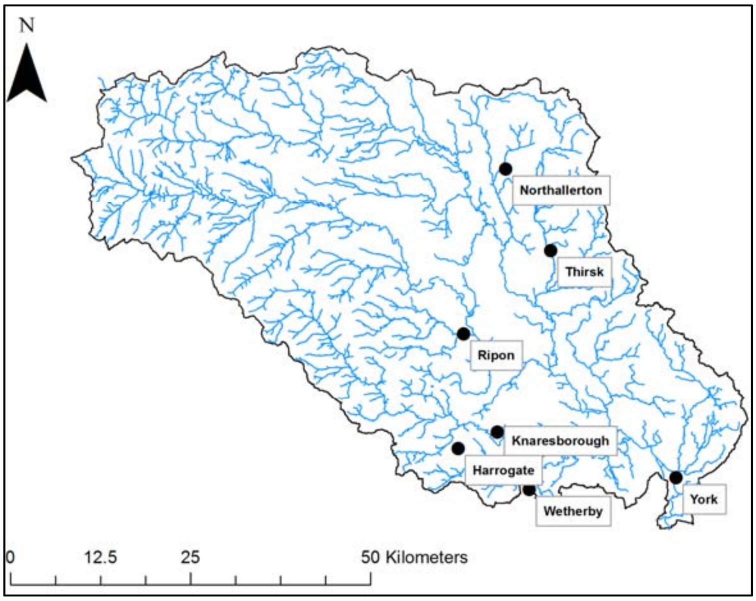

Figure 1.1: River Ouse catchment, North Yorkshire.
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The Ouse catchment has 6,475km of watercourses, an average annual rainfall of 1,086mm and over 31,000 properties are at risk of flooding. There is a long flood history, which is well documented at York where the earliest recorded flood occurred in 1263 (Environment Agency, 2010) and formal records have been collected since 1878. Notable flood events in York occurred in 1947, 1982, 1997, 2000, 2007, 2012 and 2015 (Macdonald, 2012; The Press, 2016).

1.4.2 Skell Catchment

The Skell catchment, North Yorkshire (Figure 1.2) was chosen as the study catchment to add to the knowledge of how land management may be used to alter the prevalence and extent of flooding. The Skell was chosen for six reasons. First, the catchment has a mixed land use including arable and pastoral which were needed to fulfil the objectives of the study. Previous investigations have shown that the land cover and soil type in the catchment makes it susceptible to land management impacts (JBA Consulting, 2007a). The catchment land use is representative of other catchments across England which means that the outcomes of this project can be applied, not just to this catchment but, to other hydrologically similar catchments (with similar annual rainfall, soil permeability and rural/urban extent).

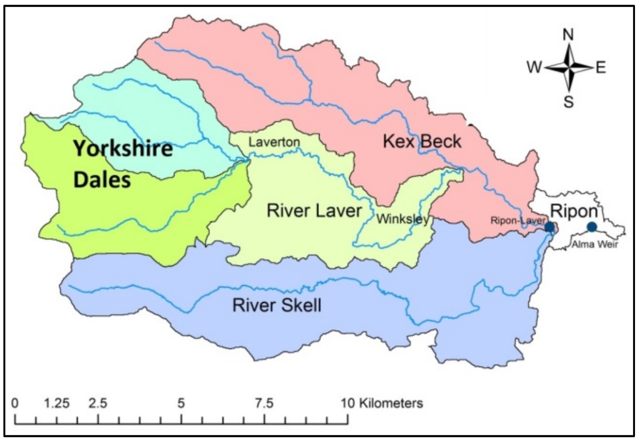

Figure 1.2: River Skell catchment, North Yorkshire.

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Second, the catchment has been used for previous research projects (Environment Agency, 2013a; JBA Consulting, 2007a; Murphy, 2007) however, there are still knowledge gaps regarding how soil hydrology influences catchment response and this thesis attempts to address these knowledge gaps. Third, there were stakeholders in the catchment who were willing to be involved with the project and who provided access to the field sites and information on their farming processes. Fourth, the city of Ripon, which stands at the confluence of the River Skell with the River Ure, has a long and well documented history of flooding (JBA Consulting, 2013) and has flooded five times since 2000 (Environment Agency, 2010). Fifth, the relatively small catchment size was a manageable area for fieldwork. Sixth, an initial analysis showed that there has been a decrease in field density and an increase in field size over the past one-hundred and twenty years indicating a loss in hedgerow field boundaries.

1.4.2.1 Geographical Location

The Skell catchment is a sub-catchment of the Lower River Ure. The River Ure is the principal river in Wensleydale, Yorkshire Dales, running for 74 miles from Abbotside common (elevation 640m A.O.D.) to the River Ouse at Linton-on-Ouse (Environment Agency, 2010). The Skell has an area of 120km^2 and contains four main watercourses, the River Laver (15.56km), the River Skell (2.36km), Kex Beck (9.5km) and the Ripon Canal (3.92km) which connects Ripon to the River Ure (Figure 1.3).

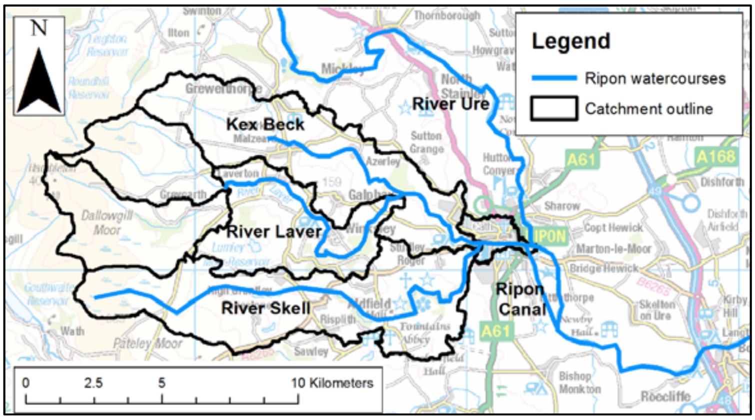

Figure 1.3: The watercourses around the city of Ripon. Copyright © Ordnance Survey, 2018.

The Skell's headwaters are on Dallowgill Moor and the river flows east until it meets the Laver just outside of Ripon. It then flows through Ripon and meets the River Ure just outside the city. The Laver's headwaters are in Kirkby Malzeard and on Dallowgill Moor in the Yorkshire Dales. Kex Beck's headwaters are also in the Yorkshire Dales and it flows approximately 10km east before joining the Laver at Ellington Banks, about 5km west of Ripon. The River Ure is not part of the Ripon catchment although it can influence the Skell when water backs up during high flows (Environment Agency, 2009).

There are a number of open water bodies (reservoirs and lakes) that may attenuate flows from within the catchment. These include the 0.1km^2 Lumley Moor Reservoir (on the upper Laver), Eavestone Lake (on the upper Skell), the Low Lake (on the middle Skell) and the Ornamental Lakes in Studley Park, Fountains Abbey (on the lower Skell).

The North Yorkshire region is generally characterised by west to east sloping ground and eastward draining rivers, due to the presence of the Pennines (Met Office, 2015). The west of the catchment reaches a maximum elevation of 413m A.O.D. and has average slopes of 4%. The middle catchment has a drop in altitude from 250-100m A.O.D., with much shallower slopes (1% gradient). The east of the catchment around the city of Ripon has an elevation around 30m A.O.D. The topography is much flatter here due to the floodplain of the River Ure (JBA Consulting, 2007a).

1.4.2.2 Climate

The region's climate is maritime temperate (Cfb) (Koppen, 1884) and the nearest climate station is Dishforth Airfield (ID: 342, Elevation: 33m A.O.D.), 11km east of Ripon. Annual rainfall at this station is 642.8mm (1981-2010 climate period). In winter, October has the highest average monthly rainfall (64.0mm) and February has the lowest (42.2mm). In summer, August has the highest monthly rainfall (60.4mm) and May has the lowest (45.1mm) (Met Office, 2015). The average annual maximum temperature is 13.4°C and the minimum temperature is 5.5°C. In summer the average temperatures range from 8.6-17.7°C and in winter from 2.4-9.0°C (Met Office, 2015).

The nearest Met Office Integrated Data Archive System (MIDAS) fifteen-minute Tipping Bucket Rain (TBR) gauge is located at Lumley Reservoir (ID: 2246, Gauge: #49901, Elevation: 172m A.O.D.) near the village of Grantley (Figure 1.4). Other operational storage rain gauges are at Hambleton Hill (ID: 2241, Gauge: #49753, Elevation: 337m A.O.D.) in Kirkby Malzeard Moor and at Ripon Sewage Works (ID: 2252, Elevation: 21m A.O.D.).

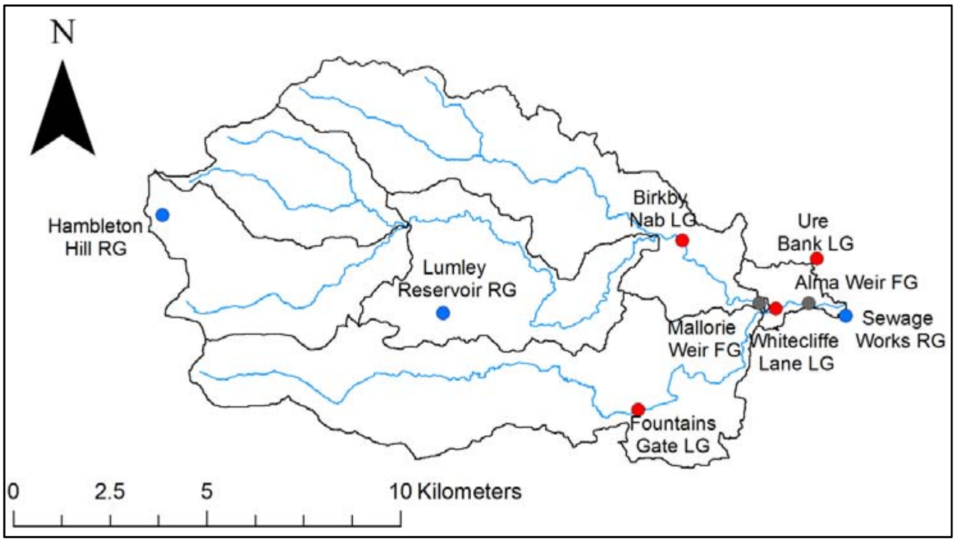

Figure 1.4: Monitoring gauges in the Skell catchment.
RG=Rain gauge, LG=Level gauge and FG=Flow gauge.
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The nearest MIDAS hourly soil moisture station provides ten and thirty centimetre data and is located at Bramham (ID: 534, Gauge: #224001, Elevation: 54m A.O.D.), 35km south of Ripon. The nearest MIDAS hourly mean wind direction and speed station is also located at Dishforth Airfield (Start date: 1993), 9km east of Ripon.

1.4.2.3 Geology and Groundwater

The bedrock geology splits the catchment, running from Azerley in the north to Fountains Abbey in the south (Figure 1.5). The west is dominated by the Carboniferous Millstone Grit group formed from mudstone, grey siltstone and fine-coarse grained feldspathic sandstone (approximately 358-298 million year old). The east is dominated by the Permian Zechstein group formed from dolomitised limestone, dolomite, evaporites, red mudstone and siltstone (approximately 298-252 million years old) (Smith et al., 1986).

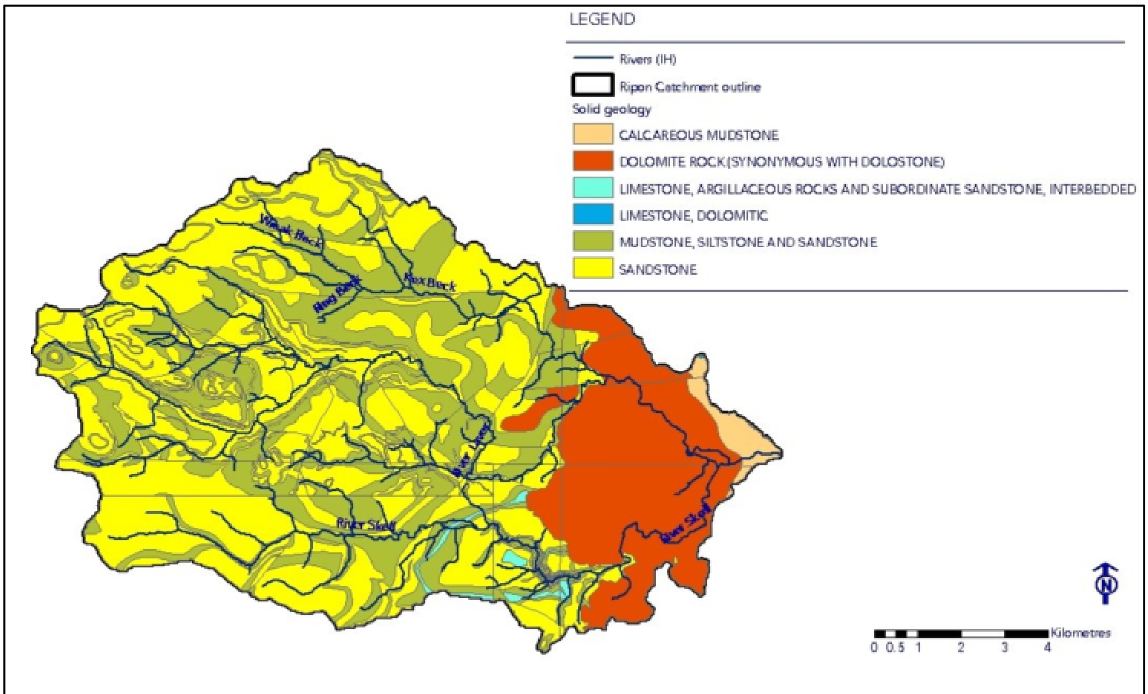

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Figure 1.5: Bedrock geology in Skell catchment.
(JBA Consulting, 2007b).

The majority of the superficial deposits in the lowland catchment are composed of the Vale of York Formation - Devensian Till Diamicton (non-sorted and poorly sorted sand in a mud matrix, deposited directly by glacier ice), (Cooper, 2006) formed two million years ago in the Quaternary Period (Figure 1.6). Near Ripon, there are also river terrace deposits and alluvium sand and gravel from seasonal and post glacial meltwaters (British Geological Survey, 2016). Groundwater flow in the catchment is dominated by two efficient groups, the Millstone Grit Group is a moderately productive aquifer up to 900m thick that flows at approximately 5-50l/s and the Zechstein Group is a highly productive, dolomitised limestone aquifer that flows at approximately 50l/s (British Geological Survey, 2016).

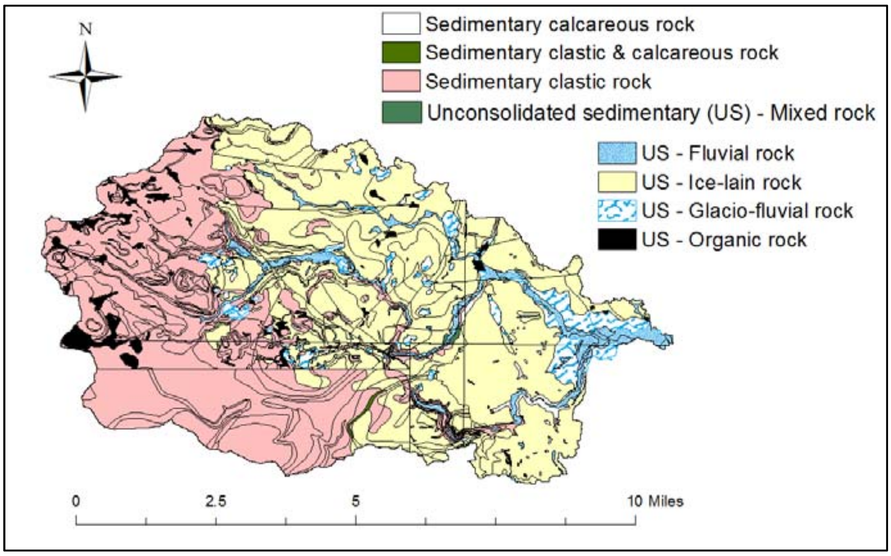

Figure 1.6: Superficial deposits in the Skell Catchment.

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1.4.2.4 Soils, Permeability and Land-Use

The headwater soils in the west of the catchment (Figure 1.7) are naturally wet blanket peat bogs (Soilscape #25) that have been drained using grips (shallow open ditches). The middle catchment is dominated by slowly permeable, seasonally wet, slightly acid, but base-rich loamy and clayey soils (Soilscape #18). These soils have impeded drainage but, are moderately fertile and suitable to grass production and some cereal production.

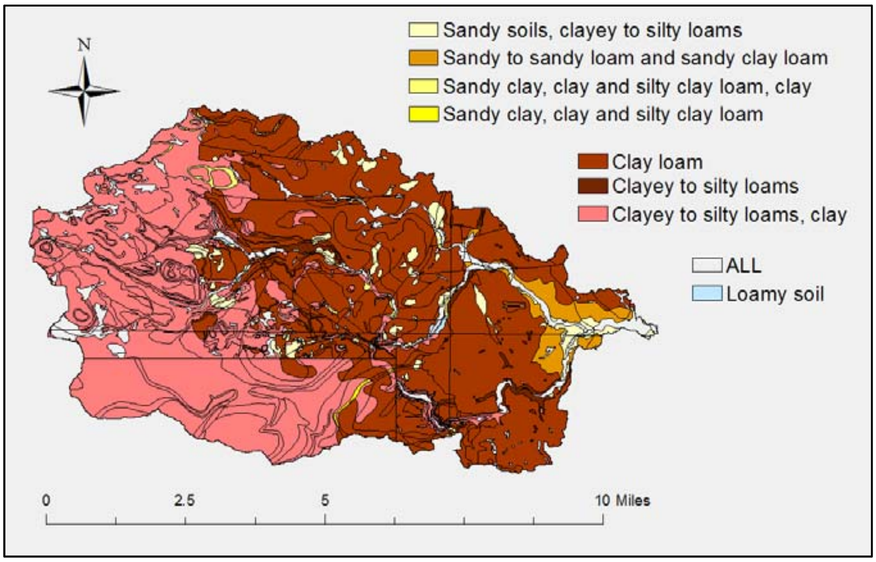

Figure 1.7: Soil textures in the Skell Catchment.

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The east of the catchment is dominated by freely draining slightly acid, loamy soils (Soilscape #6), which have low fertility however, the arable soils are suitable for a range of spring and autumn sown crops and the grasslands have a long grazing season. The good drainage in these areas can lower soil moisture levels which can limit yields, especially where it is stony or shallow (Landis, 2015). The Soilscape dataset is a simplified representation of the real soil profile due to its scale (1:250,000) and there will be greater complexity at the field and plot scale which is not included in this dataset.

The Land Cover Map 2007 (Centre for Ecology & Hydrology, 2011) classifies the west of the catchment as bog, heather, heather and acid grassland with dry stone walls (Figure 1.8). The middle catchment is dominated by improved, natural and rough grassland and conifer woodland with a rolling topography of hedgerows. Some reaches along the middle Skell and middle Laver are wooded and the reach downstream of Kirkby Malzeard on Kex Beck is wooded floodplain and wet woodland. The lower catchment is mainly arable and horticultural land with conifer woodland and the city of Ripon is mainly urban (Centre for Ecology & Hydrology, 2011).

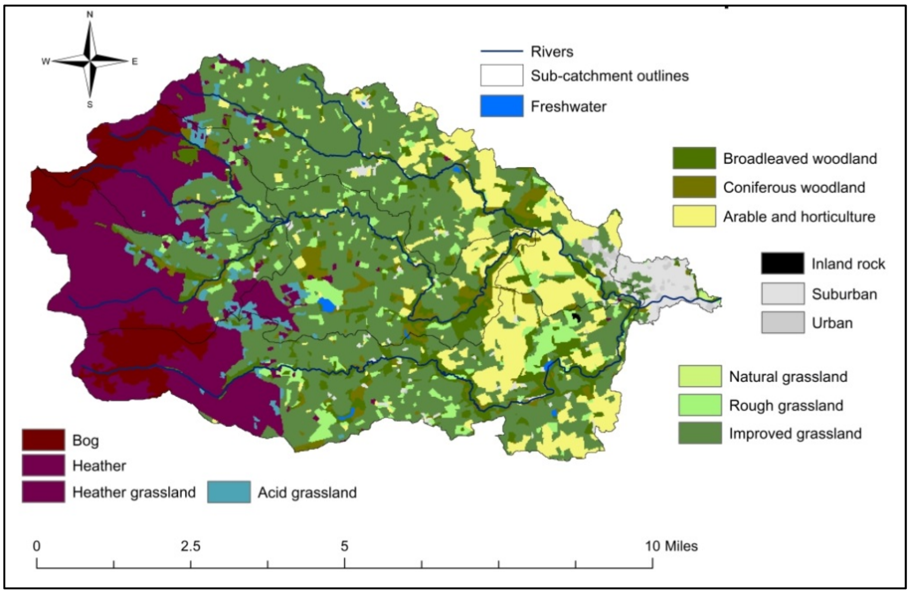

Figure 1.8: Land cover in the Skell catchment.

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The Agricultural Land Classification categorises land according to physical and chemical factors (climate, soils and site) which determine limitations on agricultural use. The western catchment is classed as non-agricultural land (Figure 1.9), the middle as Grade 4 (poor quality) and the eastern mainly as Grade 2 (very good quality), with a small area of Grade 1 (excellent quality) (Ministry of Agriculture Fisheries and Food, 1988).

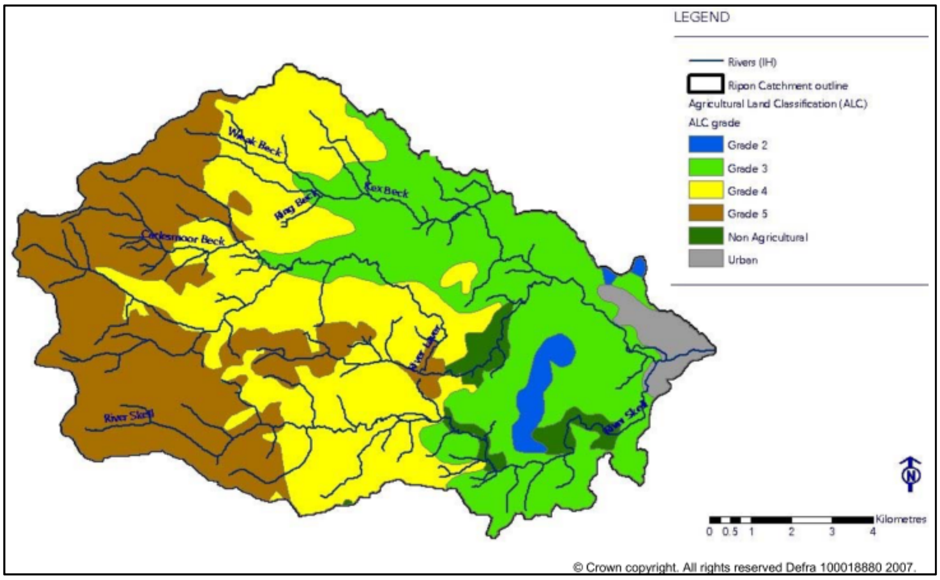

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Figure 1.9: Agricultural land classification in the Skell catchment. (JBA Consulting, 2007b).

Catchment land-use has not changed much in recent times however, land management has changed significantly (Posthumus et al., 2008). In the 1970's livestock production intensified due to a strong market and access to government grants for farm improvements and land drainage. In the western catchment the rough grassland and moorland was drained to create higher productivity grasslands for increased stock. Since the mid-nineties these incentives have been removed and replaced by schemes that compensate farmers for environmentally sensitive farming (JBA Consulting, 2007a) however, no review has classified these land management changes.

1.4.2.5 Flow Gauging and Flood History

There are two Environment Agency (EA) fifteen minute river flow gauging stations in the catchment (Figure 1.10), the first is Alma Weir (#27086) on the

River Skell (Centre for Ecology and Hydrology, 2017a). The station opened in 1984 but, was closed in 2010 and repositioned in 2012 as part of the Ripon flood alleviation scheme. It drains an area of 119.5km^2 and has a mean daily flow of 1.54m^3/sec, QMED is 27.43m^3/sec and the POT threshold is 14.88m^3/sec. Flows are generally contained within the structure except some by-passing at high flows. There are swallow holes at Fountains Abbey (south-west of Ripon) that reduce summer base-flow through the gauge.

The second station is approximately 1.8km upstream at Mallorie Weir on the River Laver (Centre for Ecology and Hydrology, 2017b) (Figure 1.11). The station opened in 1977. It drains a catchment area of 87.5km^2 and has a mean flow of 1.09m^3/sec, QMED is 21.36m^3/sec and the POT threshold is 14.68m^3/sec. The structure contains QMED without drowning and there is good correlation with Alma Weir even in the highest flows.

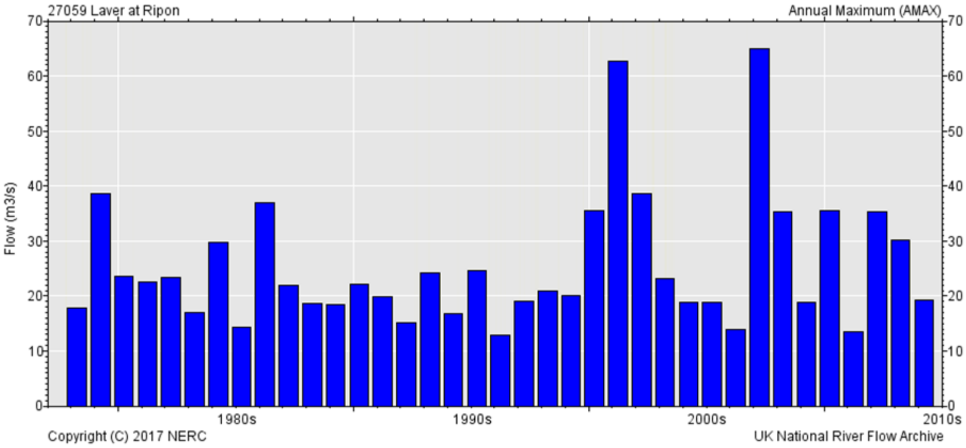


Figure 1.10: Annual maximum flow series at Mallorie Weir.
(Centre for Ecology and Hydrology, 2017b).

There is also a fifteen minute river level gauging station within the catchment at the Birkby Nab flood alleviation scheme on the River Laver and another just outside the catchment on the River Ure at Ure Bank (Figure 1.4). Flood risk in Ripon is high according to the Yorkshire Ouse catchment flood management plan and flood risk comes from fluvial, pluvial and sewer flooding (Environment Agency, 2010). Ripon’s flood risk warning and alert areas are shown in Figure 1.11.

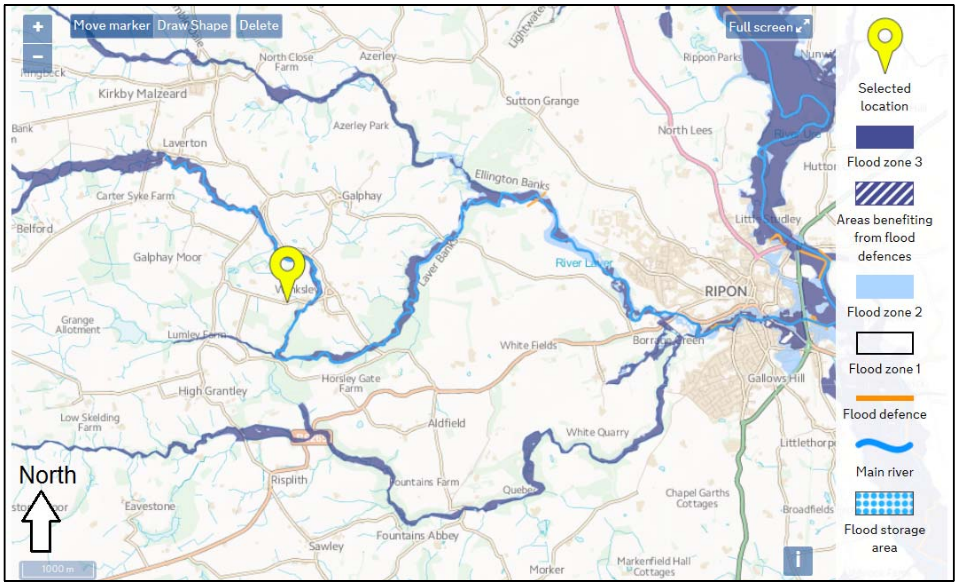


Figure 1.11: Flood map for planning, flood warning and flood alerts areas. (Environment Agency, 2017b).

Table 1.1: Major flood events in Ripon, North Yorkshire since 1980.

Date	**Flooding type(s)**	**Courses affected**	**Areas affected**	**Reference**
Jan. 1982	Fluvial Snow melt	Ripon Canal	Ripon centre	(Environment Agency, 2010)
Feb. 1991	Fluvial	Skell	Ripon centre	(Environment Agency, 2010)
Feb. 1995	Fluvial	Skell	Ripon centre	(Environment Agency, 2010)
Jan-Feb. 2000	Fluvial	Skell	Fountains Abbey Studley Royal Estate Borrage Lane Alma Weir	(Environmental Agency, 2013)
Nov. 2000	Fluvial	Skell	Borrage Lane Alma Weir, Wood footbridge and ford	(BBC, 2005)
July 2002	Pluvial	Skell	Ripon centre	(Environment Agency, 2010)
2005	Fluvial	Skell	Ripon centre	(Environment Agency, 2010)
June 2007	Fluvial	Skell & Laver	Fountains Abbey Studley Royal Estate Wolseley Hughes Borrage Lane Boroughbridge Road	(BBC, 2007; Discover Ripon, 2007)
Sept. 2012	Fluvial	Skell	Ripon centre	(ITV, 2012)

Ripon has experienced nine large flood events over the last twenty-five years (Table 1.1). Flooding in November 2000 was caused by very high flows on the Skell (70m^3/s) which contributed largely to the peak flow at Alma Weir (105m^3/s) and affected one hundred properties. This high flow event only had a 1% chance of occurring in any given year (DEFRA, 2007). Flooding in the catchment can occur at any time of the year but, the majority of floods have occurred in the winter season (Environment Agency, 2010).

In 2004, Halcrow carried out a feasibility study for Ripon and found that the Skell is affected by the diversion of water into ponds and gardens at Fountains Abbey. They identified that debris blockage at Wood Bridge was a large contributor to the 2000 flooding. The following alleviation scheme (Figure 1.12) included the construction of an earth wall (8.6m high) at Birkby Nab farm on the Laver, to create a flood storage reservoir (100,000m^3) and the installation of box culverts to divert the river. Other works included a flood wall on Borrage Lane, two earth embankments on the left bank in Fisher Green, an embankment (4m high) at North Bridge and the replacement and reduction in size of Alma Weir (Environment Agency, 2013a).

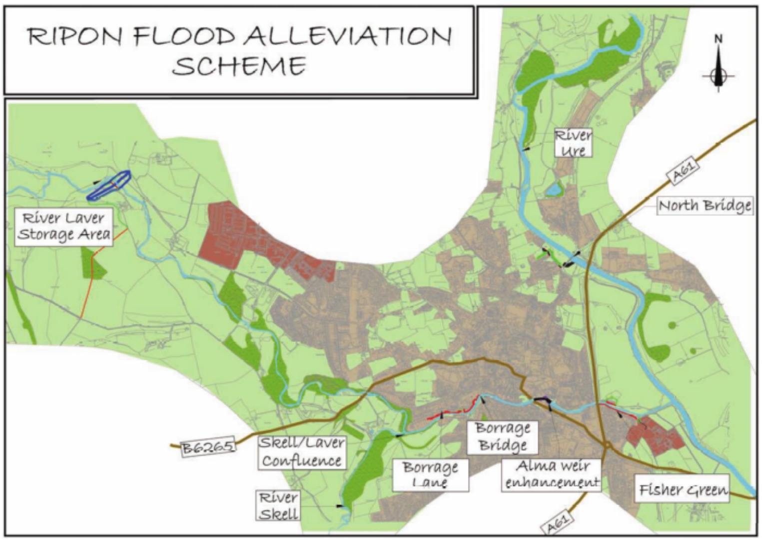


Figure 1.12: Ripon flood alleviation scheme.
(Environment Agency, 2013b).

There have been a number of studies of land management in the Skell Catchment including the Ripon Multi-Objective Project (Murphy, 2007) and the (JBA Consulting, 2007a) report for DEFRA named the Ripon Land Management Project. The project used ten probability distributed moisture (PDM) models to test the sensitivity of farm management on runoff characteristics and flood generation. Seven scenarios were tested and each was run for winter and summer events and for ten, fifty and one hundred year return periods.

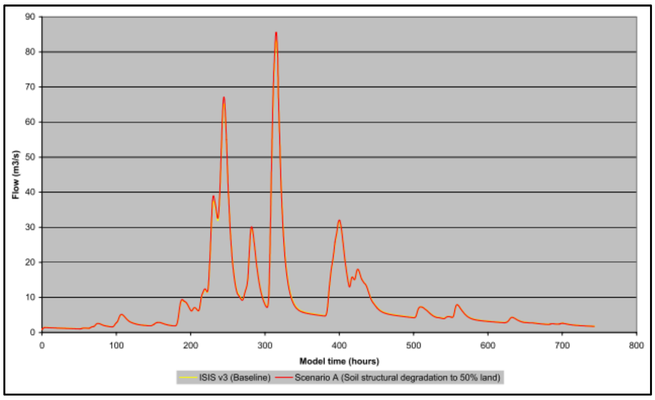


Figure 1.13: Hydrograph at Alma Weir for scenario A in winter 2000. (JBA Consulting, 2007b).

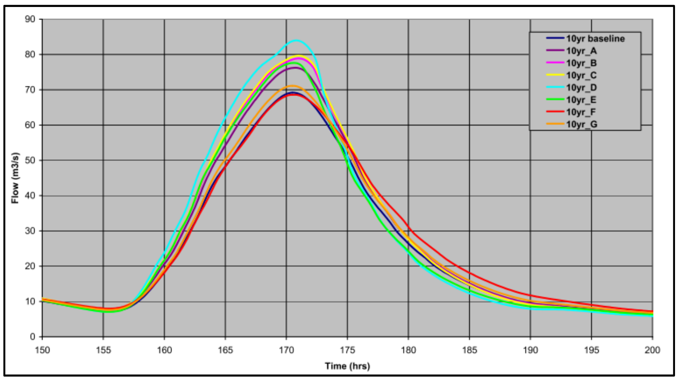


Figure 1.14: Hydrograph at Alma Weir for 10 year design event. (JBA Consulting, 2007b).

The report found that Ripon is vulnerable to negative changes in land management. In scenario ‘A’ soil structural degradation was applied to 50% of the already degraded soils. For winter events there was an increase in peak flow of 1-6% at Alma Weir and an advance in flood peak timing of fifteen minutes (Figure 1.13). For the ten year events there was a 10% increase in peak flow at Alma Weir and a fifteen minutes advance in flood peak timing (Figure 1.14).

1.5 Thesis Structure

This thesis is organised into seven chapters, which are based on the aim and objectives of this research. Chapter one has provided an introduction to the thesis. Chapter two provides an extensive literature review on which the origin of this thesis is constructed, the drivers of hydrological change, the main hydrological processes that are affected by land management and the impacts of these changes on soil hydrology and catchment response.

The thesis is then split into two main bodies of work. The first piece of work investigates and quantifies the process-based relationship between soil compaction and soil hydrology and assesses the problem of complexity. Chapter three provides information on the background of the field and laboratory methodologies used to explore the impact of soil compaction on field scale hydrology (Objective one). Chapter four provides the results and quantifies the impact of compaction on soil hydrology (Objective two).

The second half of this thesis investigates how the presence of a hedgerow modifies the hydrological cycle locally through soil-hedgerow-atmosphere interactions. Chapter five provides details of the field methodologies used to assess the impact of hedgerows on hydrology at the field scale (Objective three). Chapter six provides the results and quantifies the impact of hedgerows on soil hydrology (Objective four). Finally, Chapter seven concludes the thesis and provides recommendations on natural flood management schemes and the use of the field data in numerical modelling (Objective five).

Chapter 2 - Soil Hydrology and Land Management Change

2.1 Chapter Scope

This chapter will review the literature on soil hydrology and land management change. This will be focussed on two key areas of research, the first on the effects of soil compaction and the second on the effects of field boundaries on soil hydrology and catchment response. Section 2.1 will start by describing hydrological trends and causes of hydrological change, Section 2.2 will detail the main hydrological processes which will be studied in this thesis including infiltration, throughflow and overland flow. Section 2.3 will give an overview of the history of land management in the UK and the changes that have occurred. This section will include the history of arable farming, grasslands and the impacts of land management on hydrology. Finally, this section will look at methods that can be used to study the impacts of land management on hydrology.

Section 2.4 will look at the impacts of land management on soil compaction and soil hydrology, including the effect of arable farming on soil hydrology and the effect of pastoral grazing on soil hydrology. Section 2.5 will then focus on the impact of field boundaries on soil hydrology including an introduction to field boundaries, their history and their loss. It will introduce woody linear features including English hedgerows and then discuss hedgerows and soil hydrology. Section 2.5.4.3 will provide the chapter summary.

2.1.1 Hydrological Trends and Causes of Change

Since 1990 there have been several notable hydrological extreme events including the fluvial flooding in summer 2007 (Marsh and Hannaford, 2007) and winter 2015/16 (Marsh et al., 2016). The sequencing of extreme dry to extreme wet events caused extensive flooding in 2012. The period from January 2010-March 2012 was the driest period on record since 1779. It was immediately followed by the wettest April-July in two-hundred and thirty years. Runoff figures for May-July 2012 were 150% higher than runoff figures for the previous four months (Kendon, Marsh and Parry, 2013). These events indicate that we are currently in a flood rich period.

The clustering of these hydrological events has led people to speculate that the frequency and magnitude of flooding is increasing (Hannaford and Marsh, 2008, Kendon, Marsh and Parry, 2013) and reinforced the public believe that climate change is responsible for the increased frequency and magnitude of extreme events (Wheater and Evans, 2009). However, short term trends are not necessarily representative of longer term trends seen in UK river flows (Prudhomme, Jakob and Svensson, 2003) and for example the previous sequencing event occurred in 1903 (Kendon, Marsh and Parry, 2013).

Floods are dangerous natural hazards that cause widespread global damage every year. Their development is complex and their occurrence ranges in severity and frequency due to multiple climatic and human-induced factors. Climate change is expected to create a warmer world and therefore a wetter world due to the Clausius-Clapeyron relation for water vapour, which predicts a 1-3% increase in precipitation per Kelvin of surface warming (Wentz et al., 2007). Climate change is expected to affect seasonal precipitation patterns, although this is thought to be spatially variable due to soil-moisture-climate interactions (Huntington, 2006). Climate change is believed to have affected the Central England Temperature, which has risen by approximately 1ºC since the 1970's (Qian and Saunders, 2003, IPCC, 2014). Nevertheless, at the global scale there is a low confidence that climate change has had an impact on the frequency and magnitude of fluvial flooding. This is due to the short length of climate records and the lack of flow records, ungauged catchments and the large variability in climate cycles and oscillations (Jenkins et al., 2009).

However, the impact that humans have had on the land surface characteristics globally is clear. The main cause of change is large-scale land conversion for cultivation which includes widespread deforestation, cropland fertilisation and water and manure management. These practices have affected surface roughness and soil moisture-climate interactions which have altered the location and strength of particular climate zones and changed complex feedback loops (Dessler, 2010, IPCC, 2014). Conversely in individual catchments the impact of climate change on runoff response is highly complex and depends on individual processes that are combined and interact within the catchment system. This includes hydrological processes, catchment topography, hydrogeology, geomorphology, soil characteristics and quality, land-use and land management.

2.2 Hydrological Processes

This section will discuss the main processes in the hydrological cycle which are important for the movement of water on, above and below the earth's surface. Precipitation is the main input into the hydrological cycle (Figure 2.1) and includes all forms of water being released from the atmosphere including snow, rainfall, hail and sleet. It is also the main input into the river catchment however, rainfall is the only type of precipitation which can be measured relatively easily and is the focus of most hydrological monitoring and data analysis (Davie, 2008).

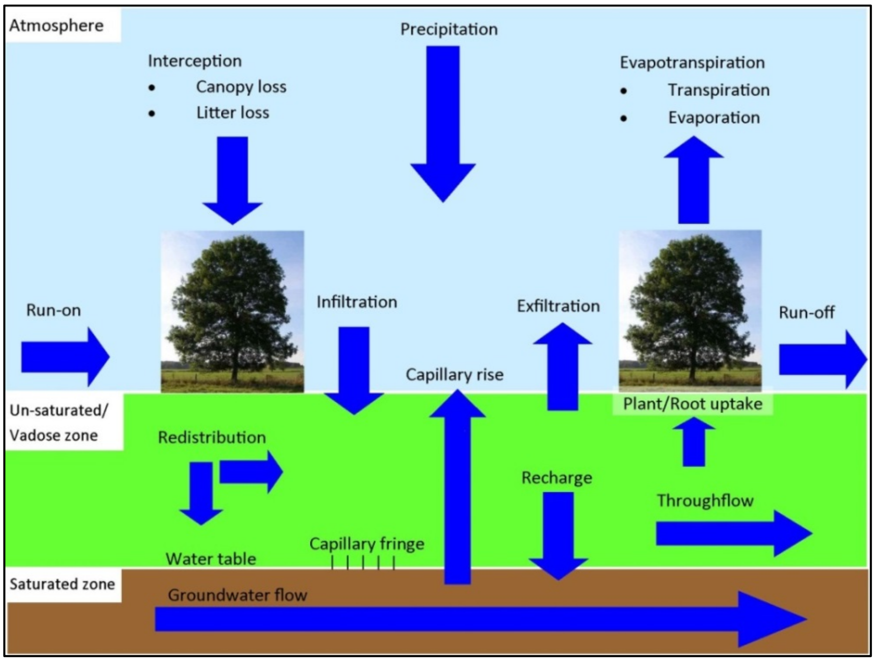


Figure 2.1: The terrestrial hydrological cycle.

When rainfall reaches the surface, it is partitioned into surface runoff and sub-surface flow. The main hydrological processes that control this are infiltration; throughflow and overland flow. These three processes will be discussed in more detail in Sections 2.2.1-2.2.4.

2.2.1 Infiltration

In unsaturated soils of good structural quality, water can infiltrate easily into the sub-surface through macro and micro-pores in the soil. The unsaturated or vadose zone is the portion of soil that is above the water table which contains small amounts of soil moisture and air in its pores (Nimmo, 2009). The rate at which water enters the soil is known as the infiltration rate f(t) and the maximum infiltration rate is known as the infiltration capacity f*(t). The rate of infiltration is dependent on two main factors. The first is the rainfall event characteristics (intensity and duration) and the second is the depth of ponding water on surface prior to an event (Nieber and Sidle, 2010).

This leads to three potential surface conditions:

- Supply-controlled: No ponding, soil is not saturated, infiltration rate = rainfall rate and is less than the maximum infiltration rate
- Profile-controlled: Ponding is present because the rainfall rate is greater than the maximum infiltration rate
- Ponding is present because the water table has risen to the surface and the entire soil is saturated, therefore there is no infiltration

The infiltration rate is also affected by three other factors. The first is the saturated hydraulic conductivity of soils which for mineral soils is primarily determined by grain size that determines the structure. However hydraulic conductivity can be reduced by low organic matter content of the surface layers, frost, swelling of clay minerals, soil sealing by rain drop impact in bare soils, in-washing of fine sediment into pores and human modification to the soil surface through urbanisation and farming (Dingman, 2002).

The second is the inclination, roughness and chemical composition of the soil. The rate of overland flow increases with increasing slope and decreases with roughness, so steeper and smoother slopes will promote rapid flow, less ponding and less infiltration. Water that falls on the ground beneath vegetation can be affected by waxy organic substances that produce hydrophobic surfaces that limit infiltration. The third is the physical and chemical properties of water which are influenced by temperature. The viscosity of fluids at high temperatures increases which affects the hydraulic conductivity and can cause large increases in infiltration rates (Dingman, 2002).

Once water has infiltrated into the soil, it is either stored as soil water, or moves vertically or horizontally through the soil. There are three main types of soil water. The first is gravitational water which occurs freely in soils that are highly saturated. The second is capillary water which occurs in less saturated soil and is held between individual particles. The third occurs in very dry soils when capillary water disappears completely and only a thin film of ‘hydroscopic water’ is left around the particles (Dingman, 2002).

2.2.2 Throughflow

Once water has entered the unsaturated zone it is redistributed through a number of processes (Figure 2.1). Soil water can be evaporated back into the atmosphere from the upper layer of the soil (evaporation). Water can percolate through the unsaturated zone into the saturated zone (recharge), or move upwards by surface tension from the saturated zone into the unsaturated zone (capillary rise), or be taken up by plants through their root systems (plant uptake). Finally flow that moves downslope laterally within the unsaturated zone is known as interflow (Dingman, 2002).

Redistribution of soil water is controlled by the soil water potential. These are hydraulic gradients created by the processes of matrix pressure, gravity, and osmosis. In unsaturated soils water is held to the mineral grains by surface-tension forces (also known as matric potential or suction (Ψ)). Pressures (p) are measured relative to atmospheric pressure. At the water table $p=0$, in saturated flows $p>0$ and in unsaturated flows $p<0$ which means in the unsaturated zone the pressure is always negative. Negative pressure is known as tension or suction, tension increases as the water content of the soil decreases.

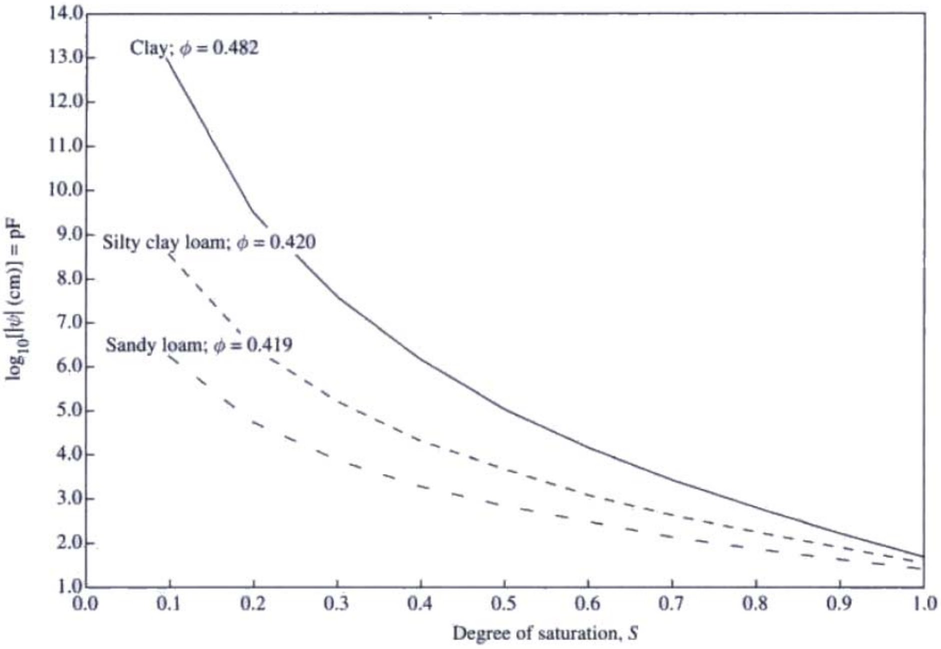


Figure 2.2: Soil water pressure vs. degree of saturation for three different soil textures.

The vertical axis gives the base 10 logarithm of the absolute value of the pressure (which is negative) expressed in cm of water (pF). Φ = porosity. The curves are based on the typical values given by Clapp and Hornberger, 1978. (Dingman, 2002).

The relationship between the tension head and the water content of the soil is the soil moisture characteristic curve. The relationship is highly non-linear and at the inflection point at the air-entry tension point (when significant volumes of air appear in the pores) the soil water content decreases quickly until it reaches very high tensions, this is where the curve becomes almost vertical (Figure 2.2). The graph shows that at a given saturation the tensions are much higher in fine grained soils than in coarse grained soils. The values of tension vs saturation are also affected by the soil's history of wetting and drying (hysteresis) which can have a significant impact on soil-moisture movement.

Redistribution of soil water is also affected by root uptake which occurs when water vapour moves out of the stomata and starts the transpiration stream (the flow of water through a plant from the roots to the leaves), an energy gradient that pulls water through the plant. Plants absorb water from the soil through the tiny hairs in their roots, by the process of osmosis. Following the absorption of water by roots in one area the adjacent soil moisture content will decrease and this induces a flow of water from a new area of soil towards the root (Dingman, 2002).

There are two types of subsurface flows; the first is uniform matrix flow. Darcy's Law (Darcy, 1856) is used to describe flow through an unsaturated porous medium at a point, known as a representative elemental volume, of the soil that includes pore spaces and soil particles (Equation 2.1). Darcian flow occurs due to spatial gradients of mechanical potential energy (gravitational and pressure potentials). It rarely exceeds speeds of a few centimetres per hours.

$$q_x = -k_h \cdot \frac{d(z + \frac{\rho}{\gamma_w})}{d_x}$$

Equation 2.1: Darcy's Law.

q_x = volumetric flow rate in the x-direction per unit cross sectional area of medium, z = elevation above an arbitrary datum, p = water pressure, y_w = weight density of water and k_h = hydraulic conductivity of the medium.

The intrinsic permeability or hydraulic conductivity is defined as the rate at which water moves through a porous medium under a potential energy gradient. In saturated flows the hydraulic conductivity is determined by the particle size and in unsaturated flows it is determined by both particle size and the degree of saturation. It is also affected by the organic matter content, as soils with lots of earthworms and roots have a high hydraulic conductivity (Figure 2.3). Bare soils, compacted soils and other impermeable surfaces have low permeability. Clay soils are prone to swelling and drying which decreases and increases their hydraulic conductivity respectively (Dingman, 2002).

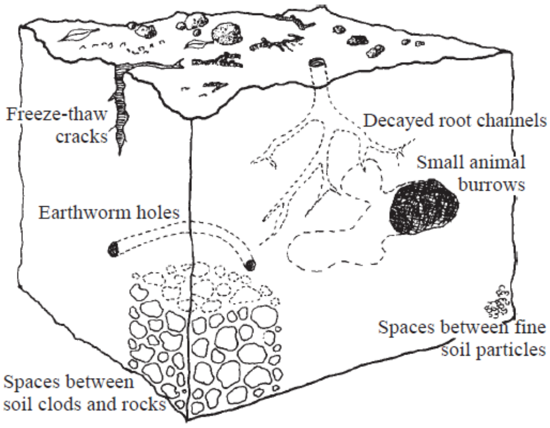


Figure 2.3: Types of preferential flow paths. (Adams, 1998).

2.2.3 Preferential flow

The second type of flow is non-uniform, preferential flow that bypasses a fraction of the porous matrix and propagates quickly to significant soil depths (Hendrickx and Flury, 2001). (Lin, 2010) defined nine different types of lateral preferential flow paths including macropore flow (bypass flow), pipe flow, film flow, mat flow and funnel flow. These pathways can be created by root channels, natural channels caused by erosion from subsurface flows, cracks and fissures caused by shrinkage and swelling of soils (Beven and Germann, 1982) and biological activity by earthworms and moles (Weiler and Naef, 2003) (Figure 2.3). Preferential flow occur can over considerable distances and at speeds of millimetres per second (Lin and Halleck, 2008) moving water quickly towards the river channel. It can be the dominant component of stormflow, with some research suggesting that preferential flows may contribute up to 50% of stormflow (Jones, 2010).

2.2.4 Overland Flow

Water that does not infiltrate into the soil moves over the soil surface as overland flow. There are two types of overland flow, saturation from below/saturation excess overland flow (Dunne and Black, 1970) and saturation from above/infiltration excess overland flow (Horton, 1933). Saturation excess overland flow occurs when the soil fills to capacity and there is no space left for water to infiltrate. If rainfall continues the saturated area (variable source area) will increase in size (Hewlett and Hibbert, 1967). Field and modelling studies have shown that saturation excess is the most common type of overland flow, producing event response, in humid regions including the UK (Dingman, 2002).

Infiltration excess/Hortonian flow occurs when the water input rate exceeds the infiltration rate of the surface layer, for a period longer than the time of ponding. Infiltration excess is an important runoff generating mechanism in arid environments. Both types of Overland Flow are thought to move water relatively quickly from the hillslope to the river initiating rapid runoff and flood events (Dunne and Black, 1970).

The term hydrological connectivity is now widely used in hydrology (Bracken and Croke, 2007). The concept consists of two elements, static refers to the spatial patterns or hydrological units in the landscape such as hillslopes, soils and vegetation and dynamic refers to the evolutionary dynamics of how systems operate and processes link in space and time to develop flow connections ((Bracken and Croke, 2007)). Due to the difficulty in measuring processes, studies have focused on static rather than dynamic connectivity.

2.3 History of Land Management

In the UK, the utilised agricultural area occupies 90,000km^2 (37% total land). Agriculture provides the UK with 75%+ of its food, employs 476,000 people (DEFRA, 2015a) and accounts for 0.7% (£9.9 billion gross value added) of Gross Domestic Product (The World Bank, 2016), down from 5% in the 1950's (Morris et al., 2005).

Before the Second World War (1930's) the UK agricultural landscape (Figure 2.4) was composed of smaller fields, with dense hedgerow boundaries and trees. The soil is thought to have been relatively un-compacted and well-structured. There is a lack of evidence of this but farmers/researchers interviewed at this time did not identify any problems with soil degradation and runoff (Evans, 2010). Water could infiltrate easily down to the water table and create runoff source areas downslope. The river network had more natural channels with more riparian buffer zones that provided a micro-climate/shelter for animals (O'Connell et al., 2004).

Figure 2.4: Pre-war vs. post 1950's landscape of the UK. (O'Connell et al., 2004).

Following the Second World War there was a drive for more intensive farming to manage and prevent national food shortages. The UK government passed the Agricultural Act (UK Government, 1947) which set prices for crops and dramatically increased levels of food production. This piece of legislation led to changes in practices (Table 2.1) which have caused major change in most/all river catchments across the UK (Bilotta, Brazier and Haygarth, 2007).

Table 2.1: Changes in agricultural practices.

Application of more fertilisers
Use of higher yielding crop varieties
Introduction of pesticides
Increased mechanisation
Monoculture
Use of bigger and heavier machinery
Removal of hedgerows and field boundaries and subsequent creation of larger fields
Conversion of grassland to arable land
Increase in farm size - expansion of arable land (87% increase in wheat and barley production in England and Wales 1947 and 1966)
Removal of riparian buffer zones along rivers
Increase in land drains that connect the hilltop to the river channel
Greater stocking densities in fields

The intensification of farming continued and was enhanced further in 1973, when the UK joined the European Common Market (ECM). The Common Agricultural Policy (CAP) paid farmers by weight of cereals produced, so UK farmers changed their practices to grow three times more autumn-sown crops, which had higher yields (Evans, 2010). It was not until the 1970's that UK researchers began to realise that intensive farming was linked to increased soil degradation and (Evans, 1971) was one of the first to ask for monitoring and research into the occurrence and causes. However, it took until 1985 for the UK's Agricultural Development and Advisory Service to publish information for farmers on soil degradation and how to manage it.

The intensification of farming continued in the 1980's, but the level of concern about the impacts of farming on the economy, biodiversity and the landscape also increased. From 1990 onwards research focused on water quality and pollution linked to the upcoming Water Framework Directive (European Commission, 2000). In early 2000 there were modifications to the CAP which set up the England Rural Development Programme 2000-2006 (Ministry of Agriculture Fisheries and Food, 2000) and then later the Rural Development Programme for England 2007-2013 (DEFRA, 2006). These two programmes provided subsidies to farmers administered through the Single Payment Scheme (DEFRA, 2015b). The subsidies encouraged conservation and restoration of the land by minimising soil erosion and runoff through cross compliance. There were different levels - Entry and Higher Level Stewardship and targeted subsidies to encourage more activity in important areas (e.g. English Woodland Grant Scheme and Farm Woodland Premium Scheme).

The most recent Rural Development Programme 2014-2020 (DEFRA, 2014a) has the objective of ‘better management of natural resources and the wider adoption of farming practices which are climate friendly’. The above schemes have now been superseded by the Countryside Stewardship scheme administered through the Basic Payment Scheme (DEFRA, 2015b). There are three elements to the scheme, mid-tier, high tier and capital grants. The aim is to provide incentives for land managers to look after their environment, with a main priority of protecting and enhancing the natural environment through flood risk management, woodland creation and management and reducing widespread water pollution from agriculture.

The next section will discuss arable farming (Section 2.3.1) and grasslands (Section 2.3.2) in the UK, the impacts of these types of land management on hydrology (Section 2.3.3) and methods that can be used to study their impacts on hydrology (Section 2.3.4).

2.3.1 Arable Farming

There is 60,000km^2 of cropland in the UK (27% of the utilised agricultural area) mainly used for wheat and barley production. Yields have climbed steadily since the 1940’s due to the governments drive for higher productivity. Wheat production increased by 87% from 1947-1966 (Evans, 2010) and since 1986 overtook barley to become the dominate cereal crop, producing 9 tonnes/0.01km^2 in 2015. Barley has been in decline since 1985, it fell by 10,000km^2 by 1995 and since 2005 barley has fluctuated around 10,000km^2.

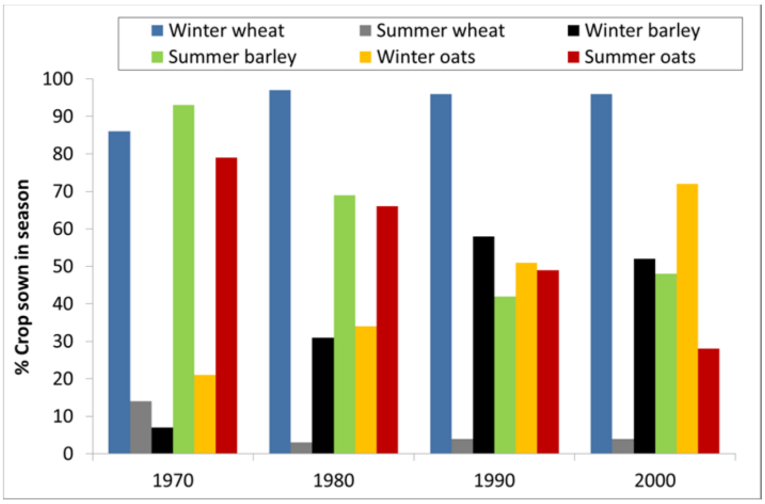


Figure 2.5: Change in seasonality of arable crop sowing. (Harris et al., 2004).

Since 1970 there has been a change in the seasonality of cereal sowing, from spring to autumn (Figure 2.5). In the 1970's most wheat and a small percentage of barley and oats were sown in winter but in the 1980-1990's, nearly all wheat and half of barley and oats were sown in winter and in the 2000's nearly all wheat and oats and half of barley were sown in winter. This trend is now starting to reverse, but the change is slow and will require a change in grants and subsides (Harris et al., 2004).

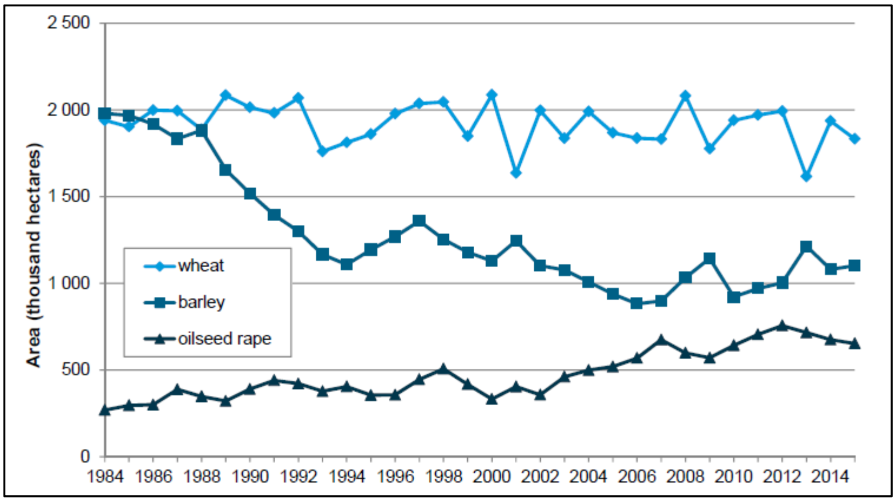


Figure 2.6: Crop areas in the UK, 1984-2015. (DEFRA, 2015).

Two new crops were introduced into UK arable cultivation over the past 50 years (Harris et al., 2004). Oilseed crops were introduced in the 1970s as a break crop in cereals and have steadily increased to become the third largest crop (Figure 2.6). Maize was introduced in the 1980's and production rose to 1,200km^2 in 2001 and 1,830km^2 hectares in 2015 (DEFRA, 2015a). Maize is a problematic crop because it is harvested in late September-middle of October which means tractors are on the land at a time when the soil is wetter and the heavy harvesters can only transverse up and down the slope, which creates tramlines that can become flow paths.

Another method of managing arable land is the use of set aside fields, where land is left to rest (fallow/ley), for a period of time (season/year). Grass set-aside schemes have proven to decrease erosion, increase soil organic matter content and reduce runoff (Fullen, 1998). When this idea was initially introduced in 1988 it was supported by European Union 'Set-aside' subsidies. This led to a five-fold increase in set-aside rising from 1,100km^2 in 1990 to 5,670km^2 in 2000. However, the scheme was suspended in 2008 due to a more demand for cereal production (O'Connell et al., 2004).

2.3.2 Grasslands

Grasslands cover large areas of the temperate land mass, 40% of the agricultural area in Western Europe and 65% in the UK (Bilotta, Brazier and Haygarth, 2007) which has 100,000km^2 of permanent grasslands (Figure 2.7) (DEFRA, 2014b). There are also expansive areas of grasslands in Canada, USA, Australia and New Zealand. The main type of grassland management in England is grazing of livestock, usually for meat and/or dairy products. There are nearly ten million cows and over thirty-three million sheep in England (DEFRA, 2014b). Grass provides 85-95% food for English beef and sheep and perennial ryegrass is the UK's most commonly sown species.

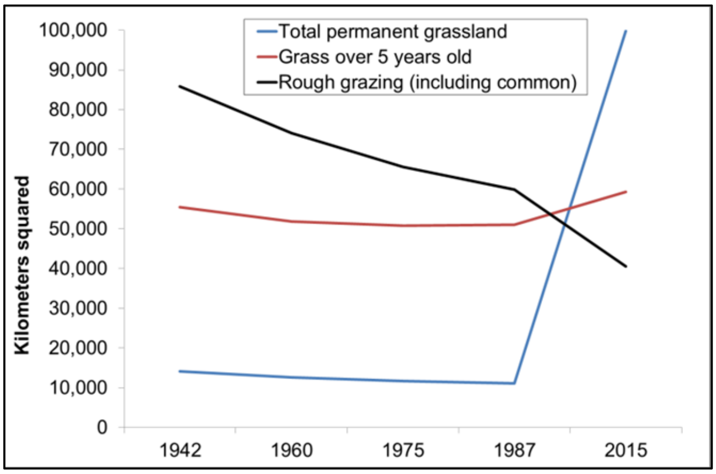


Figure 2.7: Types and amount of grassland in the UK, 2014. (Harris et al., 2004 and DEFRA, 2015).

For cattle, the target sward height prior to turnout in May is ten-fourteen centimetres and grass should be left to graze to a height of five-six centimetres (Genever et al., 2013). Badly managed grasslands are associated with high stock densities, high chemical inputs and high levels of traffic, that can lead to reduced vegetation cover through crushing, bruising and shearing, decline in fauna that causes bare patches and severe soil degradation through compaction, pugging and poaching (Bilotta, Brazier and Haygarth, 2007).

Livestock numbers in the UK rose over the period 1866-1980, cattle numbers increased from 4.47-13.43 million but declined to 10.35 million in 2002 and have stayed steady around ten million ever since. The Agricultural Act (UK Government, 1947) did not have a major impact on cattle stocking numbers, even though land became more profitable for sheep and crop production. Sheep numbers in the 1930’s were around thirty million, this dropped to seventeen million during the Second World War but, from 1950-1990 total sheep numbers increased by 142% to forty million (DEFRA, 2008a). Since then numbers have fluctuated slightly down to thirty-three million.

Over the last ten years there has been an increase in ‘Horsiculture’, defined as “the practice of keeping horses for leisure purposes” (Haigh, 2008). Old grazing land is turned into paddocks to keep horses. In addition farm land has been developed into stables, hay/food stores and manèges – arenas for exercising and training horses (Haigh, 2008). The British horse population has reached an estimated one million (British Horse Society, 2015).

Leisure horses are considered to be an issue by stakeholders because they exist outside of the farming system and so their impact on soil degradation is often overlooked (DEFRA, 2008b). The change in land management from agricultural to horsiculture has been described as an “undesirable management practice” (Countryside Agency, 2003) with environmental implications for ecosystems, including over and under grazing of land (Haigh, 2008), trampling (Newsome et al., 2002) and the pollution of watercourses (Newsome et al., 2002, Quetier and Gordon, 2003, Haigh, 2008). However, the implication of the practice of horsiculture on hydrology and soil degradation has not been widely discussed or investigated in the scientific literature.

2.3.3 Impacts of Land Management on Hydrology

Sections 2.3.1 and 2.3.2 discussed the historical changes in UK rural land management. This section will discuss how these changes have influenced soil properties and hydrological processes (Table 2.2). In general, the impact of land management on hydrology and flood response are significantly under-researched and the link between land management change and flooding are still unclear (Deasy, Titman and Quinton, 2014).

Table 2.2: Main changes to UK agricultural and the effect on the soil quality and on hydrological processes.

Driver	Impact on agriculture	Effect on soil hydrology	References
Agricultural Act and Common Agricultural Policy create drive for higher productivity - especially for cereals	Heavier machinery with heavier loads, heavy seedbed pressing after sowing	Risk of capping, compaction and erosion - Loss of surface roughness, reduced infiltration, increased runoff	(Dickson and Campbell, 1990, Chamen, 2006, Nawaz, Bourrié and Trolard, 2013)
	Larger machinery, and larger tractors with larger and wider tyres, increased mechanisation	Removal of field boundaries and increased field size - Loss of organic content and macropores, longer flow paths increased connectivity, accumulation of larger flow volumes increases erosion,	(Kiepe, 1995a, Walter et al., 2003)
	Pesticides/fertilisers enabled continuous arable cropping	Risk of compaction and loss of organic content - Reduced infiltration, increased saturation excess runoff	(Robinson and Sutherland, 2002, Harris et al., 2004, DEFRA, 2010)
	Spring cereals also sown in autumn, introduction of winter root crops & oilseed rape - Increased trafficking in wetter conditions	Surface capping, compaction and erosion - Reduced infiltration, increased saturation excess runoff, muddy floods	(DEFRA, 2009, Posthumus et al., 2011)
	Grassland converted to arable land, loss of grass leys	Increased bare soil, loss of organic content – Reduced topsoil storage capacity & higher runoff rates	(O'Connell et al., 2004, Riley et al., 2008)
	Use of un-productive land lead to increased field drainage	Dries soil out on either side - Lowers water table and risk of saturation excess runoff, concentrates flow, increases flow times to channel	(Holden, 2009)
	Intensive use of grassland - Increased grazing animals and out wintering of stock	Increased bare patches, poaching, compaction and erosion - Reduced infiltration, increased overland flow, higher flood peaks	(Environment Agency, 2015)
End of grants	Reduction in drainage and drain blocking	Relatively higher water table, increased risk of local saturation excess runoff, slows flow times to channel.	(RBSP, 2003)

2.3.4 Methods Used to Study the Impacts of Land Management on Hydrology

The next section will discuss the three main methods that can be used to study the impacts of rural land management on hydrology. In Section 2.3.4.1 the first to be discussed will be the use of field scale data collection at the local scale. In Section 2.3.4.2 the use of numerical modelling techniques at the catchment scale will be discussed and in Section 2.3.4.3 the use of experimental catchments and the paired catchment approach will be explained.

2.3.4.1 Field-Scale Data Collection

Hydrological data and information collected through field studies is essential to establish values for many model parameters and is the only means to further the knowledge of how hydrological processes and mechanisms can be extrapolated through models (Calder, 1993). Data collection can use either quantitative data collection methods, which rely on sampling and testing hypotheses using statistics. This type of method is usually in the form of experiments/trials, observations, surveys and structured interviews (Harris and Jarvis, 2011).

Sampling is a technique used in quantitative data collection to make practical, logical and sensible conclusions/theories regarding the population of interest. In research, there are several key steps to the process of sampling that will lead to a representative sample of the overall target population, relate to the scope and scale of the study and to the sampling design, parameterisation and practicalities of its implementation (Harris and Jarvis, 2011).

Sampling suffers from the problem of bias which can invalidate the research. Bias can occur regarding the geographical site or situation, the overall size of your research question, when sampling at an unrepresentative time or period, through the method used to collect the data, and when the data set is too small and the underlying variability is relatively high is comparison. During sample design the factors which are likely to affect the processes/phenomenon need to be identified to avoid over/under representation of one group of conditions over another. The collection of metadata as part of the sampling process helps to identify bias and improve future sampling (Harris and Jarvis, 2011).

Sample design is the choice of method and the scale and detail of how you plan to implement your approach. Sampling and analysis is time consuming and costly and sampling therefore must be effective and be realistically achievable. Sampling methods can be non-probabilistic that includes judgemental, snowballing and quota sampling, which are used for exploratory research where only descriptive statistics will be used. The second set of methods is probabilistic and includes systematic, simple random, stratified random, multi-stage random and clustered random sampling, which are needed for analytical and inferential statistical techniques. These types of methods are based on probability theory and are used in most quantitative geographical research because the chance of achieving an unrepresentative sample is low and can be calculated (Harris and Jarvis, 2011).

The optimal sample size is related to the underlying variability in the population you are measuring, the degree of precision you require to answer the question and the level of confidence you need to achieve. A pilot study or monitoring period is useful to estimate general characteristics and the scale of variation when there is little initial information. As sample size increases, sampling error decreases, but more homogeneous populations have a lower sample error than a more variable population. In the field an empirical rule is to stop sampling once the standard deviation of the measurements achieves a degree of stability. Past studies using similar populations can also suggest an appropriate sample size (Harris and Jarvis, 2011).

Measurement error can be caused by the instrument and the observer, if the instrument is not set up correctly or if the sample design and data collection strategy is not fit for purpose with regards to precision and scale. During analysis, there are two types of statistical errors, type one errors occur when the results suggest that you have proven a significant relationship between variables, but this is not true. Type two errors occur when you fail to detect a difference, or pattern in the results and yet a relationship does exist (Harris and Jarvis, 2011).

2.3.4.2 Catchment-Scale Modelling

In the study of catchment hydrology, it is not possible to measure every part of the hydrological system. This is due to the high heterogeneity of the catchment variables in space and time. Hydrological models are simplified depictions of reality that use mathematical equations to represent hydrological processes that occur in time and space. Models are used to test scientific hypotheses when there is only a small amount or no empirical data. They can be used to predict or forecast how a catchment will behave in the future or how a catchment will respond under a certain set of conditions.

Models can help further scientific understanding of dominant processes, catchment behaviour at different scales and in the identification of hot spot areas within catchments which can be useful for decision making (Beven, 2012). However, all model predictions are subject to uncertainty that is associated with two main things (Beven, 2012). The first is our limited knowledge of how hydrological systems work and the second is associated with the limitations in our current measurement techniques, which lead to errors in the observed data that are subsequently input into the model.

Models follow either a bottom-up/mechanistic approach which is based on an understanding at a point scale that it upscaled to the catchment, or a top-down approach which looks at catchment scale data and downscales it to calculate small scale processes. The bottom-up approach is the most widely used in hydrologic sciences due to its physical basis. However, there are concerns that the equations used in this approach, such as Darcy's law for flow of fluid through a porous medium are based on small scale observations/laboratory work which may not accurately represent how water moves over/through the soil at larger scales (Beven, 2012). There are numerous studies on the impacts of land use management on catchment hydrology. Some of the key studies are listed in Table 2.3.

Table 2.3: Modelling of land-use change (LUC) impacts on catchment hydrology.

Reference/Country	Model used	Purpose	LUC scenario	Runoff change
(Nandakumar and Mein, 1997) Victoria, south-east Australia	HYDROLOG - Physical-semi-distributed conceptual, daily version of Monash model	Quantified levels of uncertainty in predictions due to errors in hydrological/meteorological data and the implications for LUC prediction	- 12-43% deforestation	Channel not represented
(Sefton and Howarth, 1998) England and Wales	IHACRES - Lumped conceptual	Develop method to estimate model parameters from catchment characteristics, to eliminate calibration	- 33% change from grassland to woodland - 33% change from grassland to crops	- Reduction in low flows - Increase in flow volume
(Bormann, Diekkrüger and Renschler, 1999) North-west Germany	Coupled SIMULAT KINematic Runoff and EROSion model (KINEROS) - Physical coupled 1D Soil Vegetation Atmosphere Transfer (SVAT)	Investigate the effects of LUC on runoff, due to European Commission policy in Neuenkirchen catchment	- 3% increase in grassland, 15% winter wheat & 12% decrease in winter barley - 12% increase in bare fallow - Minimum tillage practices - Re-meandering channel	- 145% decrease groundwater recharge with winter cover crop - 30% increase peak discharge - 8 to 34% decrease peak discharge - 63% reduced peak discharge
(Lukey et al., 2000) South-east France	SHETRAN	Study of the impacts of afforestation on streamflow in Draix catchment (0.86km^2)	- Catchment afforestation	- 60% decrease annual runoff
HR Wallingford, 2001, EUROTAS project, Central Europe	Hydrologiska Byrans Vattenbalansavdelning model (HBV-D) - Physical-semi-distributed conceptual and LADEMO land use model	Explore the impacts of climate and LUC on the hydrological regime of the Elbe catchment (80,000km^2)	- 10% change urban to agricultural land - 10% change arable to urban/forest/grassland	
Fohrer et al., 2001 North-west Germany	Soil and Water Assessment Tool (SWATmod) - Semi-distributed daily water balance conceptual model	Explore effect of LUC on discharge in Dietzholze catchment (82km^2), divided into 218 hydrological response units	- 35% increase in grassland for forest - 27% increase in forest	- 75% increase surface runoff, but 9% increase in discharge - No effect on catchment mass

			and increase in arable	balance
(Crooks and Davies, 2001), South-east UK	Climate and Land use Scenario Simulation In Catchments (CLASSIC) - Semi-distributed conceptual	Explore effect of historical land use changes (1961-1990) on flood frequency in Thames catchment at Kingston (10,000km^2)	- 40% increase urban - 24% increase grassland - 30% decline in arable	Small, not given
Polytechnic of Milan, 2001, EC-FRAMEWORK project, Europe (Ewen, Parkin and O'Conell, 2000)	1. Water Balance Model (WBM) 2. Flash-flood Event-based Spatially-distributed rainfall-runoff Transformation model (FEST98) 3. Systeme Hydrologique Europeen-TRANsport (SHETRAN)	Evaluate sensitivity of flood risk in flashy systems to the anthropogenic influences on runoff generation mechanisms and climate change using 3 models in 3 catchments	- 12% increase urban - 15% decrease arable	Urbanisation had no impact on flood peaks
European Commission Joint Research Centre - (De Roo et al., 2001)	LISFLOOD – Water balance and flood simulation model at the continental scale – Physical, conceptual, GIS-based distributed	Investigate causes of flooding and influence of LUC, soil characteristics and antecedent moisture conditions in the upper Oder (60,000km^2).	- Increase forest and urban - Decrease arable (Change in land use 1780-present)	0.2% increase peak discharge from 1975-present
(LaMarche and Lettenmaier, 2001) Oregon, north-west USA	Distributed Hydrology Soil Vegetation Model (DHSVM) – Physical grid-based distributed	Examine effects of forest harvesting on flooding in mountainous environments using field observations in Deschutes catchment (149km^2).	- Forest removal - Forest roads	- 10% increase annual flood - 10% increase mean annual flood and increased magnitude
(Naef, Scherrer and Weiler, 2002) South-west Germany	Dominant Runoff Processes (DRP) – Binary decision tree	Develop decision support scheme to ascertain likely DRP's within a temperate catchment and identify appropriate mitigation strategies	No scenarios tested	Discharge not produced
(Niehoff, Fritsch and Bronstert, 2002) South-west Germany	Water flow and balance Simulation Model ETH (WaSiM-ETH) with the LUCK toolkit – Physical distributed	Evaluate impact of LUC on flooding by assessing spatial and temporal dynamics of rainfall events in the Lein catchment (115km^2).	- Increase in urbanisation by 6% - 10% land was set-aside	- Increase flood volume & peak (greater for convective storms) - Minor increase in runoff for

				convective event
(Calder, 2003) Nottinghamshire, England	Hydrology of Land Use Change (HYLUC) – physical daily water balance model	Investigate water use of several vegetation types to derive predictions of the impacts on recharge	Doubling UK woodland	Oak woodland reduced flows by half compared to grassland
(Wheater et al., 2008) Flood Risk Management Research Consortium (FRMRC) UK	Extended Rainfall-Runoff Modelling Toolkit (RRMT) and Soil-Plant-Water (SPW) model – meta-modelling approach: physical distributed model with conceptual model	Examine LUC on runoff generation and propagation. Used data from multi-scale experiments to inform development/calibration at different scales to make meaningful predictions for Pontbren catchment (16km^2)	- Tree strip planting - Catchment afforestation - Deforestation	- 40% reduction overland flow - 9 to 69% decrease peak flow - 6 to 18% increase peak flow
(Pattison, 2010) Thesis, north-west England	Connectivity of RUnoff Model (CRUM) 3 – Physical distributed	Study impacts of LUC on river flows in Eden catchment (2,400km^2)	- Afforestation - Soil compaction	- Coniferous forest produced highest peak discharge - Heavy compaction 65% increase peak discharge - Moderate compaction 3.7% increase peak discharge
(Ewen et al., 2013) United Utilities Sustainable Catchment Management Plan (SCaMP), North-west England	Integrated meta-model – micro-scale physically based hydrological model and lumped model parameterised with HOST soil types and Soil Conservation Service Curve Numbers (SCS-CN)	Explore nature of casual links between land management in rural river catchments and the flood hydrograph in the Hodder catchment (261km^2)	- Blocked gullies and grips - Reduced sheep grazing	Mosaic map outputs show strong spatial patterns in link between land management, soil types, travel distance to outlet and flow rates

2.3.4.3 Experimental Catchments and Paired Approach

The paired catchment approach has been the predominant method for detecting the effects of disturbance on catchment scale hydrology (Zégre et al., 2010) in small catchments. This approach involves the collection of experimental data. This is then used to establish statistical relationships for catchment outlet response between two paired catchments during a calibration period. The catchments are usually similar in size, locality and have similar land use, climate and physical features. Once they have been calibrated land use treatments are applied to one of the catchments (treated) whilst the other remains unchanged (control). The hydrological differences are then determined to show the effect of the treatment.

The advantage of this technique is the ability to remove the effect of natural climatic variability. Some examples are listed in Table 2.4. The main problem associated with this approach is that it can take time for any changes to become evident and it can be difficult to separate out the affect from land-use changes if they are well documented (Brown et al., 2005).

Table 2.4: Paired catchment studies in the UK.

Catchments and size	**Established**	**LUC scenario**	**Main findings**	**References**
Coalburn, borders, Kielder Forest, northern England (1.5km2)	1967	What are the hydrological effects of upland conifer forest afforestation?	Young forest interception losses are low and variable	(Robinson et al., 1998)
			Reduction in peak discharges is smaller for bigger precipitation events	
			Mature forest has reduced the size of peak discharges	
Plynlimon, mid-Wales – Severn and Wye (19.25km2)	1968	Do upland forested catchments yield less water than grassland catchments?	Annual evaporation losses from Severn were 200mm greater than the Wye, creating a 15% reduction in flow	(Kirby, Newson and Gilman, 1991, Robinson, Rodda and
			Forests use more	

			water than short vegetation due to the additional evaporation from the canopy	Sutcliffe, 2013)
Balquhidder, Grampians, southern Highlands, Scotland – Kirkton and Monachyle Glens (6.9km2)	1981	Are the hydrological responses of a forested catchment the same as a non-forested catchment?	Wet uplands will reduce water yield irrespective of whether they replace grass or moorland	(Blackie, 1982, Johnson et al., 1989, Calder, 1993)
			Forest transpiration is limited by environmental conditions	
			Open drainage prior to tree planting caused an approximate halving of time to peak and a 40% increase in flows	
			There is a continuing need for catchment studies	

2.4 Soil Compaction and Soil Hydrology

The next section will define the process of soil compaction and Section 2.4.1 will discuss ways to measure compaction. The following Section 2.4.2 will discuss the effect of arable farming on cropland and Section 2.4.3 will discuss the effect of grazing on pasture.

Soil compaction is the inability of soil to withstand external pressures applied to it. When a weight is applied to the soil the physical structure collapses which leads to a coarsening, or loss of soil structural units. The strength of all soil is dynamic and varies according to soil type and soil moisture content (Larson, Gupta and Useche, 1980). On rural land soil compaction can occur due to poaching on pasture and due to ploughing (plough pans) and trafficking (tramlines) on arable land.

Soil compaction causes soil erosion (Deasy, Titman and Quinton, 2014), nutrient depletion (Lipiec and Stepniewski, 1995) and pollution (Newell-Price and Whittingham, 2012) and in England has been identified as one of three key threats to the productivity of soils (Batey, 2009). A recent review by (Graves et al., 2015) estimated that 39,000km^2 are liable to soil compaction in England and Wales and an estimated cost £472 million is lost through yield reduction, flood damage and nitrogen loss associated with the impact of runoff.

Soil compaction can encourage surface capping due to the presence of bare soils. Capping occurs when rainfall breaks down soil particles (slaking) and washes the fine particles into the micropores. Over time these particles bind together and create an impermeable capped surface layer, which increases surface runoff. Soils with a high silt or fine sand content and soils lacking cementing agents such as organic matter are most prone to capping because there particles are not strongly attracted to each other (DEFRA, 2008c). Capped soils can be identified by inspecting the soil profile, or by running a slake/soil stability test in the laboratory.

2.4.1 Measuring Soil Compaction

When soil is compacted it strength, structure and drainage potential are modified. The impact of grazing and arable farming on the soil can therefore be measured by studying these changes. Compaction levels at a site are also influenced by the soil texture and soil moisture content at the time of measurement. Soils with fine sandy loam and loamy fine sands are the most susceptible to harmful compaction compared to other types (Hatley, 2005). Field capacity (soil water content after gravity drainage) has been identified as the danger zone for trafficking of clay soils (Mapfumo and Chanasyk, 1998).

Texture affects how quickly and for how long soil compaction lasts. On coarse soils (sand) compaction can naturally rejuvenate quicker (one year) compared to the response of clay soils, which might take five years to return to pre-compaction conditions. However, soils with a clay content of less than 20% have been shown to be very vulnerable to compaction (Mitchell and Berry, 2001), particularly in wet periods (Graves et al., 2015). Compacted very sandy soils have a structure of intergranular pores with short and narrow cracks. In comparison, compacted silty or loamy soils have a dense arrangement of soil aggregates with either a platy structure with highly regular horizontal fissures, or a massive structure with horizontal and vertical cracks (Horn et al., 1995). These cracks allow clay soils to recover quicker in dry years due to the positive effect of swelling and shrinkage (Spoor, 2006).

High soil water content is a primary factor that increases a soils vulnerability to compaction (Hatley, 2005). When soil water content is very high (reaching their plastic limit) the soil is prone to severe soil degradation. There is an optimum water content, at which point any further increases will not cause further levels of compaction due to soil becoming increasing plastic and incompressible (Hamza and Anderson, 2005). Advice suggest to keep the water table be kept at a depth greater than 0.5m to reduce the potential of compaction and to keep a good level of soil strength (Godwin and Dresser, 2003).

The critical moisture content (CMC), defined as being both below field capacity and the plastic limit for fine textured soils is often said to be 80% of saturation (Hillel, 1980). However, during the wet period (late autumn and winter) the soil has been shown to be more prone to compaction when the water content of the soil is greater than 43% (Houlbrooke et al., 2009) and in the spring a water content of 70% has been shown to be a critical level for the initiation of treading damage (Sheath and Boom, 1997) due to spring melt and the potential for long duration rainfall (Naeth et al., 1991).

In terms of measurement, soil water content is highly spatially and temporally heterogeneous depending on the antecedent and current weather conditions, the land use history and soil texture of the site therefore on its own it is not a good measure of soil compaction.

2.4.1.1 Soil Strength

The property of penetration resistance is a measurement of soil strength which is often used to determine the influence of grazing on soil compactness. It can be insensitive to small changes in porosity (Greenwood and Mcnamara, 1992) and is affected by soil moisture (Daniel et al., 2005) so water content values should be collected during experiments. Values of 200-500kPa have been reported to limit root growth in arable soils (Håkansson, Voorhees and Riley, 1988) but most field studies report resistance values for heavy compaction that are over this threshold (Table 2.6).

The property of unconfined compressive strength (UCS) is a measurement of soil strength that can be easily observed using a pocket penetrometer. Manually operated penetrometers can yield variable results due to differences in the rate of insertion as this can change the resistive force (Herrick and Jones, 2002). As well as variable penetration velocity different operators can exert difference physical strength and leverage. Therefore, multiple readings should be made and any that vary widely from the mean should be discarded.

2.4.1.2 Soil Structure

Bulk density (ρ_b) is a measure of the amount of soil per unit volume. The property of bulk density is widely used to determine the effects of treading due to its simplicity. However, bulk density can be insensitive to small changes in soil compactness and other properties such as the percentage of macropores which are more sensitive to compaction (Greenwood and Mcnamara, 1992). Bulk density is often constant in time but increases with depth due to the weight of the soil above it.

Table 2.5: Typical values of bulk density, porosity and organic matter content collected in field studies.

Soil texture	Bulk density (g/cm^3)	Porosity (%)	Organic matter content
Sand	1.2-1.6	40-42	Low
Silt loam	0.9-1.4	43-48	Medium
Clay	0.8-1.1	43-70	High
Organic matter	0.1-0.8	>50	High

Bulk density can also increase under certain types of land management (Dingman, 2002) and is therefore a direct measure of soil compaction and degradation (Emmett et al., 2008). Values range from 0.10-1.90 for natural soils (Table 2.5) and are dependent on soil texture, calcium carbonate content and particle density. Soils high in organic matter content have very low bulk densities and soils with high sand content have higher bulk densities (Dingman, 2002).

When soil is compacted the number and size of pore spaces are reduced or destroyed. The largest pores are lost or reduced first, this changes the pore size distribution of the soil and the water retention characteristic (Dexter, 2004). The total porosity ($\emptyset$) is the inverse of bulk density also referred to as air permeability and is defined as the proportion of pore spaces in a volume of soil. It is often measured by determining bulk density and assuming a value for particle density (Dingman, 2002). In general, fine grained soils have higher porosities than coarser grained soils due to the arrangement of particles. Fine grained particles are often more angular than sand particles which are more spherical and fine particles are held in a structure by inter-grain electrostatic forces (Hillel, 1980).

The most sensitive soil physical property is macroporosity due to its effect on air and water transmission and plant growth. Macropores transmit most water through a soil during wet conditions and can be therefore used as a good measure of the extent of soil compaction. A reduction in macropores limits the amount of connectivity and reduces the redistribution of water in the root zone (Greenwood and Mcnamara, 1992).

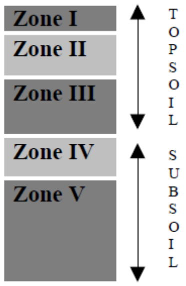
2.4.1.3 Soil Drainage

There are two properties that can be determined when assessing the impact of compaction on soil drainage. The first is the infiltration rate and the second is the saturated hydraulic conductivity. This section will look at each of these properties in turn and discuss the range of values collected in the field.

The infiltration rate is the ease with which water enters the soil and is dependent on the rainfall event intensity and duration and the depth of ponded water on the surface prior to the event. The saturated hydraulic conductivity (Ksat) is the volume rate of flow per unit area of a saturated porous medium. For mineral soils, this is determined by the grain size and the macroporosity. For very low rainfall intensities no macropore flow occurs, unless the soil is fully saturated (Burt and Heathwaite, 1996). The determination of Ksat is undertaken in the field with the double ring infiltrometer test, or in the laboratory on soil samples using either the constant or falling head test.

2.4.2 Arable Farming and Soil Compaction

This section will look at studies on the impacts on mechanical cultivation and wheel traffic on the soil by discussing the research globally that looks at this topic. Arable farming is the greatest source of soil degradation in England and Wales due to soil compaction, erosion and organic matter loss (Graves et al., 2015). The effects of arable farming on soil quality were discussed in the ‘Modern Farming and the Soil’ report (Ministry of Agriculture Fisheries and Food, 1970). All-arable rotations without a grass break were recognised as an issue because farmers needed to cultivate the land when conditions were unfit. Frequent cultivations at the same depth were also recognised to increase the potential of creating plough pans. Intensive cereal growing for four/five years without a break was recognised to destroy soil structure and lower soil organic matter, except in stable calcareous soils (Ministry of Agriculture Fisheries and Food, 1970).



Zone I	Surface crust caused by soil particle consolidation by irrigation or rain (0–5o mm)
Zone II	Loose part of the plough layer due to loosening by shallow secondary tillage operations (50–250 mm)
Zone III	*Recompacted plough layer due to compaction by vehicular traffic and irrigation after ploughing (0.25–0.35 m)**
Zone IV	Subsoil compaction due to wheel traffic in the plough furrow and implement soil interaction during primary tillage operations (0.3–0.7 m)
Zone V	Subsoil with naturally high bulk density due to genetic (*sic*) factors (0.7 m and greater)

*Note that this also applies to zones I and II.

Figure 2.8: Approximate compaction zones within arable soil. These will vary depending on farming practice and soil type (Hatley, 2005).

Soil compaction by machinery occurs when the soil is compressed under the wheels of tractors, trailers and harvesters and as tillage equipment is moved through the soil (Batey, 2009). The impacts of mechanical soil cultivation affect the soil in several distinct ways that have been identified as five main compaction zones. Repeated ploughing over time can create a compacted layer (Zone 3 in Figure 2.8) at the bottom of the topsoil known as a plough-pan. This is an impermeable soil layer in the approximately twenty-five to thirty-five centimetres deep (Coutadeur, Coquet and Roger-Estrade, 2002) that encourages more lateral throughflow and surface runoff, creates a barrier to percolation (Figure 2.9), and creates anoxic, waterlogged zones and denitrification. The pan has different soil moisture properties than the surrounding soil (Brereton, McGowan and Dawkins, 1986) because evaporation removes water from the sub-surface above the pan and it cannot be replaced with water from below (Batey, 2009).

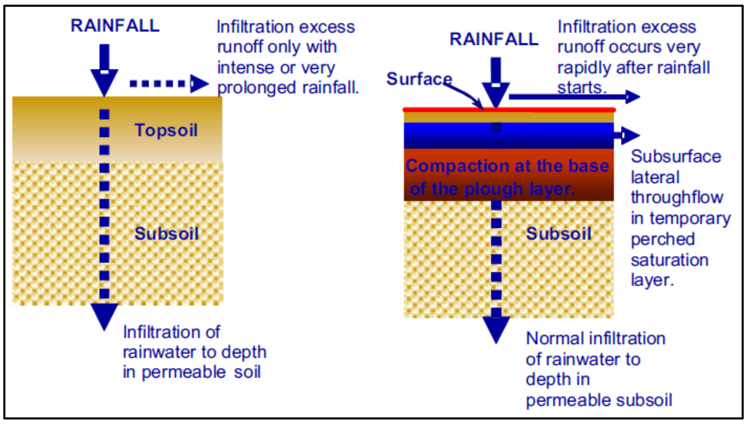


Figure 2.9: Plough-pan formation in the topsoil.
(O'Connell et al., 2004).

The influence of mechanical cultivation extends into zone four (Figure 2.8) to a depth of seventy centimetres because of primary tillage (loosening and seed bed preparation) and wheel traffic (Addiscott and Dexter, 1994). The impact of tillage leads to a dramatic decrease in the humus content in the topsoil which affects the soil stability (Horn et al., 1995) and causes capping (Environment Agency, 2015).

The impacts of wheel traffic, the frequent movement of tractors between and across fields (Posthumus et al., 2011), causes serious disturbance to the pore structure by changing the pore size distribution and the total number of pores, which has an impact on their function (Horn et al., 1995). Tramlines, also known as wheel lines, wheel tracks or wheelings are compacted lanes created on the surface by tractors and other farm machinery with tyres.

Wheel traffic does not just exert pressure through static stress but, also through dynamic forces including the vibration of the engine, wheel slip and through the movement of the attachments. Fields which are repeatedly subjected to machinery traffic experience modifications to their site-specific internal soil strength depending on three key points (Horn et al., 1995). The first is the level of external pressure applied, the second is the frequency of pressure applied and the third is the local soil water status at the time of loading.

The level of external pressure applied to the soil is related to the weight of agricultural vehicles and the size and inflation of their tyres. Vehicle weight has increased since the 1970's in the UK and the maximum gross weight of agricultural combinations (tractor, trailer, axle and load) is now thirty-one tonnes (Department for Transport, 2014). Relatively light machines will only affect the topsoil which is relatively easy to alleviate however, heavier axle loads increase stresses at much greater depths, creating sub-surface compaction, which is harder to alleviate. Axle load are believed to be the main cause of subsoil compaction (Keller and Arvidsson, 2004) with loads greater than 6000kg creating compaction at a depth of forty centimetres (DEFRA, 2007a) and loads greater than ten tonnes leading to compaction in the sub-surface (50cm+) (Håkansson, 1985).

The impact of tramlines on soil structure and moisture is greatest in the top ten centimetres (Barik et al., 2014) underneath the rear wheels of a tractor (Horn et al., 1995) although the effects have been seen to ninety centimetres depth (Berisso et al., 2012). The depth of the compacted layer is affected by the weight of the machinery (Hamza and Anderson, 2005), the soil moisture level and texture. Tramlines have been highlighted as areas that encourage surface runoff downslope (Holman et al., 2003), concentrate flow and direct it quickly towards a watercourse (Heathwaite, Quinn and Hewett, 2005). In these downstream areas water can pond and further compaction is more likely to occur (Batey, 2009).

Figure 2.10: Typical tractor set-up - John Deere 6R series. (John Deere, 2016).

Tractor tyres exert approximately 80-190kPa ground pressure depending on their size, surface area and location on the tractor (Frost, 1988). The definition of high tyre pressures have increased over time rising from 50kPa in the 1980's to 90-120kPa in the 2000's (DEFRA, 2007a) and keeps rising as productivity grows. Tractors are designed with two front tyres and two rear tyres (Figure 2.10) that are two-thirds larger than the front tyres (the front axle turns one and a half times faster than the rear). Tyres come in a wide range of tread types, diameters, widths and arrangements which are chosen for traction, fuel efficiency and soil conditions (Francis, 2013).

A flexible pneumatic tyre with moderate inflation pressure, on firm soil exerts a ground pressure of the same magnitude as the tyre inflation pressure. The vertical stresses exerted by tyres are greatest under the centre line. Stresses extend deeper into the soil with increased loading (Håkansson, Voorhees and Riley, 1988) however, partially deflated tyres increase the contact area, spread the weight over the soil, lowering the soil pressure and focus less weight in the centre of the tyre (Visagie, 1976, Raper et al., 1995). The use of dual or triple tyres further increases the contact area (Botta, Jorajuria and Draghi, 2002) and reduces the level of compaction (Håkansson, Voorhees and Riley, 1988, Keller and Arvidsson, 2004). Other important factors are the negative effects of un-even tyre pressures and the rigidness of the body of the tractor, both can cause higher levels of ground pressure (Håkansson, Voorhees and Riley, 1988).

The intensity of machinery traffic, known as traffic intensity can be measured in Mgkm ha^{-1}, which is the weight of the vehicle in megagrams multiplied by the distance driven in kilometres. This measurement includes the wheel load so a value can be assigned to the whole field, but it does not distinguish between heavily compacted tramlines and un-compacted non-tramline areas of the field. The most intensive vehicle traffic is caused by ploughing, manure spreading and sugar beet harvesting (Håkansson, 2005).

The frequency of external pressure applied to the soil is related to the number of tractor passes and the annual wheel track area (AWTA). The first pass of a tractor causes the greatest amount of soil compaction (up to 50%). After this the second pass will cause approximately 10% and then following passes will only cause <6% more compaction (National Soil Research Institute, 2001). The AWTA is a simple way to quantify the traffic intensity and is usually several times the field area because each point in the field will have a loaded vehicle pass over it at least twice a year. The AWTA for small grains (maize, soybeans and cotton) is usually three times the field area and for more intensively cultivated crops like root vegetables it can be six times the field area. Deep tillage operations (ploughing) have a much large AWTA than shallow operations because the working width is smaller. The use of AWTA is limited as it does not give values of the compressional forces of the machinery (Håkansson, Voorhees and Riley, 1988).

Since the 1990's research into compaction in the UK has been focused on the impact of soil structure on crop production (Silgram and Shepherd, 1999, Scott et al., 2005) and nutrient movement (Addiscott and Dexter, 1994, Ball et al., 1997, Harris and Catt, 2006). The 'Impact of agricultural soil conditions on floods' report (Holman et al., 2003) stated that there were no measured data sets for the UK that establish connectivity between field scale runoff and stream response during storm events. The report asked for 'field studies to investigate the potential to develop on-farm soft engineering solutions that reduce the immediate impact of field-scale runoff however, there have been limited studies published.

Two studies were conducted at Rothamsted Research, Devon on soil samples using laboratory and modelling techniques. They found that soil compaction had a clear effect on water retention at matric potentials wetter than -10kPa, with voids greater than 30μm in diameter (Matthews et al., 2008, 2010). Internationally however, there has been a great deal of research into the incidence, consequences and counter measures against compaction.

Soil compaction creates a higher risk of surface runoff in low duration and low intensity rainfall events. Arable land with bare soils is prone to runoff and can cause muddy flooding (sediment loaded runoff) in lowland areas, that causes damage to property, roads and watercourses (Boardman, 2010). Muddy flooding is different from river flooding in that its origin is in ephemeral, non-permanent channels (rills and gullies) (Butler, 2005) and are a widespread problem in southern England. Muddy flooding can be reduced, or prevented by altering the land-use over winter in cereal fields, to cover crops (Clements and Donaldson, 2002) such as mustard or rape which can reduce runoff by up to 12% (Schaefer, 1986) or to permanent grassland (set-aside) (Sibbesen et al., 1994). Other ways to break up surface runoff are to reduce field sizes and to introduce small dams on the land (Evans and Boardman, 2003).

The next three sections will look at the impact of traffic on the soil strength, structure and drainage. The variability in observed field data is due to the way in which the treatments have been assigned by different researchers.

2.4.2.1 Impact on Soil Strength

Penetration resistance observed in the field ranges widely for the no tractor passes and is narrower in range for the one-three and greater than four tractor passes (Table 2.6). There is an increasing trend in the mean penetration resistance as the number of tractor passes increases. Penetration resistance is greater (+32%) in the top fourteen centimetres following the first pass of a tractor (Barik et al., 2014) but, subsequent passes cause relatively small increases in resistance (Taghavifar and Mardani, 2014). Unconfined compressive strength observed in the field ranges widely for the one-three and greater than four tractor passes and is narrower in range for the no tractor passes (Table 2.7). There is an increasing trend in the mean UCS as the number of tractor passes increases.

2.4.2.2 Impact on Soil Structure

Bulk density observed in the field ranges slightly more (0.96-1.54g/cm^3) for the no tractor passes and is only slightly narrower for the one to three and greater than four tractor passes (Table 2.8). There is an increasing trend in the mean bulk density as the number of tractor passes increases. Bulk density increased by 17% following one pass of a tractor with rear tyres carrying 2000kg each and by 20% for rear tyres carrying 2660kg each in comparison with a control sample with no traffic (Botta, Jorajuria and Draghi, 2002). Significant differences in bulk density have been observed in trafficked areas in many studies, in different locations and climatic settings (Brereton, McGowan and Dawkins, 1986, Ball et al., 1997, Godwin and Dresser, 2003, Głąb, 2008, Garbout, Munkholm and Hansen, 2013, Barik et al., 2014, Krebstein et al., 2014). Increases in bulk density are more evident in the top fifteen centimetres of the soil because density increases naturally with depth.

Table 2.6: Topsoil (10-15cm) penetration resistance under trafficking. *measurements taken to 30cm depth.

				Tractor passes			
				0	**1-3**	**4+**	
Location	**Soil**	**Season**	**Crop**	**Penetration resistance (kPa)**			**Reference**
Buenos Aires, Argentina	Clay	Spring	Wheat, soybean	168	508	604	(Botta, Jorajuria and Draghi, 2002)
Mydlniki, Poland	Silty loam	Autumn	Lucerne	1890*	2530*	3180*	(Głąb, 2008)
Erzurum, Turkey	Silty sand	Autumn	Corn	296	-	434	(Barik et al., 2014)
Laboratory test	Clay loam	-	-	-	121-260	-	(Taghavifar and Mardani, 2014)
Range				**738**	**1327**	**1310**	
Mean				**29-1890**	**124-2530**	**316-3180**	

Table 2.7: Unconfined compressive strength, determined with a pocket penetrometer, under trafficking.

				Tractor passes			
				0	**1-3**	**4**	
Location	**Soil**	**Season**	**Crop**	**UCS (kg/cm^2)**			**Reference**
Krinec, Czech Republic	Loam	Summer	Wheat	1.02	2.55	4.08	(Hula et al., 2015)
		Autumn		0.46	1.22	1.27	
Queensland, Australia	Clay	Autumn	Wheat	0.51	1.79	-	(Radford et al., 2000)
Range				**0.46-1.02**	**1.22-2.55**	**1.27-4.02**	
Mean				**0.66**	**1.85**	**2.68**	

Table 2.8: Topsoil (0-15cm) bulk density under trafficking.

				Tractor passes			
				0	**1-3**	**4+**	
Location	**Soil**	**Season**	**Crop**	**Bulk density (g/cm^3)**			**Reference**
Osiny, Poland	Sand	Spring	Barley	1.54	1.66	1.71	(Czyz, 2004)
	Sandy loam			1.45	1.60	1.65	
Sadlowice, Poland	Sandy loam			1.51	1.63	1.71	
	Loam			1.54	1.58	1.64	
Buenos Aires, Argentina	Clay	Spring	Wheat, soybean	0.96	1.12	1.16	(Botta, Jorajuria and Draghi, 2002)
Felin, Poland	Loess	Spring	Soybean	1.29	-	-	(Lipiec, Wójciga and Horn, 2009)
Lublin, Poland	Silty sand	Spring-Summer	Soybean	1.29	1.49	1.58	(Siczek and Lipiec, 2011)
North Rhine-Westphalia, Germany	Clayey silt	Spring-Autumn	Rye, beet	1.46	-	1.57	(Hartmann et al., 2012)
Gentinnes, Belgium	Loess	Autumn	Wheat, beet	1.31	1.55	-	(Destain et al., 2016)
Range				**0.96-1.54**	**1.12-1.66**	**1.16-1.71**	
Mean				**1.37**	**1.52**	**1.57**	

Table 2.9: Topsoil (0-15cm) porosity under trafficking.

				Tractor passes			
				0	**1-3**	**4+**	
Location	**Soil**	**Season**	**Crop**	**Total porosity (%)**			**Reference**
Mydlniki, Poland	Silty loam	Autumn	Lucerne	50	-	44	(Głąb, 2008)
Erzurum, Turkey	Silty sand	Autumn	Corn	55	49	-	(Barik et al., 2014)
Jokioinen, Finland	Silty clay	Spring	Barley, oat, wheat	47	-	47	(Schjonning et al., 2013)
Kavlinge, Sweden	Sandy clay	Spring	Wheat, beet, barley	38	-	36	(Berisso et al., 2012)
Range				**38-55**	**-**	**36-47**	
Mean				**48**	**49**	**42**	

Table 2.10: Topsoil (0-15cm) macroporosity under trafficking.

				Tractor passes			
				0	**1-3**	**4+**	
Location	**Soil**	**Season**	**Crop**	**Macroporosity (%)**			**Reference**
Edinburgh, Scotland	Clay loam	Spring	Silage	23	13	13	(Ball et al., 1997)
	Loam		Barley	12	7	5	
Uppsala, Sweden	Clay	Winter	Wheat, oats, rape	16	-	9	(Mossadeghi-Björklund et al., 2016)
Azerailles, France	Silt loam	Spring	Forest	-	-	16	(Bottinelli et al., 2014)
Clermont-en-Argonne, France				-	-	4	
Range				**12-23**	**7-13**	**4-16**	
Mean				**17**	**10**	**9**	

Total porosity observed in the field ranges widely for the no tractor passes and is narrower in range for the greater than four tractor passes. There is a lot of variability in the mean total porosity but in general it increases from one-three passes to greater than four passes. Any decrease in total porosity can have a long-term influence on soil structure and decreases in porosity can persist for at least fourteen years following heavy compaction by traffic (Berisso et al., 2012).

Macroporosity observed in the field ranges widely for the no tractor and greater than four passes and are narrower in range for the one-three tractor passes (Table 2.10). There is an increasing trend in the mean macroporosity as the number of tractor passes increases. The property of macroporosity is sensitive to significant decreases in the top twenty centimetres of the soil (Mossadeghi-Björklund et al., 2016) especially large macropores (>90mm^2) which have been shown to decrease by up to 47% (Bottinelli et al., 2014).

Large pores can become blocked or disconnected from the other macropores which affects the transmission of water through the topsoil and into the sub-soil (Schjonning et al., 2013). Small and medium macropores (0.05-0.9mm^2) can rejuvenate over time (two-three years), however larger pores and channels take much longer to re-establish and are less likely to regenerate completely. The orientation of recovered large macropores may also be different to naturally occurring macropores (Bottinelli et al., 2014).

Organic matter content is important for soil stability but roots are modified underneath tramlines due to their inability to spread vertically and access essential nutrients (Głąb, 2008). Roots become shorter, wider and more prevalent in the topsoil and in just one year of traffic root length and mass in the topsoil decreased by 48 and 61% respectively (Krebstein et al., 2014).

2.4.2.3 Impact on Soil Drainage

The property of saturated hydraulic conductivity (Ksat) decreases significant (10%) following tractor induced compaction (Godwin and Dresser, 2003), compared to sites without farm traffic (Davies, Finney and Richardson, 1973, Young and Voorhees, 1982). Compaction has been shown to significantly decrease conductivity under traffic in comparison to control sites (Mossadeghi-Björklund et al., 2016). Conductivity values in the topsoil (0-10cm) were 27% higher in the control area of the field compared to the compacted tramlines (Krebstein et al., 2014).

Saturated hydraulic conductivity in the field ranges widely for the no tractor passes and are narrower in range for the one-three and greater than four tractor passes (Table 2.11). The mean conductivity at the sites with no passes was higher than the sites with trafficking, however there was a lot of variability in conductivity at trafficked sites and there was no clear trend that the number of passes increased conductivity.

Table 2.11: Topsoil (0-15cm) saturated hydraulic conductivity under trafficking.

				Tractor passes				
				0	**1-3**	**4+**		
Location	**Soil**	**Season**	**Crop**	**Ksat (mm/hr)**			**Test**	**Reference**
Edinburgh, Scotland	Clay loam	Spring	Rape	560.0	2.4	0.6	Field – Double ring infiltrometer – Constant Head	(Ball et al., 1997)
	Loam		Barley	2080.0	810.0	552.0		
Iwo, Nigeria	Sandy loam	Autumn	Maize	-	205.0	-	Field – Double ring infiltrometer - Constant Head	(Wilkinson and Aina, 1976)
Oba, Nigeria				-	251.0	-		
Entrechaux, France	Loamy sand	-	Vineyard	-	50.0	-	Field - Rainfall simulator	(Van Dijck and Van Asch, 2002)
Estrees-Mons, France	Silt loam	Spring	Pea, wheat linen	118.0	-	-	Field - Single ring infiltrometer	(Capowiez et al., 2009)
			Sugar beet, wheat, maize	68.0	-	-		
			Range	**68-2080**	**2.4-810**	**0.6-552**		
			Mean	**707**	**264**	**276**		

Table 2.12: Topsoil (0-15cm) unsaturated hydraulic conductivity under trafficking.

				Tractor passes				
				0	**1-3**	**4+**		
Location	**Soil**	**Season**	**Crop**	**Infiltration rate (mm/hr)**			**Test**	**Reference**
Uppsala, Sweden	Silty clay	Winter	Wheat, oats, rape	-	-	109	Laboratory – Falling head test	(Mossadeghi-Björklund et al., 2016)
				-	-	377		
Rohu, Estonia	Sandy loam	Autumn	Silage	0.8	0.6	-	Laboratory – Falling head test	(Krebstein et al., 2014)
Sebele, Botswana	Sandy clay loam	Summer	Sorghum	259	196	-	Field – Double ring infiltrometer - Falling head	(Moroke et al., 2009)
	Clay loam			124	10	-		
Tswidi, Botswana	Sandy loam			147	3	-		
Sese, Botswana	Sand			277	7	-		
			Range	**0.8-277**	**0.6-196**	**109-377**		
			Mean	**162**	**43**	**243**		

2.4.3 Pastoral Grazing and Soil Compaction

This section will look at studies on the impacts on animal grazing on the soil by discussing the research globally that looks at this topic. Section 2.4.3.1 will look at the impact of grazing on the soil structure and Section 2.4.3.3 will look at the impact of grazing on water movement. There are a lot of review papers over the past twenty years on the influence of grazing on the soil (Trimble and Mendel, 1995, Mitchell and Berry, 2001, Hamza and Anderson, 2005, Drewry, 2006, Spoor, 2006, Crush and Thom, 2011, Ziyaee and Roshani, 2012, Graves et al., 2015) but, there have not been many field studies. The studies which have been completed focus mainly on cattle grazing and less so on sheep grazing, with only a very small percentage on horse and deer/elk grazing.

In the UK the impacts of grazing on soil quality have been discussed since the (Ministry of Agriculture Fisheries and Food, 1970) report. Poaching by grazing animals was recognised as an ‘urgent problem in wetter areas of Britain’ (Batey, 1979). The degradation of the soil structure by dairy cows was identified as the worst offenders, due to their ‘greater weight and frequent movement’. However, following the MAFF report there were very few UK field studies published on animal grazing (Scholefield and Hall, 1986, Davies, Adams and Wilman, 1989) until the start of the 2000’s.

There have been few field studies that collect information on soil structure and water content under grazing land. The most extensive study was undertaken by (Newell-Price and Whittingham, 2012), who surveyed three hundred grassland fields under permanent pasture (greater than five years) with cattle grazing for beef (58%) and dairy production (42%) in England and Wales. They identified that 10-15% of grassland soils were in poor soil condition. However, globally there are several specific grassland/rangeland research centres which have undertaken research into the impacts of grazing on soil hydrology (Table 2.13).

Table 2.13: Main world-wide grassland research centres (1949-2016).

Country	Type of research	Research Centre	Main findings	References
UK	Government – MAFF/ DEFRA	1931-1985: National Grassland Research Institute • Woburn Experimental Station (1931-1949) • Drayton, Warwickshire (1949-1952) • Experimental Station, Hurley, Berkshire (1952-1992) • North Wyke Farm Station, Devon (1981-present)	Sheep treading caused increased soil compaction, significantly reduced herbage growth by 10% and plant root weight by 47%.	(Keen and Cashen, 1932, Curll and Wilkins, 1983, Kubo and Isobe, 1983)
			Sheep treading extended to a depth of 10cm, with maximum compression occurring at a depth of 3-4cm.	(Keen and Cashen, 1932)
		1985-1987: Animal and Grassland Research Institute	Penetrometer created to simulate stresses exerted by walking cows. Deep hoof prints are not produced immediately in wet soils, but only after a progressive loss of soil strength due to repeated treading.	(Scholefield and Hall, 1986)
		1987-1993: Institute for Grassland and Animal Production • University College of Wales (1990-2008) • Bronydd Mawr, Brecon, Wales • Experimental Station, Hurley, Berkshire (1952-1992) • NWFS, Devon (1981-present)	Cattle treading created bulk density levels which were twice as great in the 10-12cm layer, than in the 2-4cm layer. Total porosity in the 10-12cm layer was only 22%.	(Davies, Adams and Wilman, 1989)
		1993-2008: Institute of Grassland and Environmental Research (IGER) • University of Aberwyswyth • NWFS, Devon	Review of the impacts of grazing animals on the quality of soils, vegetation and surface waters in intensively managed grasslands.	(Bilotta, Brazier and Haygarth, 2007)
		2002-present: Rothamsted Research, Sustainable Soils and Grassland Systems Department • North Wyke Farm Platform, Devon	Investigated the extent to which pore sizes within soil samples can be inferred from water retention curves and the extent to which saturated hydraulic conductivity can be related to pore size distributions. Compaction had a clear effect on wate retention at matric potential wetter than -10kPa	(Matthews et al., 2010)

		- Experimental Station, Harpenden, Hertfordshire - Institute of Biological, Environmental and Rural Sciences, Gogerdann - Grassland Development Centre, University of Aberystwyth	for grassland clay topsoil and silty inorganically fertilised topsoil.	
	Independent consultancy	ADAS	Collected soil samples from 300 grassland fields. Best way to comprehensively assess and quantify compaction (at various depths) is through a combination of quantitative and visual methods. Bulk density values were inversely correlated with organic matter content.	(Newell-Price and Whittingham, 2012)
New Zealand	Government – Agriculture and biotechnology sector	Prior to 1992: New Zealand Pastoral Agriculture Research Institute Limited - Grasslands Division, Department of Scientific and Industrial Research, Palmerston North	Stock treading reduced measured herbage yields, especially when the soil was wet. There was also a significant change in the soil itself, such as limitation of soil air and gleying at 1m+ depth in winter.	(Edmond, 1963)
			Stock treading affects plant growth, soil properties and animal health. This included a loss of macroporosity, but no change in bulk density or total porosity.	(Climo and Richardson, 1984)
		1992 – present: AgResearch - Grasslands and Hopkirk Research Institute, Palmerston North - Ruakura, Hamilton - Lincoln, Christchurch - Invermay, Dunedin	Sheep treading in winter resulted in significant losses of large soil macropores and restriction of water through the soil, leading to waterlogging.	(Sheath and Boom, 1997, Sheath and Carlson, 1998, Singleton, Boyes and Addison, 2000, Russell et al., 2001, Drewry, 2003, Drewry, Paton and Monaghan, 2004, Houlbrooke et al., 2009)

			Heavier cattle treading created greater soil surface damage. Damage was also greater when a slow rotation was implemented and when cattle were grazed under wet conditions.	(Sheath and Boom, 1997)
			Cattle treading created the most damage on animal tracks and easily contoured areas. These areas created channels for surface water flow on hillslopes.	(Sheath and Carlson, 1998)
			Cattle treading regimes differences are greatest at 0-10cm depth. Soil properties on most soil types were still affected 18 months after the poaching event.	(Singleton, Boyes and Addison, 2000)
			Cattle treading caused higher post-treading roughness coefficients, bare ground, hoof print, skid densities, surface water detention volumes. Water infiltration rate was significantly related to the roughness coefficient.	(Russell et al., 2001)
			Dairy cows - Never poached fields had improved soil physical conditions than the poached fields. They had greater winter/spring growth that justifies farmers implementing ‘stand off’ management strategies.	(Drewry and Paton, 2000, Drewry, 2003, 2006, Drewry, Paton and Monaghan, 2004)
			Dairy cows - Soil macroporosity greater on the never grazed plots than on the grazed plots at post spring sampling.	(Houlbrooke et al., 2008, 2009)
Australia	Government – Commonwealth Scientific Industrial Research Organisation (CSIRO)	Prior to 1997: Department of Environmental Mechanics, Soils and Water Resources	Sheep treading caused significant differences between ungrazed and grazed pastures for unsaturated hydraulic conductivity, soil strength and bulk density. Compaction was limited to the top 5cm of the soil profile.	Greenwood et al., 1997
		1997-present: Division of Land and Water • Landscape Management • Pastoral Research Laboratory	Greater proportion of roots near the surface under higher stocking rates.	(Greenwood and Hutchinson, 1998) (Greenwood et

				al., 1998)
USA	Government – U.S. Department of Agriculture (USDA)	Agricultural Research Service (ARS) • Rangeland Resources and Systems Research, Fort Collins, Colorado • Grazinglands Research Laboratory, El Reno, Oklahoma • Sonora A&M AgriLife Research Center, Texas • Rangeland Resources Research, Cheyenne, Wyoming • Grassland, Soil and Water Research Laboratory, Temple, Texas	Heavy cattle grazing significantly decreased infiltration rates, but not for 20 minutes after rainfall.	(Rauzi and Smith, 1973)
			Cattle grazing caused a decline in infiltration rates and an increase in sediment production following short-term intense grazing in the rotational system.	(Warren et al., 1986)
			Artificial hoof used to simulate treading. Soil bulk density increased by 3% and the infiltration rate declined by 57% under severe trampling.	(Abdel-Magid, Schuman and Hart, 1987)
Canada	Government - Department of Energy, Mines and Resources and Forestry	1949-1995: Agriculture and Agri-Food scientific research centres	Heavy intensity and/or early season cattle grazing had a greater impact on soil water than light or late season intensities. In most treatments soil water in the grazed treatments was lower than in the ungrazed control sitte. Differences were least pronounced in the summer months.	(Naeth et al., 1990, 1991)
	Government - Department of Natural Resources Canada (NRCan)	1995 onwards: Agriculture and Agri-Food scientific research centres • Letherbridge Research and Development Centre • Staveley, Brook and Kinsella substations in Alberta • Semiarid Prairie Agricultural • Research Centre in Saskatchewan • Kamloops Research Branch in British Colombia • Department of Renewable Resources, University of Alberta	Cattle stocking at a light rate (1.2AUM/ha) for 32 years did not affect range condition. However, an increase to 1.6AUM/ha led to a marked decline in condition. This was due to a change in composition of rough rescue which lead to deterioration in grassland.	(Naeth et al., 1991, Douwes and Willms, 2012)
			Cattle treading caused greater soil bulk density and greater mechanical resistance compared to the ungrazed control site and in autumn in comparison to spring.	(Evans et al., 2012)

Poaching (trampling or treading) is the penetration of the soil surface by the hooves of grazing livestock that causes damage to the upper layer of soil. Poaching is visually recognised as hoof depressions on the surface that destroys existing soil aggregates (Warren et al., 1986). Repeated poaching flattens the surface and creates a compacted impermeable layer, seven-ten centimetres beneath the surface (Batey, 1979). Wet and soft soils are prone to poaching, so this risk is higher when stock are left on the land over winter and in late autumn and early spring (Environment Agency, 2015).

The risk of poaching increases in over stocked fields, when there is insufficient fresh pasture, with infrequent movement of stock (Jones, 2013) and when stock gather around feeding/drinking troughs (Newell-Price and Whittingham, 2012). Under low levels of grazing there is 20% lower infiltration rates around drinking troughs ((Pietola, Horn and Yli-Halla, 2005)). The direct impacts include of poaching are reduced infiltration capacity, which increase the risk of ponding and further poaching. Waterlogging on the surface reduces soil temperatures, limits plant growing days and promotes finer and shallower roots (Jones, 2013).

Continuous poaching has a direct impact on the amount of vegetation cover due to changes in the physical structure and biological composition of the soil. The loss of vegetation on the surface has an direct impact on multiple hydrological processes including evaporation, interception and transpiration (Naeth et al., 1991). On bare soils these processes may not be present, which encourages more surface runoff and soil erosion. This highlights the process complexity associated with soil compaction and soil hydrology (Pattison and Lane, 2012). Pasture growth is limited further in years when the soil remains wet for a long period of time (Houlbrooke et al., 2009) and can cause a 20-80% reduction in spring pasture growth depending on the soil type (Ledgard et al., 1996).

Cattle and sheep compact the soil in different ways, cattle create more individual upward and downward movement (surface depressions) compared to sheep, but sheep cause more total area surface disturbance (Betteridge et al., 1999). The same observations were made by (Jones, 2013) who noted that individual sheep are less likely to break the soil surface than cattle, but over a wider area a whole flock of sheep can produce a solid compaction layer at two-six centimetres depth. Compaction by cattle occurs in the upper 15-30cm with the formation of an impermeable dense layer at 7-11cm depth (Daniel et al., 2005). This is because this soil layer has the lowest level of bulk density and is most at risk. Heavier cattle exert more pressure and cause 45-65% more soil surface damage (Sheath and Boom, 1997).

Equation 2.2: Pressure exerted under grazing.

$$\frac{Force\ (n)}{Area\ of\ four\ hooves\ (m2)} = Pressure\ (kPa)$$

The pressure exerted on the soil, by a grazing animal can be calculated by its weight (mass) and hoof area (Equation 2). Cattle range in size depending of species and age from 380-570kg (Loucougaray, Bonis and Bouzille, 2004) and their average hoof area in the literature is 40-90cm^2 (Nuss, Sauter-Louis and Sigmund, 2011). Hoof area can be calculated by measuring the length of the claw (‘D’ in Figure 2.11) and the width of the two toes (F&G in Figure 2.11). Replica hooves, with a surface area 85-100cm^2 (Scholefield and Hall, 1986, Abdel Magid, Trlica and Hart, 1987, Di et al., 2001, Drewry, Cameron and Buchan, 2001) were used to test the impact of pressure exerted on the soil. They related the amount of vertical displacement to the soil strength by using the depth of hoof prints as a visual indicator of strength.

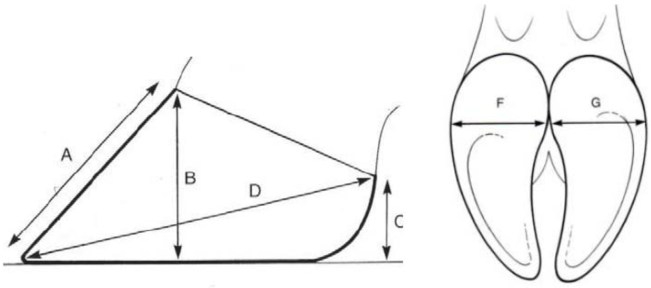


Figure 2.11: Calculating sole surface area of a cow hoof.

Radisic et al., 2012).

Hooves on a 500kg cow can exert 100-190kPa when static (van Haveren, 1983, Finlayson et al., 2002, Piwowarczyk, Giuliani and Holden, 2011) which is similar to arable machinery and up to 320kPa when dynamic (Kubo and Isobe, 1983, Willatt and Pullar, 1984, Piwowarczyk, Giuliani and Holden, 2011). Cattle exert more pressure through their two front hooves (60%) and because of this their front hooves are 20% larger than their hind hooves (Radišić et al., 2012).

Cattle tend to use the same tracks within a field and when moving in and out of the field (Holman et al., 2003) walking along easy contoured areas known as ‘cow terracette’ or ‘cowtours’ (Trimble and Mendel, 1995). Cowtours have higher levels of penetration resistance than other areas of the field (Naeth et al., 1991) and their presence encourages the development of surface channel formation, leading to preferential overland flow paths (Sheath and Boom, 1997).

There is very little literature on the surface area of sheep hooves. (Godwin and Dresser, 2003) calculated that for a 40kg sheep with 6cm^2 hooves that it would exert 160kPa when standing, 320kPa when walking and 480kPa when dynamic. Other researchers have estimated 50-80kPa when standing and 125-200kPa when dynamic (Willatt and Pullar, 1984, Finlayson et al., 2002).

Horse hooves produce substantial ground pressures (Adams, 1998) although their impact on soil compaction has not been directly studied at the plot and field scale. An average horse weighs 500-850kg (Landsberg, Logan and Shorthouse, 2001, Loucougaray, Bonis and Bouzille, 2004, Martin, 2016) and a shod (wearing shoes) horse with size one feet has a shoe area of approximately 15cm^2. An unshod horse has a greater contact area of approximately 48cm^2 (Landsberg, Logan and Shorthouse, 2001). (Aust, Marion and Kyle, 2005) estimates that horses exert pressures of 125-427kPa depending on whether they are standing, walking, trotting, cantering or galloping and with a rider to exert 430kPa (Landsberg, Logan and

Shorthouse, 2001). Horses are known to ‘fence walk’ around their paddock which enhances soil degradation in these areas (Kent Downs AONB, 2011).

2.4.3.1 Impact on Soil Strength

Records of penetration resistance observed in the field ranges widely for the low grazing treatments and are narrower in range for no grazing and high grazing treatments (Table 2.14). Nevertheless, there is an increasing trend in the mean penetration resistance as the level of grazing increases. Variability is again associated with the application of treatments by different researchers. Under high horse grazing the penetration resistance increased by three-fifteen times compared to the no grazing treatment (Beever and Herrick, 2006).

Table 2.14: Topsoil (0-15cm) penetration resistance under grazing.

			Level of grazing			
			None	**Low**	**High**	
Location	**Soil**	**Season**	**Penetration resistance (kpa)**			**Reference**
Kinsella, Canada	Sandy clay loam	Summer	207	365	414	(Naeth et al., 1990)
		Autumn	407	814	1083	
Brooks, Canada	Loam	Spring-Summer	648	1648	-	
Stavely, Canada	Clay loam	Autumn	427	986	1427	(Naeth et al., 1990)
			850	920	1270	(Douwes and Willms, 2012)
Lincoln, Canada	Silt loam	Autumn	660	790	1050	(Drewry, Cameron and Buchan, 2001)
Nappan, Canada	Loam	Autumn	-	980-1190	-	(Rodd et al., 1999)
		Spring	-	566-710	-	
Bissette Creek, Canada	Clay loam	Autumn	200	200	-	(Krzic et al., 2004)
Zumwalt Prairie, USA	Loess	Summer	1300	1800	1400	(Schmalz et al., 2013)

Atlantic, IA, USA	Silty clay loam	Autumn	1000	-	1300	(Clark et al., 2004)
		Winter	1000	-	1400	
Mead, NE, USA	Silt loam	Autumn	500	500	-	(Rakkar et al., 2016)
		Spring	500	1500	-	
Mato Grosso do Sul, Brazil	Clayey sand	Summer	290	620-810	-	(de Sousa Neto et al., 2014)
Bukit Mahang, Malaysia	Loamy sand	Autumn	161	215	-	(Majid, Awang and Jusoff, 1989)
Liberec, Czech Rep.	-	Autumn	-	-	2080-2250	(Ludvíková et al., 2014)
Grootfontein, South Africa	Silty sand	Autumn	-	150	200	(Talore et al., 2015)
Solohead, Ireland	Clay loam	Spring	-	2510	2050	(Tuohy, Fenton and Holden, 2014)
Azul, Argentina	Loamy clay	Spring	300	300	450	(Agostini et al., 2012)
Range			161-1300	150-2510	200-2050	
Mean			563	907	1095	

Experiments using artificial hoof penetrometers to mimic trampling, show that compaction does not occur immediately, but after repeated applications ((Scholefield and Hall, 1986)). Field studies in the Prairies of Canada show that under light and heavy grazing the penetration resistance is higher in autumn, than in summer (Naeth et al., 1991, Douwes and Willms, 2012).

Unconfined compressive strength observed in the field ranges widely for the no grazing treatments and is narrower in range for low grazing and high grazing treatments (Table 2.15). Nevertheless, there is an increasing trend in mean strength as the level of grazing increases. Variability is again associated with the application of treatments by different researchers.

Table 2.15: Topsoil (0-15cm) unconfined compressive strength under grazing.

			Level of grazing			
			None	**Low**	**High**	
Location	**Soil**	**Season**	**UCS (kg/cm3)**			**Reference**
Eureka, USA	Silt loam	Spring	0.83 +/- 0.19	1.87 +/- 0.49	2.59-3.11 +/-0.84	(Gifford, Faust and Coltharp, 1977)
Valley Creek, USA	Loam	Spring	1.46	1.53	2.11	(Clary, 1995)
Willow Creek, USA	Sandy loam	Autumn	1.57	1.90	-	
		Spring	1.57	2.00	-	
Wycanna, Australia	Sandy loam	Spring	0.50	0.90	-	(Braunack and Walker, 1985)
Ketereh, Malaysia	Loamy sand	Autumn	1.60 +/- 0.50	-	2.30 +/- 0.36	(Majid, Awang and Jusoff, 1989)
Belgrad Forest, Turkey	Clayey sand	Winter	0.38	-	2.26	(Kumbasli, Makineci and Cakir, 2010)
Range			0.38-1.57	0.90-2.00	2.11-2.26	
Mean			**1.10**	**1.58**	**2.19**	

2.4.3.2 Impact on Soil Structure

This section will discuss bulk densities observed in the field. Bulk densities ranged widely for the zero/no grazing treatments and are slightly narrower in range for the low grazing and high grazing treatments (Table 2.16). Nevertheless, there is an increasing trend in the mean bulk density as the level of grazing increases.

Table 2.16: Topsoil (0-15cm) bulk density under grazing.

			Level of grazing			
			None	**Low**	**High**	
Location	**Soil type**	**Season**	**Bulk density (g/cm^3)**			**Reference**
Kosciuszko National	Sand	-	0.68	-	0.90	(Dyring, 1990)

Park, Australia						
Hagerstown, USA	Clay loam	-	1.09	1.51	1.72	(Alderfer and Robinson, 1947)
Stavely, Canada	Clay loam	-	0.75	0.83	0.90	(Naeth et al., 1990)
Waikato, New Zealand	Loam	-	-	0.71	0.78	(Singleton and Addison, 1999)
Oklahoma, USA	Loam	-	1.04	1.16	1.30	(Daniel et al., 2005)
Nurin, USA	Sandy loam	Summer	-	1.37	1.45	(van Haveren, 1983)
Edmonton, Canada	Sandy clay loam	Summer	0.86	0.96	1.07	(Naeth et al., 1990)
Brydone, New Zealand	Silt loam	Summer	0.84	0.84	0.90	(Drewry and Paton, 2000)
Cantebury, New Zealand	Silt loam	Summer	1.10	-	1.25	(Drewry, Cameron and Buchan, 2001)
Lincoln, New Zealand	Silt loam	Summer	1.18	1.25	1.29	(Di et al., 2001)
Tehran, Iran	Sandy loam	Summer	1.39	1.45	1.50	(Chaichi, Saravi and Malekian, 2005)
Kamloops, Canada	Loam	Summer	1.03	1.08	-	(Evans et al., 2012)
Edmonton, Canada	Sandy clay loam	Autumn	0.89	0.95	0.99	(Naeth et al., 1990)
Armidale, Australia	Clay loam	Autumn	1.17	1.18	1.25	(Greenwood et al., 1998)
Lacombe, Canada	Silty sand	Autumn	-	1.06	1.38	(Mapfumo et al., 1999)
			-	0.98	1.05	
Whatawhata, New Zealand	Loam	Autumn	-	-	0.85	(Sheath and Carlson, 1998)
Kamloops, Canada	Loam	Autumn	-	1.03	-	(Evans et al., 2012)
Ketereh, Malaysia	Loamy sand	Winter	1.57	1.59	-	(Majid, Awang and Jusoff, 1989)
Hamilton, New Zealand	Silt loam	Winter	0.51	0.53	-	(Nguyen et al., 1998)
	Loam	Winter	0.70	0.86	0.91	
Balclutha, New Zealand	Silt loam	Winter	0.85	1.02	1.15	(McDowell et al., 2003)
Wexford, Ireland	Sandy loam	Winter	0.98	1.10	-	(Kurz, O'Reilly and Tunney, 2006)
Lacombe, Canada	Silty sand	Spring	-	1.16	1.33	(Mapfumo et al., 1999)
			-	1.03	1.06	
Invercargill, New Zealand	Silt loam	Spring	1.02	1.10	1.12	(Houlbrooke et al., 2009)
Kamloops, Canada	Loam	Spring	-	1.09	-	(Evans et al., 2012)

Hamilton, New Zealand	Silt loam	Spring	0.77	0.85	0.83	(Menneer et al., 2005)
Range			**0.51-1.57**	**0.53-1.45**	**0.78-1.50**	
Mean			**0.98**	**1.05**	**1.12**	
Standard deviation			**0.26**	**0.23**	**0.22**	

The effects of different grazing treatments on bulk density are not significant on coarse grained soils (Abdel-Magid, Schuman and Hart, 1987) however, on fine grained soils bulk density has been reported to be 6% higher under heavy grazing compared to light grazing (van Haveren, 1983). Bulk density at the start of the grazing season, here defined as the dry period (May to September), is lower than at the end of the season (Mapfumo et al., 1999). Bulk density can increase by 18% (1.31-1.59g/cm^3) over the grazing season (Chaichi, Saravi and Malekian, 2005) and very quickly (over two-three days) under heavy grazing in the winter/wet period (Nguyen et al., 1998).

Table 2.17: Topsoil (0-15cm) porosity under grazing.

			Level of grazing			
			None	**Low**	**High**	
Location	**Soil type**	**Season**	**Porosity (%)**			**Reference**
Hagerstown, USA	Clay loam	-	55	50	38	(Alderfer and Robinson, 1947)
Hamilton, New Zealand	Clay	-	73	70	63	(Singleton and Addison, 1999)
Waikato, New Zealand	Silt loam	Winter	77	75	62	(Nguyen et al., 1998)
Ramiha, New Zealand	Silt loam	Winter	-	73	-	(Climo and Richardson, 1984)
Manawatu, New Zealand	Sandy loam		-	54	-	
Jokioinen, Finland	Heavy clay	Spring	-	57	55	(Pietola, Horn and Yli-Halla, 2005)
Melbourne, Australia	Silty sand	Spring	-	50	-	(Rab et al., 2014)
Hawkes Bay, New Zealand	Silt	Spring	64	62	-	(Betteridge et al., 1999)

Whatawhata, New Zealand	Loam	Summer	-	68	65	(Sheath and Carlson, 1998)
Range			55-77	50-75	38-65	
Mean			67	62	57	

Table 2.18: Topsoil (0-15cm) macroporosity under grazing.

			Level of grazing			
			None	**Low**	**High**	
Location	**Soil**	**Season**	**Macroporosity (%)**			**Reference**
Hamilton, New Zealand	Clay	-	24	15	8	(Singleton and Addison, 1999)
	Silt loam	Winter	22	16	13	(Drewry, 2003)
Brydone, New Zealand	Silt loam	Summer	15	12	7	(Drewry and Paton, 2000)
Cantebury, New Zealand	Silt loam	Summer	20	17	10	(Drewry, Cameron and Buchan, 2001)
		Winter	12	9	7	
Lincoln, New Zealand	Silt loam	Summer	17	12	10	(Di et al., 2001)
Balclutha, New Zealand	Silt loam	Winter	19	19	8	(McDowell et al., 2003)
Invercargill, New Zealand	Silt loam	Spring	18	-	10	(Houlbrooke et al., 2009)
Bukit Mahang, Malaysia	Loamy sand	Winter	10	8	-	(Majid, Awang and Jusoff, 1989)
Range			10-24	8-19	7-13	
Mean			14	11	6	

Observations of porosity observed in the field ranges widely for the low grazing treatments and are narrower in range for no grazing and high grazing treatments (Table 2.17). Nevertheless, there is a decreasing trend in the mean porosity as the level of grazing increases. Measurements of macroporosity observed in the field ranges widely for the no grazing treatments and are narrower in range for low grazing and high grazing treatments (Table 2.18). Nevertheless, there is a decreasing trend in the mean macroporosity as the level of grazing increases.

Extensive, high density winter grazing leads to significant reductions ($P<0.01$) in the number of macropores (<10% total soil volume) throughout the A-horizon, in comparison to never grazed plots (Greenwood and Mcnamara, 1992, McDowell et al., 2003). Macroporosity levels of <10% in spring limit soil aeration and root growth (Houlbrooke et al., 2009). Following a short period of animal exclusion the macroporosity can increase by 70% in compared to normal grazing (Drewry and Paton, 2000), this is also evident over exclusion periods in winter (Nguyen et al., 1998). However, in some cases there have been increases in macroporosity over winter, in plots under no grazing. This is thought to have been caused by soil swelling in the spring (Houlbrooke et al., 2009).

2.4.3.3 Impact on Soil Drainage

Saturated hydraulic conductivity (Ksat) values observed in the field ranges widely for the low and high grazing treatments and are narrower in range for no grazing treatments. Nevertheless, there is a decreasing trend in the mean conductivity as the level of grazing increases (Table 2.19). Variability is again associated with the application of treatments by different researchers. The impact of heavy grazing has been shown to decrease the infiltration rate by 57% (Abdel Magid, Trlica and Hart, 1987) and the exclusion of grazing for a period of just four months has been shown to increase the conductivity rate by up to 200%, in comparison to sites where normal grazing continued (Drewry and Paton, 2000, McDowell et al., 2003).

Table 2.19: Topsoil (0-15cm) saturated hydraulic conductivity under grazing.

			Level of grazing				
			None	**Low**	**High**		
Location	**Soil**	**Season**	**Ksat (mm/hr)**			**Type**	**Reference**
Wyoming, USA	Sandy loam	Spring	-	84.9	90.9	Field – Double ring infiltrometer - Constant head	(Abdel-Magid et al., 1987)
		Autumn	-	101.5	78.7		
Georgia, USA	Sandy loam	-	-	81.3	96.9	Field – Constant head	(Franzluebbers et al., 2012)
Shropshire, England	Loamy sand	-	-	343.0	-	Field – Constant head	(Fullen, 1985)
Malaysia	Loamy sand	-	542.0	269.0	-	Laboratory - Constant head	(Majid et al., 1987)
Brydone, New Zealand	Silt loam	Spring-Summer	360.0	36.0	-	Laboratory - Mariotte vessel to pond water on surface	(Drewry and Paton, 2000)
Jokioinen, Finland	Heavy clay	-	72.0	29.0	10.0	Laboratory – Mariotte bubble tower	(Pietola et al., 2005)
	Sandy loam	-	132.0	-	24.0		
Balclutha, New Zealand	Silt loam	-	-	-	3.0	Laboratory - Mariotte vessel	(McDowell et al., 2003)
Range			72-542	29-269	10-97		
Mean			276.5	135.0	50.6		

Table 2.20: Topsoil (0-15cm) unsaturated hydraulic conductivity under grazing.

			Level of grazing				
			None	**Low**	**High**		
Location	**Soil**	**Season**	**Infiltration rate (mm/hr)**			**Type**	**Reference**
Northern Pakistan	Loam	-	66.0	53.0	40.0	Field – Rainfall simulator	(Bari et al., 1993)
Texas, USA	Silty clay	-	124.0	111.0	-	Laboratory - Rainfall simulator	(Warren et al., 1986)
Wisconsin, USA	Sandy loam	-	-	124.5	-	Field – Double ring infiltrometer - Falling head	(Pitt et al., 1999)
Inner Mongolia	Silty sand	-	-	55.4	38.8	Laboratory – Falling head	(Gan et al., 2012)
Range			66-124	53-125	39-40		
Mean			95.0	86.0	39.4		

2.5 Field Boundaries and Soil Hydrology

The rural landscape is made up of a pattern of fields and boundaries that have been typical since civilisation began. There are two main types of lowland landscapes known as ancient and planned countryside. Ancient countryside has altered little since 1700 and is characterised by hamlets/small towns, mixed hedgerows, lots of small, sunken roads/footpaths and pollard trees and woods (Rackham, 1986). Planned countryside was created in the eighteen/nineteen centuries by parishes as part of the Enclosure Acts. Enclosure began in the sixteenth century as an optional method for villagers to create legal property rights to land which was previously considered to be common and to 'improve' the productivity of arable farming. Before 1801 at least three quarters of the inhabitants had to agree to enclosure and a petition had to be sent to parliament to pass the act (Rackham, 1986).

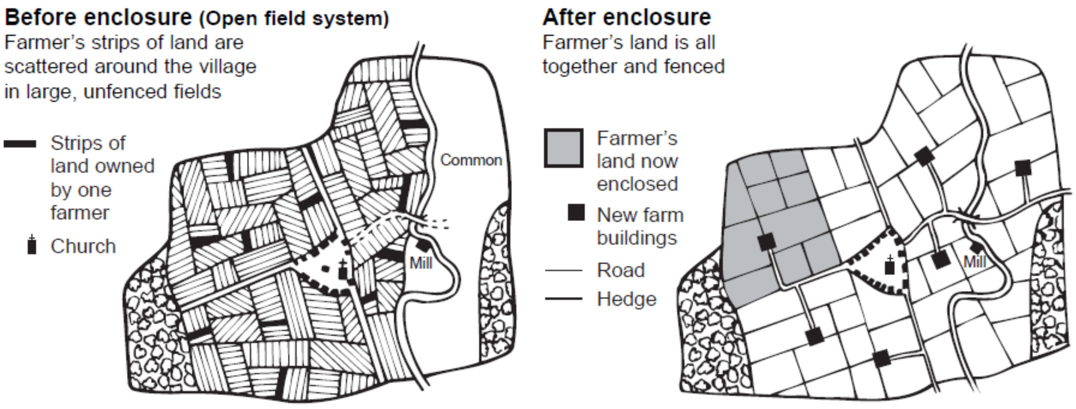


Figure 2.12: Enclosure of a village.
(University of Wisconsin, 2016).

Prior to enclosure strips of land were spread out across the parish but following enclosure land was grouped together in one area (Figure 2.12). Once agreed a new map of the parish was created and landowners enclosed their plots with straight mainly hawthorn hedgerows, fences and dry stone walls (Rackham, 1986). In 1801 the English government passed the Enclosure Act to forcefully enclose the remaining areas of land (University of

Wisconsin, 2016). From 1761 to 1844 2,500 acts were passed affecting one million hectares of land (Baird and Tarrant, 1973).

2.5.1 Defining Field Boundaries

Field boundaries are three-dimensional man-made physical barriers, which are often made from hedgerows, stone walls and ditches (Petit et al., 2003). They often follow streams, roads or wood banks and create a mosaic landscape that gives an area a distinct character and a cultural identity (Rackham, 1986, Natural England, 2009). Field boundaries have two main purposes, originally they were used as markers to show ownership of land or parish boundaries and secondly they were used as shelter for stock (Barr and Gillespie, 2000).

Stone walls have been around since the late Bronze Age (4,000 years ago) and often reflect the local geology (DEFRA, 2007b). They are prominently found in upland areas, where the climate is too harsh to grow hedgerows, although they can also be found in lowland areas and they provide a habitat for insects, spiders and mosses. Stone walls have their own micro-climate with an exposed wet-side and a dryer warmer side, a windswept top and a sheltered bottom (Dry Stone Walling Association, 2007). There is no official legislation against the removal or stone walls but, they may be protected if they are situated underneath a hedgerow, or located in a Site of Special Scientific Interest and DEFRA encouraged their retention under Good Agricultural and Environmental Condition (GAEC) 13 (DEFRA, 2007c) and now under the Cross Compliance in England: Soil Protection Standards (DEFRA, 2016).

Hedgerows and stone walls are often associated with field ditches (Marshall and Moonen, 2002) which are used to control water drainage and irrigation to extend the length of the growing season (Baudry, Bunce and Burel, 2000). Drainage of agricultural land in the UK began in Roman times but increased from the 1960’s due to the introduction of plastic pipes (Holden, Chapman and Labadz, 2004). Today over half of all agricultural land is drained, particularly in cereal producing fields in eastern England (Gruszowski et al., 2003, Robinson and Gibson, 2011).

The hydrological effect of drainage is spatially and temporally variable (Armstrong and Garwood, 1991), due to local soil characteristics (type and properties), the soil wetness regime, the drainage type, intensity and level of maintenance, the rainfall event and the topographic characteristics of the land (Oosterbaan, 1994). The hydrological response of ditches affects the transit times to the outlet and is therefore important (Environment Agency, 2007). However, the spatial configuration of field ditches is largely unknown in England (Environment Agency, 2007) and therefore they have not been mapped.

Ditches intercept overland flow from the hillslope, affect the rate of infiltration from the ditch to groundwater and increase the conveyance of water from the field to the stream due to the lack of natural obstacles (Levavasseur et al., 2012). Ditch networks control runoff by re-routing water around field boundaries, which is not always down the steepest slope that water would naturally travel down and therefore change the steepness and length of the hillslope (Moussa, Voltz and Andrieux, 2002). Ditches lower the water table locally creating more soil storage and allowing more infiltration so there is less overland flow (Levavasseur et al., 2012).

Some modelling studies have simulated the effects of ditch networks and hypothesised that denser networks decrease the amount of overland flow due to the increased runoff within the ditch itself but, increase the peak discharge in the river (Levavasseur et al., 2012). Other studies did not see a change in the peak flow, but observed a small reduction in the transit time to the catchment outlet (Lane and Milledge, 2012).

2.5.2 Loss of Boundaries

There has been a marked decline in boundaries since the start of the twentieth century mainly through their removal by farmers, to increase productivity of their land (Marshall et al., 2013). Other factors for boundary loss are neglect, lack of replacement, ground cutting and to reduce maintenance costs to land owners (Baird and Tarrant, 1973). Larger fields are preferable for the use of larger machinery and reduce the turning time. The removal of boundaries increases the headland available for cultivation by one hectare for every 0.88km of boundary removed (Baird and Tarrant, 1973). In Devon field size increased by 33% from 1956-1961 and in Somerset and Cambridgeshire field size increased by 41% and 59% from 1945-1994 (Pollard, Hooper and Moore, 1974)**.** Arable fields are 20-30% larger than pastoral fields (Robinson and Sutherland, 2002) however, in some areas there have also been large increases in field size under pastoral land (Pollard, Hooper and Moore, 1974)

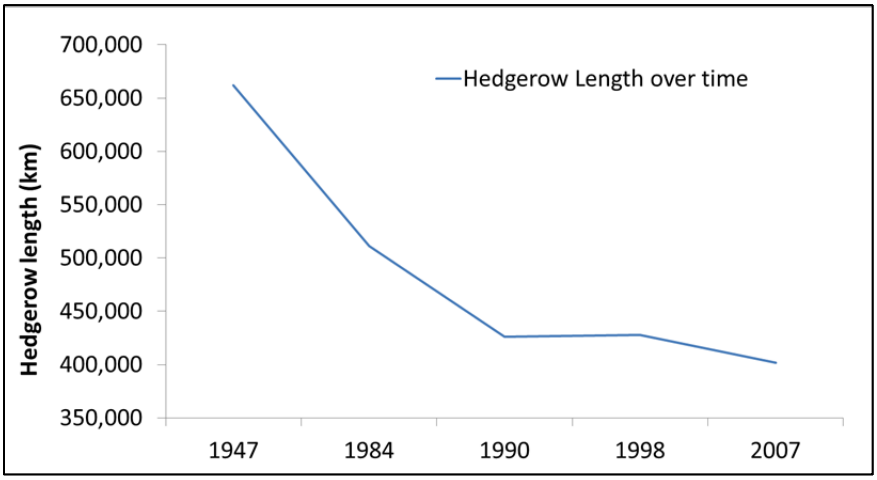


Figure 2.13: Hedgerow length (km) in England since 1984 (Barr et al., 2010).

Two thirds of England has been continuously hedged for over a thousand years, although most modern hedges were planted during the Enclosures Acts 1720-1840. The most common length of a hedgerow is two hundred and one metres, or one furlong. Another useful unit is a ‘chain’ which is 20.12m long. The average hedgerow length is twelve or eighteen chains long (Pollard, Hooper and Moore, 1974).

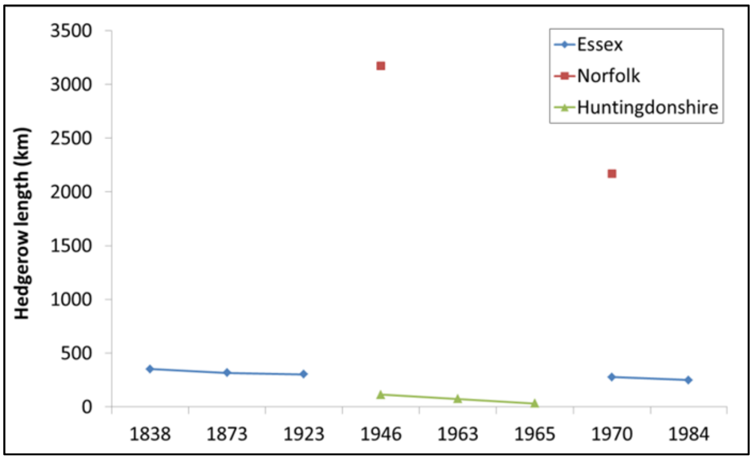


Figure 2.14: Change in hedgerow length in English counties. (Baird and Tarrant, 1973, Conyers, 1986, Barr et al., 2010).

From 1870 to 1945 there was very little change in the density of hedgerows in England. The destruction of hedgerows began after the Second World War with the introduction of the Agricultural Act, 1947 and the Farm Improvement Grant, 1957 that actively encouraged their removal, by giving out subsidies to farmers (Rackham, 1986). The Countryside Survey mapping shows that between 1984 and 2007 nearly 110,000 km of hedgerows were destroyed (Oreszczyn and Lane, 2000) and there are now only 402,000km of managed hedgerow in England (DEFRA, 2007c). It also shows that there is approximately 82,000-112,000km of field walls (DEFRA, 2007c) and 32% were lost from 1984 to 1998 (Natural England, 2009).

There are very few studies evaluating the effects of field size on catchment-scale runoff (Flather and Rodda, 2010, Fiener, Auerswald and Van Oost, 2011). (Evans and Nortcliff, 1978) identified that boundary removal created longer slope lengths and increased the propagation of surface runoff further downslope through flow paths of least surface resistance such as wheel tracks in arable fields. The lack of boundary features as a physical barrier between fields allows runoff velocities to increase and makes the land more connected to the river (O’Connell et al., 2004).

2.5.3 Woody Linear Features

Woody linear features are defined as ‘narrow bands of woody vegetation that separate fields’ (Forman and Boudry, 1984) which includes hedgerows and lines of trees (Scholefield et al., 2016). Around the world, they are also known as windbreaks, shelterbelts, tree shelterbelts, shelterbreaks, biotopes or living fences and are incorporated in agroforestry systems. Woody linear features planted along or near active watercourses are also known as riparian buffer strips.

Hedgerows are widespread in Western Europe and also appear in North America, Africa and Asia. The Institut National de la Reserche Agronomique (INRA) conduct field studies of hedgerows composed of rows of deciduous trees (mainly Oak), over 10m tall constructed on earth banks (Caubel et al., 2003, Walter et al., 2003, Ghazavi et al., 2008) and model their impact on small catchments in Brittany (Viaud et al., 2005, Thomas et al., 2012, Benhamou et al., 2013). Other INRA research has studied hedgerows in Normandy (Gascuel-Odoux et al., 2011) where there are intricate hedgerows systems known as ‘bocage’.

Table 2.21: Studies of hedgerows across the world.

Location	**Hedgerow description**	**Topics**	**Findings**	**References**
Brittany, France	Oak trees on bank, greater than 10m tall	Modelling - Soil water and nitrogen balances	In Kervidy catchment (5km^2) the hedgerow network decreased water flow by 4.5% and nitrogen flow by 3.3% compared to a catchment with no hedgerows.	(Benhamou et al., 2013)
		Field studies - Soil water movement	Hedge induced high rate of soil drying because of the high evaporative capacity of trees. Water uptake 100m greater in growing season than without a hedge. Induced drying led to 1 month delay in rewetting of soils in autumn.	(Caubel et al., 2003)
		Field studies – Hydrology: rainfall distribution, soil water, lateral flow and water balance.	Hedgerow influenced soil water potential up to 9m upslope and 6m downslope (where most of the roots were observed). The soil was driest at the end of summer, which delayed rewetting during autumn. The spatial rainfall distribution was related to distance from the hedgerow and rainfall amount.	(Ghazavi et al., 2008)
		Field studies – Hydrology: Comparison of wet and dry years.	Soil water is lower next to the hedgerow throughout the wet and dry years. Water flux in the unsaturated zone was directed towards the hedgerow for a longer period during the dry year than the wet year. The duration of delayed soil rewetting decreased from 3 months to 1 month for the wet year. The hedgerow controls water transfer in the unsaturated zone except when the soil is fully saturated.	(Ghazavi et al., 2011)
		Modelling – Hydrology	The spatial and temporal variability of the water balance components was related to the hedgerow and the meteorological conditions. There was increased capillary rise and decreased drainage near hedgerows due to high	(Thomas et al., 2012)

			transpiration.	
		Modelling – Hydrology	The impact of hedges locally depends on their location on the hillslope, the network density and the spatial structure, the groundwater level and the climate. At the catchment scale hedgerows increases evapotranspiration by 5-30%.	(Viaud et al., 2005)
		Field studies – Soil organic carbon	The thickness of the organic horizon increases slowly from the top of the hill as far as the hedge, under the hedge the bulk density is low and the soil organic carbon storage is large.	(Walter et al., 2003)
	Thin line of chestnuts and common oaks, 1.2m tall	Modelling – Process dynamics, soil redistribution	Hedges modify soil distribution and landforms by favouring deposition in the uphill position and soil erosion in the downhill position.	(Follain et al., 2006)
		Field studies – Soil organic carbon	Soil organic carbon stocks are locally significant in the vicinity of hedges, in comparison to the landscape scale.	(Follain et al., 2007)
Normandy, France	Coppiced shrubs.	Modelling – Flow pathways and connectivity	Regional DEMs, even if they include rural infrastructures do not provide a comprehensive representation of overland flow patterns in the catchment. The source areas are often of small extent and it is crucial to provide rapid localisation along with spatial explanations in terms of connectivity.	(Gascuel-Odoux et al., 2011)
Model only		Modelling – surface flow paths and pollution	Simple and functional representation of surface flow pathways in an agricultural catchment for decision support. Identified the key plots controlling stream water pollution.	(Aurousseau et al., 2009)
Freising, Germany	Dead wood hedge	Ecological impact	Release dissolved organic matter and phosphorus causing eutrophication.	(Auerswald and Weigand, 1996, Fiener, Auerswald

				and Van Oost, 2011)
Northern Italy	7-8m tall	Pesticide Drift	Reduced aerial drift 6-7m from structure when porosity was greater than 74%.	(Lazzaro, Otto and Zanin, 2008)
Central and southern Spain	Species: narrow leafed ash, woody, 4-8m tall	Micro-climate: Temperature	Significantly lower and steadier to surrounding fields.	(Sánchez et al., 2009)
Northern Netherlands	Buffer zone	Pesticide drift	A 6m buffer created no drift deposition in ditch.	(de Snoo and de Wit, 1998)
Poznan, Poland	Shelterbelt, Multiple species including acacia, poplar, pines and spruces	Micro-climate: temperatures, wind speed, precipitation, humidity.	Structure has important impact on energy flow and water cycling.	(Ryszkowski and Kędziora, 1987)
Sweden	Multiple species including hazel, hawthorn, oak and spindle.	Loss of hedgerows, increase in field size	Landscape changed considerably in past 50 years, hedges lost by 1985.	(Ihse, 1995)
Eastern Denmark	20m line biotope with more than 50% coverage of trees or shrubs, average width 3m, species: lilac and blackthorn.	Change in agricultural landscape.	Protection against removal is needed.	(Agger and Brandt, 1988)
Thessaloniki, Greece	Multiple species including hawthorn, elm, ivy and	Fertiliser deposition and micro-climate:	Concentration increased at the base of the hedge and lack of granules passing through to adjacent habitat. In cooler, winder	(Tsiouris and Marshall, 1998)

	blackthorn.	temperature and wind speed	conditions hedge is 4°C cooler than open field, in warmer, less windy conditions hedge is 2°C warmer than open field.	
Canadian Plains	Shelterbelts	Crop yield	Competition effect smaller when water is abundant, improved crop growth 10-20m from field edge related to the reduction in potential evaporation.	(Kowalchukl and Jong, 1995)
	Mixed wood	Mapping hedgerows	Developments of methods using line intersect sampling for estimating linear woody features.	(Pasher, McGovern and Putinski, 2016)
Ibadan, Nigeria	Leucaena leucocephala and Gliricidia sepium shrubs	Soil properties, runoff and erosion	Soil moisture content in the top 0-5cm in the agroforestry systems was generally higher than the control, in both the wet and the dry seasons.	(Lal, 1989)
Central Kenya	Calliandra contour hedges, 1-6m tall	Soil erosion	More soil conserved on 20% slope than on a 40% slope.	(Angima et al., 2002)
	Senna siamea, evergreen trees, grow up to 20m tall	Soil erosion, physical properties and water levels	Hedgerows control water erosion, increase 3-8% in infiltration beneath hedgerow compared to arable land, water penetrates deeper into soil beneath hedgerows.	(Kiepe, 1995a, 1995b, 1996)
Ban Bo Wi, Thailand	Leucaena leucocephala	Soil water depletion and competition	Detected differences between the cropping systems and retrieved spatial structure of the soil moisture distribution.	(Garré et al., 2012)
Nakon Pathom, Thailand	Vertier grass system	Runoff and soil erosion	Delayed runoff and reduced peak runoff rate and steady erosion rate.	(Donjadee et al., 2010)

2.5.3.1 English Hedgerows

This section will focus on English hedgerows and the definitions of a hedgerow. In Cornwall, a hedge would be a stone wall, in Monmouth, Wales it would be a hazel hedge, in Ireland it would be a turf bank and in Lincolnshire it would be a short thorn hedge. (Pollard, Hooper and Moore, 1974) defines a hedgerow as ‘a row of closely planted bushes forming a boundary to land’. (DEFRA, 2007b) defines a hedgerow as ‘a boundary line of trees and shrubs over 20m long and less than five metres wide at the base between major woody stems, provided that at one time the trees or shrubs were continuous. This includes classic shrubby hedgerows, lines of trees and shrubby hedgerows with trees and includes the whole field boundary structure (bottom flora, earth banks, field ditches and hedge trees).

A ‘hedge’ however, is just defined as the term for the aerial and vertical part of the hedgerow. In this thesis the following definition will be used for the word hedge: ‘A managed boundary line composed mainly of shrubs over 20m long and less than five metres wide, which may contain individual hedge trees, but that is not wholly composed of trees/shrubs over two metres tall’. This definition will be used because there is a clear distinction in England between a line of trees and lines of shorter shrubs and because their size will affect the local scale hydrology differently, due to the length and diameter of the root systems and their interactions with the soil. This decision was also based on literature reviewed from across Britain on traditional hedgerows which are generally regarded to be lines of shrubby vegetation less than two metres tall (Barr and Gillespie, 2000, Herbst et al., 2006) and because woody linear features over 2m tall are classed as un-managed (Barr et al., 2010).

English hedgerows are usually a mixture of species commonly including elder, ash, beech, hornbeam, hawthorn, holly, alder, hazel, cherry, sycamore, willow, yew and oak. Hooper’s Rule is used to determine the age of a hedgerow by determining the number of species it contains. As a rule, the number of woody species in a 28-metre-long hedgerow is multiplied by 110 years to define its age. The rule is useful to date hedges from before and after the enclosure act. Post enclosure act hedges were usually planted and often contain hawthorn and one other species (Rackham, 1986).

Hedgerows are an ecological pathway providing shelter for 500-600 vascular plants and birds, insects, mice, voles, rabbits and hedgehogs (Forman and Boudry, 1984). They are recognised as a UK Biodiversity Action Plan (BAP) habitat that provides refuge for 125 UK BAP priority species (Natural England, 2009). The majority of work in England on hedgerows was completed from 1963-2008 by the Centre for Ecology and Hydrology and it focused on the ecological benefits of healthy hedgerows (Hinsley and Bellamy, 2000, Garbutt and Sparks, 2002, Staley et al., 2012, 2013, 2015) and their maintenance (Croxton et al., 2004).

2.5.3.2 Hedgerow Management

To remain sustainable hedgerows require some degree of management otherwise they become tall and gappy (Barr and Gillespie, 2000). Hedgerow management includes cutting/pruning at a low level up to 0.25-m from the soil surface (Van Noordwijk et al., 1991). Under English law GAEC 7A there are strict rules that hedgerows can be laid or coppiced until 30 April each year and should not be cut from 1 March-31 August inclusive due to nesting birds breeding and rearing seasons (DEFRA, 2015b). To keep a strong healthy hedge (Hedgelink UK, 2016) recommend the following.

- Keep branches thick and dense
- Leave trimming until late winter (January-February)
- Only trim once every two-three years to allow growth of flowers and berries
- Encourage flowers, grasses and native shrubs to grow at the base
- Plant or allow hedge trees to grow in field corners
- Rejuvenate gappy or overgrown hedges by coppicing or laying at the base

Hedgerow cutting is usually done with a rotary flail hedge cutter, mounted on a tractor arm which allows farmers to cut hedgerows at low cost (Natural England, 2007). In 1997 the Hedgerow Regulations were introduced to stop the removal of healthy hedgerows without planning permission and penalties can be imposed for a breach of the regulations. To qualify for protection hedgerows must be at least twenty metres long and located on land used for agriculture, forestry, horse keeping, common land, a village green, a Site of Special Scientific Interest, a local nature reserve, or a public right of way (DEFRA, 2015b). Since 1997 the number of English hedgerows being destroyed has decreased by at least 40% (CPRE, 2010).

DEFRA policies that encourage hedgerow construction and restoration include the Countryside Stewardship Entry Level Stewardship 2005-2014 (Staley et al., 2015), Environmentally Sensitive Areas 1998-2004 (CPRE, 2010) and Environmental Stewardship schemes (Hedgelink, 2011). These schemes funded the creation and restoration of 27,000km of hedgerows from 1991-2012 (Barr et al., 2010).

2.5.4 Hedgerows and Hydrology

Prior to 1995 there was very little work completed on the hydrological role of hedgerows in temperate climates and even now there is very little data and information on English hedgerows therefore, our knowledge of the impact of hedgerows on hydrological processes is extremely poor (Ghazavi et al., 2008). However, there is lots of anecdotal evidence that the loss of hedgerows may be responsible for increased flood risk (Marshall et al., 2013) and the study of hedgerows is necessary to determine how hedgerows affect micro-climate and soil-water movement and what the impact of their removal or construction may be having at the local and catchment scale.

2.5.4.1 Hedgerows and the Surface Water Balance

Hedgerows have their own micro-climate (Merot, 1999) by creating a shelter zone on the leeward side of the structure. Hedgerows act as a windbreak

(Brenner, Jarvis and van den Beldt, 1995) and the primary effect is to alter the wind speeds immediately around the feature (Figure 2.15). Most hedgerows are semi-permeable and provide a more effective shelter than a solid barrier, such as a stone wall, because low pressure areas can form on the leeside of a wall creating turbulent gusts. A permeable structure allows some air to travel through to the leeside which prevents gusting (Pollard, Hooper and Moore, 1974).

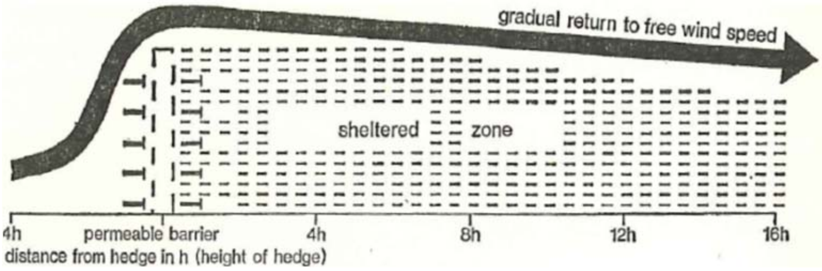


Figure 2.15: Shelter zone on leeside of permeable hedgerow barrier. (Pollard et al., 1974).

Hedgerows can act as a solid barrier in summer but, also as a permeable barrier in winter depending on the amount of trimming, age and health of the hedge. At optimum permeability (40%) the shelter zone can extends up to ten-twelve times the height of the hedge. For a hedge of two metres tall this would be twenty-twenty-four metres. On the windward side of the hedge there is also a cushioning effect that diverts air upwards which can extend up to four times the height of the hedge (Pollard et al, 1974).

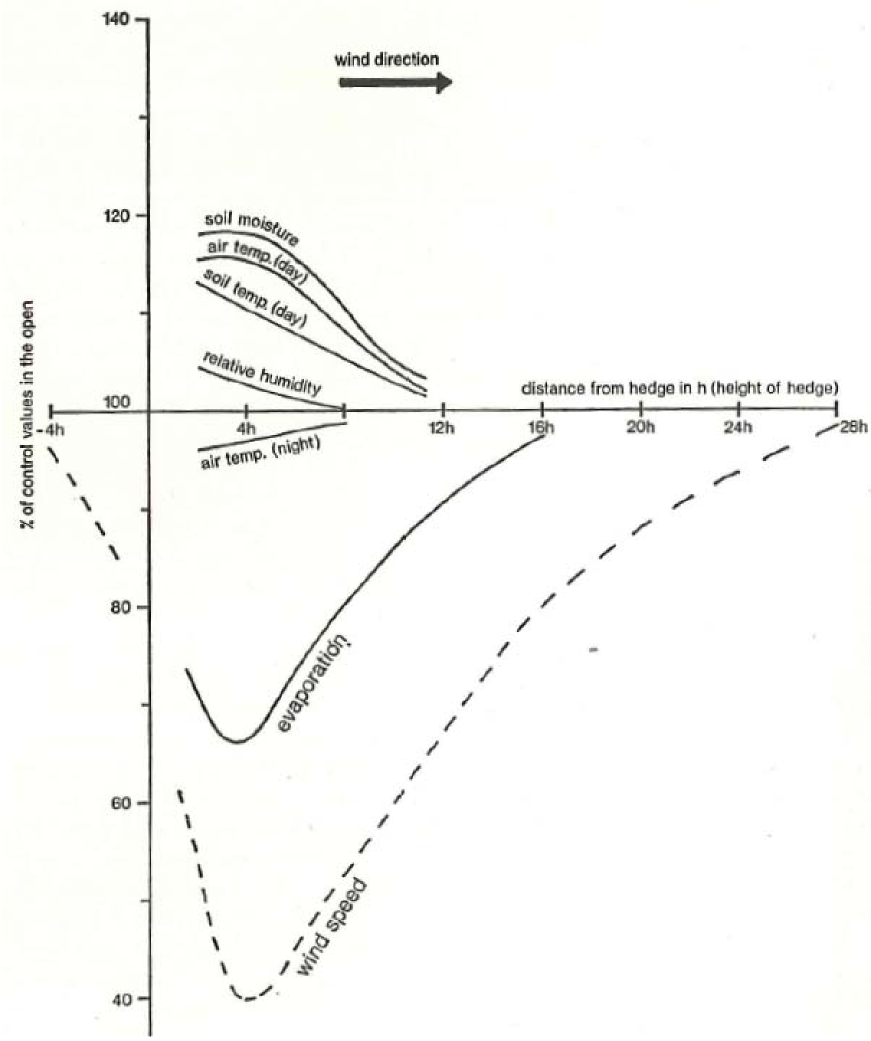


Figure 2.16: Summary of the effect of a hedgerow on various climatic factors. (Pollard et al., 1974).

In terms of interception, during periods of full leaf cover the amount of gross rainfall intercepted by the canopy area is 57% and in winter the interception loss is 49% of gross rainfall (Herbst et al., 2006). Observations from small storms show that hedgerows intercept large fractions of rainfall that would have otherwise fall to the ground. A third of gross rainfall falls as throughfall in summer and a half of gross rainfall as throughfall in winter (Herbst et al., 2006). A higher percentage of rainfall penetrates the canopy on the windward edges (Herbst et al., 2006).

Deciduous plants are also affected by seasonality due to leaf drop. Hedgerows in temperature climates have a leafed season (Nov 1-April 30) and a leafless season (May 1-Oct 31) and these two periods correlate to a wet and a dry season (Thomas et al., 2012). Throughfall is rainfall that drips from foliage or branches in the canopy or reaches the floor by passing directly through the canopy. Throughfall can be a notable contribution to the hydrological cycle, in forest areas (Hosseini Ghaleh Bahmani et al., 2012).

Stemflow occurs when rainfall runs down the stem of a plant (Williams, 2004) and enter the soil around the main trunk (Cape, 1991). The volume of stemflow can depend on the branching structure of the plant. Stemflow is one of the less well known and studied hydrological processes (Martinez-Meza and Whitford, 1996) however, there has been an increase in the number of studies since 2000 (Levia and Germer, 2015). In general, it is often seen as a minor process in the hydrological cycle and one that is dealt with as a figure, calculated by subtracting gross and net rainfall to determine an interception value (Liang, Kosugi and Mizuyama, 2009).

Stemflow collars and collectors are used in forest research at the Alice Holt Forest, in Hampshire, UK (Williams, 2004) and Hubbard Brook Experimental Forest in New Hampshire, USA (Lovett et al., 1996). Research on tree stemflow shows a wide variety depending on the species (bark roughness, canopy density). In forests the precipitation type in the leafless period can affect the stemflow yield, for example high stemflow occurred in rain-to-snow events in comparison to snow, or rain events (Levia and Germer, 2015). (Staelens et al., 2008) found that stemflow in beech trees in Ghent was high in the leafed (9.2% gross rainfall) and leafless (10.6%) periods due to the smooth bark. However, in shrub species seasonality has less of an influence on stemflow (Martinez-Meza and Whitford, 1996).

In the UK, (Herbst et al., 2006) installed nine stemflow collars on a North-South orientated Hawthorn hedgerow in Swindon. Stemflow volumes were related to the canopy surface area by determining the average stem diameter in a sixty-three metre section of hedgerow. Rainfall diverted to the trunks was estimated from a regression of stemflow versus gross rainfall. Their results showed that stemflow accounted for less than half a percent (0.2%) of gross rainfall in summer and 0.5% in winter (Herbst et al., 2006).

In terms of precipitation, there was no change in the quantity of annual rainfall around a hedgerow but, the spatial heterogeneity of rainfall increased (Merot, 1999). The influence of the hedgerow on the distribution of rainfall is called a rainfall shadow and has been observed next to the structure (Figure 2.17) and up to four metres away from it (Herbst et al., 2006, Wheater et al., 2008). The shadow was not confined to summer as the same trend was also observed in winter (Herbst et al., 2006). The shadow has been observed at hedgerows with different orientations, for example there was a decrease in the level of rainfall on the leeward side in comparison to the windward side at two hedgerows at a site in Swindon, England (Herbst et al., 2006).

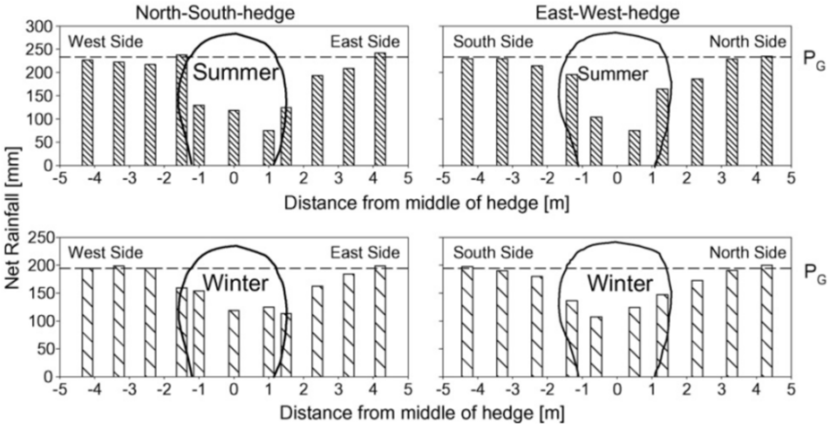


Figure 2.17: Spatial distribution of rainfall around a hedgerow. (Herbst et al., 2006).

In terms of temperature, the shelter zone affect an area which is one-two times the height of the hedge (Figure 2.16) (Pollard, Hooper and Moore, 1974). A study investigating woody linear features consisting of ash in the Segovia region found that in summer, temperatures were lower and steadier beneath the hedgerow than the surrounding areas (Sánchez et al., 2009). Studies in the UK have shown that during the day the leeward/shaded side had higher air and soil temperatures than the westward/sunnier side. At night the westward side had higher temperatures (1-2°C) than the leeward side (Pollard, Hooper and Moore, 1974).

Transpiration is the movement of water through the vascular system of plants, initially absorbed through their roots and then translocated to the stem, branches and then to their leaves (Pearcy, Schulze and Zimmermann, 1989). Stomata on leaves allow the passage of water and gas in or out of the plant during the process of photosynthesis. The waste product of which is water which is emitted onto the leaves and passes into the atmosphere due to a vapour-pressure gradient between the stomata and the air. In a constant climate more water is drawn up from the plant to replace the water which is being lost. However plants can exert a control on transpiration through their guard cells which close when there are low levels of light, humidity and water content in the leaf cells. They are also affected by temperature, carbon dioxide levels and wind (Sack et al., 2003).

The shelter zone decreases the amount of evaporation and transpiration from the ground and plants on the leeward side of the hedgerow due to an increase in the humidity of the air and a decrease in the wind speed (Pollard, Hooper and Moore, 1974). This affect is thought to extend up to three times the height of the hedgerow on the windward side (Cleugh, 2003) and ten-sixteen times the height of the hedgerow on the leeward side (Forman and Boudry, 1984). This affect is dependent on hedgerow density, climate and water availability (Viaud et al., 2005).

During the leafless period there are low levels of transpiration but, during the leafed period hedgerows experiences high levels of transpiration often higher than local precipitation rates (Thomas et al., 2012). Shelterbelt evapotranspiration rates in Poland were 18% greater than meadows, 28% greater than wheat fields and 43% greater than bare soils in the summer season (Ryszkowski and Kędziora, 1987). English hawthorn hedges have peak evapotranspiration rates of 8mm/day which is significantly greater than from forests (4-5mm/day) (Herbst et al., 2007).

The expected sap flow velocities of the majority of plant species, in most environments will be in the range of <60cm/hr for conventional/acropetal flow and no greater than -5 to -10cm/hr for reverse/basipetal flow (ICT International Pty Ltd, 2014). However, the rate varies widely amongst species (Nadezhdina et al., 2007) for example the daily mean rate in mountain ash is 10-12cm/hr (Dunn and Connor, 1993), in conifers it is 0-35cm/hr and in diffuse porous hardwoods it is usually 0-20cm/hr (Swanson, 1983). In woody species the peak is usually 35-45cm/hr (Burgess et al., 2001). Sap flow is much lower at night than during the day, typically decreasing from sunset to sunrise (Becker, 1998) It is lower in winter than summer and lower in understorey species (Burgess et al., 2001) and it can vary across the sap wood area due to different properties of conductance (Delzon et al., 2004).

2.5.4.2 Hedgerows and the Subsurface Water Balance

Hedgerows have a strong influence on local soil properties through their well-developed root system, which extend to depths of 0.45-1m (Kiepe, 1995b, Caubel et al., 2003). The increased organic matter under a hedgerow significantly increases the number of macropores in the topsoil and decreases the bulk density (Walter et al., 2003). The improved soil properties increases the level of infiltration for both the wet (94%) and dry (30%) seasons compared to arable fields (Kiepe, 1995b). Pruning encourages more fine roots in the topsoil and also dieback in the roots system creating dead root channels (Kiepe, 1995a). This facilitates increased vertical drainage and preferential flow through the sub-surface (Van Noordwijk et al., 1991).

Leucaena intercropping created more water depletion close to the hedge, than further away in the summer season (Garré et al., 2012, 2013) although soil water content underneath a tree-line are always higher than the water content underneath ploughed or bare ground (Lal, 1989). Results from the Pontbren catchment in Wales showed complex soil moisture patterns around a tree shelterbelt but, there is an effect on moisture content both within and on the leeward side of the shelterbelt. The soil moisture content at twenty-forty centimetres depth from March-June was lower next to the shelterbelt than at five metres and greater away (Wheater et al., 2008).

Experiments in Brittany, France showed that oak tree-line hedgerows caused a soil water deficit in the land surrounding the tree-line at the end of the dry period that lasted one to three months. This deficit created soil storage for winter rainfall and influenced the speed taken for the soil to wet back up in winter (Ghazavi et al., 2008). The tree-line had an influence on soil moisture levels under it but, also nine metres upslope and six metres downslope. This created hydraulic gradients that increased the lateral transfer of water and created occasional vertical gradients in dry periods (Ghazavi et al., 2011).

A land owner in Norfolk, England changed one 61ha field into four fields and planted new hedgerows. The new hedgerows decreased runoff path lengths by creating disconnections across the fields ((Evans, 2006)) as well as providing an important barrier to erosion and runoff (Barr and Gillespie, 2000). Other anecdotal evidence from Normandy, France states that hedgerow removal has increased surface runoff as hedges used to slow down the flow of water and trap debris (Wolton et al., 2014).

2.5.4.3 Hedgerow Modelling

The soil-plant-atmosphere continuum (SPAC) is a conceptual model that explains the pathways that can transport water from the soil through plants to the atmosphere (Philip, 1966). Plants have powerful regulatory mechanisms that moderate water transport in response to changes in soil water availability and atmospheric evaporative demand. During a season, water transportation is primarily dominated by physiological responses at the stomata and the hydraulic transport system that connects the soil with the leaves (Klingaman et al., 2007).

There are a wide range of SPAC models that are based on the initial concepts. These models are generally complex due to the vast number of physical processes and feedback loops that they are aiming to represent. Due to the complexity of SPAC models and the extensive data that are required to parameterise them, each part of the soil-plant-atmosphere continuum can be studied and modelled individually to provide a better representation of each individual part.

2.6 Chapter Summary

The key findings from this chapter are that there is a link between rural land management and flood risk, at a range of spatial scales. This was highlighted in the FD2114/TR DEFRA report (O'Connell et al., 2004). However; the links are very complex, vary in time and space and are often catchment specific. There is a lack of empirical data available to quantify the impact of rural land management on flood risk and it is harder to identify at larger scales. More experimental data from field studies is needed to investigate the potential use of on-farm soft engineering solutions (Holman et al., 2002) and to parameterise physically-based distributed hydrological models.

The key findings from the soil compaction literature were that most field based studies globally have focused on the impact of arable land management on flood risk. Within the UK field studies have focused almost entirely on the impact of sheep grazing on compaction. There is a research gap in terms of the impact of cattle and horse grazing on soil compaction in the UK. There are studies globally on the hydrological impacts of cattle grazing but no known published studies on the impacts of horse grazing.

In recent years there has been a number of monitoring based catchment-scale studies that have attempted to gather more field evidence of the impacts of land management change on flood risk (FRMRC - Hodder, Pontbren, Parrett (Wheater et al., 2008)). There is still a research gap in the collection of field data from multiple sites which are needed to quantify the significant inter-plot and inter-site heterogeneity that has been observed at site (Marshall et al., 2014).

The key findings from the field boundaries literature was that there is a research gap in field studies globally that quantify the impact of hedgerows on hydrology. There are few studies that highlight how UK hedgerows can affect the soil properties and soil hydrology (Herbst, 2006). The research done by (Ghazavi et al., 2008, 2011, Thomas et al., 2012) provides insight into forest hydrology, however since their work focuses mainly on lines of tall oak ‘hedgerow’ trees, it is felt that their impact on hydrology and that of UK hedgerows will be slightly different. UK research has also focused more on the implications of tree planting on hydrology (Pontbren) and the potential impact this may have on flood risk.

The literature review also highlighted that there is a research gap in that there are no known studies that have completed a water balance around a hedgerow. There is also a research gap in mapping the spatial distribution or effect of hedgerow features on water movement at the catchment scale. The report by (Wolton et al., 2014) states the need to quantify the effect of the UK hedge networks in reducing flood risk, especially in areas with different catchment characteristics and during extreme rainfall events.

The next chapter will provide details of the methodological approaches and field-scale techniques that were used to fulfil Objective one, “to develop a holistic methodology to study the process-based relationship between soil compaction and soil hydrology”.

Chapter 3 – Quantifying the Impact of Soil Compaction on Soil Hydrology: Methodology

3.1 Chapter Scope

The previous chapter provided a broad literature review on the dominant theoretical effects of the intensification of agriculture on hydrological processes and soil conditions. Chapter three will provide details of the methodological approaches and field-scale techniques that were used to fulfil Objective one, “to develop a holistic methodology to study the process-based relationship between soil compaction and soil hydrology”.

Section 3.2 provides details of the four types of agricultural land management sites (inter-field) used in this study. Section 3.3 will then break these sites down into the targeted zones (intra-field) which were studied to provide high spatial resolution data about the soil conditions. Section 0 discusses the two study periods which were chosen to assess the effect of seasonality on soil compaction.

Section 3.5 discusses the sampling strategy and design used to collect the data. Section 3.5.1 and 3.5.3 provide the methodology used to determine the soil characteristics and soil structure, including the collection of soil core samples and determination of soil characteristics in the laboratory. Section 3.5.4 discusses the field methodology used to determine the level of soil compaction at each site. Section 3.5.5 provides the methodology for the soil water field tests and Section 3.5.6 provides the methodology for the analysis of the experimental data. Finally, Section 0 gives a summary of the chapter.

3.2 Site Selection: Inter-Field

Prior to choosing the sites a brainstorming meeting was organised in Ripon with stakeholders from the National Trust, the Forestry Commission and the Yorkshire Dales National Park Authority. The attendees were asked 'How do different types of land-use affect rivers flows?' The main responses were focused around socio economic factors that were determined to be the main barrier to implementing successful flood risk reduction locally.

The stakeholders discussed several local projects including the Ripon Multi Objective Project that provided grants for tree/woodland creation, hedge planting, grip blocking and riverbank management. The Upper Nidderdale Heritage Landscape Partnership scheme which aims to restore the fabric of the landscape and to deepen people's understanding and capacity to maintain it. The Woodland for Water study which provides strong evidence to expand woodlands in appropriate locations for soil and water benefits. Catchment sensitive farming aims to reduce pollution on the River Laver, re-naturalise the system and try to prevent gravel deposition from intense runoff.

More general issues centred on the rise of horsiculture due to the riding boom, cleaning debris from culverts to prevent blockages and rock falls at Hackfall woods caused by heavy rainfall. During the meeting the stakeholders provided several contacts in the local area who were contacted and from these communications meetings were set up with land-owners to visit and discuss potential field sites. Along with information collected during the literature review this helped determine which sites were suitable for the project.

This research looks at the impact of soil compaction on both arable and grassland soils in the Skell catchment, North Yorkshire (Chapter 1). To assess the spatial variability in the relationship between soil compaction and soil hydrology this thesis will study four different types of rural land management, Arable Farming, Cattle Grazing, Horse Grazing, and Sheep

Grazing (Figure 3.1). This study will be one of the first to measure and compare all these different types of variations together. The four sites will now be discussed in more detail.

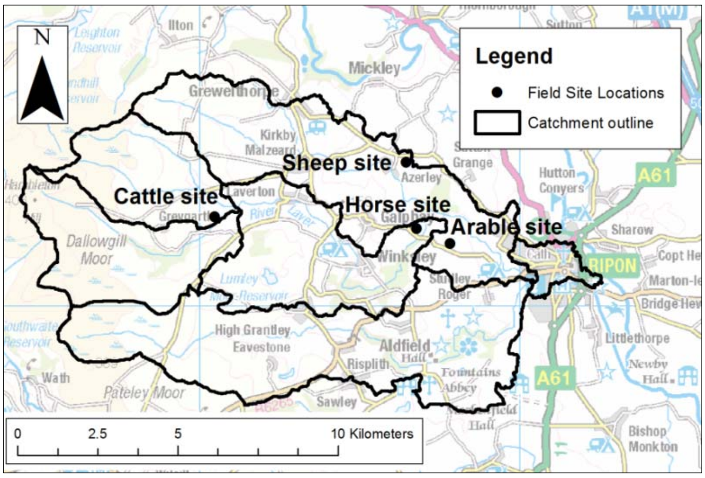


Figure 3.1: Skell catchment with location of four field sites.
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3.2.1 Site 1: Arable Farming

This site was chosen for this study because this type of land management represents a significant portion (27%) of the utilised agricultural area in the UK and 13% of land cover in the Skell catchment (Centre for Ecology and Hydrology, 2016). The Arable Site was located at Birkby Nab Farm at an elevation of 80-90m A.O.D. The site is two miles west of Ripon and slightly south of the confluence of the River Laver with Kex Beck (Figure 3.2). The area receives 675-700mm annual rainfall and has a highly permeable bedrock with highly productive aquifers (Centre for Ecology and Hydrology, 2016). The study field was approximately rectangular and 0.047km^2 in size. It was located next to Dick Hill Wood to the east and Galphay Lane to the south. A bridleway ran through the middle of the field.

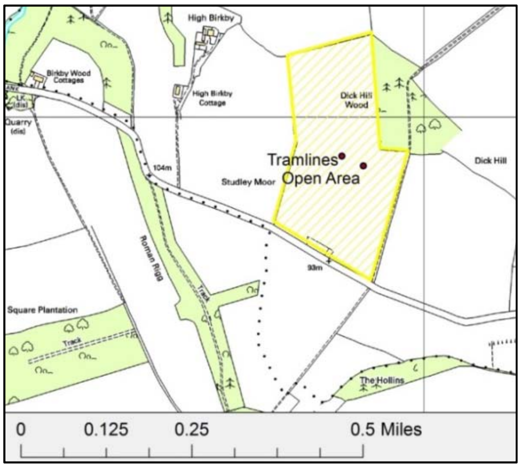

Figure 3.2: Arable Site at Birkby Nab Farm (highlighted in yellow). Copyright © Ordnance Survey 2018.

The bedrock geology at this site is the Cadeby formation composed of Dolostone. The superficial deposits are the Vale of York formation, part of the North Pennine Glacigenic Subgroup. They are Devensian aged, composed mainly of glacial till with interbedded sand, gravel and laminated clay and are generally ten-thirty metres thick (British Geological Survey, 2016a).

Figure 3.3: Arable Field Site - July 2014 & April 2015.

In a conversation on 23 July 2014 V. Lawson confirmed that the Arable Site implements a crop rotation to reduce the loss of nutrients in the soil and protect against pests that thrive when only one type of crop is grown. During the study period the following crop rotation was planted – spring maize, winter wheat and spring barley. The practices in Table 3.1 were undertaken during the study period (Personal communication).

Table 3.1: Practices and number of tractor passes at Arable Site.

Date	Crop	Tractor passes	Farming practices
April 2014	Maize planted	5	Manure spread from a trailer
			Sumo-Rippa (3m wide) used to remove plough pan and aerate soil to 25-30cm depth
			Soil left for a week to dry out
			Maize sowed and covered by seed drill (4m wide)
			Fertilised with urea (2.5cm from the plant) from a trailer
			Rolled to compact soil with a 9.5m wide roller
Sept. 2014	Maize harvested	2	Maize cut & harvested using 12-tonne forager trailer and tractor (total weight=19.9 tonnes)
Oct. 2014	Wheat planted	6	Manure spread from a trailer
			Sumo-Rippa (3m wide) used to remove plough pan and aerate soil to 25-30cm depth
			Soil left for a week to dry out
			Power harrowed to break up soil/prepare seed bed
			Wheat sowed and covered by seed drill (4m wide)
			Fertilised (2.5cm from the plant) from a trailer
			Rolled to compact soil with a 9.5m wide roller
March 2015	Wheat harvested	2	Wheat cut & harvested using 12-tonne forager trailer
April 2015	Barley planted	6	Manure spread from a trailer
			Sumo-Rippa (3m wide) used to remove plough pan and aerate soil to 25-30cm depth
			Soil left for a week to dry out
			Power harrowed to break up soil/prepare seed bed
			Barley sowed and covered up by a 4m wide seed drill attached to a tractor
			Fertilised (2.5cm from the plant) from a trailer
			Rolled to compact soil with a 9.5m wide roller
Sept. 2015	Barley harvested	2	Barley cut & harvested using 12- tonne forager trailer

Two tractors were used at this site and the tyres had constant inflation pressures (Table 3.2) throughout the study period. These pressures have been shown to avoid compaction during dry conditions (Hatley et al., 2005).

The individual tramlines were fifty centimetres wide with a gap of 1.8m in the middle making the area 2.8m wide in total.

Table 3.2: Two tractors used at field site during study period *depending on ground conditions and weather during practices. (Tractor Data, 2016).

	Tractor 1	**Tractor 2**
Type	New Holland TM190	New Holland TM115
Use	Main cultivations	Rolling the ground
Length	4.81m	4.71m
Height	2.88m	2.88m
Width	2.82m	2.01m
Weight	7.9 tonnes	5.3 tonnes
Front tyre construction	Radial	Radial
Tyre rim diameter	71.12cm	60.96cm
Tyre width	60cm	38cm
Rear tyre construction	Radial	Radial
Tyre rim diameter	96.52cm	96.52cm
Tyre width	71cm	42cm
Inflation pressure front	110kPa*	138kPa*
Inflation pressure rear	55kPa*	124kPa*

3.2.2 Site 2: Cattle Grazing

This site was chosen because Cattle Grazing is one of the top two pastoral land management practices in the UK (DEFRA, 2015) and the land cover in the Skell catchment is dominated (48%) by grassland (Centre for Ecology and Hydrology, 2016). The Cattle Site was located at Hedge Nook Farm in the foothills of the Yorkshire Dales at an elevation of 143-177m A.O.D (Figure 3.4). It is in the west of the study catchment, approximately eight miles from the city of Ripon, two miles west of Kirkby Malzeard and nine miles north of Pateley Bridge. The area receives 850-900mm annual rainfall and has a moderately permeable bedrock with locally important aquifers (Centre for Ecology and Hydrology, 2016). It is underlain by the Millstone Grit Group. The total farm area is 1.13km^2 with a mixture of sized fields for grazing and silage.

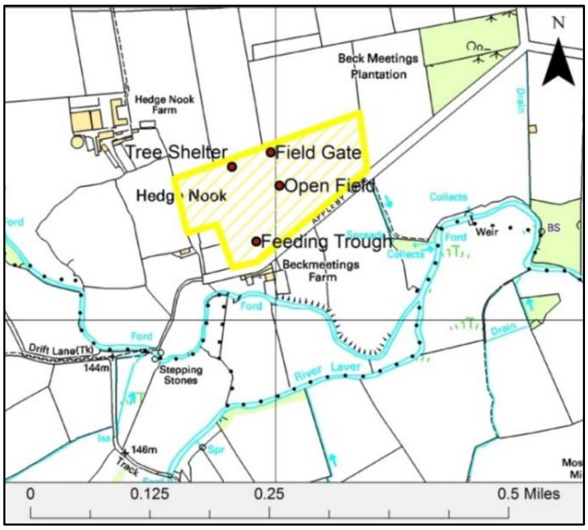

Figure 3.4: Cattle Site at Hedge Nook Farm (highlighted in yellow). Copyright © Ordnance Survey 2018.

The bedrock geology at this site is the Upper Brimham Grit which is part of the Hebden Formation and is composed of thick bedded, trough cross-bedded, grey, coarse grained, feldspathic sandstone approximately five-fifteen metres thick. The superficial deposits are Devensian age Till Diamicton deposited as moraines and outwash sand and gravel from post glacial meltwaters (British Geological Survey, 2016).

The study field (Figure 3.4) was located south of the farm buildings on the slope next to Appleby Lane and Carlesmoor Beck, near the confluence with the River Laver. The field is approximately rectangular and 0.045km^2 in size. The field has been used for pasture for the last thirty years, prior to that it was a ley field that was alternatively seeded for grain and left fallow for hay. The farmer does not receive any European Union or UK grants for this field (Personal communication).

The farm has a dairy herd of four-hundred cows with approximately one hundred cows in a field at any one time (Figure 3.5). The average weight of the dairy cows at the farm is 700-750kg and they have heart shaped hooves with a contact area of 0.0128m^2. The pressure exerted when stood on four feet is therefore, 536-598Pa. The farmer implements rotational grazing where the cows are strategically moved every three-four days into fresh fields, which allows the grass in the previous field to regenerate. Rotational grazing suits cattle as they frequently like to change the area that they graze. The fields are left fallow for two-three weeks to allow the grass to grow to ten-thirty centimetres tall.

Figure 3.5: Dairy cows at Cattle Site.

In a conversation on 23 July 2014 with K. Nicholson he confirmed that the cows are only on the field in the dry summer period (April-October) during daylight hours and are kept inside during the wet winter period (November-March). In January/February manure is placed on the field to put nutrients back into the soil, this includes nitrogen and potash. Before the cattle are released back into the field, around March time it is harrowed to pull out the dead grass and rolled to flatten it back down. In summer, artificial fertilisers including nitrogen are spread (0.005kg/m^2) from a trailer to kill off weeds and increase grass growth. No silage is cut (Personal communication).

3.2.3 Site 3: Horse Grazing

There is a relatively high horse population in the catchment and thirty-five liveries, stables and equestrian centres in North Yorkshire (Horse Network Ltd., 2015). The Horse Site is located at Lindrick Livery Stables on Cow Myers Farm, four miles to the north-west of Ripon and at an elevation of 83-93m A.O.D (Figure 3.6). The Livery sits between Kex Beck to the North and the River Laver to the South. The area receives 700-750mm annual rainfall and has a highly permeable bedrock with highly productive aquifers (Centre for Ecology and Hydrology, 2016). The site geology is classified as Carboniferous Limestone with superficial deposits of stony clay till to a depth of seven metres. Boreholes drilled at the site previously have shown that the soil is 0.2m thick and the ground water level is sixty-five metres deep (Strong and Giles, 1983).

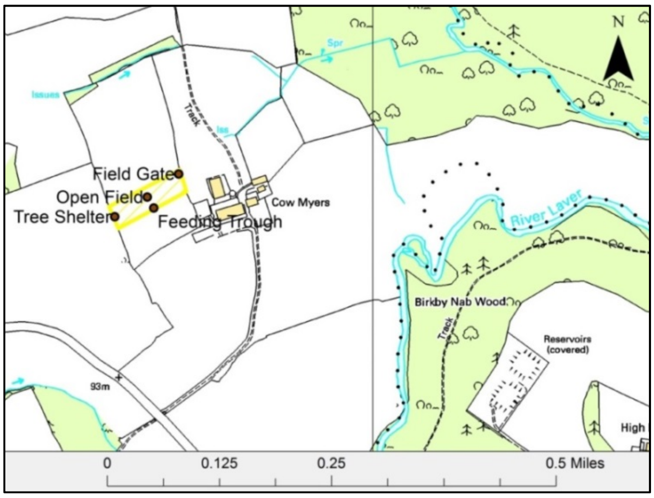

Figure 3.6: Horse Site at Lindrick Livery (highlighted in yellow). Copyright © Ordnance Survey 2018.

The bedrock geology at this site is the Pennine Lower Coal Measures Formation. It is composed of interbedded grey mudstone, siltstone and pale grey sandstone, commonly with mudstones containing marine fossils in the lower part and more numerous in the thicker coal seams in the upper part. The maximum thickness can reach seven-hundred metres. The superficial deposits are the Vale of York formation, which is part of the North Pennine Glacigenic Subgroup. The deposits are composed mainly of glacial till (sandy clay, clayey sand and clay with gravel and boulders) with interbedded sand, gravel and laminated clay and are generally ten-thirty metres thick (British Geological Survey, 2016).

The Livery has thirty-six stables and twelve paddocks where the horses are turned out as often as possible (up to three-hundred and sixty-five days a year). The horses who reside at the livery are usually turned out of their individual stables at sunrise and returned at sunset. Over the summer period, when the stables are full the horses may be left in the field twenty-four hours a day. In a conversation on 24 July 2014 L. Ruddock confirmed that the horses are not turned out in very bad weather conditions, such as in very cold or snow conditions to avoid over-grazing and poaching.

Figure 3.7: Horse Site with thoroughbred horse in field – October 2014.

The study paddock (Figure 3.7) used in this research is a rectangular section of grazing pasture 0.006km^2 in area and is enclosed with permanent electric fencing (1.2m high). The average grazing requirement for one horse is 0.005-0.01km^2 depending on the type of grass, ground conditions and the time of the year (DEFRA, 2009; Surrey County Council, 2015). The paddock size is therefore appropriate for one horse. One two-year-old thoroughbred horse was kept in the paddock throughout the study period. The density is 167 horses/km^2. During June/July 2015 an additional young horse was also kept in the upper section of the field.

An average sized equine is classed as 0.80 livestock units and weighs approximately 500kg (Eurostat, 2013). With an estimated foot surface area of 0.0062m^2 and a contact area of 0.025m^2. The pressure exerted when stood on four feet is 196kPa. Horses naturally graze and their natural diet is grasses which have high roughage content (DEFRA, 2009). Horses can eat up to 4% of their body weight, as grass, per day (British Horse Society, 2015).

To prevent over-grazing horses should not graze grass until it is established (ten-fifteen centimetres long) to allow the root system to develop (British Horse Society, 2015). Drainage is essential to maintain pasture health, especially when the land is being grazed all year round. In a conversation on 24 July 2014 L. Ruddock confirmed that there is an annual schedule to keep the paddock healthy. In spring the paddock is harrowed, reseeded, rolled and sprayed for weed control. Over summer and autumn, it is managed for weed control and in winter the paddocks are evaluated and rotated where possible. Due to problems with drainage the land owner has put hard core (rubble aggregate) in the gate area.

3.2.4 Site 4: Sheep Grazing

Sheep Grazing is one of the top two pastoral land management practices in the UK (DEFRA, 2015). The Sheep Site is located at Home Farm on the Azerley Chase Estate, a small settlement about four miles north-west of Ripon (Figure 3.8). The land stands at an elevation of 96-101m AOD. Kex Beck runs to the south of the site and Kirkby Road runs to the north of it. The area receives 700-750mm annual rainfall and has a moderately permeable bedrock with locally important aquifers (Centre for Ecology and Hydrology, 2016). There are numerous land drains in this area with flushing points and a pump house to the left of the field at Azerley Chase.

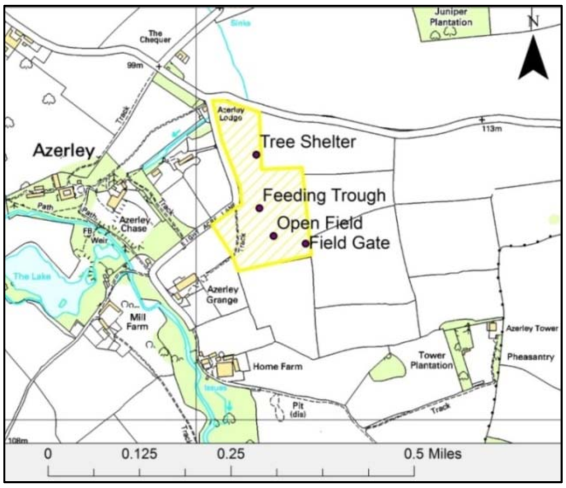

Figure 3.8: Sheep Site at Home Farm (highlighted in yellow).
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The site geology is classified as Carboniferous limestone and sandstone with superficial deposits of glacial sand and gravel to a depth of sixteen metres.

Boreholes drilled at the site previously have shown that the soil is 0.1m thick and the ground water level is 89-92m deep (Strong and Giles, 1983). The bedrock geology is the Laverstone sandstone, part of the Millstone Grit series and is composed of medium-thickly bedded grey, medium-coarse grained cross bedded sandstone, with beds of grey siltstone. The superficial deposits in the northern part of the field are Devensian Till Diamicton and in the southern part of the field the deposits are Devensian Glaciofluvial sand and gravel (British Geological Survey, 2016). The study field is 0.05km^2 in size and is approximately rectangular with undulations known as ridge and furrows which are typical of ancient ploughing practices (Figure 3.9).

Figure 3.9: Ridge and Furrows at Sheep Site and from above. (Google, 2016).

An average sized sheep in Europe is classed as 0.10 livestock unit (LSU) and weighs approximately 60kg. There are variations in weight due to sheep species, gender and age with nursing ewes weighing up to 130kg and mature rams weighing up to 205kg (Eurostat, 2015). Ewes breed once a year and give birth in spring time, usually to just one lamb or twins. Lambs have an average birth weight of 2-4kg (North Carolina State University, 2015).

In a conversation on 25 October 2014 with N. Colver he confirmed that the farmer has English sheep that are bred for meat with an average weight of 70kg (Personal communication). Sheep have an approximate foot area of 0.0006m^2 (D. Eldridge, personal communication) this gives a contact area of 0.0024m^2. The pressure exerted when stood on four feet is 286kPa. The sheep reside in the field for twenty-four hours a day and twelve months of the year at a stocking density of 12.3 sheep/km^2. There were seventy-five sheep in the study field during the fieldwork period (Personal communication).

Sheep eat plant based food (grass, clover, forbs) with average daily food consumption from 1-2.5kg per day (North Carolina State University, 2015). Sheep have narrow faces which allow them to graze very close to the ground and in this study they grazed on pasture plants and sheep nuts to supplement their diets. The nuts are placed in feeding troughs during the cooler months and spread over the field by the farmer during the warmer months which helps to spread the animals across the field, so they are not congregated in one area.

3.3 Site Selection: Intra-Field

The information gathered in the literature review, and photographs and observations collected during initial catchment visits were used to determine a priori ‘non-compacted’ and ‘compacted’ areas of each field site. They were identified as areas with bare soils, lack of vegetation growth extremely dry and cracked soils and muddy and ponded surfaces in comparison to surrounding areas. The main observations were that compacted areas occurred where animals congregate, or machinery frequently travels (Figure 3.10). The non-compacted areas were harder to define, although in general in the field, they were observed to be well vegetated, non-muddy soils, with no ponded surface water. In general, it is thought that animals do not congregate in these areas as often as they do in the compacted areas, although this theory was not tested and no survey was undertaken.

At the Arable Site two areas were identified:

- Open Field – assumed to be less compacted than the tramlines area.
- Tramlines – tractor wheel lines in the crop, where the tractor commonly moves up/down the field (Figure 3.11).

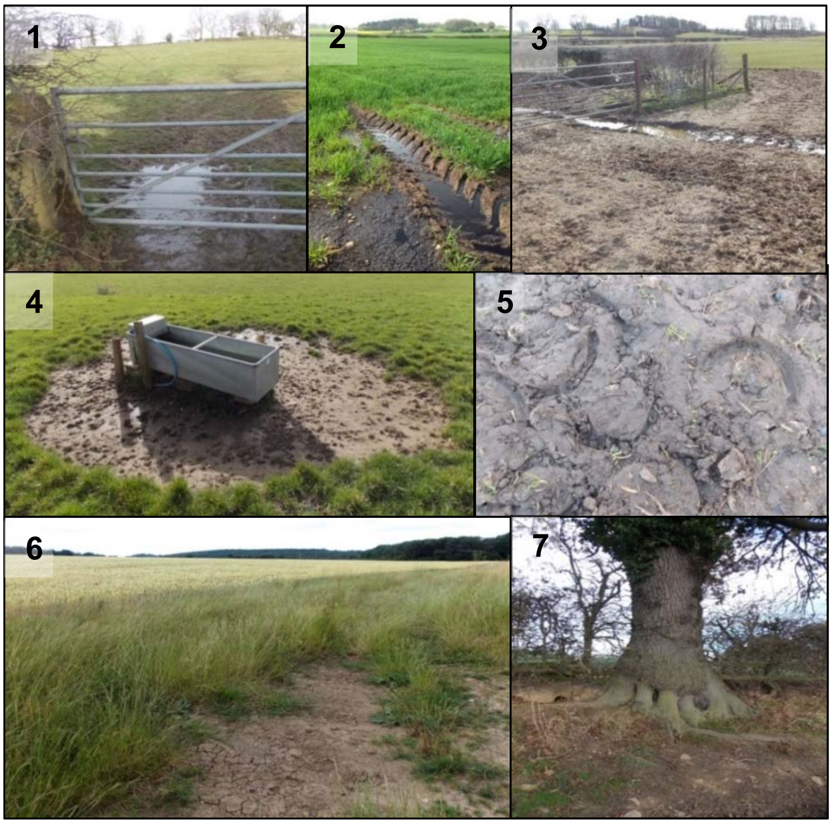

Figure 3.10: Evidence of ‘compaction’.

Photos 1, 2 & 4: Lack of vegetation, muddy soils and ponded water

Photos 3 & 5: The presence of machinery and animals

Photos 6 & 7: Dry and cracked soils at the Arable Site and beneath a tree.

Figure 3.11: Arable Tramlines - April and August 2014.

At the Cattle, Sheep and Horse Sites four sites were identified (Figure 3.12):

- Feeding Trough – where food/water is put and animals regularly stand.
- Field Gate – where animals are frequently moved in and out of the field.
- Tree Shelter – where animals stand or rest to shelter from the weather.
- Open Field – an area assumed to be less compacted than the other three sites due to the lack of a feature that animals congregate around.

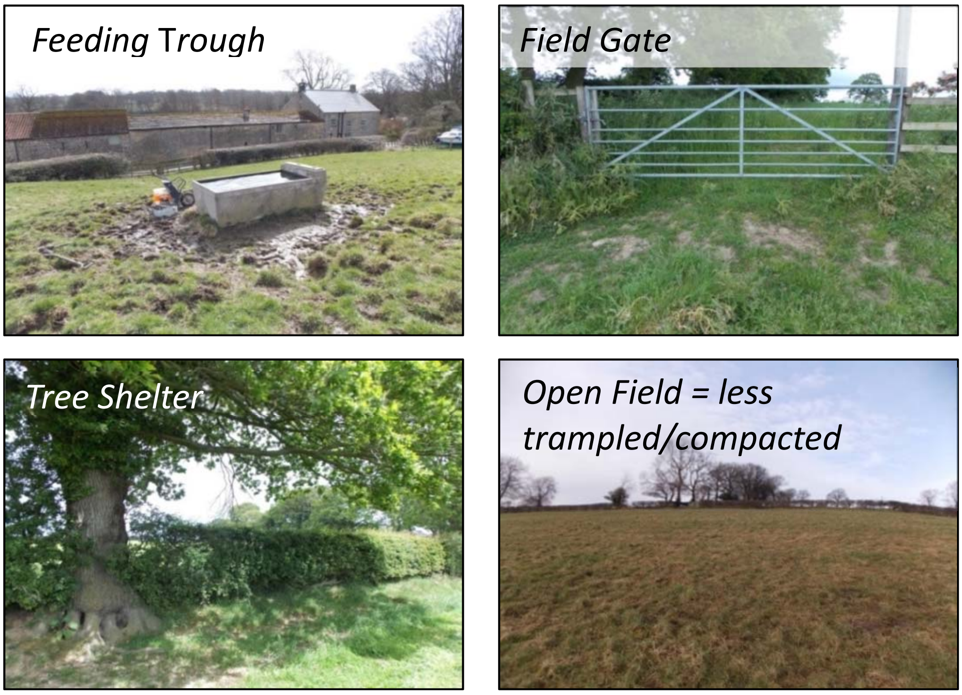

Figure 3.12: Pastoral Intra-Field areas in October 2014.

The Cattle Site had one rain water collecting trough located at the bottom of the slope (elevation 146m A.O.D). The trough was set in this position throughout the study period. A hedge line with numerous hedge trees run across the top of the field (elevation 167m A.O.D.) and provides natural shelter. The field has two metal field gates including the one used in this study that is located at the top of the slope (elevation 161m A.O.D.). The cattle are moved in and out of the field through this gate creating frequent hoof traffic (Figure 3.12).

The Horse Site slopes downhill from west to east and has one self-filling water trough located about half way up the slope (elevation 87m A.O.D.) which was set in this position throughout the study period. A hedge line and hedge tree at the top of the paddock (elevation 93m A.O.D.) provides natural shelter. The paddock has one metal field gate, at the bottom of the slope (elevation 83m A.O.D.). The horse is moved into the paddock through the field gate in the morning and evening, creating frequent hoof traffic (Figure 3.13). Horses are also known to collect and stand around gates and run along field margins (The British Grassland Society, 2015).

The Sheep Site contains movable feeding troughs called single sided creep feeders 2.4m long and 1.2m wide. They have four rubber wheels' underneath which make it easy to move them up and down and helps to stop poaching. They were located in the middle of the field at an elevation of 95m A.O.D. The field is bordered by hedgerows which are gappy and therefore enhanced by a fence running in front of it. There are four field gates out of the field, three of which are trafficked by the sheep when they are moved into different fields or into the farm area for shearing. The field gate used in this study is located on the eastern edge at an elevation of 101m A.O.D.

Figure 3.13: Sheep Feeding Trough and Tree Shelter.

There are several large oak hedge trees that provide natural shelter areas for the sheep. The tree used in this study is located on the eastern edge in the top part of the field (elevation 100m A.O.D.). It is a mature, isolated tree standing at over twenty metres tall (Figure 3.13). Oak trees are deciduous, broad-leafed and have deep rooting systems that have been known to spread over thirty metres from the trunk (Chandler and Chappell, 2008). They have high bark roughness and bark water storage capacity (Hosseini Ghaleh Bahmani et al., 2012).

3.4 Seasonality: Study Periods

Two points of the year were chosen for fieldwork to allow a comparison between two seasons. The first point was in October 2014, at the end of the slightly drier, warmer summer period (May-October) which is associated with higher vegetation growth due to less average monthly rainfall (52mm/month), higher average temperatures (9-18°C) and more sunshine hours (157 hours). The second point was in the April 2015, at the end of the slightly wetter, cooler winter season (November-April) which is associated with lower vegetation growth due more average monthly rainfall (57mm/month), lower average temperatures (2-9°C) and less sunshine hours (83 hours). This increases the risk of bare and wet soils which can exacerbate soil compaction by livestock (Greenwood and Mcnamara, 1992). April is a key time of the year for grass/crop growth which is important for protecting against compaction (Ball et al., 1997).

The fourteen field sites used in this study were designated with a code that is used throughout this chapter (Table 3.3). The Tramlines, Feeding Trough, Field Gate and Tree Shelter Sites are assumed to have a higher potential of compaction due to frequent machinery or animal traffic, compared to the Open Field sites which are assumed to have a lower level of compaction due to lower levels of trafficking.

Table 3.3: Site codes used within this chapter.

Land management type and sub-field area	Code
Arable - Open Field	AOF
Arable - Tramlines	ATL
Cattle - Feeding Trough	CFT
Cattle - Field Gate	CFG
Cattle - Open Field	COF
Cattle - Tree Shelter	CTS
Horse - Feeding Trough	HFT
Horse - Field Gate	HFG
Horse - Open Field	HOF
Horse - Tree Shelter	HTS
Sheep - Feeding Trough	SFT
Sheep - Field Gate	SFG
Sheep - Open Field	SOF
Sheep - Tree Shelter	STS

3.5 Sampling Strategy and Design

Before measurements and testing began a sampling strategy was devised for use at all fourteen sites. The technique had to be efficient and easy to replicate. A stratified random sampling technique was used at each site because the subpopulations of interest, which were the a priori ‘compacted’ and ‘non-compacted’ areas were easily identified within the field (Harris and Jarvis, 2011). A metre squared grid was set up around the areas of interest and all the samples and field tests taken within it (Figure 3.14). All measurements were assumed to be from the same sub-field population.

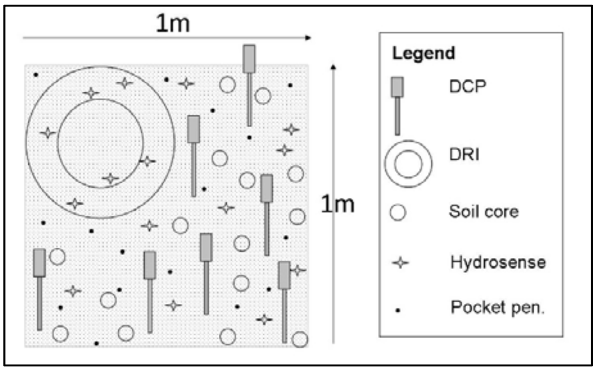

Figure 3.14: Sampling grid showing all the different techniques used at site. DCP: Dynamic Cone Penetrometer, DRI: Double Ring Infiltrometer, Soil core indicates the 15 cores, Hydrosense probe and pocket penetrometer

This technique provides greater precision than simple random sampling of the same size as it requires fewer sample points and is more cost effective than sampling a large area. It guards against collecting unrepresentative samples because all the samples are collected from the same subpopulation. The technique assumes that bare soils indicate more compacted areas, which may or may not be true and the subsoil is a good reflection of the underlying soil characteristics. This type of sampling relies on good scientific knowledge of the processes which affect the phenomenon being studied (Harris and Jarvis, 2011).

A pilot study was undertaken in August 2014 to practice the experiments at the field sites and soil samples were collected from the Arable and Cattle

Sites and analysed in the laboratory. This helped to inform the variability in the soil characteristics which was not known beforehand. From the pilot study the data was used to determine the number of samples needed for the study using the standard equation for sample size. When n is the sample size, $Z_a/2$ is the z-value, σ is the standard deviation of the population (in this case the pilot study population) and E is the margin of error. Equation 3.1 was used to determine that a z-value of 1.96 (95% confidence interval) and an error of one that a sample size of fifteen would be sufficient as long as the standard deviation within the samples were less than 1.95.

Equation 3.1: Determination of sample size.

$$n = \left[\frac{Za/_{2\ x\ \sigma}}{E}\right]2$$

To collect the data needed to assess the process based relationship between soil compaction and soil hydrology three types of tests were undertaken at all four field sites. Section 3.5.1 and 3.5.3 discusses the soil core extraction and description techniques. Section 3.5.4 discusses the soil sample laboratory tests and Section 3.5.5 and 3.5.5 discusses the soil strength and drainage tests.

3.5.1 Soil Core Extraction

To gather background information about the soil horizons and soil drainage a one metre long soil core was extracted at each field site. Cores from the two areas of the Arable Site and the four areas of the Sheep Site were collected in December 2014 and from the four areas of the Cattle and Horse Sites in February 2015.

Three techniques were used to collect the cores due to accessibility issues at some of the sites. Before any sampling commenced a cable locator was used to check for the presence of electronics or metal pipes beneath the ground. The first piece of equipment used was a Honda Premier 110 series percussion hammer driven sampling drill rig (Premier Plant Engineering Ltd.,

2014) with a ten centimetre diameter corer which was used at the Arable and Sheep Sites (Figure 3.15). It was chosen to collect the soil cores because it has been specifically designed for soil sampling and geotechnical testing.

Figure 3.15: The Honda drilling rig at the Arable Site, the Atlas Copco Cobra at the Cattle Site, and a Gouge Auger used at the Horse Site. (Eijkelkamp Agrisearch Equipment, 1999).

The hammer weighed 63.5kg and falls 760mm with each blow. The average hammer speed was thirty-five blows per minute. The automated hydraulic pullback system allowed for quick extraction of the sampler in plastic tubes. The total weight of the rig was 850kg making it awkward to transport to site due to restrictions on driving with heavy loads. However, once on site the rig was easily moved (remote controlled) by a trained technician. The rig sat on tracks which coped well with soft and wet soils. It was not moved over the sample area prior to sampling. The drill rig is destructive to the soil in the area that the core is taken from and no other measurements could be made in the same area.

The second piece of equipment was a motor-driven Atlas Copco Cobra Combi percussion hammer (Atlas Copco, 2012) connected to a five centimetre diameter sampler by a RD32 rope thread and was used at the Cattle Sites (Figure 3.5.1.1). The Cobra was smaller and lighter (25kg) than a full drill rig which meant it could be used in more environments and was less likely to damage the soil surface. It was carried rather than driven onto site, had a quick set up time and was easier to transport than the drill rig. However, the sampler extraction can be tricky and takes longer than the drill rig method.

The core sampler used with the Cobra hammer had a cutting head made from hardened steel and was used to collect undistributed samples in a closed chamber (Van Walt Ltd., 2014). A foil liner was inserted into the sampler prior to use to make sample retrieval easy and so the core could undergo further analysis when back in the laboratory. The samples were extracted manually by levering the sampler out of the ground. The Cobra theoretically works well in homogeneous soils however it did not work as well at the heterogeneous rocky soils found in this study. If stones are larger than the diameter of the core sampler then the core must be taken again. Soil can be lost during the removal of the core samples from the borehole and during the removal of the foil liner from the core sample.

The third piece of equipment was a gouge auger (Eijkelkamp Agrisearch Equipment, 1999) with a two centimetre diameter which was used at the Horse Sites (Figure 3.5.1.1). The drilling rig and Cobra were not used at the Horse Site because it would have upset the horses and damaged the ground. An auger was chosen because they cause minimal disturbance. The diameter of the auger is good for sampling in medium to soft soil and is used for rapid sampling. The auger had an almost half cylindrical cutting head with parallel cutting edges running from top to bottom to help with insertion and was made of high grade steel to prevent torsion of the body.

The auger was placed vertically on the soil surface and pushed and then hammered into the soil using an impact absorbing hammer. After the auger had reached the desired depth it was revolved to cut loose the sample and then pulled upwards. The cylindrical soil column was cut off along the cutting edge and analysed in the field because there was only one auger. Samples of the core were wrapped in cling film and taken back to lab for analyses.

At greater depths, the auger encounters greater levels of resistance and was continually revolved to stop the build-up of resistance. The sample can be lost from the auger, if it is not revolved before/during the extraction due to the possible suction under the auger, during the insertion of the auger, or from excessive revolving which can lead to a loss of horizon cohesion. If the auger encountered a stone which is greater than its diameter then the test was stopped.

3.5.2 Soil Core Description

Once back in the laboratory the cores went through many tests to characterise the physical and chemical properties of the soil (Table 3.4). The main soil horizons were determined using the soil horizon designations (Appendix 1) in Chapter 5 from the World Reference Base for Soil Resources (Food and Agriculture Organisation of the United Nations, 2006). The horizon designation was determined by assessing the colour and composition of each layer. The O and the E Horizons generally only occur in forested areas although the E Horizon can also occur where there is a perched water table. The B-Horizon is important in that is reflects the chemical or physical alterations in the soil and accumulates the clays, salts and irons as they are washed down from the surface. The C-Horizon is below the zone of biological activity.

The soil cores were described in the following order using the standards described in Section 33: Description of Soils from (The British Standards Institution, 2015) BS5930 Code of Practice for Ground Investigations. The soil horizons material characteristics were described using a visual assessment of the soil’s composition (Table 3.4). Each of these tests will be described below. The first characteristic is colour determined using the Munsell Soil Colour Chart which assigns every colour a value (lightness) from black (0) to white (10), a specific hue (relation to colour) Red, Yellow, Green Blue or Purple and a chroma (strength) to represent the purity of the colour (0-14). It is written as a notation in this order e.g. 5YR 5/10 which means a yellow-red of medium lightness with a chroma of ten. The determination of colour can be difficult and there are wide variations in opinion between individuals (Munsell, 1905).

Table 3.4: Description of soil tests used to determine soil characteristics.

Order	Characteristics	Test	Reference
Additional	Mottling	Visual assessment - Colour, abundance and presence	(Food and Agriculture Organisation of the United Nations, 2006)
1	Colour	Munsell Soil Colour Chart	(Munsell, 1905)
2	Particle shape	Visual assessment after dry sieving	BS1377-2 Part 3.2
3	Particle size	1. Dry sieving and oven dry method	BS1377-2 Part 3.2
		2. Mastersizer 2000 particle size analyser using laser diffraction method	ISO13320
4	Secondary soil type	1. Dry sieving and oven dry method	BS1377-2 Part 3.2
		2. Mastersizer 2000	ISO13320
Additional	Calcium carbonate	Acid soluble test	BS14688-1
5	Principle soil type	1. Dry sieving and oven dry method	BS1377-2 Part 3.2
		2. Mastersizer 2000	ISO13320
6	Structure of the soil	Visual assessment	(Environment Agency, 2015)
7	Geological unit and age	Literature review	BGS Lexicon of Named Rock Units (British Geological Survey, 2016b)
8	Type of superficial deposit	Literature review	British Geological Survey's Rock Classification Scheme (McMillan and Powell, 1999).

The second characteristic was shape, form and surface texture of the coarser particles (>2mm) determined by the dry sieve method (The British Standards Institution, 1998a) BS1377-2 and described using the terms in Appendix 1. A soil sample was taken from the middle of each soil horizon and placed in a metal tray. The tray was placed in an oven at 105 degrees Celsius for twenty-four hours to dry. When removed the tray was placed in a desiccator for thirty minutes to allow it to cool. The oven dried sample was weighed and then sieved through a 2mm sieve. The portion over 2mm was weighed and the portion under 2mm was used in the next stage of the experiment.

The third, fourth and fifth characteristics were the particle size (Appendix 1) and the secondary and principle soil types (Appendix 1) which were determined using the results from the dry sieve method and by calculating the particle size distribution for the finer particles (0.01μm-2000μm) using the Mastersizer 2000 particle size analyser (Malvern Instruments Ltd, 2007). The Mastersizer 2000 determined the size of the particles in μm and the percentage volume of the sample broken down into 106 categories. The samples were sorted into the soil classes based on their size using the international standard scale (International Organization for Standardization, 2002) in Appendix 1 and soils with 35% or more fine material (clay or silt sized particles) described as fine soils and soils with 65% or greater coarse material (sand and gravel sized particles) described as a coarse soils. The principle and secondary soil type of each horizon was then determined using Appendix 1 (BS 5930:2015).

Before using the Mastersizer the soil samples were prepared. A sub-sample of the sample (<2mm in size) was taken, too little soil and there was not enough scattered light to be detected, too much soil and the light scatter from an individual particle would be scattered by other particles (multiple scattering). The dispersant sodium hexametaphosphate $(NaPO_3)_6$ at the concentration 33g/litre pure water was chosen due to its ability to break down clay and other soil particles. The dispersant was kept in the same room as the Mastersizer and soil samples to ensure it had the same temperature and pressure. Before the test, 20ml of the dispersant was added to the sample, shaken for two minutes and left for twenty-four hours to mix further. Immediately prior to the measurement in the Mastersizer the sample was shaken for two minutes by hand. To start the analysis, the optical unit was aligned by running the optical alignment system to make sure the laser was hitting the centre of the detector. A background measurement was made that accounted for impurities in the dispersant, on the windows/lenses of the machine and any electrical noise. This background information was subtracted from the measurement to ‘clean’ the data.

A pipette was used to transfer drops of the soil mixture to an 800ml glass beaker filled with pure water. To make sure the particles were fully deflocculated, to reduce re-agglomeration and to remove any final bubbles, ultrasonics (application of sound energy to agitate the particles) were run for two minutes before each measurement. The system measured the concentration of the sample by calculating the amount of laser light lost by passing through the sample. This is known as the obscuration percentage and the ideal obscuration range is 10-20%. It must be higher than 5% and lower than 50% and in these cases additional sample, or more dispersant were added (Malvern Instruments Ltd, 2007). Once in the ideal obscuration range the measurement of the scattering pattern took place.

Using a dispersant reduces the chances of the sample sticking together, or floating on the surface, which will lead to poor results. However, some particles may still have stuck together even after using a dispersant. The lenses and cell windows were removed and cleaned after every twenty sample measurements and the tubing was replaced every one-hundred samples to reduce degradation caused by excessive dirt and sample build up within the system (Malvern Instruments Ltd, 2007).

The sixth characteristic was soil structure but it was not possible to determine this from a small diameter core sample. The seventh and eighth characteristics were determining the geological unit, age and type of deposit (Appendix 1). This was done using the BGS Lexicon of Named Rock Units (British Geological Survey, 2016b) to distinguish the geology of the area and when the characteristics were clearly evident to match the superficial deposit to the terms from the British Geological Survey's Rock Classification Scheme (McMillan and Powell, 1999).

In addition to these eight characteristics, if present the state of mottling was included at the start of the description which refers to the quality of drainage (Clayden and Hollis, 1984). The presence of spots and streaks, often grey and blue, that are not associated with the background colour of the soil are known as mottles (Appendix 1). Mottles develop due to the lack of air which also causes the reduction of iron compounds leading to orange and yellow colours (Moore, 2001). Mottling occurs when soils are frequently wet for long periods of time either in soils with a high water table (gley soils) or when waterlogged soils take a long time to percolate (surface water gley soils). Mottling can occur in any horizon and the extent of mottling indicates the amount of waterlogging. However, when it occurs in the B-horizon it can also indicate repeated wetting and drying (Environment Agency, 2015).

If present, calcium carbonate ($CaCO_3$) was also included in the description, before the principle soil type and was assessed by placing a drop of dilute 10% hydrochloric (HCl) acid onto a sub-sample of soil. The sample was left for fifteen-thirty seconds and a hand lens was used to look for bubbles escaping in the reaction. The presence of $CaCO_3$ indicates that the soil is alkaline (has a high pH) and indicates a past shallow marine environment (The British Standards Institution, 2013).

3.5.3 Soil Sample Laboratory Tests

To supplement the field work, fifteen soil samples were collected from each site in the October fieldwork (two-hundred and ten samples) and another fifteen in the April fieldwork (two-hundred and ten samples). In total four-hundred and twenty samples were collected, composed of sixty samples from the Arable Site and one hundred and twenty from each of the Cattle, Horse and Sheep Sites. Samples were collected from the field using the core cutter method (The British Standards Institution, 2015) and brought back to the laboratory for testing. This method was chosen because it is suited to fine agricultural soils that are sufficiently cohesive and because it is a simple and efficient means of collecting soil samples (Lichter and Costello, 1994).

(The British Standard Institution, 2007) BS1377-9: In-situ tests standard size for core cutters is thirteen centimetres high with a ten centimetres internal diameter. However, it was not practical to create cutters this size, or to collect samples this large in the field. To make the four-hundred and twenty individual cylindrical core cutters, lengths of plastic piping were cut to size and given a bevelled end for easier entry into the soil. Four different sized core cutters were used due to the different diameter of the piping and the need for a set number of cutters (Table 3.5).

Table 3.5: Core cutter internal dimensions used in the soil sampling.

Core	**Height (cm)**	**Width (cm)**	**Volume (cm^3)**
1	7.05	4.00	88.59
2	6.20	3.60	63.11
3	5.90	4.20	87.14
4	5.80	3.60	59.04

In general cutter size one and two were used in the October sampling and cutter size three and four were used in the April sampling. The cutters created (Figure 3.16) are similar in size to the ones used by (UMS GmbH, 2012) in their benchtop saturated hydraulic conductivity instrument (five centimetres high and eight centimetres wide). Small volume samples can affect the representativeness of the soil characteristics if the heterogeneity of the sample is high however in this study the variability across each site was expected to be low.

Figure 3.16: Core cutters used to collect soil samples from field sites.

In the field the top layer of vegetation was removed to create a bare and flat surface and the core cutter was pushed into the soil surface vertically until it was completely full following the (The British Standard Institution, 2007) BS1377-9: In-situ tests. The cores were carefully excavated with a trowel to keep them in an undisturbed state. The sample and cutter were wrapped well in cling film to prevent soil or moisture loss, labelled and put into a storage box and transported back to the laboratory.

In accordance with (The British Standards Institution, 1981) BS5930 Code of practice for site investigation, the samples were stored in the cold fridge at 4°C before being processed. All the samples were processed in the same manner going through steps 1-6 (Table 3.6). The October set of samples (210) also went through steps 7-15 to determine the particle size. The methods for each of these steps will now be outlined.

In the first step a mini permeameter was used to study the behaviour of soil with respect to laminar water flow. The Falling Head Test (FHT) was chosen because it is a common laboratory method to determine the saturated hydraulic conductivity (Ksat). The FHT was chosen over the Constant Head Test because the samples contained fine grained soils that drain slower than coarse grained soils (Humboldt Mfg. Co, 2016). This was determined from pilot study. Also, because the soils were thought to be compacted and expected to have slow permeability (Ksat =<10^0mm/hour) (UMS GmbH, 2012). It is also easier to read the flow rate using the FHT so the results are more accurate (UMS GmbH, 2012). The FHT can last for a few minutes for sandy soils to longer than twenty-four hours for very impermeable soils (UMS GmbH, 2012).

Table 3.6: Laboratory work schedule.

	Equipment	Test/Method	Outcome	BS1377
1	Mini permeameter	Falling Head Test - Remove excess soil - Attach filter paper - Saturate for 24 hours	Saturated hydraulic conductivity	Part 5 - 5.5
2	Scales	- Remove from cores - Weigh sample to 3 decimal points	Gravimetric water content	Part 2 - 3.2
3	Oven, scales	Oven Dry Method - Dry at 105 degrees for 18 hours - Weigh to 3 decimal points	Dry bulk density, total porosity, volumetric water content	Part 2 – 3.2
4	Furnace, scales	Mass Loss on Ignition Test - Furnace at 420 degrees for 6 hours - Weigh to 3 decimal points	Organic matter content	Part 3 - 4.3
5	Pestle and mortar, 2mm sieve, base	Ground up sample for 1 minute and put the whole sample through a 2mm sieve, make note of size and quantity of large stones	- Break soil up - Particle size above 2mm	Part 2 - 9.3
6	Glass tube	Fill half of the glass tube with some of the material that has passed through the 2mm sieve	Storage for particle size analysis (PSA)	
7	1.5 litre beaker, sodium hex., water, stirrer	Add 33g of sodium hexametaphosphate to a litre of water and mix up until fully in solution.	Preparation for PSA	
8	Scales, sample, sodium hex. water mix., beaker, stirrer	Weigh out 0.4g of soil sample and mix with 20ml of sodium hexametaphosphate & water mixture in a 800ml beaker and shake for 1 minute	Preparation for PSA	

9	Sample, 800ml beaker, stirrer, MasterSizer	Add drops of the mixed sample (#12) into the 800ml beaker, until the obscuration is between 10-15%, run stirrer for 2 minutes, then run ultrasonic dispersion for 2 minutes, then run MasterSizer for 7 measurements and take the averaged result	Particle size analysis of fine particles (<2mm)	

Any additional soil protruding from the core was removed using a sharp knife to get a flat surface and a piece of filter paper was secured to the top and bottom of the core to stop sample escaping (UMS GmbH, 2012). The samples were soaked in de-ionised water for twenty-four hours to allow them to saturate and swell. This was the expected length of time needed to saturate silt soils (UMS GmbH, 2012) which are representative of the soils at the sites, although this method does not render full saturation as some air will always remain in the pores (Eijkelkamp Agrisearch Equipment, 2013).

The sample was placed in a mini-permeameter cell (Figure 3.17-A), which was created for the small samples. The cell was based on the BS1377-5 constant head permeameter cell specification (The British Standards Institution, 1998b) and had the same functionality, to cause water to flow through the sample during measurement, as it would in a natural situation.

The sample was held in place by a rubber O-ring which stopped water escaping horizontally (Figure 3.17-B). The seal was tested before the start of each experiment to make sure it was completely tight and no water was being lost from the top of the sample, before it ran through the sample. A circular piece of filter paper was placed on the bottom of the sample to prevent the loss of large amounts of sediment during the experiment. The mini-permeameter cell with sample (Figure 3.17-C) was immersed entirely in a soaking tank (bucket of de-ionised water) and left for two minutes to allow any additional bubbles to escape (Figure 3.17-D).

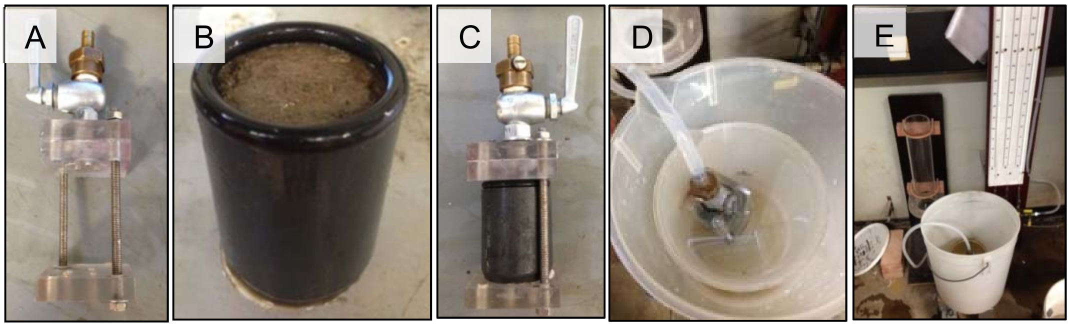

Figure 3.17: Falling Head Test - Sample preparation.
A: Mini-permeameter cell, B: Sample with synthetic O-ring, C: Permeameter with sampling tube inside, D: Permeameter immersed in water and E: Wooden manometer tube stand.

A free standing wooden manometer tube stand with a 1.5mm glass standpipe and a one-hundred centimetres long scale was used (Figure 3.17-E). The standpipe was filled with de-ionised water and connected by plastic piping to the top of the permeameter. Air was removed from the system and the water level in the standpipe was allowed to drop to a starting level of one-hundred centimetres. At this point a stop watch was started and the experiment ran until the water level in the standpipe had dropped to forty centimetres for consistency across all measurements. Time measurements were recorded every five centimetres.

Equation 3.2: Saturated Hydraulic Conductivity.

$$\boldsymbol{k = \left(\frac{a * L}{(A * \Delta t)}\right) * \log(\frac{h_U}{h_L})}$$

Equation 3.3: Temperature correction for saturated hydraulic conductivity.

$$k_{20°C} = k_{T°C} * \eta$$

The permeability of the sample was determined using Equation 3.2. Where k = saturated hydraulic conductivity, L = length of the sample column, A = sample cross section, a = standpipe cross section, Δt = recorded time for the water column to flow though the sample, h_U and h_L = upper and lower water level in standpipe measured using the same water head reference. The permeability was corrected for temperature using Equation 3.3. Where $k_{20°C}$ =

saturated hydraulic conductivity corrected to 20°C, $k_{T^\circ C}$ = actual water temperature during the test and Ƞ = correction factor for the viscosity of water (The British Standards Institution, 1998b).

There were limitations associated with the method that had been collected, the first is that to meet the British Standard the diameter of the permeameter should be twelve times greater than the largest particle size (The British Standards Institution, 1998b), which due to the smaller nature of the sample corers meant that the pebbles had to less than 0.3 or 0.35cm to qualify. Four of the samples had pebbles inside which did not meet this requirement but, were not evident until the sample was removed from the corer. The results from these tests were discarded. Eleven of the cores, five from the Horse Sites and four from the Arable Sites, had cracks in them that had occurred during sampling but, were not identified at site. The test could not be run on these samples as water ran straight out of the side, rather than through the sample.

In the third step the oven method was chosen to determine bulk density and total porosity because it is the British Standards Institution, 1990b: 1377-2 for the determination of density in fine grained soils. The soil sample was removed from the cylindrical corer and placed in a metal tray which had already been weighed, and then the tray and the sample in its fully saturated state were re-weighed. The tray was placed in an oven at 105°C for eighteen hours to dry. When removed the tray was placed in a desiccator for thirty minutes to allow it to cool, then the tray was re-weighed. Equation 3.4 and Equation 3.5 were used to calculate the gravimetric water content and the dry bulk density.

Equation 3.4: θ_g = Gravimetric water content (g/g).

$$\theta_g = \frac{m_{water}}{m_{soil}}$$

Equation 3.5: ρbulk = Dry bulk density (g/cm^3).

$$\rho_{bulk} = \frac{m_{dry}}{volume}$$

Equation 3.6: ϵ = Total soil Porosity.

$$\varepsilon = 1 - (\frac{\rho_{bulk}}{\rho_{solid}})$$

Where, m_{water} = mass of wet soil minus mass of dry soil, m_{soil} = mass of dry soil, m_{dry} = mass of dry soil and the volume = volume of soil sample. High bulk densities indicate poor soil structure, low levels of total porosity and high levels of soil compaction. Low bulk densities indicate good soil structure, high levels of porosity and low levels of compaction.

The results of the experiments were used to calculate the total porosity of the soil, using Equation 3.6. Where, Ɛ = porosity, ρsolid = particle density of the solid soil fraction. The particle density was calculated in the laboratory using the gas jar method. A soil sample of one kilogram from each site was sieved through a 37.5mm sieve and two sub-samples of 200g were removed and oven dried at 105°C for twenty-four hours to remove the water. Two one litre glass jars and two ground glass plates were cleaned, dried and weighed. The first sub-sample was put into the first jar and weighed with the ground glass plate. 500ml of distilled, room temperature water was added to the jar and the rubber stopper was inserted into the top.

The jar was shaken by hand for two minutes and then put in the shaking apparatus for thirty minutes. The stopper was removed and particles washed back into the jar, any froth was dispersed and additional water was added to within 2mm of the top of the jar. After a few minutes the jar was filled to the brim with more water and the glass plate was placed on top of the jar, taking care not to trap air under the plate. The jar and plate were carefully dried on the outside and the weighed again. Then the jar was emptied, washed and filled with room temperature distilled water, before again sliding the plate on top, preventing air getting trapped under it and then drying the outside and weighing. The whole process was repeated for sub-sample two and particle density determined using Equation 3.7.

Equation 3.7: ρ_s = Particle density (Mg/m^3).

$$\rho_s = \frac{m_2 - m_1}{(m_4 - m_1) - (m_3 - m_2)}$$

Where, m_1 = mass of the jar and ground plate, m_2 = mass of jar, plate and soil in grams, m_3 = mass of jar, plate, soil and water in grams and m_4 = mass of jar, plate and water in grams. The two results were compared to check they are within 0.3Mg/m^3 of each other, which they were and a figure of 2.6g/cm^3 was determined for all four sites. Some of the samples were unsuitable for use in the test due to the loss of large quantities of soil during the soaking stage and they were removed to prevent errors in the results. The eleven samples with cracks in the cutter were not deemed suitable for these tests either.

In the fourth step the organic matter content was determined using the mass loss on ignition (LOI) method rather than the more widely used (Walkley and Black, 1934) (WB) method (IUSS Working Group WRB, 2014). The LOI method was chosen because of the relatively simple nature and cost-effectiveness of the LOI method and because it does not involve the use of any toxic chemicals. It was also chosen because it is relevant for sandy soils that contain little clay as were found at the study sites in the catchment (The British Standards Institution, 1990).

The samples had already been dried in the oven at 105°C for eighteen hours and left to cool in the desiccator. The samples were left in their whole state, rather than sub-sampled. This was done because a larger sample gave a better representation of the site, especially due to the variety in organics (NRM Laboratories, 2015), which were not homogeneous throughout the site. The samples were not sieved as it was thought that a lot of the organic matter (mainly grass roots, seedlings) would be lost during this process.

Crucibles were heated for an hour to remove any moisture, left to cool in a desiccator and weighed empty. The samples were broken down using a pestle and mortar and then transferred to the crucibles and re-weighed. Five crucibles at a time, containing samples from the same site area, were placed in the muffle furnace. The British Standards Institution, 1990a - Part 3 suggest that the test should be undertaken at 440+/-25°C and maintained for at least three hours. Following a literature review it was decided that 420°C would limit the loss of inorganic carbon and calcium carbonate in the test (Prévost, 2004; Wright et al., 2008). The furnace took an hour to heat up to a constant temperature of 420°C and the test was run for six hours. This longer period of time was required because the samples were quite large and needed longer to ignite. After the test the samples were transferred to a desiccator to cool and then re-weighed. Equation 3.8 was used to calculate the organic matter content of the samples.

Equation 3.8: Organic Matter Content

$$\text{\% organic matter} = \frac{\text{pre-ignition weight (g)- post-ignition weight (g)}}{\text{pre-ignition weight (g)}} \text{ x } 100$$

The loss on ignition method can be affected by factors that are unrelated to the organic matter content of the soil (The British Standards Institution, 1990) for example the loss of inorganic carbon (gypsum, clay or carbonates) at 425-520°C produces an over-estimation of organic matter content (Santisteban et al., 2004). However, studies have shown that furnace temperatures between 400-430°C do not show any significant bias or errors in the loss on ignition results, in comparison to the WB method, mainly due to the fact that calcium carbonate does not ignite at these temperatures (NRM Laboratories, 2015; Ben-Dor and Banin, 1989; Davies, 1974).

Other potential errors occur due to handling errors, the position of the crucibles in the furnace, the crucible size, sample size, cooling times and reabsorption of moisture from the atmosphere. However, studies have found that as long as each step in the loss on ignition method is consistent for all samples then these errors will be majorly reduced (Hoskins, 2002; Schulte et al., 1991). Mineral soil can contain anywhere from 0-30% organic matter however, most soils contain 2-10% organic matter. Soils with more than 30% organic matter are known as organic soils and any amount over 6% helps to bind the soil together into strong structural units that facilitate good root growth and earthworm activity.

3.5.4 Soil Strength Field Tests

These tests were undertaken in the field to assess the soil physical structure in the top one metre and to assess the level of soil crusting on the surface. Two types of penetrometers were used, the Dynamic Cone Penetrometer (DCP) and the Pocket Penetrometer. Penetrometers are simple tools that are used to measure the resistance of the soil (load bearing capacity) to penetration and can help to determine the homogeneity of the soil.

First, the hand-held DCP instrument (Figure 3.18) was chosen due to its ability to take rapid, in-situ measurements and because it is robust and quite simple to use. The DCP was used to determine the structural properties of the soil to a maximum depth of one metre. The DCP was positioned vertically on the soil surface and was allowed to sink under its own weight, until it was stationary. The instrument consisted of an 8kg hammer, which was manually lifted 575mm to a handle at the top and then allowed to drop freely onto an anvil in the middle of the instrument, to achieve a standard amount of penetration effort. Underneath the platform is a 902mm long steel rod, with a hardened steel cone tip (60°, 20mm diameter) and to the side a meter ruler which is used to determine the distance of penetration. After each drop the depth change in millimetres per blow was recorded.

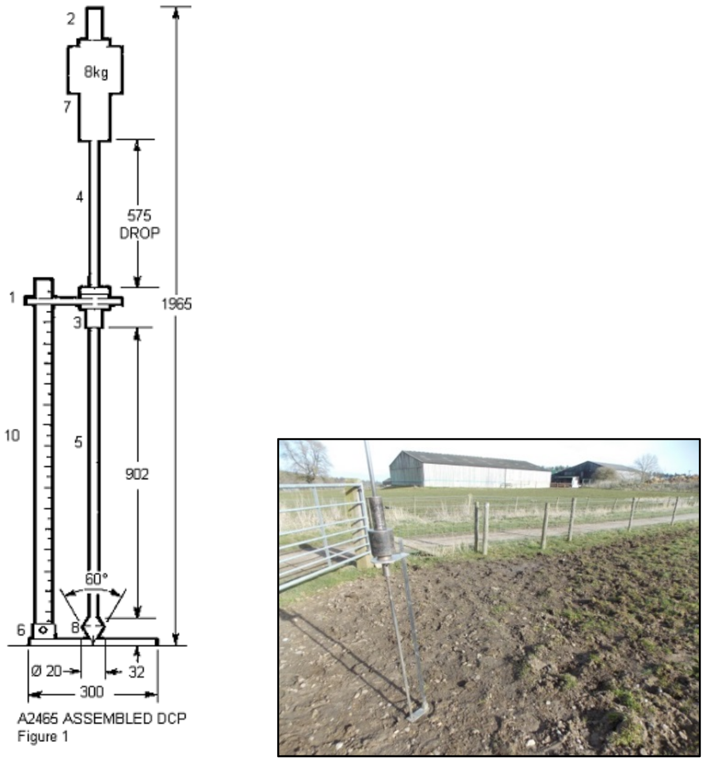

Figure 3.18: The dynamic cone penetrometer and in use at Horse Field Gate.

The DCP was used to determine four things (Figure 3.18) that helped to quantify soil strength:

- The starting depth, where the DCP naturally stops when it is placed on the soil surface.
- The first hit with the DCP, which is affected by the amount of loose and unconsolidated material, indicated the topsoil thickness.
- The penetration resistance at approximately ten centimetres depth, which indicated the compactness of the subsoil.
- Maximum penetration resistance (MPR) is a useful field indicator to assess the depth of maximum resistance (Newell-Price and Whittingham, 2012).

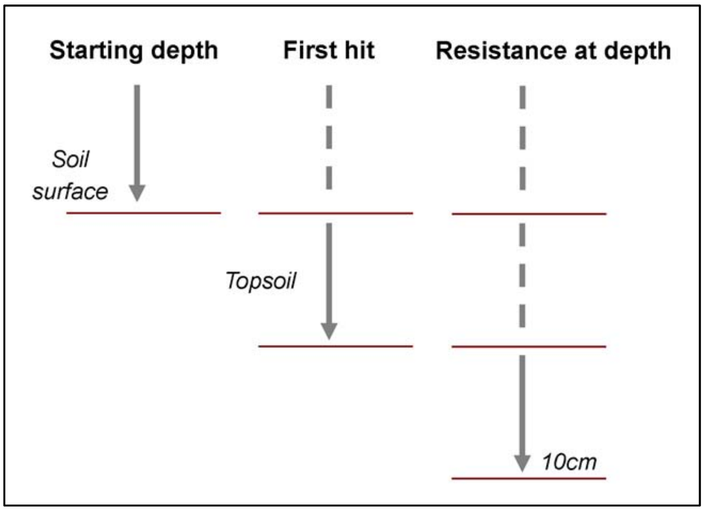

Figure 3.19: Observation types made with dynamic cone penetrometer.

The starting depth, or the depth to which the DCP naturally sinks when it is placed on the soil surface, gives information about the softness of the surface and the values in Table 3.7 were used in this study. The higher the value recorded the greater distance into the soil the DCP travelled before the first hit and therefore the softer the ground was deemed to be.

Table 3.7: Level of topsoil softness.

Depth travelled into soil (mm)	Softness descriptor
0-49	Very hard
50-99	Hard
100-149	Medium
150-199	Soft
200+	Very soft

The DCP was dropped once at each site five times (within the 1m^2 area of interest). This was only repeated five times because it was thought that the topsoil would not differ much at one site. The DCP was just used twice at each site but, it was dropped twenty five times to a maximum depth of 900mm (Figure 3.20). If this depth had not been reached after twenty-five drops then the test was stopped. This test gave information on the penetration resistance at 10cm depth, the depth of maximum penetration resistance and the soil horizons at each site.

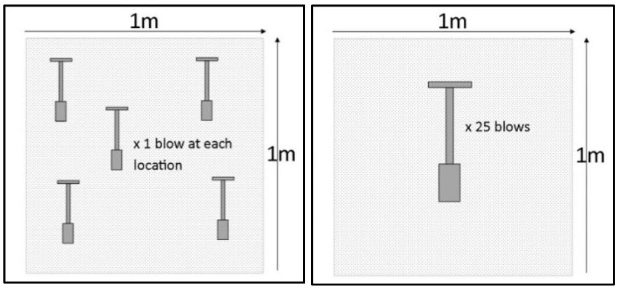

Figure 3.20: Sampling design for the dynamic cone penetrometer tests.

The penetration resistance was calculated after each drop (Equation 3.9). Where, R = penetration resistance (Pascals), N = number of impacts, M = mass of the sliding weight (kg), g = gravity = $9.81 m/s^2$, SD = sliding distance of the hammer (metres), A = surface area of the cone (m^2) and PD = penetration distance (metres). Errors can arise whilst using the DCP if the hammer lifts the instrument when it is being moved upwards, if the weight is lowered with the user's hands and if the DCP leaves the vertical. Upmost care was taken so this did not happen.

Equation 3.9: Penetration resistance.
(International Maize and Wheat Improvement Center, 2013).

$$R = \frac{(NxMxgxSD}{(AxPD)}$$

The second penetrometer that was used was the pocket penetrometer (Figure 3.21). It was used to classify the soils because of its ability to determine the approximate unconfined compressive strength (UCS) of the soil surface and penetration resistance in the top 5mm depth of the soil (Humboldt Mfg. Co., 2009). It was chosen due to its ease of use, readability and repeatability in the field. In this study the pocket penetrometer was used to assess the presence of soil crusts which are created on bare soils when rain drops disrupt and erode the topsoil. Crusts have a platy surface and have an accumulation of salts and silica. They are one of the visual signs of soil compaction.

Figure 3.21: Pocket penetrometer in use at the Sheep Tree Shelter.

A CL-700 (Ele International, 2016) Pocket Penetrometer (PP) with a 6.35mm pin was pushed into the ground until it encountered the force of the ground. A slip ring on the pin moved along the scale on the side of the instrument and indicated the maximum force that had been found. The PP can measure from 0-500kPa and has an accuracy of 3%. The scale is calibrated in kilograms per square centimetre Unconfined Compression Strength (UCS). The PP was pre-calibrated using correlation studies relating the effective spring compression to unconfined compressive strength values determined through other methods. The small area involved in the PP tests can lead to misleading results as an area next to the area sampled may give different readings. The test location must be chosen with care to avoid gravel or other particles in the field that would influence the reading.

The PP was pushed into the surface layer twenty times to give a reading of the UCS in the range of 0.25-4.5kg/cm^2 +/-0.124kg/cm^2 (24.5-441.3kPa) (Ele International, 2016). The PP results can be classified into three types, type A are cohesive soils with an unconfined compressive strength of 1.5kg/cm^2 (147.1kPa) or greater and are usually clay, silty clay, sandy clay, clay loam, silty clay loam or sandy clay loam. Type B are cohesive soils with an unconfined compressive strength greater than 0.5kg/cm^2 (49kPa) and less than 1.5kg/cm^2 and are usually angular gravel, silt loam and previously disturbed soils. Type C soils are cohesive soils with an unconfined compressive strength of 0.5kg/cm^2 or less and include granular soils such as gravel, sand and loamy sand, submerged soil and unstable rock (Humboldt Mfg. Co., 2012).

3.5.5 Soil Drainage Field Tests

A double ring infiltrometer (DRI) from Eijkelkamp Agrisearch equipment was chosen to measure infiltration directly in the field (Figure 3.22). A double ring, rather than a single ring infiltrometer, was chosen because the presence of the outside ring limits the lateral spread of water through the soil and because it can be used in most environments. Two different sets of rings were used to allow multiple measuring and to save time. The first set consisted of two rings (28/53cm in diameter) and the second set consisted of two rings (30/55cm in diameter). Before starting the experiment the surface vegetation and large stones were removed to create a more homogeneous soil surface and to allow the float to sink to the surface. The rings were driven around five centimetres vertically into the soil using a metal driving plate which was placed on top of the rings and hit with a hammer.

Figure 3.22: Installation and set-up of infiltrometer at Horse Tree Shelter.

A bridge and a measuring float were placed across the inner ring to determine the change in head height over time. A video camera was installed in line with the float, to capture the fall in head height over a maximum period of twenty-eight minutes. This time was chosen following the pilot study at the Arable and Sheep Sites in August 2014, which showed that the majority of the water infiltrated into the soil within the first twenty-thirty minutes and because the cameras would only record for twenty-eight minutes.

To start the experiment, the outer ring was filled with water to a depth of five-eight centimetres and then the inner ring to an identical height and measurement started immediately. Water levels were kept as low as possible to prevent lateral flow, which is not technically classed as infiltration (Assouline, 2013) and to ensure vertical flow (Moroke et al., 2009). Water was taken from a local farm house so it was of a similar quality and temperature.

As the water level dropped in the outer ring it was topped up with water to sustain a buffer that was sufficient to lateral spreading. However, the water level in the outer ring was never higher than the inner ring, as this would have caused negative infiltration and invalidated the experiment. The outer ring also was not allowed to go completely dry, as this would have eliminated the advantage gained from using the second ring (Eijkelkamp Agrisearch Equipment, 2012). The experiment gives two variables were analysed, firstly the total infiltration over the twenty-eight minutes of the experiment and secondly the infiltration rate (f(t)) in mm/hour was calculated using Equation 3.10.

Equation 3.10: Infiltration Rate.

$$f(t) = \frac{Total\ infiltration\ during\ experiment}{Length\ of\ experiment} * 60$$

The double ring infiltrometer experiment was run once at each site in the October fieldwork and once in the April fieldwork. This was because the experiment took a long time to set up and run. To reduce measurement error, where possible the infiltration tests were not conducted in the rain or when the temperature was less than freezing (Stoeckeler and Weitzman, 1959), or within twenty four hours of a significant rainfall event. In October 2014 this was not a problem because there was little rainfall in the week before fieldwork, and only small amounts twenty four hours before the experiments took place (Table 3.8). However, in April 2015 there was quite a lot of rainfall in the week before fieldwork and in the twenty four hours before, although all the experiments took place on the same day so the affect should be similar across all sites.

Table 3.8: Date and rainfall quantity before and during DRI experiments.

		Rainfall (mm)		
October	Sites	7 days before	24 hours before	On day of test
26	AOF, ATL, HFT	8.6	0.4	0.6
27	SFT, SFG, SOF, STS, HTS	9.2	0.6	0.2
28	CFT, CFG, COF, CTS, HFG, HOF	7.0	0.2	0.0
April	Sites	7 days before	24 hours before	On day of test
1	All 14 sites	54.1	14.3	17.0

Factors that can cause lower than expected rates of infiltration are biological soil crusts (Fischer et al., 2010) and water containing sediments which can cause clogging of the micropores. Factors that can cause higher than expected infiltration rates are high levels of macropores in the soil caused by cracks/fissures (Burgy and Luthin, 1957), roots/animal burrowing (Beven and Germann, 2013) and ploughing (Garbout et al., 2013), stony soils and excessive disturbance of the soil surface during the installation of the rings (Eijkelkamp Agrisearch Equipment, 2012).

3.5.6 Analysis of Experimental Data

Descriptive statistics were run on the samples to provide information including the mean, maximum and minimum and the range of the data. The sample standard deviation and standard error of the mean were then calculated to provide information on the spread and the presence of extremes in the data sets. Hypotheses testing were used to determine firstly the Intra-site variability, secondly the Inter-site variability and thirdly the seasonal variability in soil compaction and soil hydrology at each field site. Once the normality of the data had been tested a one-way Analysis of Variance (ANOVA) (Fisher, 1925) parametric test was run to compare the means of the samples collected from each field site, to see if there were significant differences between them. The one-way ANOVA test is a simple special case of the linear model and it returns a p-value, the sum of the squares due to each source, the degrees of freedom, the mean squares, the f-statistic and a hypothesis result (one or zero) which is again based on comparing the p-value to alpha (0.05) to decide whether to reject the null hypothesis.

Several assumptions have been made to use the ANOVA test. The first is that the populations that have been sampled have the same level of variance (homoscedasticity), the second is that the populations that have been sampled have a normal distribution and the third is that each data point is independent of the other data points. However, the ANOVA test was chosen over a non-parametric test like the Kruskal-Wallis (Kruskal and Wallis, 1952) because non-parametric tests do not assume that the data is normal and that the data cannot be described by the mean and the standard deviation. Also, in non-parametric tests the observed data is ranked and during this process the original data is lost and the power of the test is diminished.

3.6 Chapter Summary

This chapter identified four types of rural land management in the Skell catchment which are common across the UK, as well as five common sub-field features that are associated with arable farming (tractor traffic) and pastoral farming (animal traffic). In total fourteen sites were chosen. Furthermore, the chapter identified two main study periods that are known to be associated with changing temperatures and weather conditions. These sites and time periods will help to determine the spatial (inter and intra) and temporal (seasonal) variability in soil compaction and soil hydrology.

Primary data collection is hugely important but, time consuming and costly. Therefore, a well-formulated and achievable plan was devised to explore the complex, process-based relationship between soil compaction and soil hydrology. A sampling strategy was designed to collect data to determine the soil characteristics, the level of soil compaction, the soil water content and soil water movement at all sites. A methodology was also outlined to explain how the field data will be analysed in the laboratory and with statistical tests. The next chapter will present the results of these tests.

Chapter 4 - Quantifying the Impact of Soil Compaction on Soil Hydrology: Results

4.1 Chapter Scope

This chapter presents the results of fieldwork and laboratory work undertaken to achieve Objective four, "to assess the problem of complexity in the relationship between soil compaction and soil hydrology". The methodologies can be found in Chapter three. Initially, a conceptual model is presented (Section 4.2) that identifies how natural soil characteristics and human pressures can influence soil hydrology on a local scale. The model was used to identify five key research questions (listed below) which are presented in Sections 4.4-4.7. Finally, Section 4.8 provides the chapter summary.

1. Which sites have the highest potential for soil compaction? (4.3)
2. Which sites have the lowest soil strength, best soil structure and best drainage potential? (4.4)
3. Does the potential for compaction correlate with the sites that experience the highest levels of compaction? (Section 4.5)
4. Are there significant differences between the intra and inter-sites? (4.6)
5. Are there significant differences between the two fieldwork periods? (4.7)

The datasets from each site were analysed statistically using the ANOVA test, more information can be found in Chapter 3. To compare the literature review datasets the with the datasets collected in this study, cumulative probability graphs are used to show the range of values observed previously and the likelihood of specific values being observed in this study.

4.2 Conceptual Model

This section will describe the conceptual model that was developed to explain how natural soil characteristics and human induced pressures can affect soil hydrology including the soil structure, strength and water movement. In terms of natural characteristics (Figure 4.1), the location/slope of a site will affect the propensity for water to pond, or runoff. If the site is at the top of the hill then water can easily runoff downslope however, if it is located at the bottom of the hill then it is more likely to suffer from saturation and ponding. The location also often relates to the distance to nearest stream network. The location at the top of the hill is likely to be further from the river than the location at the bottom of the hill.

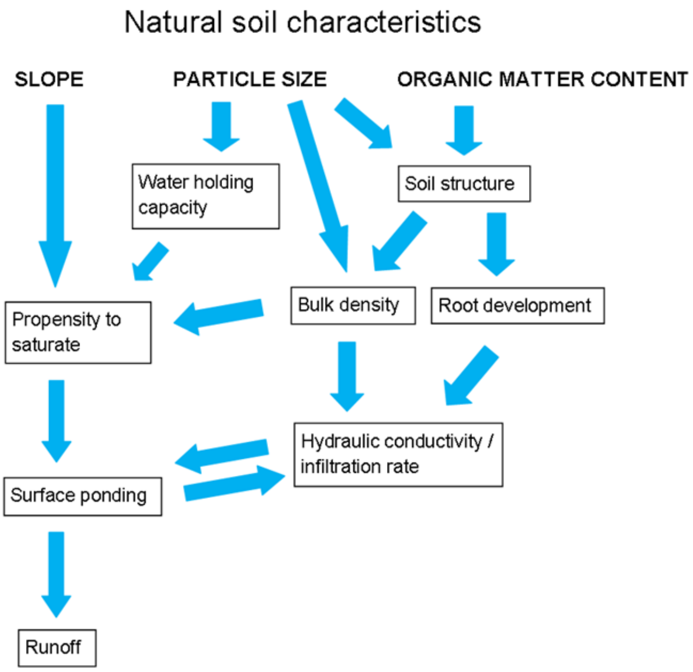

Figure 4.1: How do natural site characteristics affect soil hydrology?

The particle size of the soil affects its water holding capacity. Soils with high levels of clay can be detrimental because they are slowly permeable soils and can easily become waterlogged. However, in general soils with a low clay content are more likely to have a low overall stability and can readily slake (breakdown) in water causing internal slumping (Environment Agency, 2015). Sandy/silty soils tend to be less cohesive, easily break up into finer structures and have a relatively low porosity in comparison to soils with high clay content (Bronick and Lal, 2005). Although, they are also more likely to have greater macroporosity (Newell-Price et al., 2013) which leads to good drainage and relatively high saturated hydraulic conductivity in comparison to soils with a higher clay content (Dingman, 2002).

Theoretically, well-structured soils are free draining, have abundant roots are more stable with a lower runoff potential. The presence of organic matter in the form of crop or grass cover helps to bind the soil together, increasing stability and reducing the potential for runoff and erosion of particles. But, when sandy soils have low organic matter they are prone to surface sealing and capping (Environment Agency, 2015) which can limit infiltration, cause ponding on the surface and imped ground evaporation (Holman, Hollis, Bramley and Thompson 2003). However, sandy soils with low bulk density, high porosity and good root growth can exhibit good structure.

Human induced pressures (Figure 4.2) such as the use of heavy machinery and high stocking densities can affect the strength, structure and drainage of the soil. The strength of soil is indicative of the packing density of its particles. A moist cube of soil that cracks under gentle force is described as friable and is the optimal structure for growing plants due to its low packing density and good drainage. However, if a soil fails when high pressures are applied to it, it is described as very firm and indicates poor structure and drainage. In coarse textured soils the dominant penetration of stress is in the vertical direction (Ziyaee and Roshani, 2012) and therefore, sandy soils have a higher strength than finer textured soils (Newell-Price et al., 2012).

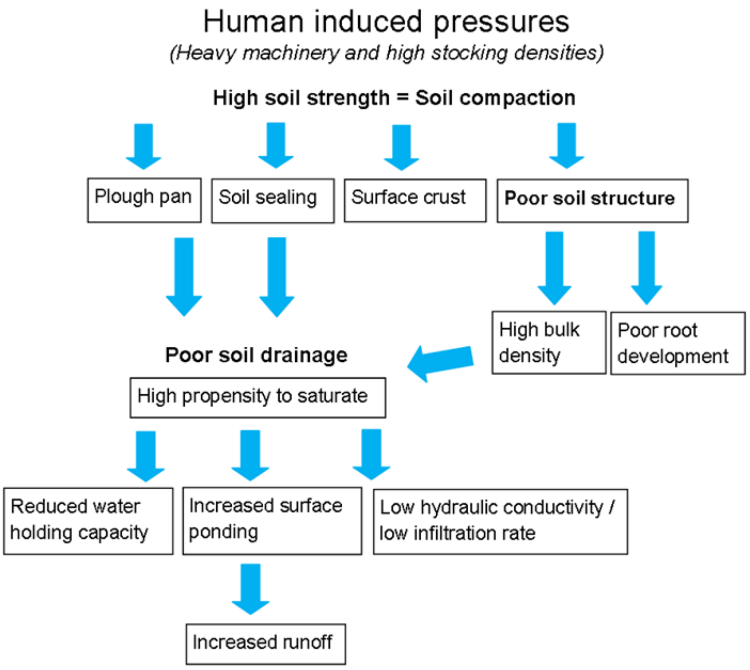

Figure 4.2: How do human induced pressures affect soil hydrology?

Poor soil structure is indicated by high bulk densities, these soils have very low porosities which limited space to store water and have very slow drainage of water into the subsoil. This also has an impact on root development as the roots may not be able to penetrate the more compacted layers. Soils with a very low bulk density are open textured and porous but, they may be so loose that they may have poor water retention and dry out quickly making them prone to degradation (Sparling et al., 2006).

Plough pans, impermeable layers and soil sealing, all caused by soil compaction, can limit the amount of soil drainage indicated by low infiltration rates. This increases the risk of soil saturation and surface ponding which can lead to increased runoff. To prevent soil compaction the water table should be kept lower than 0.5m to ensure that the soil strength remains high (Harris, et al., 2004). This is because when water content is high the soil starts to act more like a liquid and degradation is more likely to occur in this state (Duiker, 2002).

4.3 Potential for Compaction

This section will answer the question ‘Which sites have the highest potential for soil compaction based on soil texture, organic matter content and position on the slope?’ This was achieved by ranking four variables (clay, sand and organic matter content of the soil and elevation) from one to fourteen and adding the four rankings together.

In this study the site soils were all classed as ‘Sandy and light silty soils’ (Environment Agency, 2015) because they have a clay content less than 18% (Figure 4.4) and therefore, high clay content is assumed to be a positive factor to increase soil stability. The AOF had the highest mean clay content (11.0%) out of the fourteen sites indicating that the samples had the most cohesive structure, followed by the ATL. The COF had the largest range (12.1%) indicating the most variability in the amount of clay in the samples. The SFT had the lowest mean clay content (2.5%) indicating a less cohesive structure and a greater risk of degradation and erosion (Environment Agency, 2015) followed by the HOF. These sites also had the smallest range (1.9 and 1.2%) in values indicating the least variability in the amount of clay in the samples.

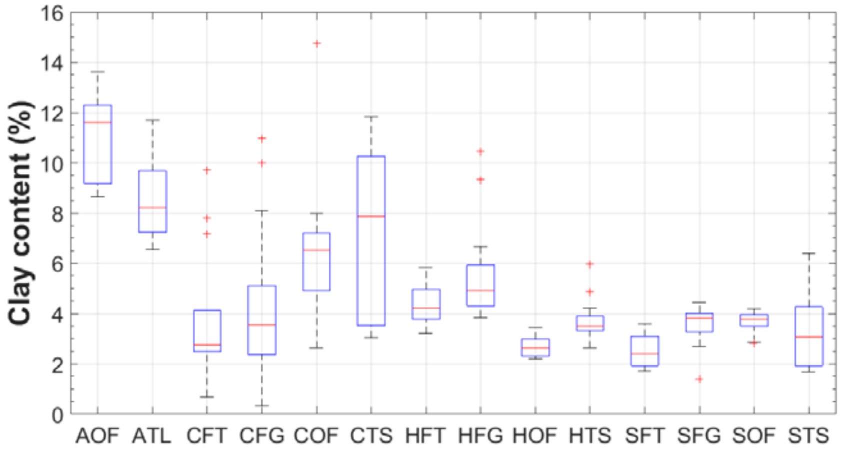

Figure 4.3: Clay content at the fourteen sites.

The ATL had the highest mean sand content (40.8%) out of the fourteen sites (Figure 4.4) indicating that the samples had the best drainage, followed by the AOF. The CFT had the largest range (36.9%) indicating the most variability in the amount of sand in the samples. The COF had the lowest mean sand content (12.2%) indicating a higher portion of finer particles followed by the HTS. The SFG had the smallest range (13.7%) indicating the least variability in the amount of sand in the samples.

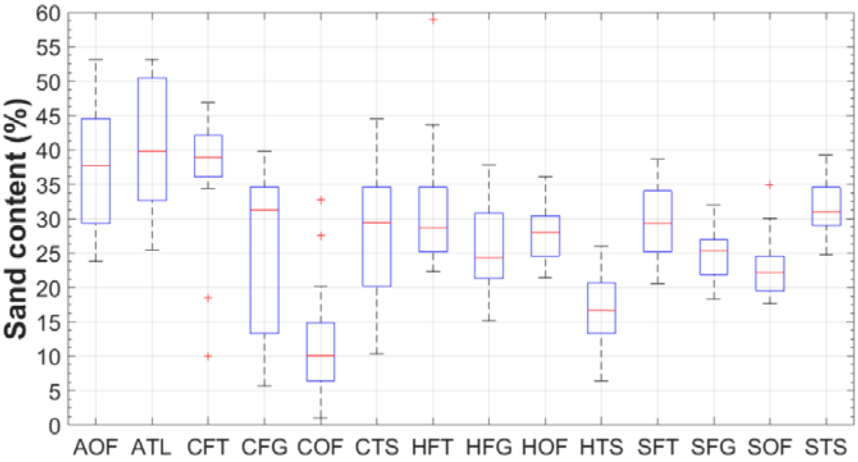

Figure 4.4: Sand content at the fourteen sites.

The highest mean organic matter content (Figure 4.5) were observed at the COF (11.7%) and HTS (11.6%) The lowest mean organic matter content was observed at the AOF (3.6%) and ATL (3.7%). There is a serious decline in soil quality when organic matter levels are less than 3.4% (Loveland and Webb, 2003) and 5% of the samples collected in this study had levels less than this threshold indicating poor soil quality. Nearly a quarter of the samples collected from the Arable sites (22%) had levels less than the threshold indicating poor aggregate stability (Loveland and Webb, 2003) at these sites. However, only 3% of samples at the Cattle and Sheep sites and none of the samples from the Horse sites had values less than the threshold. This indicates good aggregate stability, increased pore sizes and better structure (Loveland and Webb, 2003) at these sites.

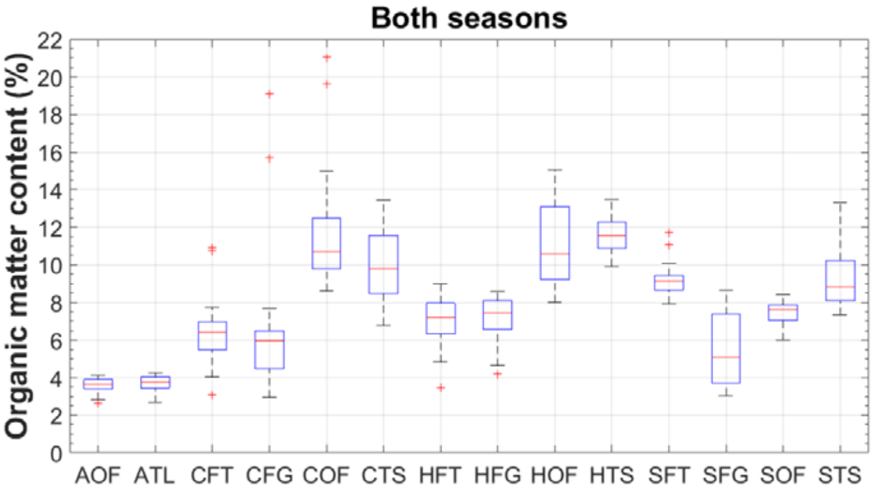

Figure 4.5: Organic matter content at the fourteen sites.

In terms of elevation (Figure 4.6), the CTS and CFG are located at the highest elevation in the Yorkshire Dales. The Arable and HFG are located at the lowest elevations due to their location, further east towards the city of Ripon.

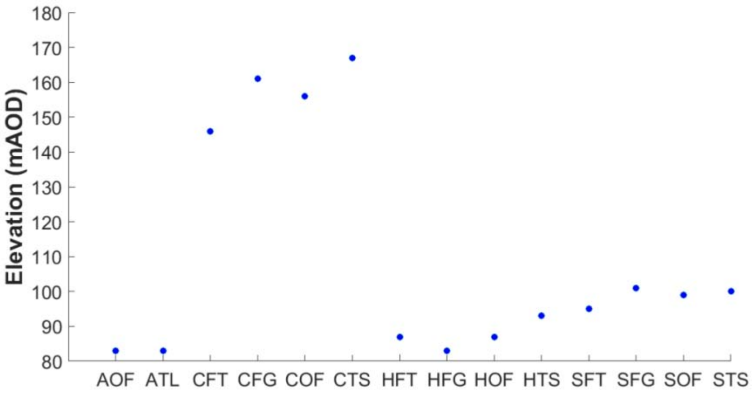

Figure 4.6: Elevation at the fourteen sites.

The four rankings from the above analysis were added together to give an overall rank (Table 4.2) and show the differences in the potential for compaction across the sites. The ranking showed that the CTS and COF had the lowest potential for compaction based on the four characteristics tested in this study and the SFG and HOF had the highest potential for compaction.

Table 4.1: Potential for compaction ranking.

CTS = Highest ranking / best natural characteristics

SFG = Lowest ranking / worst natural characteristics

Site	Clay%	Rank	Sand%	Rank	OMC%	Rank	Elevation	Rank	Total	Rank
AOF	11.0	1	37.2	2	3.6	14	83	12	29	7
ATL	8.5	2	40.8	1	3.7	13	83	12	28	6
CFT	3.8	8	36.8	3	6.4	10	146	4	25	3
CFG	4.4	6	25.9	9	6.3	11	161	1	27	4
COF	6.3	4	12.2	14	11.7	1	156	3	22	2
CTS	**7.3**	**3**	**27.8**	**7**	**10.1**	**4**	**167**	**2**	**16**	**1**
HFT	4.4	6	32.0	4	7.0	9	87	10	29	7
HFG	5.6	5	25.8	10	7.2	8	83	12	35	11
HOF	2.7	13	27.7	8	11.1	3	87	10	34	13
HTS	3.7	9	16.4	13	11.6	2	93	9	33	9
SFT	2.5	14	29.3	6	9.2	5	95	8	33	9
SFG	3.6	11	24.9	11	5.6	12	101	5	39	14
SOF	3.7	9	23.2	12	7.5	7	99	7	35	11
STS	3.1	12	32.0	4	9.2	5	100	6	27	4

4.4 Site Variations in Level of Compaction

This section will answer the question ‘Which of the fourteen sites have the lowest soil strength, best soil structure and best soil drainage?’ This was achieved by ranking three variables (soil strength, soil structure and soil drainage) from one for the best conditions to fourteen for the worst conditions and adding the three rankings together.

4.4.1 Quantifying Soil Strength

Soil strength was determined using the dynamic cone penetrometer (DCP) and pocket penetrometer. The DCP experiments showed that the average starting depth was highest at the AOF (123mm +/-47) indicating a soil surface with a medium level of hardness (299kPa) and lowest at the HTS (78mm +/-11) indicating a surface with a hard level of hardness (424kPa). The topsoil thickness was deepest at the AOF (97mm +/14) indicating that the site had the most loose and unconsolidated topsoil (342kPa), which may be due to ploughing and shallowest at the CFT (25mm +/-12) indicating that it had the firmest and most consolidated topsoil (1965kPa).

Resistance at 10cm depth was chosen as the best indicator for showing a difference in strength at compacted and un-compacted sites (Singleton, Boyes and Addison, 2000). The mean resistance (Figure 4.7) was highest at the SFT (367kPa) and CFG (340kPa) which were similar resistances to four or more tractor passes at a clay site (316kPa) in Buenos Aires, Argentina (Botta, Jorajuria and Draghi, 2002) and under low grazing at a sandy loam site (365kPa) in Kinsella, Canada (Naeth et al., 1990). The mean resistance was lowest at the SOF (281kPa) and HOF (294kPa) which were similar resistance to no grazing at a sandy site (290kPa) (Sousa Neto et al., 2014) and under low grazing at a loamy sand site (215kPa) in Bukit Mahang, Malaysia (Majid, Awang and Jusoff, 1989).

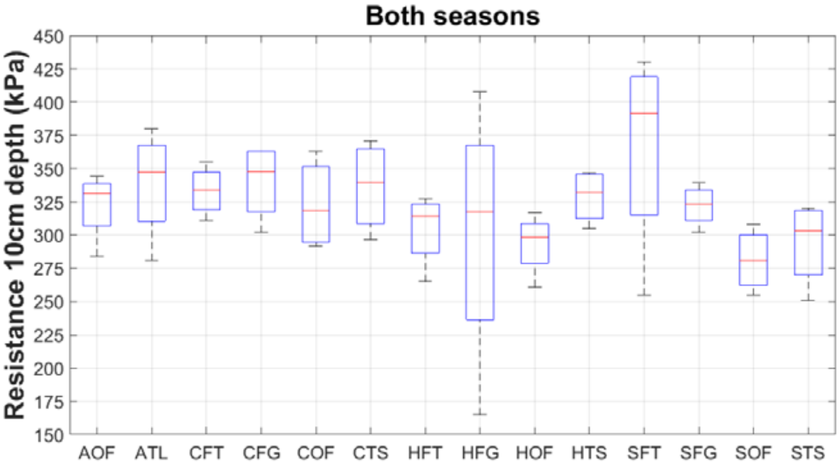

Figure 4.7: Resistance at all fourteen sites.

The resistance measured in all tests in this study had a relatively small range, between 165 and 430kPa. In seventeen other studies the range in the level of resistance observed was much higher, between 150kPa and 2510kPa, at a clay loam site in Solohead, Ireland (Tuohy et al., 2015). Out of these studies, the mean resistance under no grazing was 563kPa, under low levels of grazing it was 907kPa and in twelve studies under high levels of grazing it was 1095kPa. These findings suggest that the compaction levels caused by machinery and animals in this study are relatively low.

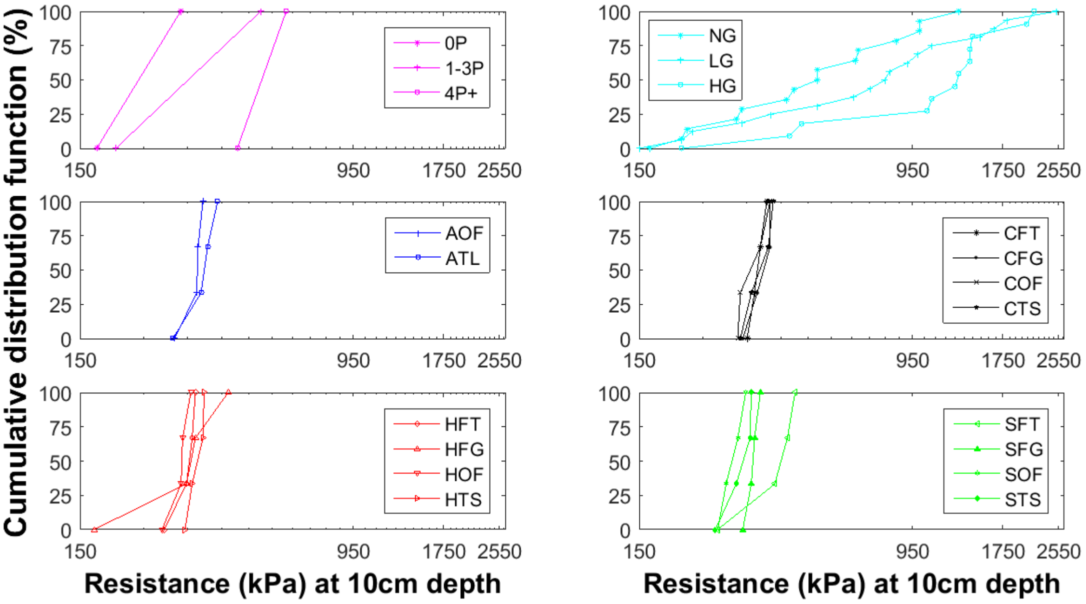

Figure 4.8: Resistance at sites from the literature and in this study.

The first graph (Figure 4.8) shows that there is a 25% chance that, a random sample collected under zero tractor passes, will have a resistance of less than, or equal to 200kPa and a 100% chance that it will be under 296kPa. However, the third graph shows that there is only a 25% chance that, a random sample collected at the AOF site, will have a resistance that is less than, or equal to 300kPa and a 100% chance that it will be less than or equal to 344kPa. This suggests that the AOF is slightly more compacted than has been observed in other studies under no compaction in the literature.

The mean maximum penetration resistance (MPR) was highest at the CFT (1965kPa) at a depth of 25mm (Figure 4.9) and the HTS (1100kPa) at a depth of 37mm. The lowest MPR was observed at the AOF (350kPa) at a depth of 73mm and the SFT (409kPa) at a depth of 80mm. The mean depth of MPR across all sites in this study was 50mm. There were slight differences by type of site the mean depth of MPR was 65mm+/-39 for Arable, 42mm+/-22 for Cattle, 48mm+/-23 for Horses and 60mm+/-25 for Sheep.

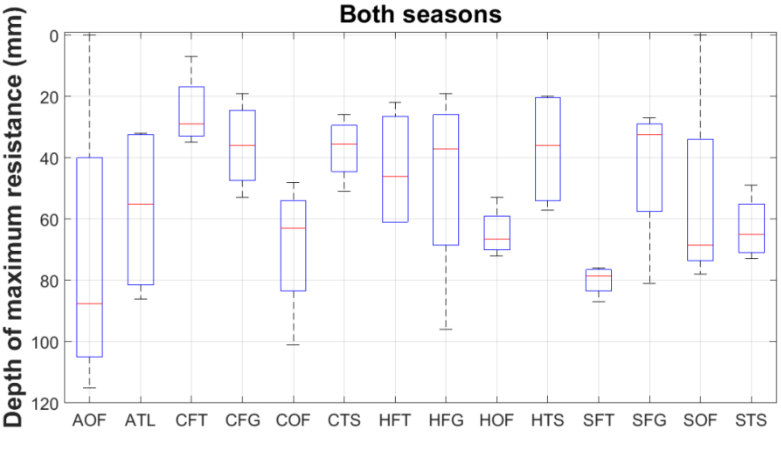

Figure 4.9: Depth of maximum penetration resistance at all sites.

The results suggest that the human induced pressures compact the soil in different ways depending on their weight and hoof surface area. Other studies have identified that sheep cause more surface compaction and cattle cause more compaction at greater depths however, this study suggests that cattle and horses cause compaction at shallower depths and sheep at greater depths.

The pocket penetrometer results (Figure 4.10) showed that the mean unconfined compressive strength was highest at the STS (3.12kg/cm^2) which was similar to a horse grazed site (3.60kg/cm^2) in Nevada, USA (Davies, Collins and Boyd, 2014), a heavily cattle grazed silt loam site (2.85kg/cm^2) in Eureka, USA (Gifford et al., 1977) and a cattle grazed loamy site (2.30kg/cm^2) in Ketereh, Malaysia (Majid et al., 1989).

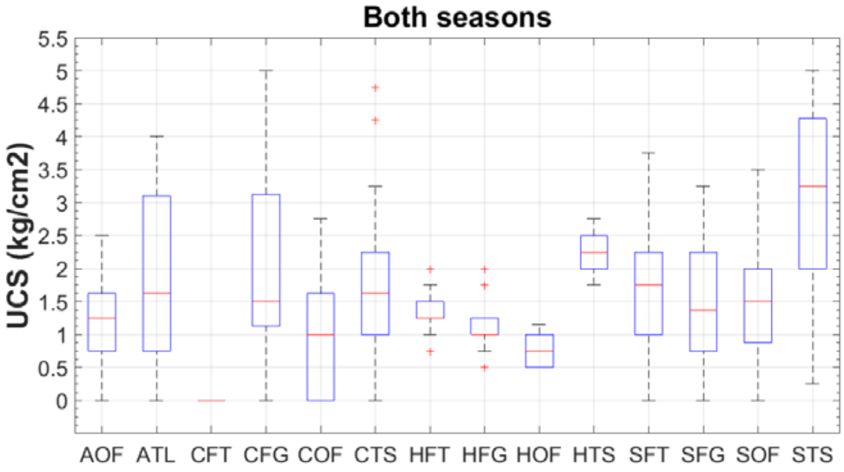

Figure 4.10: Unconfined compressive strength at all fourteen sites.

The unconfined compressive strength was lowest at the HOF (0.76kg/cm^2) which was similar to under light cattle grazing at a sandy loam site (0.90kg/cm^2) in Wycanna, Australia (Braunack and Walker, 1985) but lower than at a cattle grazed sandy loam site (1.90kg/cm^2) in Willow Creek, USA and a loam site (2.11kg/cm^2) in Valley Creek, USA (Clary, 1995). This suggests that the level of surface compaction at the HOF is very low and the site is less compacted than in most other studies. No unconfined compressive strength values were obtained at the CFT because there was ponded water at the site throughout the year.

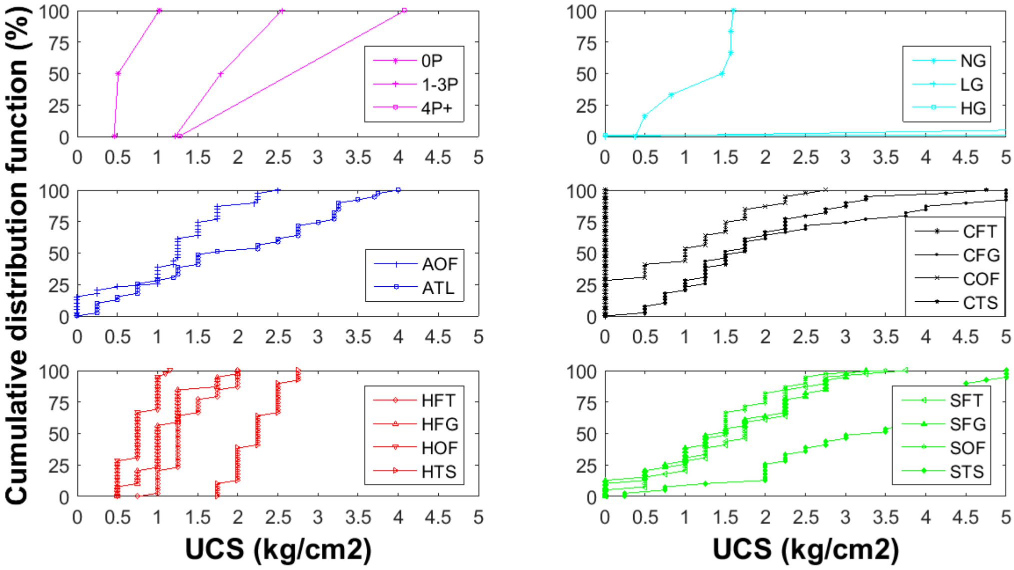

Figure 4.11: UCS at sites from the literature and in this study.

The first graph (Figure 4.11) shows that there is a 50% chance that, a random sample collected under zero tractor passes, will have a UCS of less than, or equal to 0.51kg/cm^2 and a 100% chance that it will be under 1.02kg/cm^2. However, the fifth graph shows that there is only a 28% chance that, a random sample collected at the HOF site, will have a UCS that is less than, or equal to 0.50kg/cm^2 and a 100% chance that it will be less than or equal to 1.15kg/cm2. This suggests that the HOF is slightly more compacted than has been observed in other studies under no compaction in the literature.

The unconfined compressive strength measured in all tests, at all sites ranged between 0 and 5kg/cm^2 showing the total range of values possible with the pocket penetrometer. The normal range of strength values for a granular, cohesion-less soil like silt are 0.5-1.5kg/cm^2 and therefore the soil surface at the ATL, CFG, CTS, HTS, SFT and STS are likely to have been affected by the processes of capping and crusting. In sixteen other studies the mean strength under no grazing was 1.13kg/cm^2, low levels of grazing it was 1.64kg/cm^2 and high levels of grazing it was 2.38kg/cm^2. The very high UCS values at the Cattle and Sheep sites are indicative of very high soil strength and compaction.

There was no correlation ($r^2<0.3$) between the surface, maximum or 10cm depth resistance and the unconfined compressive strength on the soil surface in this study. This may be due to high heterogeneity in compaction levels at site and because the dynamic cone and pocket penetrometer measurements were taken on different parts of the sampling area.

4.4.2 Quantifying Soil Structure

Soil structure was determined from soil samples collected in the field and the bulk density measured in the laboratory. The soil samples showed that the highest mean bulk densities across all fourteen sites (Figure 4.12) were observed at the ATL (1.46g/cm^3) and AOF (1.23g/cm^3) indicating that they were the most compacted soils (Sparling et al., 2008) in this study. These values are similar to those recorded at a heavily grazed, clay loam site in Armidale, Australia (1.25g/cm^3) (Greenwood et al., 1998) and under light grazing (1.25g/cm^3), implemented by a mechanical cow at a silt loam site in Lincoln, New Zealand (Di et al., 2001).

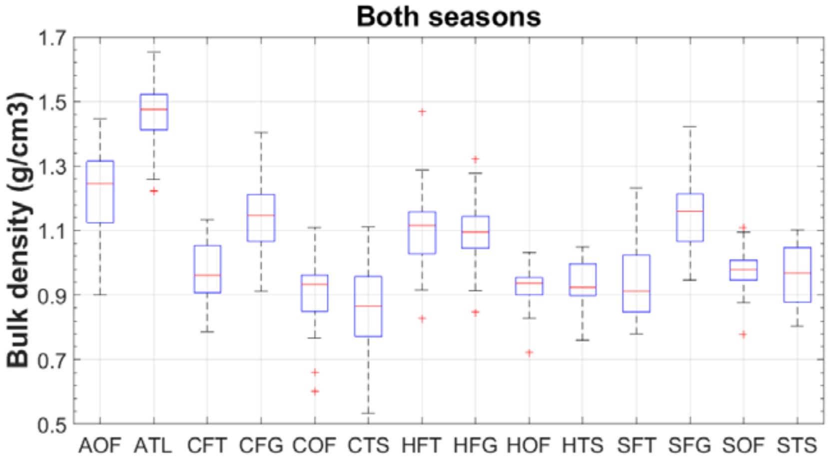

Figure 4.12: Bulk density at all fourteen sites.

The lowest mean bulk densities were observed at the CTS (0.85g/cm^3) and COF (0.90g/cm^3) with 13% of the samples from the COF and CTS in October and 20% of samples from the CTS in April having bulk densities less than 0.70g/cm^3 indicating lower levels of compaction. These values are similar to those at a heavily grazed feral horse, montane site (0.90g/cm^3) in Kosciuszko National Park, Australia (Dyring, 1990) and under light cattle grazing at a sandy loam site (0.95 g/cm^3) and at a clay loam site (0.96 g/cm^3) in Edmonton, Canada (Naeth et al., 1990). This suggests that these sites are only lightly compacted.

The bulk densities measured in this study (0.38-1.65g/cm^3) are similar to those measured by (Newell-Price et al., 2012) at grassland sites across England and Wales (0.53-1.57g/cm^3). The average bulk density across all the fourteen sites (1.04g/cm^3) was similar to that at a heavily grazed sandy clay loam site in Edmonton, Canada (1.07g/cm^3) and a silt loam site (1.15g/cm^3) in Balclutha, New Zealand (McDowell et al., 2003).

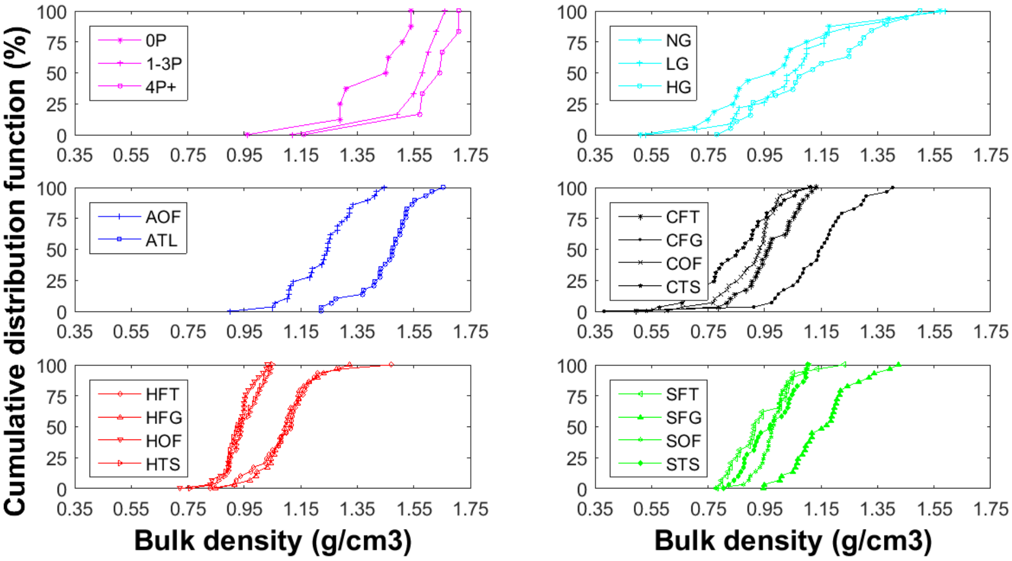

Figure 4.13: Bulk density at sites from the literature and in this study.

The second graph (Figure 4.13) shows that there is a 25% chance that, a random sample collected under no grazing, will have a bulk density of less than, or equal to 0.84g/cm^3 and a 100% chance that it will be under 1.57g/cm^3. However, the sixth graph shows that there is only a 24% chance that, a random sample collected at the SFT site, will have a bulk density that is less than, or equal to 0.85g/cm^3 but a 100% chance that it will be less than or equal to 1.23g/cm^3. This suggests that the SFT is slightly less compacted than has been observed in other studies under no compaction in the literature.

4.4.3 Quantifying Soil Drainage

Soil drainage was determined by the unsaturated peak infiltration rate (IR) using the double ring infiltrometer (DRI), and the saturated hydraulic conductivity (Ksat) determined using the falling head laboratory test. The highest average peak infiltration rate (Figure 4.14) was observed at the AOF (135mm/hr +/-76) which is similar to the infiltration rate observed after more than four tractor passes at a silty clay site (109mm/hr) in Uppsala, Sweden (Mossadeghi-Björklund et al., 2016) but a lot lower than the value quoted for non-degraded soils (500mm/hr) in the UK (Godwin and Dresser, 2003) suggesting that the AOF is degraded to some degree.

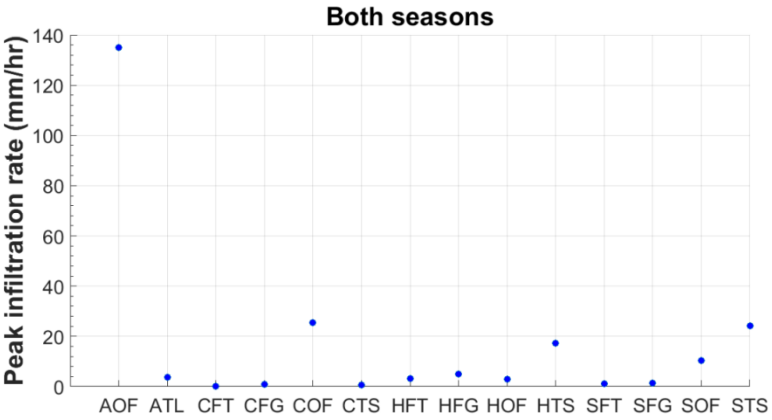

Figure 4.14: Peak infiltration at all fourteen sites.

The second highest average peak infiltration was observed at the COF (25mm/hr +/-34) which was slightly lower than the infiltration rate for non-degraded silt loam soils (40mm/hr) in the UK (Godwin and Dresser, 2003), lower than the infiltration rate at a heavily grazed silty sand site (Figure 4.15) in Inner Mongolia (39mm/hr) (Gan et al., 2012), a lightly grazed loam site, in Alpuri, Pakistan (53mm/hr) (Bari et al., 1993) and much lower than at lightly grazed sandy loam site (125mm/hr) in Wisconsin, USA (Pitt et al., 1999). This suggests that the drainage potential at the grassland sites in this study is low. There was no infiltration during the experiments at the CFT, HOF and SFG in April indicating no drainage potential.

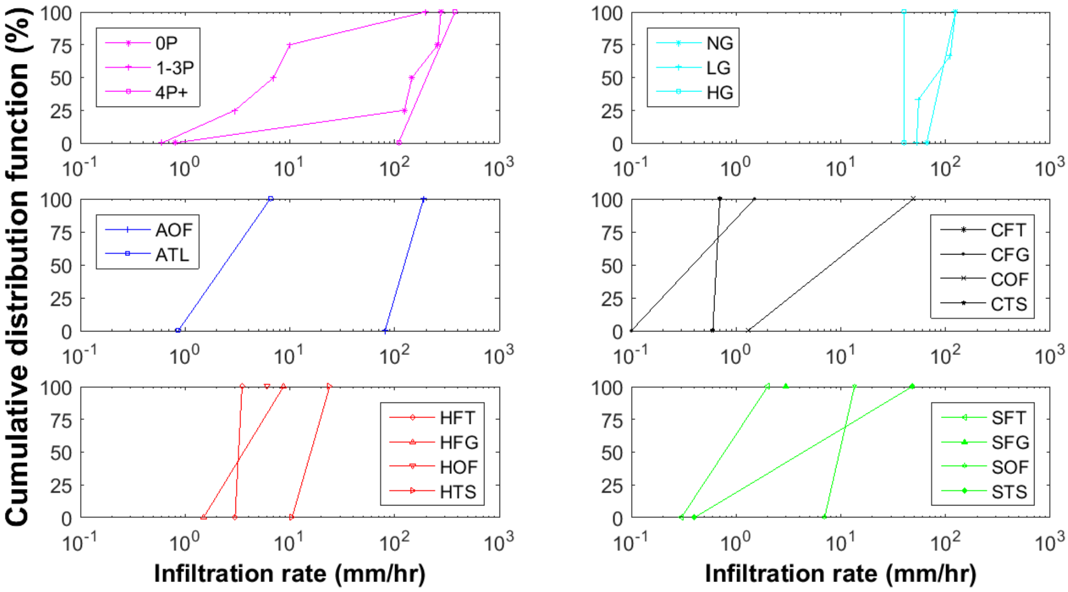

Figure 4.15: Infiltration rates at sites from the literature and in this study.

The highest average saturated hydraulic conductivity (Figure 4.16) was observed at the AOF (181mm/hr +/-313) which was significantly higher ($p<0.01$) than the other thirteen sites, indicating the best drainage potential. The saturated hydraulic conductivity at the AOF was higher than in a ploughed field at a silt loam site in Estrees-Mons, France (68-118mm/hr) (Capowiez et al., 2009) but similar to the conductivity observed after one to three tractor passes at a sandy loam site (205mm/hr) in Iwo, Nigeria (Wilkinson and Aina, 1976)). The lowest average conductivity was recorded at the CFT (0.001mm/hr +/-0.002) and STS (0.02mm/hr +/-0.05) indicating very poor drainage potential that were lower than more than four tractor passes at a clay loam site (0.6mm/hr) in Edinburgh, Scotland (Ball et al., 1997).

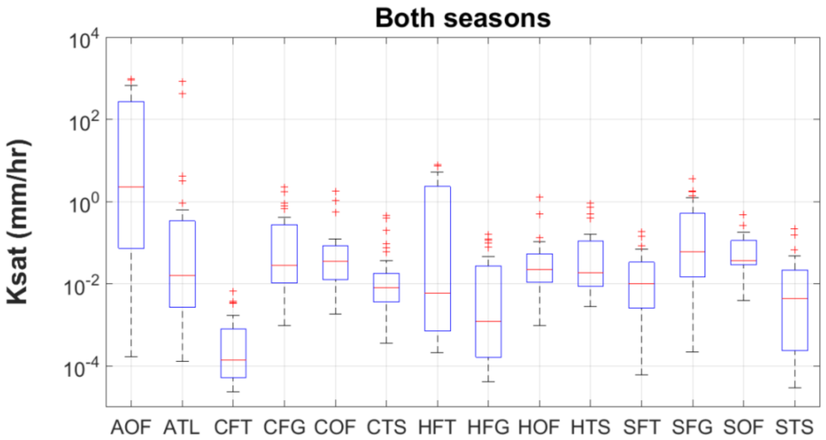

Figure 4.16: Saturated hydraulic conductivity at all fourteen sites.

Apart from the two arable sites, all the grassland sites had average saturated hydraulic conductivities lower than 1.6mm/hr indicating that they had low drainage potential. These low conductivities were similar to those seen after one to three tractor passes at a clay loam site (2.4mm/hr) in Edinburgh, Scotland (Ball et al., 1997) and a grazed silt loam site (3.0mm/hr) in Balclutha, New Zealand (McDowell et al., 2003). However, they were significantly lower than conductivities observed at heavily cattle grazed, sandy loam sites (79-91mm/hr) in Wyoming, USA (Abdel-Majid et al., 1987) and Georgia, USA (97mm/hr) (Frazlubbers et al., 2011). This may be due to naturally higher drainage potentials at the sandy loam soils.

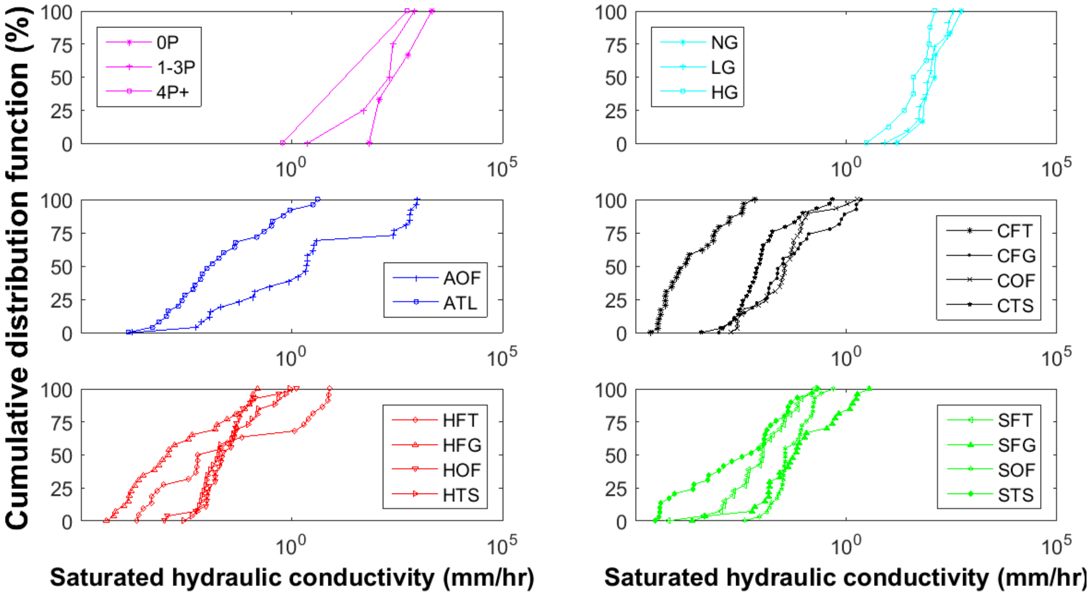

Figure 4.17: Ksat at sites from the literature and in this study.

The second graph (Figure 4.17) shows that there is a 25% chance that, a random sample collected under high grazing, will have a Ksat of less than, or equal to 24mm/hr and a 100% chance that it will be under 129.0mm/hr. However, the fourth graph shows that there is only a 24% chance that, a random sample collected at the CTS site, will have a Ksat that is less than, or equal to 0.004mm/hr and a 100% chance that it will be less than or equal to 0.465mm/hr. This suggests that the CTS is heavily compacted even in comparison to observations in other studies under no compaction in the literature.

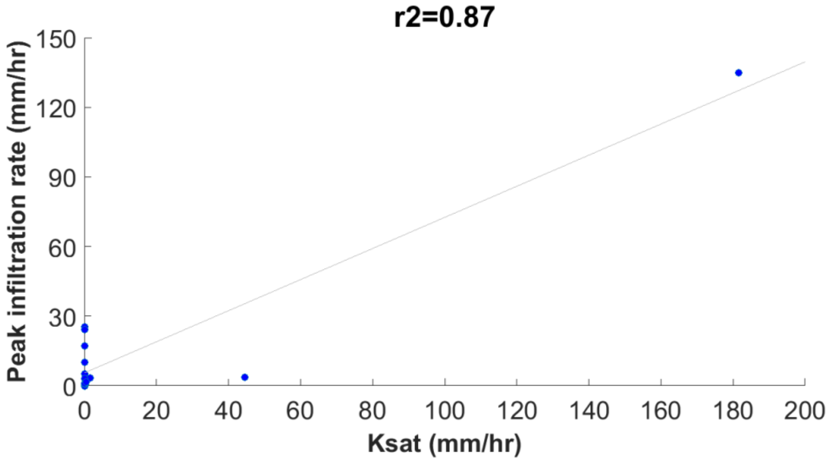

Figure 4.18: Correlation between infiltration rate and Ksat.

There was a strong positive relationship between peak infiltration rate and saturated hydraulic conductivity in this study (Figure 4.18). This indicates that if the peak infiltration rate at the surface is high, then there is a good chance that the topsoil will also have a high saturated hydraulic conductivity.

4.4.4 Ranking of Site Variations

Three of the rankings (resistance, bulk density and saturated hydraulic conductivity) from the analysis in sections 4.4.1-4.4.3 were added together to give an overall ranking for the level of compaction at each individual site out of a total score of forty two (Table 4.3). The HOF had the lowest score (13/42) and compaction rank out of the fourteen sites in this study, based on the three characteristics used in this study, followed by the COF indicating that they had the lowest soil strength, best soil structure and the best soil drainage out of the sites. The CFT and had the highest score (30/42) and compaction rank, followed by the CFG and SFT, indicating that these sites had the highest soil strength, worst soil structure and worst soil drainage.

Table 4.2: Level of compaction ranking.

Site	Resistance (kPa)	Strength rank	BD (g/cm3)	Structure rank	Ksat (mm/hr)	Drainage rank	Total	Overall rank
AOF	323	7	1.23	13	181.476	1	21	6
ATL	339	12	1.46	14	44.551	2	28	11
CFT	**333**	**10**	**0.96**	**6**	**0.001**	**14**	**30**	**14**
CFG	340	13	1.13	11	0.329	5	29	12
COF	323	8	0.90	2	0.151	6	16	2
CTS	337	11	0.85	1	0.05	10	22	7
HFT	305	5	1.10	10	1.603	3	18	3
HFG	302	4	1.09	9	0.026	12	25	10
HOF	**294**	**2**	**0.93**	**3**	**0.095**	**8**	**13**	**1**
HTS	329	9	0.94	4	0.125	7	20	5
SFT	367	14	0.94	4	0.029	11	29	12
SFG	322	6	1.16	12	0.448	4	22	7
SOF	281	1	0.98	8	0.084	9	18	3
STS	294	2	0.97	7	0.024	13	22	7

The results are in contrast to the results from Section 4.3 where the CTS was shown to have the best natural soil characteristics but was only seventh in the terms of the level of compaction. However, the COF was second in terms of having the best natural characteristics and second in terms of the level of compaction.

4.5 Comparison of Potential and Level of Compaction

This section will discuss the question “Did the sites with the lowest potential for compaction have the lowest soil strength, best soil structure and best soil drainage?” To assess whether the variables related to one another in a monotonic function, a Spearman’s rank test was undertaken. The output was a Spearman’s correlation coefficient (rho) with values close to minus one indicating a negative correlation, values closer to one indicating a positive correlation and values around zero indicating no correlation.

There was a weak to moderate linear correlation ($r^2<0.3$) between clay, sand, organic matter content and resistance (Figure 4.19). The Spearman’s rank tests showed that there was a weak correlation between resistance and clay (rho=-0.26), sand (rho=-0.20) and organic matter content (rho=0.16). There was only a slightly higher correlation with elevation (rho=0.30). These low levels of correlation may be due to the sample size, high heterogeneity in resistance at the sites, or because the mean values were used to undertake the analysis and this simplified the complexity in the range of values collected across the fields.

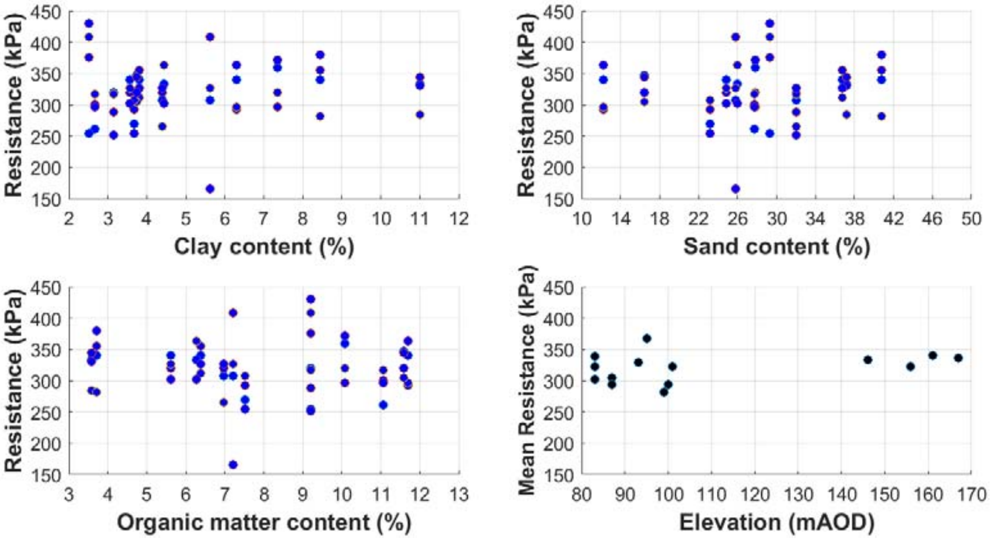

Figure 4.19: Resistance vs. mean clay, sand and organic matter content and elevation at all fourteen sites.

In other studies bulk density has been shown to increase with increasing sand content (Newell-Price et al., 2013) however, in this study there was a low linear correlation (r2<0.2) between these two variables (Figure 4.20) and between clay content and bulk density. There was however, a stronger negative linear correlation (r2=0.42) between organic matter content and bulk density. Other studies have shown that organic matter is strong predictor of bulk density and (Newell-Price et al., 2012) found a negative correlation (r^2=-0.53) on grassland sites in England and Wales. There was also a weak to no linear correlation (r^2<0.2) between clay, sand and organic matter content and saturated hydraulic conductivity (Figure 4.21).

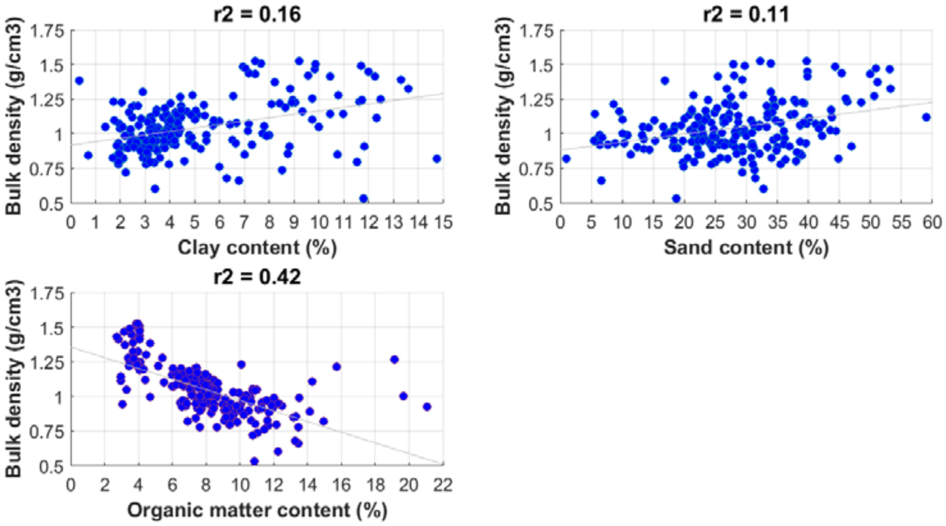

Figure 4.20: Bulk density vs. clay, sand and organic matter content.

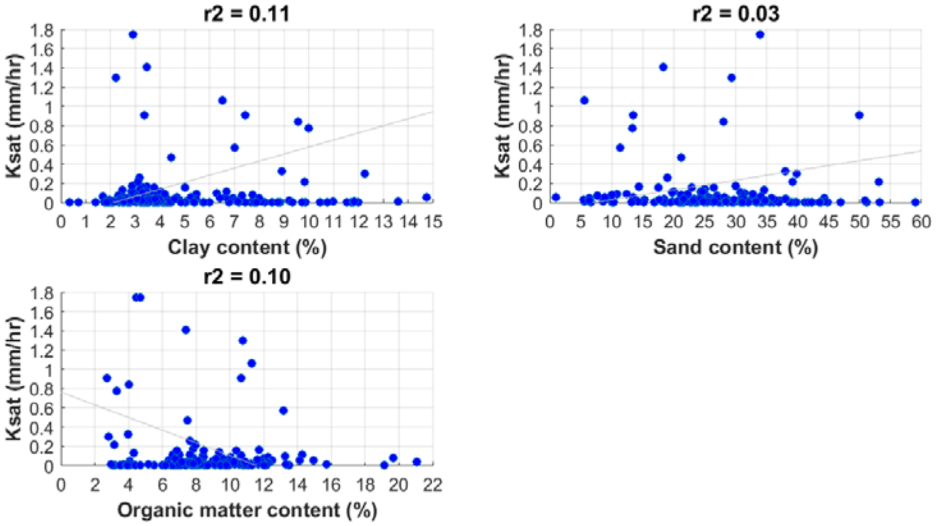

Figure 4.21: Ksat vs. clay, sand and organic matter content

4.6 Intra-Site and Inter-Site Variations

This section will answer two questions, “Are there significant differences within the four intra-sites (Arable, Cattle, Horse and Sheep) during the study period?” and “Are there significant differences between the four inter-sites (Feeding Trough, Field Gate, Open Field, Tree Shelter)?” Statistical significance in this study is classified as when p<0.01.

4.6.1 Arable Sites

There was no significant difference in the resistance at the two Arable Sites although the unconfined compressive strength at the ATL was significantly higher than the AOF indicating higher soil strength. The bulk density at the ATL was also significantly higher than the AOF suggesting a better soil structure. There was no significant difference in the peak infiltration rate or saturated hydraulic conductivity between the sites.

4.6.2 Cattle Sites

There were no significant differences in the resistance between the sites but the unconfined compressive strength was significantly higher at the CFG than the COF and CFT indicating the highest surface strength. The bulk density at the CFG was significantly higher than the other sites which indicated the worst soil structure. There were no significant differences in the peak infiltration rate between the sites and the saturated hydraulic conductivity at the CFG was only significantly higher than the CFT indicating a similar level of drainage potential at the other sites.

4.6.3 Horse Sites

There were no significant differences in the resistance but the unconfined compressive strength at the HTS was significantly higher than the other sites. The bulk density at the HFT and HFG were significantly higher than the HOF and HTS which may be due to significantly higher organic matter content at these sites during the study period. There was no significant difference in the peak infiltration rate at any of the sites but the saturated hydraulic conductivity at the HFT was significantly higher than the other sites indicating the best drainage potential.

4.6.4 Sheep Sites

There were no significant differences in the resistance, however; the unconfined compressive strength at the STS was significantly higher than the other sites indicating the highest surface strength. The bulk density at the SFG was significantly higher than the other sites. The saturated hydraulic conductivity at the SFG was only significantly higher than the STS but, not the other sites. There was no significant difference in the peak infiltration rate at any of the Sheep Sites.

4.6.5 Feeding Trough Sites

The FT sites were positioned fourteenth, third and twelve (CFT, HFT and SFT) out of the fourteen sites with an average of tenth. There were no significant differences in resistance or unconfined compressive strength between the sites indicating no difference in soil strength. The bulk density was significantly higher at the HFT than the CFT indicating the worst structure but, it was not different to the SFT. Conversely, the saturated hydraulic conductivity was significantly higher at the HFT than the other two sites, indicating the best drainage potential.

4.6.6 Field Gate Sites

The FG sites were positioned twelfth, tenth and seventh (CFG, HFG and SFG) out of the fourteen sites with an average of tenth. There were no significant differences in resistance or bulk density but the unconfined compressive strength at the CFG was significantly higher than the HFG indicating the highest surface strength. The saturated hydraulic conductivity was significantly higher at the SFG than the HFG but not the CFG indicating the best drainage potential at the Field Gate sites. The average

4.6.7 Open Field Sites

The OF sites were positioned sixth, second, first and third (AOF, COF, HOF and SOF) out of the fourteen sites with an average of third. There were no significant differences in resistance but the unconfined compressive strength at the SOF was significantly higher than the HOF indicating the highest surface strength. The bulk density at the SOF was also significantly higher than the COF and HOF indicating the worst structure. However, there were no significant differences in saturated hydraulic conductivity between the Open Field sites indicating that the soil drainage potential was very similar.

4.6.8 Tree Shelter Sites

The TS sites were positioned seventh, fifth and seventh (CTS, HTS and STS) out of the fourteen sites with an average of sixth. There were no significant differences in resistance but the unconfined compressive strength at the STS was significantly higher than the two other sites indicating the highest surface strength. The bulk density at the STS was also significantly higher than the CTS but not the HTS indicating the worst soil structure. However, there were no significant differences in the saturated hydraulic conductivity at the Tree Shelter sites showing no difference in the drainage potential between them.

4.7 Seasonality

This section will answer the question “Are there significant differences in soil strength, structure and drainage between the two fieldwork periods (October 2014 and April 2015)?”

There was no significant change in resistance at the majority of sites (ATL, CFT, CFG, CTS, HFT, HFG, HTS, SFG, SOF and STS) between the fieldwork periods. The mean UCS did not change significantly at the COF, HOF and HTS. There was no significant difference in saturated hydraulic conductivity at the ATL, COF, HFG, HOF and HTS in April compared to October. The results show that there was no change (improvement or deterioration) in soil conditions (strength, structure and drainage) at the ATL, CFT, HOF and HTS sites between the two fieldwork periods.

At the HOF this may be because the site was not compacted in either period, as shown in Section 4.4 where it was ranked the least compacted out of all fourteen sites. At the ATL and CFT it may be because these sites were already heavily compacted in October and did not recover over winter as shown in Section 4.4 where they were ranked the eleventh and fourteen most compacted out of the sites.

The AOF was the only site where the resistance and bulk density was significantly lower in April compared to October indicating that the topsoil was thicker, the strength was lower and the structure was better, after the winter period. The UCS was significantly lower in April at the Arable, CFG, COF, CTS, HFT, HFG and Sheep sites indicating that the surface was softer and the strength was lower. The peak infiltration rate was higher in April than in October at the AOF, ATL, CFG, CTS and HFT and a significant increase in the saturated hydraulic conductivity in April at the AOF, CFT, CFG, CTS, HFT, SFG and SOF showing an improvement in soil drainage potential after the winter period.

These results show that the AOF, CFG, CTS and HFT saw the most improvement in strength, structure and drainage between the two fieldwork periods. These differences may be due to natural soil recovery through processes such as freeze-thaw, wetting and drying or biological and fauna activity (Bottinelli et al., 2014). They could have been caused by very high spatial heterogeneity in strength, structure or drainage potential. They could be because the sites were less compact in April than in October due to less working of the land and the exclusion of animals over the winter exclusion period. At the Arable site winter wheat was planted before the October fieldwork and the land was not worked over the winter until the crop was harvested in March.

Conversely, resistance was significantly higher and the starting depth and topsoil thickness were shallower in April compared to October at the COF, HFG and SFT indicating that the surface was harder after the winter period. The peak infiltration rate was higher in October than in April at the COF, HFG, HOF, HTS and Sheep Sites and there was a significant decrease in saturated hydraulic conductivity in April at the SFT and STS which suggests deterioration in the drainage potential at these sites after the winter period.

These results show that the COF, HFG, SFT and STS saw the most deterioration in strength, structure and drainage between the two fieldwork periods. The differences could be due to an increase in the level of soil compaction over the wet period, at the HFG the horse was still moved in and out of the paddock through the gate during the winter period and at the Sheep site a vehicle was used to move feed in and out of the field through the gate during the early part of winter.

The drainage results may have been affected by the cooler soil temperatures in April (6°C) compared to October (11-15°C) which will have changed the drainage potential of the soil. It could also be due to different antecedent conditions in April when there was 17mm of rain in the previous twenty-four hours in comparison to just 0.6mm in October.

4.8 Chapter Summary

In summary, this chapter has presented the results of fieldwork and laboratory work that were undertaken to achieve Objective two – ‘to assess the problem of complexity in the relationship between soil compaction and soil hydrology. A conceptual model was design that was based on previous literature and fieldwork. This model defined how natural soil characteristics and human pressures can affect soil hydrology. From this model, a number of research questions were planned with the aim of creating new datasets and adding to the previous knowledge of the relationship between soil compaction and hydrology.

Firstly, the chapter looked at the potential for compaction at each land management site based on the natural soil characteristics (soil texture, organic matter content and elevation) which were collected. The results showed that the potential for soil compaction based on the natural, individual site soil characteristics was highest at the SFG and HOF and lowest at the CTS and COF.

Secondly, it quantified the variations in the level of soil compaction, based on three characteristics (soil strength, soil structure and soil drainage) between the fourteen field sites. The results showed that the HOF and COF had the lowest level of compaction and the CFT, CFG and SFT had the highest level of compaction. The COF had a low level of potential compaction based on its natural characteristics and low levels of compaction were measured at the site.

Thirdly, it compared the potential for compaction against the actual level of compaction quantified in Section 4.3 using the Spearman’s Rank test. The results showed that there was a weak correlation between clay, sand and organic matter content and soil strength but a moderate correlation between elevation and strength. In terms of soil structure, there was a weak correlation with sand and clay content but a stronger negative correlation with organic matter content. Finally, in terms of soil drainage there was again a weak correlation with sand, clay and organic matter content.

Fourthly, it looked at intra and inter-site variations in soil strength, structure and drainage. The results showed that at the Arable Sites that the ATL had significantly higher soil strength and the worst soil structure in comparison to the AOF. At the Cattle Sites the CFG had significantly higher soil strength and the worst soil structure compared to the other sites. At the Horse Sites the HTS had the highest strength however; the soil structure and drainage results seemed to show contradictory results. This may indicate that there were problems with the sampling or laboratory methods that were used to analyse these samples. At the Sheep Sites the STS had the highest soil strength and the SFG had the worst structure indicating that the SOF and SFT had lower levels of compaction.

Out of the three intra-sites, the average position in terms of level of compaction showed that the Feeding Trough and Field Gate Sites had the highest levels of compaction and out of the four intra-sites the Open Field Sites had the lowest levels of compaction.

Finally, it looked at variations between the two fieldwork periods. The results showed that some of the most compacted sites (ATL and CFT) and the least compacted site showed no difference between periods. It also showed that there was a strong improvement in soil conditions at four sites (AOF, CFG, CTS and HTS) and a strong deterioration at four sites (COF, HFG, SFT, STS).

In terms of strength, the results showed that the half of sites (50%) showed no difference in resistance between October and April but the majority of sites showed a significantly lower UCS values in April than October. In terms of structure, the majority of sites (93%) showed no difference between the two periods. In terms of soil drainage, the majority of sites (57%) showed that the peak IR was higher on October than in April but that in terms of Ksat that there was either no difference (50%) between the seasons or that Ksat was significantly lower (50%) in April than in October.

In conclusion, the results show that there is great complexity in soil compaction and soil hydrology at the intra-field and inter-field scales. One limitation of the ranking method used in this study is that it is very subjective to the perception of which key physical processes have the most impact on soil hydrology. It is assumed that the ranking method developed in this study does work successfully. The other assumption is that the mean values which were used to undertake some of the analysis are representative of each individual site. However, the mean is a simplification of the complexity in the range of values that were collected across the fields. Therefore, the use of the maximum or the minimum values in the analysis may have produced different results.

The results of the method do show that overall the expected results that the Open Field Sites were less compact and had better soil properties than the more compacted sites. The next chapter will focus on Objective three, “to develop a conceptual model to assess how the presence of a hedgerow modifies the hydrological cycle locally” and the field methodologies that were used to assess the impact of hedgerows on soil hydrology at the field scale.

Chapter 5 - Quantifying the Impact of Hedgerows on Soil Hydrology: Methodology

5.1 Chapter Scope

The previous chapter quantified the effects of soil compaction on hydrology. This chapter will provide the details of the approach used in Objective three, “to develop of conceptual model to assess how the presence of a hedgerow modifies the hydrological cycle locally”. Section 5.2 will introduce the conceptual hedgerow model and the hypotheses that were made focusing around three main areas. Section 5.3 will present the three research questions. Section 5.4 will provide information about the main hedgerow site and Section 5.5 will present the secondary sites used in this study.

Section 5.6 will discuss the field methodologies that were used to collect data on the hedgerow characteristics, the surface water balance and the subsurface water balance. This includes the methodology behind the site set-up at the Hedgerow Site and the installation of monitoring equipment. Finally, Section 5.4.3.4 will conclude the chapter.

5.2 Conceptual Hedgerow Model

This section presents the conceptual model that was developed to assess how the presence of a hedgerow modifies the hydrological cycle locally (Figure 5.1). This was done by undertaking an extensive literature review which focused on hedgerows in the UK and Europe but, also wider afield and included other woody linear features including lines of trees, shelterbreaks and windbreaks. The review identified three main areas which are thought to be affected by the presence of a hedgerow, firstly the hedgerow characteristics, secondly the surface water balance and thirdly the subsurface characteristics. They are discussed in more detail in Sections 5.3.1-5.3.3.

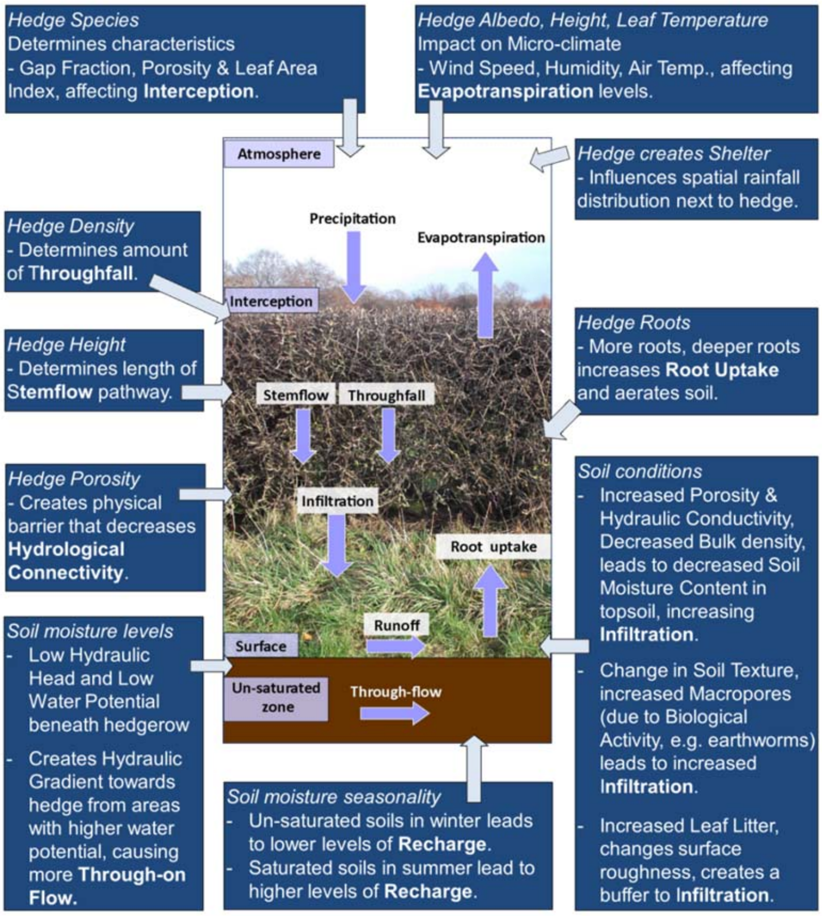

Figure 5.1: Conceptual model - Hedgerow impacts on Hydrology.

Previous researchers have reported a hedgerow shelter affect which influences the wind speeds on the windward and leeward sides of the structure. The affect is thought to modify a variety of climatic factors including rainfall, temperature, evaporation, humidity and soil moisture (Pollard et al., 1974) and have an impact out to a distance of twenty-eight times the height of a hedgerow.

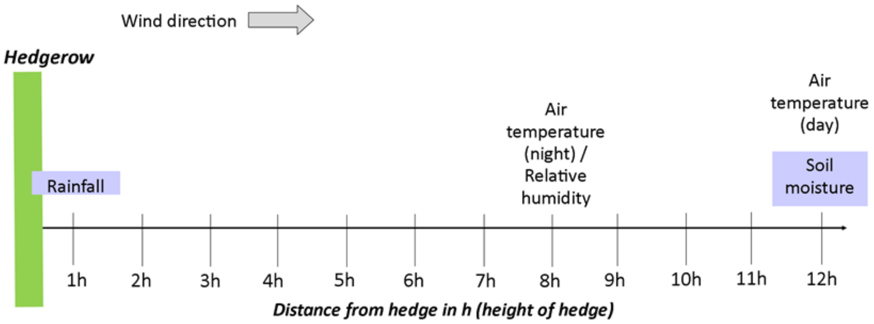

Figure 5.2: The shelter effect of a hedgerow on climatic factors. (Redrawn from Pollard et al., 1974 to include other research).

5.2.1 Hedgerow Characteristics

In terms of the root characteristics, the hedgerow species is the main control on the rooting depth, root size and extent. The roots aerate the soil through the creation of macropores and increase the amount of root uptake throughout the year. When hedgerows are managed, through pruning, the number of finer roots in the topsoil increases and part of the biomass of the hedge dies. It is hypothesised that the hedgerow will create larger and denser roots in the area beneath and on either side of the hedgerow in comparison to surrounding open fields. It is hypothesised that the hedgerow structure itself and the density of the hedgerow feature will create a physical barrier, that may decrease hydrological connectivity depending on its location and orientation in the flood plain.

In terms of the leaf characteristics, the leaf surface is the interface between the plant and the atmosphere and is therefore important in the exchange of gases, water and energy (Pocock et al., 2010). The hedgerow species is the main control that defines the size and shape of the leaves. The species will determine the specific leaf area, gap fraction, canopy porosity and the leaf area index of the hedgerow. It is hypothesised that a denser canopy cover will increase the amount of interception and reduces the amount of throughfall.

The management of the hedgerow (frequency and extent of pruning) will change the physical leaf area. The leaf characteristics will also be affected by the soil type, local soil moisture content, the aspect and positioning of the hedgerow on the slope and the positioning of the leaves within the hedgerow. The leaves on the outside of the hedgerow are known as sunlit leaves and are generally larger and thicker. The leaves on the inside of the hedgerow are known as shade leaves and are generally smaller and thinner. Finally, it is hypothesised that the darker the hedgerow leaf and the higher the leaf temperature the higher the evapotranspiration rates.

In terms of the soil characteristics, dead roots created by pruning and the general decaying process underneath the hedgerow creates organic matter and forms macropore paths for bypass flow (Kiepe, 1995). Therefore, it is hypothesised that the activity of the rooting system of the hedgerow will change the soil structure. An improved soil structure encourages earthworm activity which is important which will create more macropores. This will lead to an increase in the amount of infiltration. It is hypothesised that there will also be a decrease in local bulk density, an increase in hydraulic conductivity and an increase in overall porosity.

There is no known research that provides information on how the shelter affect influences the hedgerow characteristics. However, immediately next to the hedgerow, the plant removes water from the soil through its roots, for use in photosynthesis and growth. The hedgerow also creates a better soil structure and better drainage which is assessed by determining the bulk density and saturated hydraulic conductivity at the soil next to and further away from the hedgerow. As you get further from the hedgerow, root uptake decreases, the benefits to the soil structure diminish and the open field is affected by other factors such as soil compaction by animals and machinery.

5.2.2 Surface Water Balance

In terms of rainfall, the hedgerow is thought to influence the spatial distribution of rain falling on the windward and leeward side of the structure. Hedgerows create a rainfall shadow on their leeward side that is as wide as it is high (Herbst et al., 2006). Therefore, it is hypothesised that the hedgerow will affect the rainfall next to the hedgerow in comparison to the surrounding open fields. The shelter affect is thought to have an influence out to one times the height of the hedgerow on the distribution of rainfall (Herbst et al., 2006).

In terms of interception, the leaf characteristics will determine the canopy density. It is hypothesised that there will be more interception at the more dense parts of the canopy and less interception at the less dense parts of the canopy. Hawthorn hedgerows in southern England have been shown to intercept 50-60% of rainfall in summer and 40-50% in winter (Herbst et al., 2006). Therefore, it is hypothesised that the hedgerow canopy will intercept more rainfall than the surrounding open fields.

It is hypothesised that there will be more interception, less stemflow and less throughfall at the hedgerow in the leafed period than in the leafless period. Conversely it is also hypothesised that there will be less interception, more stemflow and more throughfall at the hedgerow in the leafless period than in the leafed period. It is also hypothesised that the height of the hedgerow will determine the length of the stemflow pathway. Therefore, taller hedgerows may have a longer stemflow pathway.

In terms of micro-climate, the hedgerow orientation and height will have an impact on the wind speed, humidity and air temperature which will affect evapotranspiration rates (Pollard et al., 1974). The permeability of a hedgerow structure affects local wind speeds by forcing air up and over it but, also through it (Pollard et al., 1974). Optimum permeability is 40%, when the hedge is less permeable there is an insignificant reduction in wind speed and when the hedge is denser it acts as a solid barrier and there is potential for turbulent strong winds in the zone. It is hypothesised that in the sheltered zone that the day time air temperature is higher, night time air temperature is lower, relative humidity is higher and the evaporation rates are lower than in surrounding fields.

5.2.3 Subsurface Water Balance

In terms of the subsurface soil water content, the antecedent conditions, the water holding capacity of the soil and the position in the landscape in terms of slope and aspect all have an effect. It is hypothesised that the soil at north and west facing hedgerows would be wetter than the south and east facing hedgerow because.

The improved soil characteristics caused by the presence of the hedgerow are thought to create lower soil moisture levels in the topsoil, a low hydraulic head and low water potential directly beneath the hedgerow, due to good drainage and soil drying. Soil moisture content next to the hedgerow may be reduced further due to root uptake by the structure for use in transpiration in comparison to further away from the hedgerow in the open field. It is hypothesised that this could create a hydraulic gradient towards the hedgerow from areas with higher water potential (e.g. further away from the hedgerow). This could cause more through-on flow.

It is hypothesised that the presence of the hedgerow may change the seasonality of soil moisture. In winter, un-saturated soils may cause low levels of recharge to groundwater, creating additional soil storage capacity for long duration rainfall events. In summer, saturated soils may cause high levels of recharge providing additional water to plants in periods of high temperatures and low rainfall.

Alternatively it is hypothesised that the topsoil will contain a higher level of organic matter content due to an increase in leaf litter, which is abundant under hedgerows and which conserves soil moisture by reducing soil temperatures and evaporation (Willms et al., 1986). The litter may also change the surface roughness and could cause a buffer to infiltration and lead to higher local soil moisture content.

Hedgerows have been shown to affect local wind speed (Pollard et al., 1974) by creating a buffer on the leeward side. Therefore it is hypothesised that there will be a decrease in soil moisture levels, especially on the leeward side of the structure. South facing hedgerows receive more sunlight and so the soil here would also experience more evaporation. The shelter affect is thought to influence the soil moisture content up to twelve times the height of the hedgerow (Figure 5.2).

5.2.4 Hedgerow Research Questions

Based on the outcomes of the conceptual model this research will investigate three main questions:

1. What are the physical hedgerow characteristics including the extent of vertical roots and the leaf area index and the soil properties around the hedgerow?
2. Does the hedgerow affect the surface water balance by altering the distribution of rainfall, throughfall, and stemflow?
3. Does the hedgerow affect the subsurface water balance by altering the soil moisture distribution?

An experimental design was set up to assess the soil and hedgerow characteristics along a transect either side of a hedgerow and to monitor the micro-climate around a hedgerow. Measurements were conducted to define the physical structure of the hedgerow and to gain knowledge about interactions between the hedgerow and the local hydrology. A weather station was also set up nearby to provide a control for the data being collected. Additional hedgerow sites in the same catchment were used to compare the results and assess processes seen at the main hedgerow. Each field and laboratory test will now be explained.

5.3 Monitoring Sites

The selection of the main Hedgerow Site was influenced by five main criteria, the first criterion was its aspect and the second was its position in the landscape. A west-east orientated hedgerow was needed to investigate the impact of the structure as a barrier to rainfall. A hedgerow orientated perpendicular to the main slope in the field was needed so that both sides would experience the same drainage affects from the slope above it. The third criterion was that the hedgerow needed to be typical in species and structural density as the other hedgerows in the study catchment. But, the fourth criterion was the hedgerow needed to contain both dense and gappy sections to allow for processes like throughfall to be tested under different hedgerow sections (dense canopy, thin canopy, gaps in hedge). The fifth criterion was that the site needed to have good access points (field gates) which were necessary for transporting the equipment to and from site.

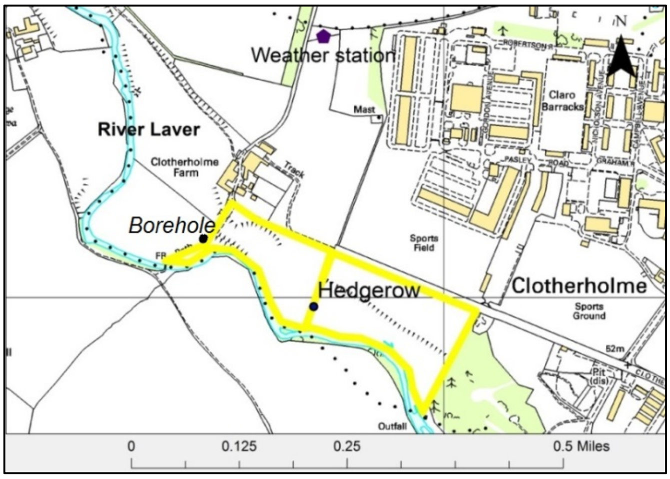

Figure 5.3: Hedgerow Site – Clotherholme Farm, Ripon.

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A hawthorn hedge was chosen as it also represents >50% hedgerows in England and Wales (Barr et al., 2004). The Hedgerow Site (Figure 5.3) was located at Clotherholme Farm (elevation 48-52m A.O.D.). This hedgerow was selected because it filled all five of the original criteria needed to assess the hypotheses outlined above. The site is 1.8 miles west of the city of Ripon just east of the confluence of Kex Beck and the River Laver. The River Laver runs along the southern edge of the farm and the Laver Dam is located along the north-west boundary of the farm. The farm is situated in the area of Clotherholme. The word comes from the word ‘clod-holme’ that means stone enclosure. The Claro army barracks are north of the field site. Clotherholme Road runs through the farm and is a public footpath. The farm was purchased by the current owner in 1935 and the farmer employs mixed farming including cattle and sheep farming and rotated arable farming.

The bedrock geology in the Clotherholme area is the highly permeable Cadeby Formation composed of Dolostone with highly productive aquifers (Centre for Ecology and Hydrology, 2016), overlain by Quaternary age fluvial and alluvium superficial deposits (British Geological Survey, 2016). The Industrial Minerals Assessment Unit (IMAU) took a borehole (1981) approximately one-hundred metres west of the hedgerow at Clotherholme Farm (Figure 5.3). It showed that the soil was 0.8m thick and the ground water level was greater than fifty metres deep (Strong and Giles, 1983). The groundwater influences were not quantified in this study because they were considered not to confluence the local hedgerow hydrology and they were outside the scope this study.

Figure 5.4: Glacial Till at Hedgerow Site and a Hedgerow trimmer.

This hedgerow borders two fields, the field on the west of the hedgerow is 0.025km^2 in size and has been used as permanent pasture continuously for over 40 years. The field on the eastern side of the hedge is 0.025km^2 in size and is classed as a temporary lay and has been sown with seeds or silage grass for the last five years. The grasses are cut early in the season in May or June, depending on the weather. Prior to this, the field was used for arable farming including potato, winter fodder beet, turnips, wheat, barley and oats

(Person communication). To the east of the field is a wood. Running across the middle of both fields is an out crop of glacial till deposits (Figure 5.4).

This hedgerow is a stock proof barrier that prevents livestock passing into the adjacent field. It is relatively dense and retains a neat rectangular 'A' topped shape (DEFRA, 2007). It is trimmed annually in late autumn/early winter using a tractor mounted flail master (Figure 5.4) which is the standard method of trimming. There is evidence of past coppicing of the hedgerow identified by the multi-stemmed vertical growth. During the monitoring period the hedgerow was trimmed to maintain the same shape.

Once the study hedgerow had been selected, a five metre section was identified that included dense and gappy sections that could be used to assess the original hypotheses. There are no hedgerow trees in the section and it is slightly leggy and thin near the base (lower than 0.5m) with few horizontal branches or leafy shoots (DEFRA, 2007). The monitoring equipment was installed in a moderately dense section so the effect of the hedgerow structure on hydrology could be tested.

The monitored section stands at an elevation of 48m A.O.D and is located on the flattest part of the field to eliminate the effects of slope. The hedgerow was monitored for a period of sixteen months, using a variety of equipment which will be detailed in Section 5.4. The tests were designed to test the hypotheses from the conceptual model and were based on previous literature on hedgerow studies (Ghazavi et al., 2008, 2011; Herbst et al., 2007, 2006; Thomas et al., 2012).

Figure 5.5: Hawthorn hedgerow leaves, twigs and fruit.

The landowner stated that the hedgerow had been in place since the family purchased the farm (Personal communication) and the boundary line is evident on OS maps from the 1890's. The monitored section is composed of two main woody species, the deciduous Common Hawthorn (*Crataegus Monogyna)* also known as single seeded hawthorn (Figure 5.5) and the evergreen Holly (*Ilex aquifolium*) which are both native UK species (DEFRA, 2007). This indicates the hedgerow is at least 200 years old (Pollard et al., 1974).

To supplement the hydrological information gained at the main Clotherholme Farm hedgerow site, two other hedgerows at Clotherholme were studied, plus two hedgerows at Hedge Nook Farm and four at Holme Farm (Figure 5.6). The secondary sites had similar characteristics to the main hedgerow site to try and eliminate the influence of other factors on the results. All the secondary sites had either cattle or sheep grazing in the fields on either side of them. Most of the sites were located on flat ground, with the exception of Hedge Nook Farm and all the hedgerows chosen contained Hawthorn and were a similar density, size and shape to the main Clotherholme hedgerow. Hedgerows with a bank, or ditch were not used due to their potential impact on local conditions.

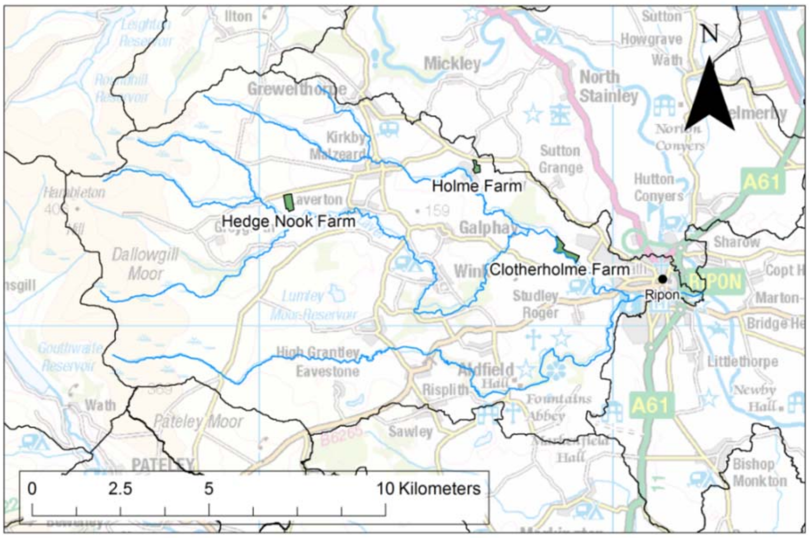

Figure 5.6: Secondary hedgerow sites in Skell catchment.

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5.4 Field Methodologies

This section will outline the methodologies used to complete the fieldwork at the main hedgerow and secondary sites to determine the impact of hedgerows on soil hydrology. Section 5.4.1 will provide the methods used to determine the subsurface soil characteristics at the main hedgerow site. Section 5.4.2.6 will provide the methods used to determine the subsurface soil moisture content at the main hedgerow and secondary sites. Section 5.4.1 will show the methods used to determine the hedgerow characteristics and monitor hydrological processes at the main hedgerow sites. Section 5.4.2 will provide the methods used to monitor the surface water balance and Section 5.4.2.4 will provide the methods used to monitor the micro-climate at the main hedgerow site.

5.4.1 Hedgerow Characterisation

To assess the main study hedgerow, the standard UK procedure was used to undertake a hedgerow survey (DEFRA, 2007). A thirty metre section of Hawthorn hedgerow was surveyed that included the part of the hedgerow that was monitored for the duration of the study. The average height, width and base of the canopy was calculated using ten random measurements of the woody growth, excluding any bank, gaps and hedgerow trees (DEFRA, 2007). The average stem circumference was calculated using ten random measurements and the number and width of gaps were recorded.

5.4.1.1 Determination of Root Characteristics

Plant roots are an important property to measure because they exude and absorb air, water and nutrients from the surrounding soil (Pasquale et al., 2012). Water can enter plants by osmosis through their root hairs, travel into the root cortex cells and up into the plants xylem vessels where it can then be transported to the leaves and lost into the atmosphere (Burgess et al., 2001). Roots are also important for the soil as they hold the soil together and prevent erosion but, their growth is affected by soil texture and soil compaction (Popova et al., 2016). There is no documentation regarding the vertical or horizontal length of UK Hawthorn hedgerow roots but, it is generally suggested that they extend deep into the soil to access deeper water supplies but, that root density decreases with distance from the plant stems (Mulia and Dupraz, 2006).

In this study, the presence of roots was observed to find out how far from the hedgerow the roots extended and to quantify how the density of roots changed with distance from the hedgerow. A survey was undertaken across a twenty metre transect that ran perpendicular to the hedgerow in October 2015. Four soil pits (approximately 60cm wide x 60cm long and 40cm deep) were dug at systematic locations (at zero, one, three, and ten metres) along the transect line on both sides of the hedgerow. These locations were chosen as they match the location of the soil moisture probes under the ground, so they could inform the analysis of the data collected and to assess how far the hedgerow roots extend laterally from the hedgerow.

The standard belt transect method with quadrat sampling (Stehman and Salzer, 2000) was used to analyse this property because it gives a good estimation of the abundance of roots, due to their sedentary nature. The method was chosen due to its repeatability and ease of use (Dodd, 2011). It allowed the estimation of the absolute density (number of individuals per unit area) which is comparable to other sites.

Roots are generally classified in three categories, fine (<1mm diameter/3.1mm circumference), medium (1-5mm diameter/3.1-15.7mm circumference) and coarse (>5mm diameter/15.7mm circumference) (Plante et al., 2014), although sometimes they are referred to as >10mm diameter/31.4mm circumference (Bouillet et al., 2002; Genet et al., 2008). Root density was assessed at ten and thirty centimetres in all pits to assess vertical changes of density.

Measurements were taken using a 50cm wide x 50cm long square quadrat divided up into a grid of twenty five equal squares (10cm wide x 10cm long) each representing 4% of the total area. This allowed the percentage root coverage within each division and over the whole quadrat area to be estimated. The absolute root density (D) was also calculated using Equation 5.1 (Stehman and Salzer, 2000), where y_u = percentage cover in division ‘u’ and a_u = area of division ‘u’.

Equation 5.1: Absolute root density.

$$D = \frac{y_u}{a_u}$$

The quadrat size was appropriate for the average size of the roots observed at the site and because quadrats greater than 1m^2 are difficult to use (Stehman and Salzer, 2000). The process of quadrat sampling is subjective so all quadrats were analysed by one person in order to reduce error. The quadrat method has the following assumptions, that the number of individuals in each quadrat is counted, that the size of the quadrat is known and that the quadrat samples are representative of the study area as a whole. These assumptions were met for the roots over five millimetres in diameter but, not for smaller roots because it was difficult to measure them in the field.

5.4.1.2 Determination of Leaf Characteristics

Leaf area index (LAI) is an important property to measure because it characterises the canopy-atmosphere interface (Bréda, 2003) and is a key parameter in hydrological models (Pocock et al., 2010). The LAI of a plant is the total single-sided leaf area per unit area of ground. There are a number of methods available to determine LAI including direct methods including destructive harvesting of plants (Magarey et al., 2005) and scanning every leaf (Fuentes et al., 2014) or indirect methods such as remote sensing from satellites/aircraft (Hagiwara et al., 2002), hemispherical photography (Martens et al., 1993) and the point quadrat technique, that passes needles through the stand and recording the number of contacts with foliage (Neumann and Den Hartog, 1989). The most widely used method is the Gap Fraction Inversion procedure which provides robust estimates of LAI from the transmittance of light in five angular bands (Pocock et al., 2010).

For robustness, two methods were used to determine LAI at the Hedgerow Site at six different locations: high, medium and low density hedgerow canopy, no canopy at all, edge of the hedgerow and dense understory vegetation. This allowed the effect of spatial heterogeneity in the hedgerow to be evaluated.

The first method that was chosen to monitor LAI was the direct collection of leaves (Ishihara and Hiura, 2011) during leaf fall to determine the Specific Leaf Area (SLA) based on dried weight and also by measuring average leaf size of a sample. This method was chosen because it is the only method that gives the real shape and size of the leaves in the canopy and because it can be used as a reference for the calibration and evaluation of the second indirect method. The litter fall method is widely used for assessment of deciduous broadleaf species and well adapted for small woody structures like hedgerows (Bréda, 2003).

Ten litter fall collection traps (23.5cm wide by 34.1cm long and 14.5cm tall, 800.6cm^2 in area, rectangular shape) where spread out through the thirty metre section of the hedgerow (**Error! Reference source not found.**), ensuring they were level to maintain the same size of surface area. Following the method used by (Granier et al., 2000), the traps were left for two weeks in the study period, during leaf fall from 26 October-10 November 2015 (days 299-314), to collect the leaves. The litterfall was sorted into leaves, branches and miscellaneous in the laboratory following the method of (Muller-landau and Wright, 2010). Following the gravimetric method, the leaves were dried in an oven for forty-eight hours at a temperature of 65°C (Qi et al., 2012) and weighed immediately when removed, to stop the uptake of water from the air. The specific leaf area (m^2) was related to dry mass (grams) using Equation 5.2.

Equation 5.2: Specific Leaf Area.

$$SLA = \frac{\boldsymbol{Total\ leaf\ area}}{\boldsymbol{Dry\ weight\ of\ sample}}$$

Figure 5.7: Leaf litter trap at site and leaves on a cardboard plate.

A random sub-sample of leaves was selected from each site to determine the average dried leaf area. The leaves were places on a cardboard plate which had a green rectangle of a known length (50mm). A piece of glass was placed on top of the leaves to keep them in position (Figure 5.7). The leaves were then photographed using a camera. The leaf images were opened in a piece of software called ImageJ and the photosynthetic (green) portion was identified. This software is a public domain java-based image processing program that was developed at the National Institutes of Health in Maryland, USA (Ferreira and Rasband, 2012). The images were resized and then converted into eight-bit grayscale. A line was drawn over the fifty millimetre rectangle and set as the known distance and a threshold was set to give good contrast between the leaves and the background. Individual leaves were outlined and their width, length and area were automatically measured using the ‘analyse particles’ function (Reinking, 2001).

The major source of error in using leaf litter collection traps to determine leaf area index is from the relationship of litter weight to leaf area. Specific leaf area can be overestimated due to leaf decomposition (Bouriaud et al., 2003). To prevent this error the collection traps had small holes in the bottom to allow drainage of water and the leaves were collected after two weeks. Another source of error is from within stand variability however, the location of traps in different locations along the hedgerow should highlight this variability and allow it to be determined.

The second method that was chosen to measure leaf area index was the Gap Fraction Method (Welles and Cohen, 1996), based on Beer’s Law (Beer, 1852). Gap fraction is the contrast between the sky and the canopy, or the probability of a ray of light passing through the canopy without encountering foliage, or other plant elements (Zhao et al., 2012). Images are divided into a grid of cells which are categorised into either canopy or sky using a light intensity value, known as binarisation (Glatthorn and Beckschafer, 2014). Where both categories occur in a cell, a threshold value is used to determine which category to assign the cell. There are a number of different methods to do this, including the automatic Otsu and Entropy Crossover methods and the manual threshold method (Negrón Juárez et al., 2009).

The VitiCanopy mobile phone application was used to compare the results generated by the specific leaf area method. It is designed to measure grapevine canopy architecture and was developed at the School of Agriculture, Food and Wine at the University of Adelaide in Australia (De Bei et al., 2016). It was assumed that the Australian grapevines are a similar size and have a similar canopy structure to that of the woody linear features such as the English hedgerow. The application was chosen as a low cost and easy to use method.

The application uses digital photography and automated analysis by applying gap size assessment algorithms (Fuentes et al., 2014). An iPhone 5s was used to take photographs from the front facing camera at a distance of 60-70cm beneath the canopy. The manual threshold method was used to determine the gap fraction within the application. A value of 75% was set, meaning that if 75% of the cell corresponds to sky, then the cell is considered to sky. This value was chosen because it is the optimal threshold for grapevine applications (Fuentes et al., 2008).

The initial value of LAI was calculated using Equation 5.3, where f_c is the crown cover, which assumes the crowns to be solid, Φ is the crown porosity, which is the gap fraction within the crown perimeter that ignores large gaps in the crown (Macfarlane et al., 2007) and k is the light extinction coefficient at the zenith. For grape vines the parameter ‘k’ has been reported to be between 0.65-0.75 and again this was assumed to be similar for hedgerows and was set to 0.70 in the application.

Equation 5.3: Leaf Area Index.

$$LAI = \frac{-f_c ln(\Phi)}{k}$$

To improve this value of LAI, four equations are implemented automatically within the application. The first accounts for the crown cover (f_c, Equation 5.4), where l_g is the large gap pixels count (>75%) and t_p is the total gap pixels. The second is the fractions of foliage projective cover (f_f, Equation 5.5), which means the proportion of ground area covered by the vertical projection of foliage and branches and where t_g is the total pixels in all gaps. The third is the crown porosity (Φ, Equation 5.6) which means the proportion of ground area covered by the vertical projection of foliage and branches, within the perimeter of the crowns of individual plants. The fourth is the clumping index (Equation 5.7), a non-random spatial distribution parameter that accounts for the complex canopy architecture found in canopy structures (Gonsamo and Pellikka, 2009). Following this, the effective LAI (LAI_e, - Equation 5.8) was calculated.

Equation 5.4: Crown cover.

$$f_c = 1 - \frac{lg}{t_p}$$

Equation 5.5: Fraction of foliage projective cover.

$$f_f = 1 - \frac{t_g}{t_p}$$

Equation 5.6: Crown porosity.

$$\theta = 1 - \frac{f_f}{f_c}$$

Equation 5.7: Clumping Index.

$$\Omega(0) = (1 - \Phi)\frac{\ln(1 - f_f)}{\ln(\Phi) f_f}$$

Equation 5.8: Effective Leaf Area Index.

$$LAI_e = LAI\ \Omega(0)$$

There are two major sources of error with optical LAI measurements first the clumping effect that occurs from beyond and within shoot clumping (non-random distribution of foliage elements). The second is an error from non-synthetic components including stems and branches (Qi et al., 2012). To reduce errors during measurement, a binary image appears on the iPhone before measurement and this was used to check that there were no obvious problems caused by the presence of the operator's body, understorey vegetation or fences in the camera frame. It also helped to identify if the threshold (75%) was appropriate for identifying the sky and hedgerow cells in the image. To prevent problems occurring with the sun, the measurements were taken when the sun was not directly overhead. To make sure the image included the whole canopy width, the iPhone was positioned on the leaf litter on the surface, at least fifteen centimetres from the bottom of the canopy.

5.4.1.3 Subsurface Soil Characterisation

To provide site specific soil characterisation, one metre long soil cores were collected in May/June 2015 from a twenty metre transect at one, three and ten metres on both sides of the main hedgerow using the Atlas Copco Cobra Combi percussion hammer (Atlas Copco, 2012). An additional core was collected from the middle of the hedgerow (classed to be 0m) using the gouge auger due to the dry and dis-aggregated nature of the soil.

The following tests were then completed on the cores in the laboratory, using the methodologies explained in Chapter 3 – Section 3.5.

- Determination of soil horizons (Avery, 1973)**.**
- Soil colour determination.
- Amount of soil mottling.
- Determination of the soil structure, strength (grade), size (class) and shape (type).
- Presence of calcium carbonate using the Acid Test.
- Determination of bulk density and porosity.
- Loss on ignition test (The British Standards Institution, 1990)

- Particle size analysis determined using the Mastersizer 2000 laser diffraction particle size analyser (Malvern Instruments Ltd, 2007)**.**

5.4.2 Rainfall and Interception Monitoring

To assess the impact of the hedgerow on the spatial rainfall distribution and on interception losses, the following hydrological processes were studied (precipitation, stemflow, throughfall and interception). This section will describe how each of these processes was monitored.

5.4.2.1 Determination of Precipitation

Tipping bucket rain (TBR) gauges were chosen to monitor this hydrological process so only rain and drizzle were captured and monitored. TBR gauges were chosen because they are the standard automated device used to measure rainfall rate in the UK (Met Office, 2014). Maplin electronics N25FR TBR gauges, with an accuracy of +/- 5% (Personal communication – Russell Stephens) and a water proof rating of IPX3, were chosen due to their low cost due to the number that were needed.

The TBR gauges had a collecting funnel with a sampling area of 55cm^2 that tipped when 0.28+/-0.1mm of water passed through them. To determine this volume all the TBR gauges were calibrated separately in the laboratory before use (Figure 5.8). A pipette with 2ml of water was attached to a clamp stand. The pipette was placed above the rain gauge and squeezed slowly to replicate light, steady rainfall over the rain gauge. When the bucket was heard to tip no more water was released from the pipette. The amount of water left in the pipette was deducted from 2ml to calculate the amount of water taken to tip the bucket. The rest of the water in the pipette was then removed and replaced with a new 2ml of water. The rain gauge was taken apart and the buckets and lid were dried using a paper towel. These steps were repeated ten times to determine the average volume required for the buckets to tip.

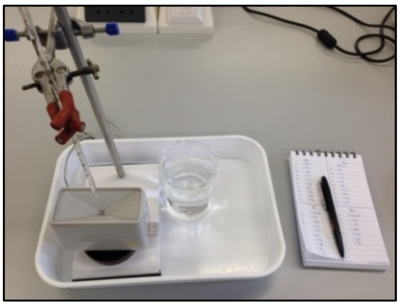

Figure 5.8: Rain gauge being calibrated in the laboratory.

New cables were fixed to half of the gauges, so that they could be positioned at zero, one, three and ten metres from the hedgerow. Each rain gauge was attached to a triangular metal plate using two screws, one at either end, to provide a level base on the grass surface. The metal plate had holes drilled into the middle of it, to allow water to drain from the gauge when the buckets tipped. Three long metal screws (fifteen centimetres length) were attached to the three corners of the metal plate and fixed in position using washers and nuts.

Figure 5.9: TBR gauge installation at Hedgerow Site.

TBR gauges are associated with a number of errors firstly that they do not release the water they are holding in between rainfall events. Therefore, when a new event occurs, there may already be water sat in the gauge, from a previous rainfall event. This leads to two things, gauges can show higher levels of rainfall than have actually fallen and gauges are prone to tipping at slightly different times from one another. TBR's can be affected by animals moving or landing on the gauge creating spurious readings and by rodents chewing on the cabling but, this affected the two throughfall gauges in November 2014-February 2015. The rest of the TBR gauge cables were buried ten centimetres beneath the ground, to reduce disturbance when walking over them and to stop animals from chewing through them however, if the experiments were to be repeated then the cables could be placed in a plastic tube. The sampling area can become blocked by vegetation which can prevent rain from running into the funnel. To prevent this butterfly netting was placed over the top of the gauges are secured in place. To prevent issues with grass growth the area was trimmed frequently (monthly) and sometimes more often in early summer.

Figure 5.10: TBR gauges installed on west-side of the Hedgerow.

An array of eight automatic TBR gauges were installed at the hedgerow site (Figure 5.9) at zero, one, three and ten metres on the west and east-side (Figure 5.10 and 5.11), inside a purpose built wooden fenced area (3m x 22m). Once installed in the field, the cable from the rain gauge was attached to an enclosure box and attached to a HOBO 4-channel pulse input data logger (UX120-017x) (Onset Computer Corporation, 2014), which ran on two AA batteries, and was placed inside a waterproof enclosure box. The logger recorded the number of tips that occur in five minutes, using the HOBOware software program. The TBR gauges were set up for sixteen months from 29 April 2014 to 30 August 2015. The operating range of the logger was between -40 to 70°C and it was chosen due its ability to store large numbers of measurements.

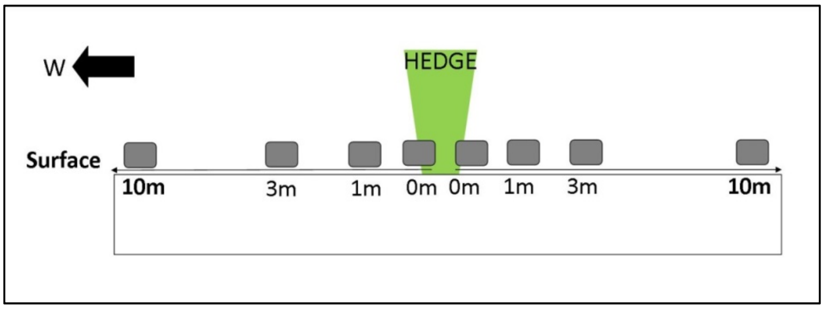

Figure 5.11: Side view of the location of the TBR gauges at site.

The gauges were positioned on the grass surface, rather than at the British Standard height which is four-hundred and fifty millimetres above the ground (Met Office, 2014). This was done to detect differences in precipitation next to the hedgerow and further away from it and on the leeward and windward sides. To stop grass growth, plastic sheeting 3,750cm^2 in size were laid out and held in position using large rocks. The gauges were then positioned on top of the bags. A bubble level was used to make sure the rain gauge was perfectly level.

To be more confident of the data that had been collected at the TBR gauges a threshold was set to remove some of the ambiguous records. The threshold stated that any amount above >0.81mm recorded on any of the gauges in five minutes, was removed, when there was no rainfall on any of the other seven gauges at the same time stamp. These uncertain records may have been caused by one of the issues stated in the above section.

The TBR gauge data was analysed using the standard precipitation definitions from the Met Office (Table 5.1) for the size and intensity of precipitation (Met Office, 2011). The heaviest intensity downpours were assessed for the summer season by analysing how much rain fell in an hour. The longest duration showers were assessed by analysing the five minute rain gauge data. Rainfall was said to be continuous if there was a tip of the bucket once every thirty minutes, this was because the gauge does not tip until it has collected 0.28mm rainfall. Therefore, when there is less rainfall than this in five minutes the bucket does not tip and the data records zero rainfall. This method assumes that when low intensity rainfall occurs it will make the bucket tip at least once every thirty minutes.

Table 5.1: Precipitation intensities (Met Office, 2011).

Type of precipitation	Intensity (mm/hour)
Slight rain	<0.5
Moderate rain	0.5-4
Heavy rain	>4
Slight shower	0-2
Moderate shower	2-10
Heavy shower	10-50
Violent shower	>50

5.4.2.2 Determination of Throughfall

Two main methods were used to determine throughfall, the first was to assess the spatial distribution and the second was to continually monitor it during different events and seasons. Both methods involved the use of a collector (troughs and rain gauges). Throughfall data is usually compared to a control rain gauge which is located away from the forest study site to assess the amount of throughfall that is occurring.

Figure 5.12: A throughfall gauge installed at site.

The first method chosen to measure throughfall was TBR gauges (Figure 5.12) which were chosen because they were easy to set up and had a known sampler area. Two throughfall TBR gauges were installed underneath the centre of the hedgerow to minimise the amount of lateral rain entering the sampling area. One limitation of this method was that rain falling on the top of the gauge may have been blown in from the side rather than fall from the hedgerow canopy above it. Another limitation was leaf litter collection in the funnel, which was a problem in the first few months before butterfly netting was attached to the top of the gauges to prevent build up between site visits.

For robustness, a second experiment was conducted using rainfall storage collectors along a thirty metre section of hedgerow. This allowed a comparison of throughfall under six different canopy densities and to the net rainfall collected by a control collector. Plastic beakers (250ml) were placed in triplets (Figure 5.13), in the same locations as for the LAI experiments.

Figure 5.13: Throughfall buckets in triplets underneath the hedgerow.

Small holes were dug into the soil and the beakers placed into them to give them stability and stop them from being blown over. In each set, one of the three beakers had a funnel in it which would stop any evaporation occurring. This was done as a control for the effect of evaporation, to see if there was any difference in water levels collected with the other two containers (which were left open to the atmosphere). The beakers were left for four weeks (29 September-26 October) and then for two (26 October-10 November 2015) to collect rainfall. The rain in the beakers was transferred into sampling tubes and taken back to the laboratory to be measured.

5.4.2.3 Determination of Stemflow

Twenty major woody stems along the thirty metre long hedgerow were sampled to determine their circumference because the amount of stemflow increases with stem size and so that the results could be compared to other studies. A stem flow collar was chosen to monitor this hydrological process because it is the widely used method for measuring stemflow (Herbst et al., 2006; Hosseini Ghaleh Bahmani et al., 2012; Levia and Germer, 2015; Majid et al., 1989). The general guidelines suggest that the collar should be connected around the stem and funnelled towards a collector there is no standard design. Therefore a design was created and tested in the laboratory and then used in the field.

Figure 5.14: Stemflow Collar at Hedgerow Site.
A: Bottom of collar with silicone waterproof seal.
B: Top of collar showing gap between the funnel and the stem.
C: TBR gauge with funnel over the top.
D: View of stemflow collar and the piping attaching it to the TBR gauge.

A stem flow collar was created from two plastic powder funnels and some plastic tubing (Figure 5.14). The end (narrow part) of the two powder funnels was cut off using a pen knife. A hole, (two centimetres in diameter) for the tubing was drilled into the bottom of one of the funnels, to allow water to flow down the stem and collect at that point. The size of the tubing was determined by the average flow expected down the stem of the hedge. The funnels were both cut all the way down one side, so that they could be opened and wrapped around the stem of the hedge. The two powder funnels were stuck together to form a bipyramid.

At the field site a main stem was selected, that was large enough to accommodate the stemflow collar and did not have too many branches near to the ground, so that all the stemflow from the individual stem was collected by the collar. The chosen stem had to be located in the fenced off area to prevent the cattle from accessing it. The chosen stem had a circumference of sixteen centimetres. The funnels were wrapped around the base of the stem, thirty centimetres from the ground and beneath all other stems coming out of the main stem, so that all the branches on the stem were above the stemflow collar.

Duct tape was used initially to re-close the gap in the funnels. Silicone was then inserted all the way up the gap, to create a water tight seal between the stem and the funnels and to fix the bottom of the funnel in place. The silicone stopped water running out of any part of the stemflow collar and forced it towards the hole, where the tubing would be attached. The tube (diameter= 0.25cm, length=30cm) was inserted last, through the hole in the bottom funnel. Extra silicone was applied to fill the space from the bottom of the funnel up to the top edge of the tube, to create a gradient to encourage water towards the tube and around the tube to hold it in place. The end of the tube was fed through a third powder funnel and placed over the top of a TBR gauge that collected the water running down the stem. This was done to prevent rainfall falling as throughfall, or debris blowing into the gauge and was sealed to the gauge using duct tape. The TBR gauge was installed following the same method as described in Section 5.4.2.15.6.2.1 and data was recorded every five minutes.

Errors associated with the stemflow collar may have occurred due to the small diameter of the pipe, which would only allow a maximum amount of water through it. This may have led to water backing up in the funnels around the stem in heavy intensity events and having to wait to drain down towards the TBR gauge, although this was not observed. The TBR gauge was affected by grass growing up around it and getting stuck underneath the funnel therefore, the grass was frequently trimmed to stop any spurious readings.

5.4.2.4 Determination of Interception

Leaf wetness sensors (LWS) were chosen to monitor interception because they are easy to set up and do not need to be individually calibrated. They can detect the presence of miniscule amounts of water and ice and are therefore more accurate that TBR gauges. The LWS' are very affordable and are easy to clean and maintain at site. They are also very rugged so not affected by the weather conditions. LWS have been used worldwide to study a variety of tree species (Burgess and Bleby, 2006; Burgess and Dawson, 2004; Staelens et al., 2008) but not linear woody features. This study will be the first to use LWS to measure interception by Hawthorn Hedgerows in England.

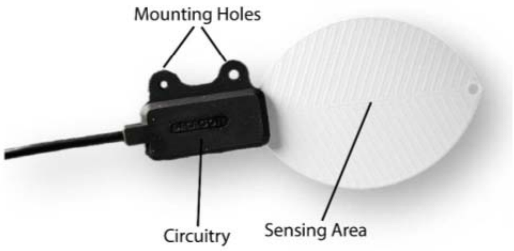

Figure 5.15: Leaf Wetness Sensor.

Leaf wetness sensors look like a typical oval-shaped, broad leaf (Figure 5.15) and an area of 51.02cm^2 (11.2x5.8cm). However, common hawthorn leaves are ovate but, have three-five toothed lobes and are typically 4.5-6cm long (Sterry, 2007). This means that there surface area is a lot smaller than the LWS'. In this study the leaf areas ranged from 0.36cm^2-10.56cm^2 and the hawthorn leaves were on average 96% smaller. This means that the LWS may overestimate the value of interception in this study.

The LWS' imitate the thermodynamic properties of a leaf with a specific heat of 3750 Jkg/K, density of 0.95g/cm^3 and thickness of 0.4mm. The coating on the LWS absorbs well in the near infrared region but, reflects most visible radiation matching closely with the radiative properties of a healthy real leaf. However, the hydrophobic coating of the LWS does not match the non-hydrophobic leaves of the hawthorn, which has non-waxy cuticles. This means that rainfall is more likely to runoff the LWS' than the real leaves.

Leaf wetness sensors infer the wetness of nearby leaves, by detecting very small amounts of water or ice on their surface. This is done by measuring the dielectric constant of the zone approximately one centimetre from the upper surface of the replica leaf. Water has a dielectric constant of ~80mV, ice ~5mV and air ~1mV making it easy to distinguish moisture. The output from the sensor is proportional to the dielectric of the measurement zone and therefore the amount of water/ice/frost/moisture on the replica leaf. Duration of leaf wetness can be determining in post-processing of the data. The sensor has a measurement time of ten milliseconds and an operating temperature from -20 to 60°C.

The leaf wetness sensors are factory calibrated to read less than 445 raw counts or 271mV when dry and they suggest the use of a threshold of anywhere up to 500 raw counts or 305mV for the transition point from dry to wet (Campbell Scientific Inc., 2009). The literature suggests that dielectric sensors should be recalibrated following installation in the field as the transition point from dry to wet varies for different areas and vegetation (Campbell Scientific Inc., 2013a). Therefore, the sensors were calibrated from the time series data collected over the first month at the Hedgerow site in order to determine an accurate transition from dry to wet. A threshold value of 278mV was chosen to split the data into periods of wetness and dryness. This was determined by looking at the timing of individual rainfall events and the response of the LWS (Figure 5.16). Values under 278mV were classed as dry and values of 278mV or over were classed as wet.

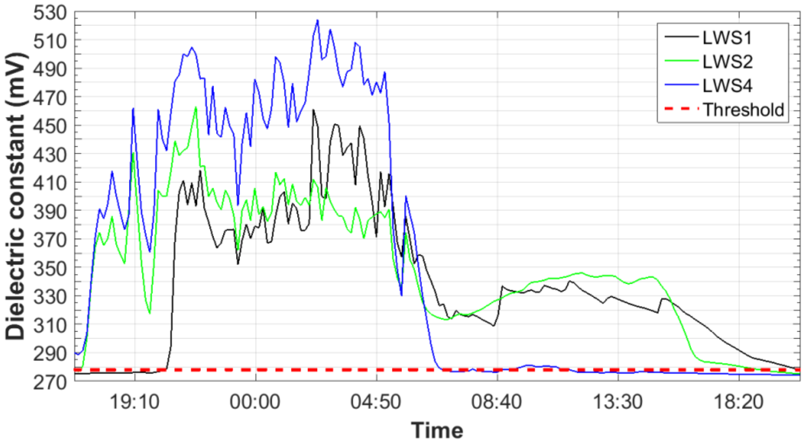

Figure 5.16: LWS data at three probes on 1-2 June 2015 at site.

The leaf wetness sensors required an excitation voltage of 2.5-5 VDC which was supplied through a solar panel. Unfortunately in the winter times there was not always enough sunlight during the day to power the device. The accumulation of dust, debris and avian faecal matter can give false readings (Campbell Scientific Inc., 2009). To avoid this LWS were cleaned on each site visit using a cloth.

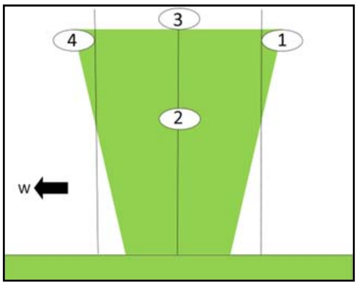

Figure 5.17: Location of leaf wetness sensors installed at site.

Four leaf wetness sensors were tied to small diameter wooden canes that were pushed into the ground on the east-side (LWS1), the inside (LWS2), the top (LWS3) and west-side of the hedgerow (LWS4). These locations (Figure 5.17) were selected to determine if there were any differences caused by the prevailing weather conditions and differences caused by the density of the hedge canopy. The position of LWS2 means that it is positioned like a shade leaf, which experience lower levels of transpiration and evaporation than sun leaves (LWS3) (McCain et al., 1988), as they are less exposed to wind and high temperatures. The inside of the hedgerow (LWS2) could also be more humid than the surrounding air meaning that once moisture has settled on the leaf it will be harder for it to evaporate.

The LWS were set to record every five minutes, to capture the changes in wetness occurring on the leaves. For the analysis, the west-side zero metre TBR gauge was plotted against the data from the LWS4 to determine the level of rainfall that was intercepted by the LWS. The same was done using the east-side zero metre TBR gauge with the LWS1 and the throughfall gauge with the LWS2.

5.4.2.5 Weather Station Monitoring

A Delta-T WS-GP1 compact weather station was installed at the Clotherholme Farm, five-hundred metres north of the Hedgerow Site, to provide a baseline level of meteorological information. The weather station was chosen due to its ease of use, light weight, rapid installation in the field, reliability and durability. The installation site was chosen because it was a level surface on short grass, away from trees, bodies of water and buildings. This eliminated any effects of local thermal and humidity microclimates and allowed for the true local conditions to be measured. The station was also located away from any animals or machinery which could cause disruption to the readings. The weather station was positioned east-west, attached to a two metres tall M2-TRPD tripod mast with U-bolts and secured into the ground with WS-GWSK guy wires.

The weather station consisted of a D-034B-CA wind speed sensor with a range of 0-75m/s and an accuracy of +/-0.1m/s. It contained a RG2+WS-CA tipping bucket rain (TBR) gauge with a 160mm diameter funnel and a sensitivity of 0.2mm/tip. It also had an RHT3nl-CA combined temperature and a relative humidity (RH) sensor with a range of -30 to 70°C (accuracy +/-0.3°C). All the sensors were attached to a GP1 logger fitted on a cross-arm which was powered by a 9V battery (Delta-T Devices, 2007) and measurements were collected every five minutes.

To maintain the weather station it was inspected on every site visit to check that all the pieces of equipment were not loose, or clogged with debris. The TBR gauge is prone to errors that are listed in Section 5.6.2.1. The relative humidity and air temperature sensor is affected by drift (-1.5 to -2% in the first year, decreasing to -1% in the second year and -0.5% in the third year) (Delta-T Devices 2007). Unfortunately no adjustment of the element is possible.

5.4.2.6 Interception Loss Modelling

Canopy interception is an important component of the water balance because it affects the amount of water available to the understory and to the soil (Klingaman et al., 2007). There are a number of different types of models available to study interception losses. The first types are simple, empirical linear regression models that describe the relationship between interception loss and gross rainfall. A simple interception loss model is described by Equation 5.9**Error! Reference source not found.**. These models do not take into account the effects of differences in rainfall intensity, duration and distribution, seasonal differences in weather, or vegetation characteristics (Teklehaimanot and Jarvis, 1991).

Equation 5.9: Simple interception loss model.

$$Interception\ loss = Precipitation - throughfall - stemflow$$

The second type of models are canopy surface water flux models that can estimate various components of interception loss, such as the proportion lost during storm events, or after rainfall has ceased (Carlyle-Moses and Price, 1999). There have only been a few studies that look at interception loss from linear vegetation structures like hedgerows (Herbst et al., 2006). This study parameterised the original Gash model using rainfall, stemflow and weather station data that was collected at two hawthorn hedgerows near Swindon, UK. The results showed that the Gash model predicted interception loss from the hedgerow with reasonable accuracy.

Surface water flux models require more data than the simple interception loss model, including parameters for use in the interception and evaporation equations which were not derived in this study. Catchment averaged regional parameters could have been used instead however; it was felt that this would incorporate additional levels of uncertainty into the calculations. Therefore, the simple interception model will be used in this thesis.

5.4.3 Subsurface Soil Moisture Monitoring

Soil moisture content is an important variable that controls the flux of heat and water energy between the land surface and the atmosphere. It is useful in a wide range of applications including farming, erosion prevention and flood control and drought prediction. The classical method to measure soil moisture content is to collect a soil sample in a known volume and use the gravimetric technique (mass of water per mass of solids). Indirect methods such as the Neutron scattering techniques emit particles and detect and measure the returning slow neutrons however, they are inflexible and very expensive (Visvalingam and Tandy, 1972). Other indirect methods measure the dielectric properties and conductivity of the soil, or the soil suction using tensiometers (Skye Instruments Limited, 2014).

Two methods were chosen to measure subsurface soil moisture content. The first method was the collection of intermittent field measurement collected with the HydroSense II (HS2) device. The second method was a continuous Time Domain reflectometer (TDR) measurement system which was installed at site.

5.4.3.1 Discrete Field Measurements

The HydroSense II device (HS2) is a handheld display paired with the CS658 soil water probe (Figure 5.18). The CS658 probe consists of two twelve centimetre long rods that measure the soil dielectric permittivity (measure of the resistance that is encountered when forming an electric field in a medium) to determine the volumetric water content (VWC) in percent. A high frequency electromagnetic energy is generated by the HydroSense II and passes along the waveguide formed by the rods, polarising the water particles. The time taken for the reflected signal to be detected relates to the dielectric permittivity of the soil and is automatic calculated into VWC within the HydroSense II.

Equation 5.10: The Topp equation for volumetric water content.

$$\boldsymbol{\theta v = -5.3 * 10^{-2} + 2.9 * 10^{-2} * K_a - 5.5 * 10^{-4} * K_a 2 + 4.3 * 10^{-6} * K_a 3}$$

The probe reads the average output period in microseconds (μs) over the length of the rods and calculates the VWC in the range 0-50%, which is the typical range for agricultural soils. The HydroSense II calculates VWC using the time domain reflectometry (TDR) measurement principle which is based on Equation 5.10 (Topp et al., 1980). Where, θv is the VWC and Ka is the apparent dielectric constant.

Figure 5.18: The HydroSense II probe in use at site.

There are a number of user errors associated with the use of the HydroSense II. If the rods are not fully inserted into the soil, it the rods hit a stone or a root, or if the rods are not parallel then the reading will not be accurate. The Hydro Sense II can be affected by the physical properties of the soil. Soils with a large clay fraction, or high electrical conductivity, or high organic matter content can create misleading results by altering the response of the HydroSense II. Rocky soils do not hold water in the same manner as finer soils and can lead to great differences in measurements over a small area. The sensor has an accuracy of 3% and a precision of <0.05% in a soil with an electrical conductivity of less than 4dS/m (Campbell Scientific, 2014).

The HydroSense II device was chosen because it was originally designed for agricultural soils like the ones being tested in this study and because it employs an established method for measuring VWC. It is also very compact in size, light weight and easy to use which allowed multiple field tests (Campbell Scientific, 2014). The HydroSense II was used to measure VWC along an eight metre transect at the main hedgerow site (Clotherholme 1) because most of the changes in VWC were observed within this distance. To provide high resolution data a transect ran for four metre away from the hedgerow on either side and approximately two metres to the north of the line that contained the TDR probes. Measurements were taken horizontally, every twenty centimetres on 28 April, 15 July, 18 September, 25 October 2014 and 15 January, 20 February, 31 March and 19 June 2015.

The HydroSense II was also used once at two other hedgerows at Clotherholme Farm (Figure 5.19), two hedgerows at Hedge Nook Farm (Figure 5.20) and four hedgerows at Holme Farm (Figure 5.21) on 19 June 2015. The same transect method was used at all additional hedgerow sites however measurements were only taken every fifty centimetres and it was not always possible to collect measurements of both sides of the same hedgerow due to access issues.

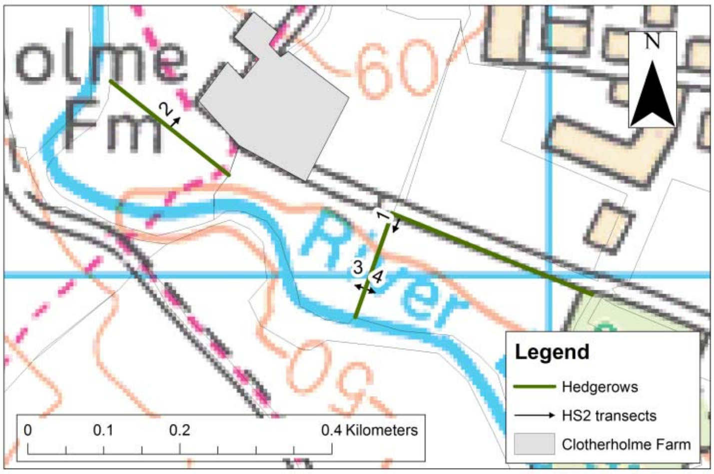

Figure 5.19: Hydrosense transects at Clotherholme Farm.

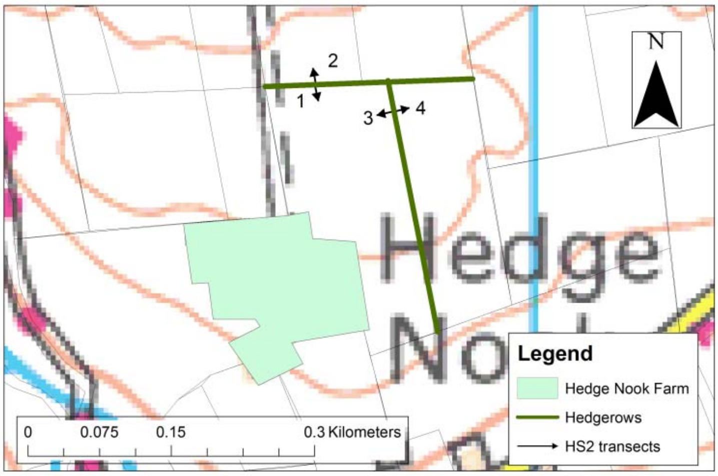

Figure 5.20: Hydrosense transects at Hedge Nook Farm.

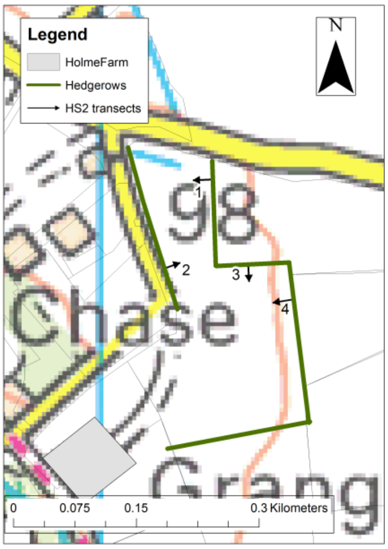

Figure 5.21: Hydrosense transects at Holme Farm.

5.4.3.2 TDR Calibration

The second method was a Time Domain Reflectrometry (TDR) measurement system that was installed using Campbell Scientific CS616 probes were chosen for their ruggedness, high accuracy and precision (0.1% volumetric water content) in the field. The TDR probes use the dielectric constant method which is also used by the HydroSense II (described in Section 5.4.3.1). The probes consisted of two stainless steel rods that were 300x3.2mm in size and connected to a printed circuit board. A shielded four conductor cable was connected to the circuit board to supply power, enable the probe and monitor the pulse output. A solar panel was attached to recharge the battery and a logger set up with a program.

Campbell Scientific provides standard calibration coefficients for the linear and quadratic forms (Equation 5.11) that they derived in their soils laboratory. However, to optimise the accuracy of the VWC measurements and to reproduce the soil conditions, including the heterogeneity of soil type where the probes were installed, a site specific calibration was undertaken. There is no standard method for calibrating TDR probes but, a literature review highlighted common methods that have been used and a method was developed which was based on their work (Table 5.2).

Table 5.2: Site Specific TDR probe laboratory calibration methods.

Reference and probes	Calibration cell information	Step 1	Step 2	Step 3
(Zhao et al., 2016), 1 x probe	Mould 116mm high. Six VWC's and bulk density ranged from 1.1-2.3g/cm3.	Oven dried soil, pulverised, sieved and mixed with tap water. Compacted into mould, temperature 20°C.	Probe inserted into soil and measurements taken.	Probe removed and sample taken for GWC, determined using oven dried method.
(Campbell Scientific Inc., 2013b), CS616 & CS625	PVC tray or cylinder 10x35cm diameter enclosed at one end. Probes bound by >110mm of soil.	Add soil to tray, or cylinder in three equal portions, compact each layer separately to a target bulk density.	Probes buried in a tray/inserted into a column. Care should be taken to reduce movement and create air voids around probes.	Probe removed and 3 samples taken in tube of known volume for GWC and VWC, determined using oven dried method.
(Kim, 2010), CS616	Wooden box 60x60x30cm, probe bound by 160mm soil. VWC ranged from 0-18%.	Mixed soil, put into box in three layers and compact using a board.	Inserted two/three probes at a time in second layer, connect probes to logger and measure.	Upper soil layer removed, sample taken for GWC determined using oven dried method.
(Take et al., 2007) , 36 x CS635	Plastic pipe 15x20cm, probe bound by 50mm soil with bulk density (1.6g/cm3)	Air dried soil, mixed in rotary mixer. Compacted soil in cell, into three layers, using Proctor hammer.	Inserted one probe at a time, by hand as in field, ensuring good soil contact. Surface covered over and measurement taken.	Probe removed and sample taken for GWC, determined using oven dried method.
(Diefenderfer et al., 2000), CS615 & CS610	Wooden box 84x85x45cm, probe bound by 150mm soil. VWC ranged from 0-22%	Soil mixed in concrete mixer, put into box in three layers (150mm thick) and compacted.	Inserted four probes at a time in middle layer.	Middle soil layer removed, sample taken for GWC determined using oven dried method.

Equation 5.11: Standard linear and quadratic calibration coefficients.
(For use in soils with clay content less than 30%, bulk electrical conductivity less than 0.5dSm and bulk density less than 1.55g.cm$^{3)}$.

$$-0.4677 + 0.0283 * period$$

$$-0.0663 - 0.0063 * period + 0.0007 * period2$$

The TDR probes were calibrated individually in the laboratory under seven different water contents (0, 9, 15, 18, 20, 22 and 24%) which were similar to (Diefenderfer et al., 2000). A plastic box 54.5cm long and thirty-six centimetres wide was filled with soil (Figure 5.22) from the Hedgerow Site to a depth of twenty centimetres. Before the first experiment (0% water content) the soil was sieved with a two millimetres sieve, dried in an oven for forty eight hours at a temperature of 105°C to remove all the water and then transferred to a desiccator to cool for twenty four hours. The soil was put into the box in three layers and compacted by applying body weight through a plastic plate. This was done to mimic the level of compaction in the field where the TDR probes were installed (Take et al., 2007). The bulk density of the soil in the box was determined using the standard method (The British Standards Institution, 1998) and had an average across all tests of 0.88g/cm^3 +/-0.16, which was similar to the bulk density at the site (0.93g/cm^3 +/-0.22, based on twenty four soil samples).

Figure 5.22: Calibration box, TDR probe in the box and compaction plate.

Prior to the start of the other six experiments the soil was mixed with water in batches of 5kg, in a rotary mixer for fifteen minutes. The specific soil water content was calculated by adding a specific amount of water to a known weight of soil. For example, to create soil water content of 15%, 825ml of water was added to 4,675kg of soil to make a total weight of 5,500kg. Before the start of each set of experiments the HydroSense II device was used to take three readings of volumetric water content of the soil mixed in the box. The soil temperature was also taken to correct the TDR readings.

Table 5.3: Output periods in field and laboratory tests under various VWCs.

	Field values		Laboratory tests							
Probe	Min.	Max.	Air	Soil dry	Soil 9%	Soil 15%	Soil 18%	Soil 20%	Soil 22%	Soil 24%
1	11.70	37.19	14.93	15.79	19.04	21.57	23.34	24.79	30.25	30.54
2	9.32	29.35	14.99	15.95	18.84	21.38	23.77	25.13	29.49	31.05
3	11.22	27.62	14.84	15.79	19.10	22.33	23.86	24.65	29.86	30.76
4	10.50	35.23	14.98	15.76	18.81	21.82	23.83	24.40	28.32	28.32
5	10.50	34.67	14.82	15.87	18.57	21.05	23.41	24.82	28.91	29.99
6	12.40	31.18	14.93	15.90	18.97	22.35	23.50	25.72	30.48	30.81
7	14.88	39.44	14.84	15.92	18.79	20.71	23.78	25.03	27.97	30.54
8	-0.23	32.63	14.92	15.62	19.03	21.24	24.04	24.53	28.86	31.28
9	11.89	39.88	14.92	16.21	19.03	21.82	23.72	25.06	29.47	30.40
10	9.86	45.98	15.00	16.11	19.12	21.34	24.24	25.44	29.14	30.48
11	11.92	36.32	15.03	15.92	18.59	21.77	23.50	25.80	29.17	30.97
12	9.38	35.75	14.89	16.43	18.71	21.24	22.76	24.43	29.08	30.25
13	8.46	33.22	15.00	16.17	18.81	21.34	23.45	25.41	30.67	30.92
14	14.16	42.40	15.01	16.12	18.48	21.52	23.94	24.70	29.71	30.15
15	17.71	45.82	14.85	15.91	19.02	21.75	23.43	25.73	30.11	30.63
16	-0.05	95.54	14.95	16.48	19.04	21.00	24.05	25.79	29.07	30.19

To set up the experiment, soil was dug out of the middle of the box so that one TDR probe at a time could be laid down horizontally. The soil was refilled over the top of the probe and compacted again with the plastic plate. The probe was bound by at least fifty millimetres of soil to ensure good contact, remove air gaps and eliminate boundary effects (Take et al., 2007) which can have a significant effect on the calibration (Siddiqui et al., 2000). Finally, a plastic lid was put on the top to prevent loss of moisture due to evaporation (Take et al., 2007).

The TDR measurement system scanned the probes every ten seconds and recorded the output period in microseconds (Table 5.3). Sixty-four readings were taken in each experiment to check for fluctuations in the readings and to see if the VWC increased/decreased over time however, there was little variation in output period during the calibration tests (+/-0.04μs). At the end of the experiment, three soil samples (dry weight 58-103g) were collected using core cutters at the same depth as the probe to quantify the soil moisture content across the compacted soil mass. The gravimetric water content (GWC) and bulk density were calculated using the standard oven dried method (The British Standards Institution, 1998).

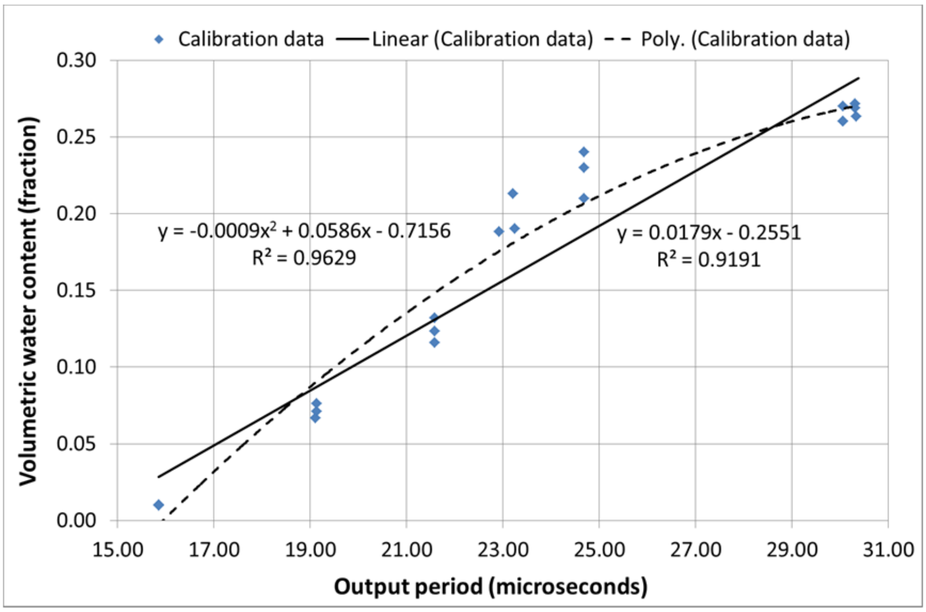

Figure 5.23: Probe 1 calibration results.

Average TDR period vs HydroSense II VWC.

The calibration data (average output period) from the TDR probes were plotted against the VWC determined from the HydroSense II device (Figure 5.23) and the linear and quadratic forms were applied to determine the calibrations coefficients. The goodness of fit (r-squared) indicated that the quadratic fit was higher for all probes (Table 5.4), although both forms of the equation fitted the data well (r^2=>0.9).

Table 5.4: R-squared values for linear and quadratic fit of laboratory data.

Probe #	Linear	Quad	Probe #	Linear	Quad
1	0.919	0.963	**9**	0.940	0.973
2	0.933	0.978	**10**	0.958	0.983
3	0.923	0.956	**11**	0.945	0.976
4	0.962	0.967	**12**	0.911	0.976
5	0.948	0.982	**13**	0.926	0.980
6	0.930	0.965	**14**	0.940	0.976
7	0.941	0.985	**15**	0.943	0.973
8	0.926	0.970	**16**	0.966	0.990

The average output period in air, across all sixteen probes was 14.93μs +/- 0.07 and the average output when the probes were immersed in water was 38.49μs +/-1.00, which are similar to those calculated by the manufacturer (Campbell Scientific Inc., 2013b). Based on these figures, a sensitivity analysis of the calibration coefficients were undertaken on each probe, for the output periods 14-42 μs. The range of output periods that could be transformed into physically realistic volumetric water content's (not negative) using the linear and quadratic coefficients are displayed in Table 5.5.

Following the sensitivity analysis, the data was assessed to determine the amount of data that would be lost using the linear and the quadratic equations. The results showed that more data would be lost using the quadratic equation for all probes except for probes four and eight, which would lose the same amount of data. In some cases the loss of data using the quadratic equation was much higher. For example, probe fourteen would have lost 43.51% more data using the quadratic and probes six and sixteen would have lost over 12% of the data.

Table 5.5: Sensitivity analysis of linear vs quadratic fit to calibration data. The range of periods collected in the monitoring period is in yellow. The negative, non-realistic VWC's are in tan. The blue number highlights the highest calculated VWC at the peak of the quadratic curve.

	Volumetric water content (%)							
	Probe 1		**Probe 2**		**Probe 3**		**Probe 4**	
Output period (µs)	**Linear**	**Quad.**	**Linear**	**Quad.**	**Linear**	**Quad.**	**Linear**	**Quad.**
14	-1.73	-7.16	-0.65	-6.94	-0.89	-5.18	-2.79	-4.90
15	0.06	-3.91	1.16	-3.50	0.92	-1.92	-0.63	-2.14
16	1.85	-0.84	2.97	-0.24	2.73	1.20	1.53	0.54
17	3.64	2.05	4.78	2.84	4.54	4.18	3.69	3.14
18	5.43	4.76	6.59	5.74	6.35	7.02	5.85	5.66
19	7.22	7.29	8.40	8.46	8.16	9.72	8.01	8.10
20	9.01	9.64	10.21	11.00	9.97	12.28	10.17	10.46
21	10.80	11.81	12.02	13.36	11.78	14.70	12.33	12.74
22	12.59	13.80	13.83	15.54	13.59	16.98	14.49	14.94
23	14.38	15.61	15.64	17.54	15.40	19.12	16.65	17.06
24	16.17	17.24	17.45	19.36	17.21	21.12	18.81	19.10
25	17.96	18.69	19.26	21.00	19.02	22.98	20.97	21.06
26	19.75	19.96	21.07	22.46	20.83	24.70	23.13	22.94
27	21.54	21.05	22.88	23.74	22.64	26.28	25.29	24.74
28	23.33	21.96	24.69	24.84	24.45	27.72	27.45	26.46
29	25.12	22.69	26.50	25.76	26.26	29.02	29.61	28.10
30	26.91	23.24	28.31	26.50	28.07	30.18	31.77	29.66
31	28.70	23.61	30.12	27.06	29.88	31.20	33.93	31.14
32	30.49	23.80	31.93	27.44	31.69	32.08	36.09	32.54
33	32.28	**23.81**	33.74	27.64	33.50	32.82	38.25	33.86
34	34.07	23.64	35.55	**27.66**	35.31	33.42	40.41	35.10
35	35.86	23.29	37.36	27.50	37.12	33.88	42.57	36.26
36	37.65	22.76	39.17	27.16	38.93	34.20	44.73	37.34
37	39.44	22.05	40.98	26.64	40.74	34.38	46.89	38.34
38	41.23	21.16	42.79	25.94	42.55	**34.42**	49.05	39.26
39	43.02	20.09	44.60	25.06	44.36	34.32	51.21	40.10
40	44.81	18.84	46.41	24.00	46.17	34.08	53.37	40.86
41	46.60	17.41	48.22	22.76	47.98	33.70	55.53	41.54
42	48.39	15.80	50.03	21.34	49.79	33.18	57.69	**42.14**

Table 5.6: Data lost from analysis using the linear and quadratic form at zero and the peak of the curve.
Difference (Diff. %) in data lost using the two forms and equation used in the analysis.

	Linear form		**Quadratic form**						
Probe	**Zero (µs)**	**%**	**Zero (µs)**	**%**	**Peak (µs)**	**%**	**Total lost**	**Diff. %**	**Equation used**
1	15	1.92	17	3.52	33	0.03	3.55	**1.63**	Linear
2	15	16.44	17	24.37	34	0.00	24.37	**7.93**	Linear
3	15	16.07	16	20.74	38	0.00	20.74	**4.67**	Linear
4	16	14.74	16	14.74	42	0.00	14.74	**0.00**	Linear
5	15	27.00	16	32.64	34	0.01	32.65	**5.65**	Linear
6	15	7.64	17	20.30	36	0.00	20.30	**12.66**	Linear
7	15	0.43	17	3.94	32	5.20	9.14	**8.71**	Linear
8	16	58.47	16	58.47	36	0.00	58.47	**0.00**	Linear
9	15	3.27	16	4.36	37	0.38	4.74	**1.47**	Linear
10	16	20.01	16	20.01	37	0.87	20.88	**0.87**	Linear
11	15	9.33	17	19.01	34	0.09	19.10	**9.77**	Linear
12	15	27.01	17	35.62	31	1.93	37.55	**10.54**	Linear
13	15	57.06	17	63.58	32	0.06	63.64	**6.58**	Linear
14	15	0.57	17	4.68	33	39.40	44.08	**43.51**	Linear
15	15	0.00	16	0.00	38	1.66	1.66	**1.66**	Linear
16	16	19.17	17	19.40	33	12.10	31.50	**12.33**	Linear

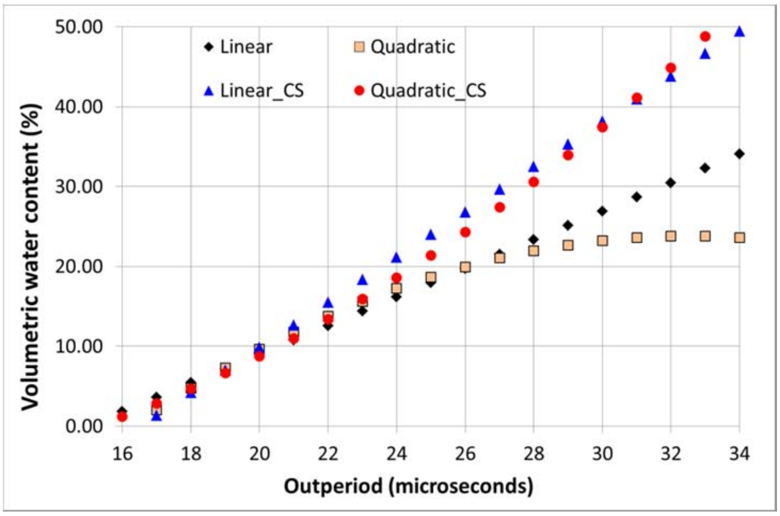

Figure 5.24: Probe one - Differences in the linear and quadratic fit for site specific and Campbell Scientific calibration coefficients. (Linear_CS and Quadratic_CS).

The linear calibration (Figure 24) will be used to determine volumetric water content in this study, due to the more simplistic nature of the equation and its ability to successfully calculate VWC in the range of expected water contents. When the linear calibration is applied to the data there is less data lost than when the quadratic calibration is applied. Campbell Scientific state that their laboratory linear calibration is within +/-1.25% VWC of their quadratic calibration and that the linear equation underestimates water content at the very wet and very dry ends (Campbell Scientific Inc., 2013b). In this study, the linear calibration also overestimates VWC by approximately 1.20% at 20% VWC, which is very similar to the Campbell Scientific calibration.

5.4.3.3 TDR Field Installation

An enclosure box was prepared in the laboratory by drilling sixteen holes into the side and fitting them with cable glands. A Campbell Scientific CR200(X) series data logger was placed inside the box with a 12V lead acid battery. At the field site a ten metre tape was laid out from the centre of the hedge, a hole was dug at zero, one, three and ten metres from the centre of the hedge on the west and east side. Each hole was forty centimetres deep, forty centimetres long and thirty centimetres wide. The first CS616 probe was placed at a depth of thirty centimetres, horizontally in order to detect the passing of wetting fronts through the soil (Figure 5.25). The probe was covered over with soil and compacted. A second CS616 probe was placed on top of the infilled soil, at a depth of ten centimetres and covered over with soil and turf.

Figure 5.25: Campbell Scientific 616 TDR probes installed at site.

In total eight probes were positioned at approximately ten centimetres depth and eight probes at thirty centimetres depth, creating a network of sixteen probes at different distances and depths away from the hedgerow (Figure 5.26). A solar panel was fixed to the wooden fence and connected up to the lead acid battery, so that it could be recharged in the field. The probes were programmed to record a measurement every five minutes. The insertion of TDR probes can create air voids, which can reduce the measurement accuracy, so the first three weeks of data were excluded from the analysis to give the soil structure time to recover. The probes were positioned twenty centimetres apart to prevent any interference and erratic measurements.

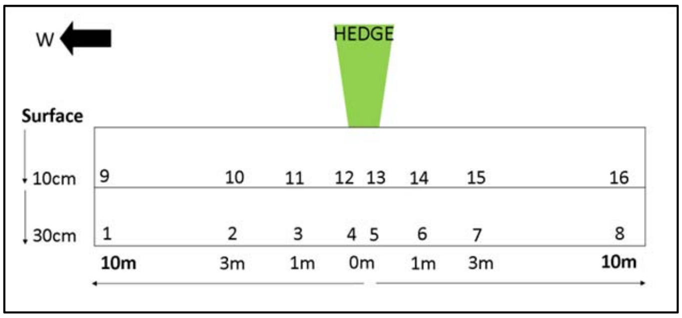

Figure 5.26: Location of TDR probes installed at Hedgerow Site.

The measured output contains an error caused by the temperature dependence of the probes (Benson and Wang, 2006), so a standard temperature correction (Equation 5.12) was used to analyse the output data. When $\tau_{uncorrected}$ is the CS616 output period and τ_{Soil} is the soil temperature. The temperature correction assumes that the water content and temperature do not vary over the length of the probes rods. The sensitivity of the CS616 probe changes with VWC, low output periods (low VWC) are less sensitive to changes in temperature, whereas higher output periods (high VWC) are very sensitive to changes in temperature.

Equation 5.12: Temperature correction for TDR probes.

$$\tau_{corrected\ (\tau_{Soil})} = \tau_{uncorrected} + (20 - \tau_{soil}) * (0.526 - 0.052 * \tau_{uncorrected} + 0.00136 * \tau_{uncorrected} 2)$$

Continuous temperature measurements were not collected at Clotherholme Farm, they were taken from the MIDAS soil temperature dataset (Met Office, 2006) collected at Bramham, West Yorkshire. This site is twenty four miles south of Clotherholme but, the soil temperature at ten centimetres depth was assumed to be similar at the two sites due to the slow response of soil to heating and cooling at this depth (Sauer and Horton, 2005). The original hourly dataset was interpolated to create a five minute dataset. The temperatures at Braham ranged from 0.7-28.2°C during the study period with an average of 11.4°C +/-5.71. Only 0.9% of the temperatures were greater than 24°C however, these measurements of VWC will have the greatest amount of uncertainty (Figure 27).

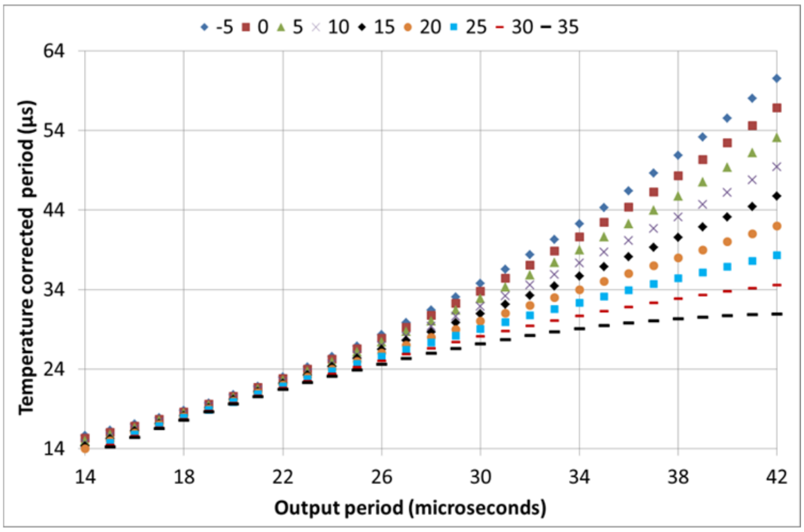

Figure 5.27: Effect of temperature (-5°C to 35°C) on probe output period.

5.4.3.4 Subsurface Water Balance Modelling

The modelling of water after it has infiltrated into the root zone is complicated due to upward and downward pressure gradients that are caused by soil drainage, evapotranspiration from the soil surface and hysteresis that affects the soil moisture characteristics relationships (Dingman, 2002). Drainage through the soil layer can be modelled using a simple equation based on Darcy's Law (Equation 5.13), where q_z is the vertical water flux and $k_h(\theta)$ is the analytical approximation of the hydraulic conductivity-soil moisture content relationship based on the power law equations by Campbell, 1974. The capillary layer is ignored in this model and the water content is averaged over the soil layer.

Equation 5.13: Darcy's Law.

(Dingman, 2002).

$$q_z = K_h\,(\theta)$$

Black et al., 1970, incorporated Equation 5.13 into Equation 5.14 to determine the change in soil water content over time, in a soil layer at an arable field. Where k_h θt is the analytical approximation of the hydraulic conductivity-soil moisture content relationship, ET_T is total evapotranspiration, F_t is total infiltration during period, Δ_z is the thickness of the soil layer.

Equation 5.14: Simple water balance for soil layer.

(Black et al., 1970).

$$\Delta\theta_t = \frac{-K_h(\theta_t)\cdot\Delta t - ET_T - F_t}{\Delta z}$$

There are a number of other root water balance equations which focus on the hydrological processes such as the one expressed using Equation 5.15 (Zhang et al., 2002), where ∆S is the change in root zone soil water storage over time, P is precipitation, I is interception loss, E is direct evaporation from the soil surface, T is transpiration by plants, RO is surface runoff and DD is deep drainage out of root zone. DD is often only 5% of the total precipitation.

Equation 5.15: Root zone water balance.
(Zhang et al., 2002).

$$\Delta S = \mathrm{P} - \mathrm{I} - \mathrm{E} - \mathrm{T} - \mathrm{RO} - \mathrm{DD}$$

Unfortunately the direction evaporation, transpiration, surface runoff and deep drainage parameter needed for these types of equations were not collected in this study and therefore, no subsurface water balance will be used to analyse the data.

5.5 Chapter summary

This chapter presented a conceptual model with hypotheses regarding how the presence of a hedgerow modifies the hydrological cycle locally. The model identified three key areas which are the hedgerow characteristics and the surface and subsurface water balance. The model was used to determine three research questions based around these three areas. The requirements for the hedgerow study site were identified based on five criteria that would help to answer the research questions. A suitable hedgerow site was presented as well as a number of secondary sites which will be used to supplement the data collected at the main site.

The chapter then discussed the field methodologies and monitoring equipment that were installed at the Hedgerow Site. To determine more about the hedgerow characteristics, discrete tests of root density and leaf area index were undertaken and soil samples were collected and analysed in the laboratory. To learn more about the surface water balance continuous monitoring equipment were installed at the main hedgerow site, to study the processes of rainfall, stemflow, throughfall and interception. To determine more about the subsurface water balance, discrete tests and continuous monitoring of VWC were implemented.

The next chapter will present the results of the discrete field tests and the continuous monitoring of the Hedgerow Site that are used to answer Objective four.

Chapter 6 - Quantifying the Impact of Hedgerows on Soil Hydrology: Results

6.1 Chapter Scope

This chapter will provide the results of the work undertaken to answer Objective four – 'To test and revise the conceptual model through an intensive monitoring programme of the hydrological cycle and assessment of soil-hedgerow-atmosphere interactions'. This will be done by examining three main questions:

1. What are the physical hedgerow characteristics including the extent of horizontal roots and the leaf area index and the soil properties around the hedgerow?
2. Does the hedgerow affect the surface water balance by altering the spatial distribution of rainfall, throughfall, stemflow and interception?
3. Does the hedgerow affect the root zone water balance by altering the soil moisture content?

Section 6.2 describes the hedgerow site characteristics including the root, leaf and soil characteristics. Section 6.3 presents the results of the impact of the hedgerow on the spatial rainfall distribution and calculates the interception losses. Section 6.4 presents the results of the impact of the hedgerow on subsurface soil moisture distribution. Finally, Section 6.5 provides the chapter summary.

6.2 Defining the Hedgerow Characteristics

The hedgerow characteristics were determined at the Clotherholme Farm site. This included measurements of the size and shape, as well as two important characteristics that may play a role in the local hydrology around the hedgerow, the first is the root characteristics and the second is the characteristics.

Table 6.1: Biometric characteristics of the Clotherholme and other hedgerows.

	Clotherholme Hedgerow	Herbst et al., 2006	Herbst et al., 2007	
Location	Ripon	Swindon	Swindon	
Altitude (m.A.O.D.)	50	100	100	105
Orientation	East-west	North-south	North-south	East-west
Section length (m)	30.0	63.0	Unknown	
Height (m)	1.37 (+/-)	2.00	3.8	4.0
Width (m)	1.16 (+/-)	1.6-2.2	4.0	4.0
Base of canopy (m)	0.70 (+/-)	Unknown	Unknown	
Stem circumference (cm)	25.79 (+/-15.1)	Unknown	Unknown	
Stem area (cm^2)	70.14 (+/-99.5)	Unknown	Unknown	
Shape	Topped A	Unknown	Unknown	

The hedgerow measurements in Table 6.1 were made in June and July 2015. There was a gap of 3.8m in the thirty metre section that was analysed, so overall there were more than 10% gaps meaning that it had poor continuity. The UK Biodiversity Action Plan defines a hedgerow in good structural condition as being 1m high, 1.5m wide and having a canopy less than 0.5m above the ground. The study hedgerow does not meet the hedgerow management requirement (Barr et al., 2004) which means that the cutting may be too severe or too frequent. The hedgerow used in this study is smaller than the hedgerows used by (Herbst et al., 2006) and (Herbst et al., 2007a).

6.2.1 Root Characteristics

No hedgerow roots were found at W10, E10 or E3 (Table 6.2) and there was only one small root at W3-30cm (28mm circumference). At W1-30cm, E1-10cm and E1-30cm, approximately 1% of the quadrat contained roots and the largest root circumference was 35-55mm (Figure 6.1). At W1-10cm 6% of the quadrat contained roots and the largest root circumference was 100mm which was 55-65% greater than the other one metre location. This may be because the top ten centimetres of soil on the west (windward) side receives more sunlight and higher temperatures than the east (leeward) side. There was also 12% more roots at W0-10cm than E0-10cm and the largest root circumference was also 52% bigger. However, the reverse was seen at E0-30cm where there were 52% more roots than at W0-30cm and the largest root circumference was 14% greater.

Table 6.2: Root density at distances away from the hedgerow on the east side.

	1 metre		0 metre	
Depth	**% roots**	**Largest (mm)**	**% roots**	**Largest (mm)**
10cm	**1.1**	**35**	**3.0**	**50**
30cm	**1.3**	**35**	**7.1**	**60**

Root density at distances away from the hedgerow on the west side.

	3 metre		1 metre		0 metre	
Depth	**% roots**	**Largest (mm)**	**% roots**	**Largest (mm)**	**% roots**	**Largest (mm)**
10cm	**0**	**-**	**5.9**	**100**	**14.8**	**105**
30cm	**0.5**	**28**	**1.4**	**55**	**3.4**	**70**

Without removing the hedgerow completely it was difficult to determine the vertical extent of the roots and the soil texture at the site made it difficult to dig down any deeper than 0.3m. Hedgerows have been shown to transpire more than grassy vegetation due to their deeper rooting systems (Viaud and Merot, 2005). (Caubel et al., 2003) believed that *Quercus robur* hedgerows extend to a depth of 0.8m. In the UK, hawthorn hedgerow roots are thought to extend vertically to a depth of at least 0.9m (Lisa Norton, Personal Communication), and *Cassia siamea* hedgerows were shown to extend to a depth of 0.5m (Kiepe, 1995).

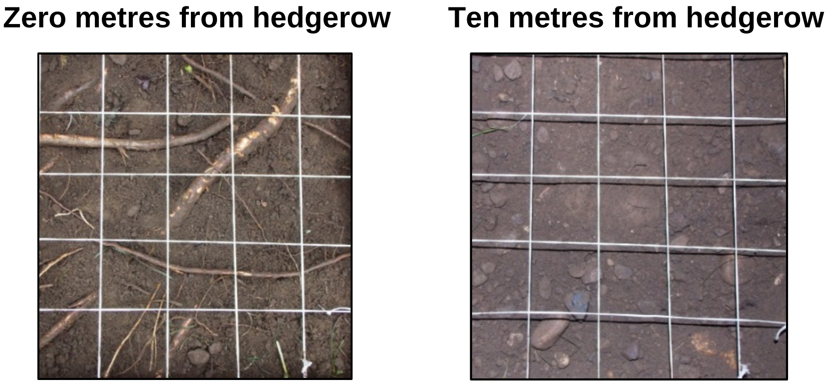

Figure 6.1: Roots on the west side of hedgerow at 10cm depth.

In terms of differences in density with depth, this study showed there was a higher root density in the topsoil (ten centimetres) which decreased with depth. These findings are similar to those found by (Plante et al., 2014) who noticed that 67% of roots occurred in the top thirty centimetres and root density was higher in the top thirty centimetres, than at one metre depth. The bulk density of the soil increases with depth which makes it harder for roots to penetrate to greater depths (Barr et al., 2004).

The roots extended further on the windward (three metres) than the leeward side, where they only extended to one metre from the hedgerow. This may be because of the North-South orientation of the hedgerow, which means the west-side receives more sunlight and potentially more rainfall. These findings are similar to (Caubel et al., 2003) who found that hedgerow roots extended up to ten metres from the structure on the north-west side but, did not extend out hardly at all on the south-east side. This was thought to be due to saturated soils on the downslope.

Another reason for the difference seen on the two sides of the hedgerow could be due to a difference in soil type. (Plante et al., 2014) found that lighter, sandy soils had higher root densities because roots could easily access soil water during moist periods and because the roots have to spread out further, due to low nutrients levels. This was also found in this study as the windward side had 37% more sand particles than the east, which had 23% more silt sized particles and roots can penetrate easier through sandy soils.

In conclusion, the results show that hawthorn hedgerow roots at this site only extend laterally one to three metres from the structure. This is similar to a study that showed that the roots of a shrub (*Calliandra calothyrsus)* extended out laterally up to four metres (Utomo and Sunyoto, 1995) and (Plante et al., 2014) who showed that the root density of poplar, spruce and willow windbreaks was four times higher at two metres than at six metres from the windbreak.

6.2.2 Leaf Characteristics

This section will examine the biophysical structure of the Clotherholme hedgerow using the litter fall method and the VitiCanopy application (De Bei et al., 2016) to determine the parameters, leaf area (LA) and leaf area index (LAI). To assess the variability within the hedgerow, five different canopy densities (High, Medium, Low, Edge and None) were assessed. The LA at the High (2.18cm^2 +/-0.17) and Medium (2.90cm^2 +/-2.11) Density Sites were significantly larger than the Low (1.56cm^2 +/-0.01) Density Sites (Figure 6.2). The No Canopy Site contained two large leaves which are assumed to have been blown in from the hedgerow and not included in the analysis.

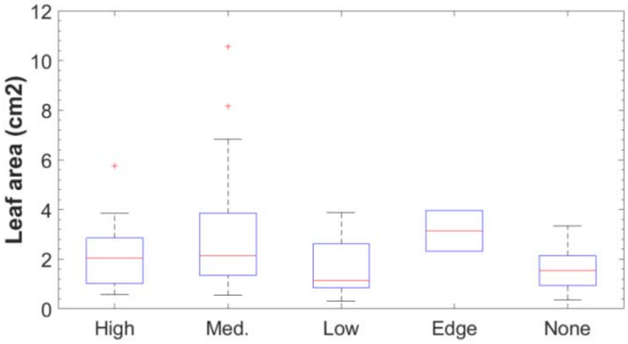

Figure 6.2: Leaf area at sites with different canopy densities.

The largest LA (10.56cm^2) was observed at the Medium Density Site. This was the only leaf in all the baskets which was larger than 10cm^2, the area (Herbst et al., 2007b) used as a definition for a 'big' hawthorn leaf. Nearly half of the leaves (46%) at the Medium Density Site had a LA larger than 5cm^2 but, only 7% of the total leaves in this study had a greater LA. The smallest LA (0.36cm^2) was observed at the Low Density Site and 25% of the leaves at this site had a LA less than 0.75cm^2. At the Medium Density and Low Density Sites, 21% and 17% of the leaves had a LA of less than 0.75cm^2. However, only 12% of the total leaves collected in this experiment had a LA that was 0.75cm^2 or smaller.

Overall, the litter fall experiment showed that the average LA of the hedgerow was 2.16cm^2 +/-1.58 and that 57% of the leaves had a LA of 1-3cm^2. This is smaller than in previous studies, (Herbst et al., 2007a) found that 68% of a *Crataegus monogyna* hedgerow leaves had a LA of 5-15cm^2 and (Kuppers, 1984) found an average LA of 4.8cm^2 for *Crataegus macrocarpa* hedges (Table 6.3). The reason for this may be because the Clotherholme hedgerow is shorter (1.37m) than the hedgerow in other studies and the height of the hedgerow has been shown to strongly influence the LA (Pocock et al., 2010).

Table 6.3: Variations in LAI values measured for hedgerows.

Species	Height (m)	LAI	Method	Location	Reference
Crataegus monogyna	**1.5-5.5**	**4.6**	**Canopy Analyser**	**Somerset, UK**	**Pocock et al., 2010**
Crataegus monogyna	**3.8**	**4.2-5.2**	**Canopy Analyser**	**Swindon, UK**	**Herbst et al., 2007**
Crataegus monogyna	**3.8**	**4.8**	**Litter**	**Swindon, UK**	**Herbst et al., 2006**
Crataegus macrocarpa	**6-8**	**4.7**	**Vertical column**	**Bavaria, Germany**	**Kuppers, 1984**

The VitiCanopy application photographs (Figure 6.3) calculated the LAI using the gap fraction method and showed that the High Density Sites had the highest LAI (3.14cm^2) and that the No Canopy Site had the lowest LAI (0.51cm^2). This indicates some error in the method because this site should have a LAI of zero. The LAI of the Low Density Sites was 46% lower than the Medium Density Sites due to the larger gaps in the canopy.

1. High **2. Medium** **3. Low** **4. Canopy edge** **5. No canopy**

Figure 6.3: Photographs of the canopy taken with an iPhone 5s.

The average across all LAI readings taken under all types of canopy cover, was 2.50cm^2 +/-1.24. This means that for every 1m^2 of ground there were 2.5m^2 of leaves. The LAI of the Clotherholme hedgerow (Figure 6.4) is at the lower end of the global LAIs, which has been derived for fifteen different land cover classes, 1.31+/0.85 for deserts to 8.72+/-4.32 for evergreen tree plantations (Scurlock et al., 2001). It is also smaller than other studies, (Pocock et al., 2010) calculated a LAI of 4.6 for a *Crataegus monogyna* hedgerow and (Herbst et al., 2006) calculated LAIs of 5.2 and 4.2 for North-South and East-West orientated *Crataegus monogyna* hedgerows (Table 6.3). Again, the reason for this may be related to the height and size of the Clotherholme hedgerow which is a relatively small plant.

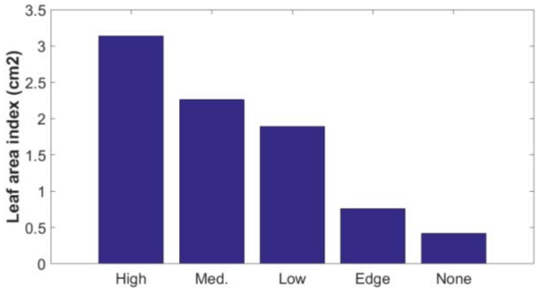

Figure 6.4: LAI measured at different canopy densities by the VitiCanopy app.

In conclusion, the average LA of the hedgerow was 2.16cm^2 and the average LAI was 2.50cm^2 +/-1.24. The canopy density did not affect the LA but, it did affect the LAI of the hedgerow. The most dense canopy sites had the highest LAI (4-5cm^2) and these higher LAI are similar to values collected in other studies (**Error! Reference source not found.**Table 6.3). However, the lower LAI at the less dense canopy sites are a lot lower than in other studies. This may be because other experiments took place earlier in the summer when the canopies were denser.

6.2.3 Soil Characteristics

This section will examine 'Are the soil properties next to the hedgerow better than further away from it?' This will be done by investigating whether the soil properties are the same or different next to the hedgerow and at three distances away from it. Soil cores and soil samples were collected from the main hedgerow site to determine the soil properties including the soil horizons, particle size, organic matter content (OMC), bulk density and saturated hydraulic conductivity (Ksat).

At the zero metre locations (E0m and W0m) there were lots of small roots and earthworms indicating good topsoil structure and there was a lack of mottles in the soil cores, indicating good drainage on both sides of the hedgerow. The A Horizon was largest in the middle of the hedgerow (37cm) and shallowest at W10m (19cm) (Figure 6.5). The soil texture was classified as a silty loam at all the locations. The percentage of clay was low at all sites (<6%) which meant that the soil was at high risk of degradation and erosion.

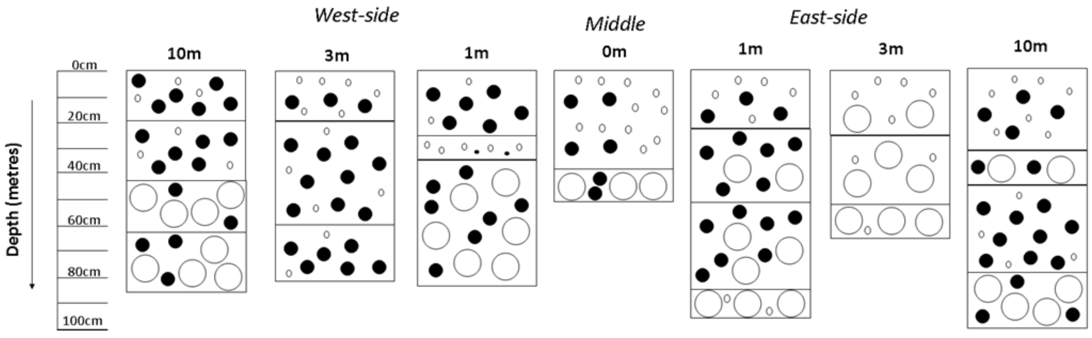

Figure 6.5: Soil Horizons at the Clotherholme Hedgerow.

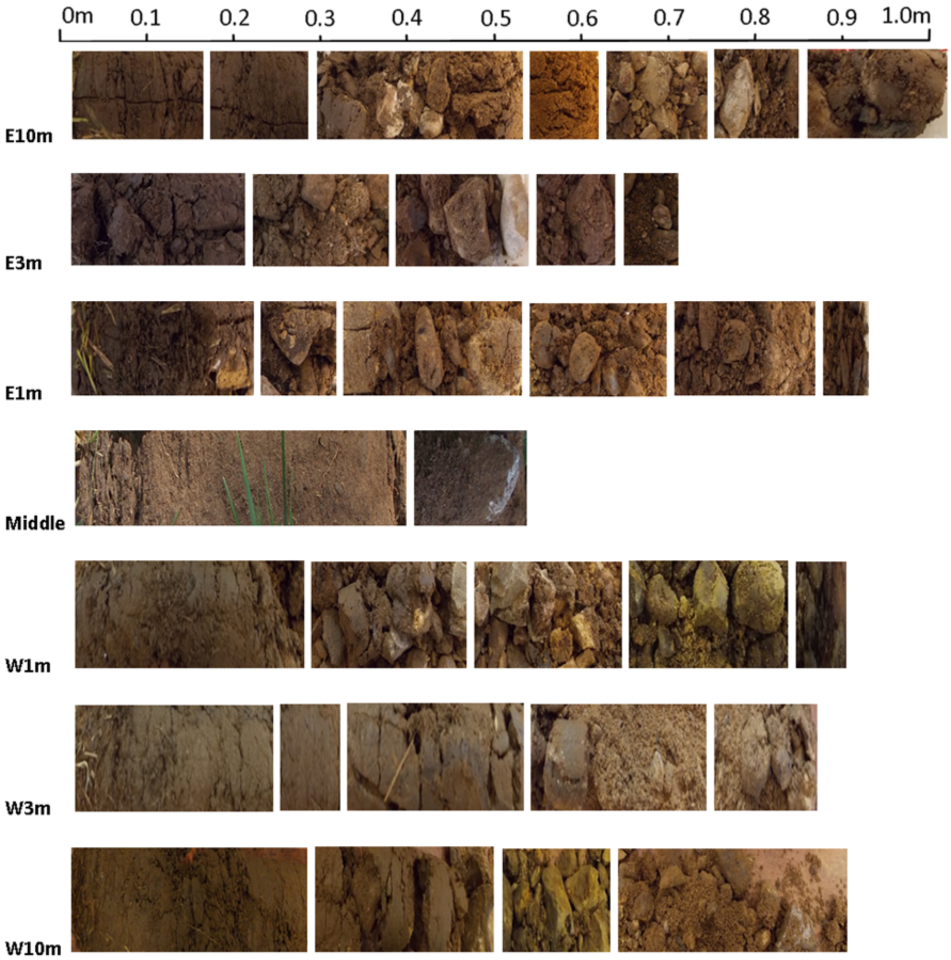

Figure 6.6: Soil cores collected from Hedgerow.

Sand and coarser sized particles were dominant at the bottom of all cores (Figure 6.6) and there was a high percentage of sand at all locations (>43%) indicating good drainage potential (Figure 6.7). This was highest at the E0m and E3m locations. On the east-side the percentage of sand decreased with distance from the hedgerow but, this was not the case on the west-side.

The middle of the hedgerow had the highest OMC (15-19%) which was due to the leaf litter on the surface and the roots. These values are similar to those collected at *Rubus fruticosus* hedgerows (15% +/-2) (Hegarty and Cooper, 1994). However, all sites had an OMC greater than 8% which indicated a good soil structure and was probably due to the grass cover

(**Error! Reference source not found.**Figure 6.8). OMC decreased with distance from the hedgerow on both the sides of the hedgerow.

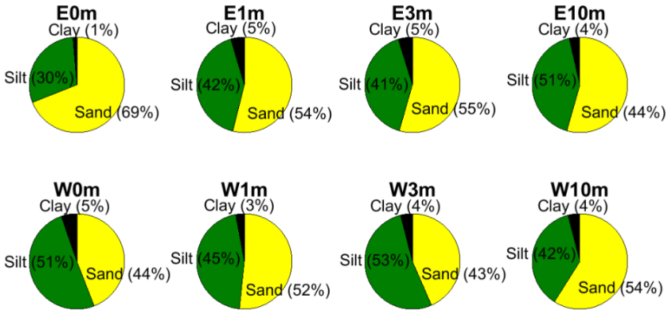

Figure 6.7: Particle size distribution in A Horizon.

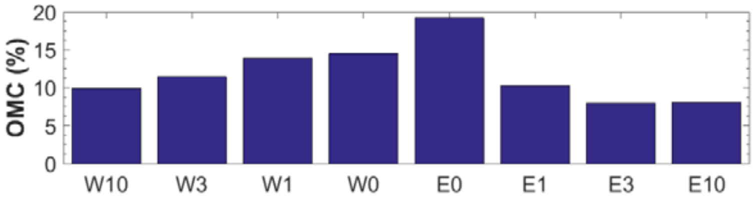

Figure 6.8: Organic matter content in the A Horizon.

Bulk densities were lowest in the topsoil at W0m (0.83g/cm^2 +/-0.20) and W1m (0.89g/cm^2 +/-0.21) and they generally increased with distance from the hedgerow and with depth into the soil but not significantly (Figure 6.9). These values were similar to those in lowland woodland (Emmett et al., 2010) which may be due to the high OMC. The highest bulk densities were recorded at thirty centimetres at E3m (1.61g/cm^2 +/-0.22) and E10m (1.62 g/cm^2 +/-0.18). The bulk densities further from the hedgerow are similar to those at a Kenyan (1.31g/cm^3) hedgerow (Kiepe, 1995) and an agroforestry site (1.26g/cm^3) (Udawatta and Anderson, 2008). Overall, the range of bulk densities seen at the site were similar to silt-loam grasslands in England and Wales (Merrington, 2006), improved grassland (Emmett et al., 2010) and grassland soils (Newell-Price et al., 2012).

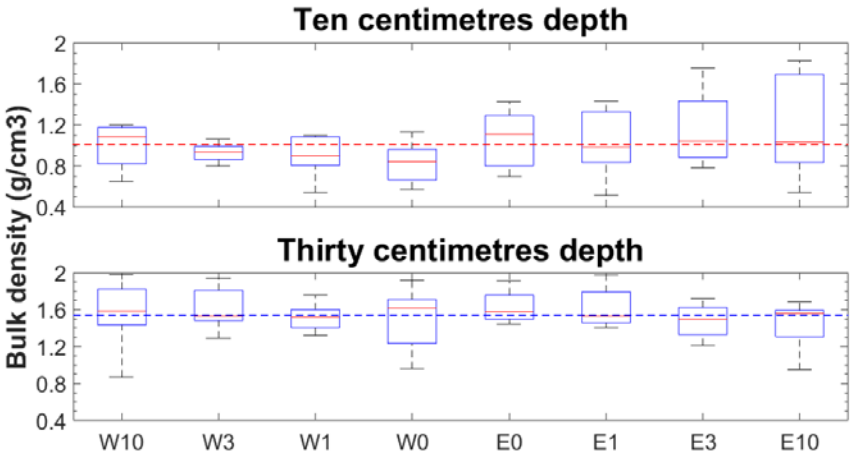

Figure 6.9: Bulk density on west and east-side of hedgerow.

Average density 10cm: 1.04g/cm3 (red line) and at 30cm: 1.54g/cm3 (blue line).

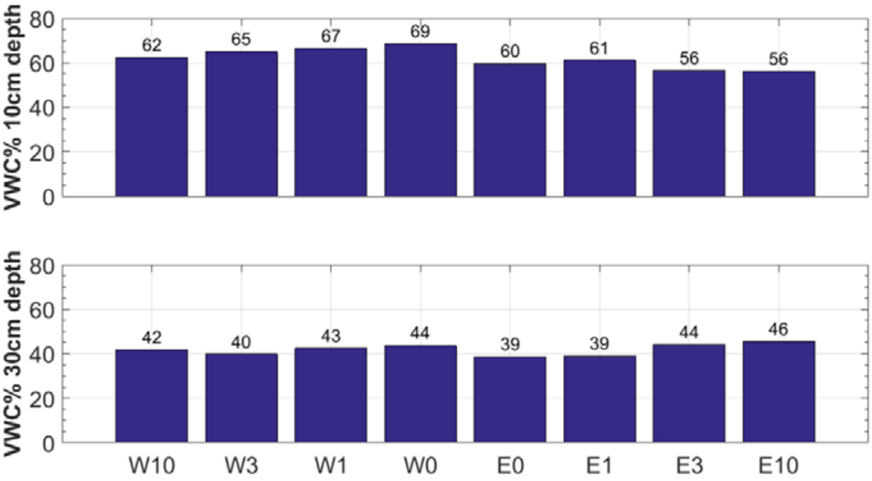

Figure 6.10: Average porosities at the hedgerow.

The range of soil VWC (θ) at the hedgerow is limited by the soil porosity (Φ) which is determined by the soil texture and degree of compaction (Figure 6.10). Equation 6.5 shows how VWC and porosity can be used to calculate the degree of saturation (S) and determine the maximum possible VWC at 100% saturation at each location. This ranges from 56-69% and 39-46% at the 10cm and 30cm depths.

$$S = \frac{\theta}{\Phi}$$

Equation 6.1: Degree of saturation.

The saturated hydraulic conductivity (Ksat) rates at W0/E0 (0.16 and 0.07mm/hr) were 98% and 99% higher than at W10/E10 (2.48×10^{-3} mm/hr), suggesting a positive effect of the hedgerow on the drainage potentials (Figure 6.11). The W0/E0 locations were also 58% and 76% higher than W1/E1 indicating that the positive affect on the soil started to diminish less than one metre from the hedgerow.

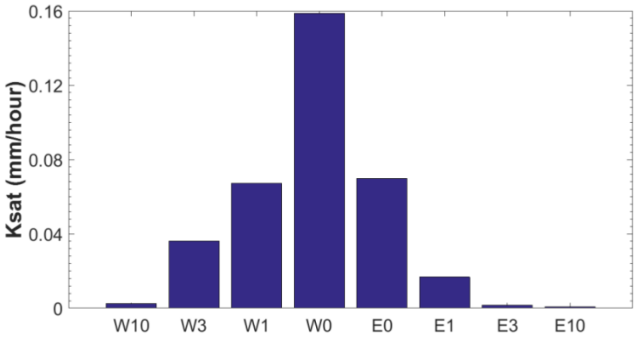

Figure 6.11: Saturated hydraulic conductivity at the hedgerow.

Conductivity rates were higher (66-95%) on the west than the east-side of the hedgerow, at all locations. This suggests that the east-side is more compacted and could be because the two sides of the hedgerow have different land-use histories. However, these rates are based on one set of samples/falling head tests and more would be need to give the result more significance.

The rates in this study were lower than at a silt loam tree buffer (47mm/hr) site (Udawatta and Anderson, 2008), at a sandy forest (121mm/hr) site (Taylor et al., 2008) and at a sandy loam hedgerow (61mm/hr) site (Kiepe, 1995). This suggests that the conductivity values collected in this study, for both the open field and the edges of the hedgerow are affected by soil compaction. This may be due to cattle grazing in the field on the west-side, or the use of tractors and vehicles on the east-side of the hedgerow.

In conclusion, the soil properties next to the hedgerow (W0m/E0m) were better than further away from the structure, in the open grassland field. The A-horizon, the sand and OMC and the saturated hydraulic conductivity rate were the greatest at the zero metre locations and the bulk density was the lowest. The OMC and conductivity decreased and the bulk density increased with distance from the hedgerow. All these indicators showed that the soil directly next to the hedgerow structure had the best soil structure and the highest drainage potential. It also showed that the positive influence diminished with distance from the structure.

6.3 Quantifying the Impact of the Hedgerow on the Spatial Rainfall Distribution

This section quantifies and discusses how the Clotherholme hedgerow had an impact on the spatial rainfall distribution. This was done by examining four questions:

1. Is the hedgerow sheltering effect on rainfall, which is observed in other studies, also present in this study?
2. If, the sheltering effect is present, how does it influence the spatial rainfall distribution at the hedgerow and further away from it?
3. How much rainfall is transported through the hedgerow structure as stemflow and throughfall?
4. How much rainfall is intercepted by the hedgerow structure?

Questions one and two were examined in Section 6.4.1 by analysing the Tipping Bucket Rain (TBR) gauges data from the hedgerow site. Question three was examined in Section 6.4.2 and 6.4.3 by analysing the quantity of throughfall and stemflow that occurred at the site during the monitoring period. Question four was examined in Section 6.2.4 by analysing the percentage of time that the four Leaf Wetness Sensors (LWS) were wet, or dry. The LWS did not work from 18-30 September 2014. The Lumley Moor Reservoir (LMR) hourly TBR gauge data, seven kilometres west of the Clotherholme hedgerow, was used as the control site. This section also presents the results of the hedgerow interception model.

6.3.1 Rainfall Distribution

The dominant wind direction in northeast England is from the west due to the prevalence of storms tracking over the Atlantic Ocean and therefore, more rain would be expected on the west-side of the hedgerow. In May the majority of storms came from the west (29%) and north (28%), in June they came from the north (44%) and in July they came from the north (35%) and west (32%). Only 20%, 19% and 13% of storms came from the east during the three months. This confirmed that the dominant wind direction was mainly from the north and west and only occasionally from the east. It also confirmed that more rainfall would be expected on the west-side hedgerow gauges than the east-side ones due to the sheltering affect.

The Clotherholme hedgerow is 131m lower in elevation (50mAOD) than the LMR gauge (181mAOD) and further east so less rainfall would be expected to fall at the site. The data shows there was 42%, 44% and 39% less rainfall fell across the seven Clotherholme gauges than at the LMR gauge during May, June and July 2014 (Figure 6.12).

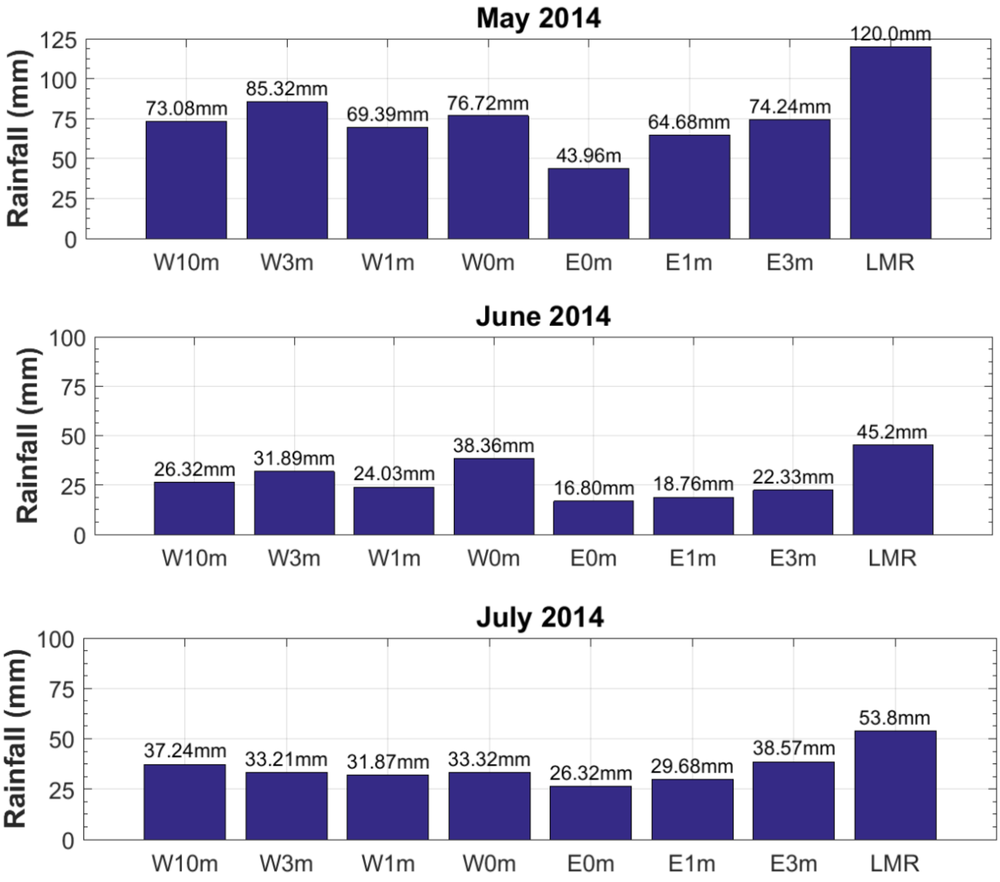

Figure 6.12: Quantity of rainfall at Hedgerow and DWS.

The data from the TBR gauges showed that in May 2014 there was less rainfall (43%, 7% and 13%) respectively at the E0, E1 and E3 gauges than at the W0, W1 and W3 gauges (Figure 6.12). This was also the case in June 2014 when there was again less rainfall (56%, 22% and 30%) at the east-side than west-side gauges. However, in July 2014 there was less rainfall at the E0 and E1 gauges than at W0 and W1 (21% and 16%) but there was 14% more rainfall at E3 than W3. The results show large variability in the quantity of rainfall on the two sides of the hedgerow. At zero metres there was 21-56% less rainfall on the east-side than the west-side, at one metre there was 7-22% less rainfall on the east-side and at three metres there was 13-30% less rainfall on the east-side but in July there was more rainfall on the east-side than west-side.

In conclusion, the results show that the hedgerow sheltering affect is influencing rainfall on the leeward side of the hedgerow, in this case the east-side, where turbulence was reduced by the presence of the hedgerow. This result is the same as (Herbst et al., 2006). The sheltering affect appears to extend out to at least three metres from the hedgerow in May and June but only to one metre in July.

To increase the robustness of the TBR gauge results, the percentage of time that the four Leaf Wetness Sensors (LWS) were wet or dry was analysed (Table 6.4). The data showed that the east-side LWS was 6% drier than the west-side LWS during the period July 2014-September 2015 and confirms the shelter effect on the spatial rainfall distribution at the hedgerow (zero metres). The east-side was also drier than the west-side in the two summer periods (5-6%) and in the winter period however; it was much larger (29%) in winter. This suggests that the sheltering affect is greater when the hedgerow is leafless.

Table 6.4: Percentage of time (%) the Leaf Wetness Sensors were wet.

	East-side (LWS1)	West-side (LWS4)	Difference
01/07/14-01/09/15	33	39	6
Summer 14	40	45	5
Winter 14/15	56	85	29
Summer 15	28	34	6

The TBR gauges and the LWS' measure slightly different things, the gauges record the number of tips in five minutes due to a specified quantity of water falling on them and the LWS are much more sensitive to any kind of wetness, which includes dew condensing on their surface. This may explain why the difference observed and why the sheltering effect on the TBR gauges was greater than the difference seen by the LWS'. Both methods do show that less water/moisture was recorded on the leeward side of the hedgerow in comparison to the windward side and this confirms the sheltering effect of the hedgerow.

The results in this study showed that the shelter affect influences rainfall to at least one metre from the hedgerow which was less than one times its height. This is similar to the (Herbst et al., 2006) study where the shelter effect on rainfall only extended up to three metres from the structure, or one times its height (3.30m). This may be due to the high permeability of the study hedgerow which had gaps at the bottom of the structure. A more permeable structure is thought to create a better shelter than a less permeable one because the air is also filtered through the hedgerow rather than just being forced up and over it. Permeable structures prevents turbulence occurring on the leeward side and have a more gradual return to free wind speed (Pollard et al., 1974).

In conclusion, the hedgerow sheltering effect was observed in this study by a reduction in the quantity of rainfall collected on the east-side of the Clotherholme hedgerow. The gauges on the east-side recorded 7-56% less rainfall than those on the west-side and the west-side LWS was 5-29% wetter than the east-side LWS. The sheltering affect was shown to extend out to at least one times the height of the hedgerow, which is similar to other studies. It was assumed that all precipitation captured by the gauges was rainfall but other types of precipitation (snow and hail) may have also been recorded.

6.3.2 Throughfall Losses

Throughfall was compared to gross rainfall (GR), classed as the average of the W3, W1 and W0 gauges. In the two summer periods (Figure 6.13) the hedgerow was fully leafed. The GR from 18 June to 18 July 2014 was 21.41mm and the total quantity of throughfall (4.48mm) was 21%. The GR from 18 July to 18 August 2014 was 100.93mm and throughfall was 33% (33.32mm). This means that the hedgerow intercepted a high percentage (67-79%) of GR. There was significantly more rainfall in the second period when there were a number of heavy intensity thunderstorms and this appears to have increased the amount of throughfall. The results show that throughfall varied by 12% in the two summer periods.

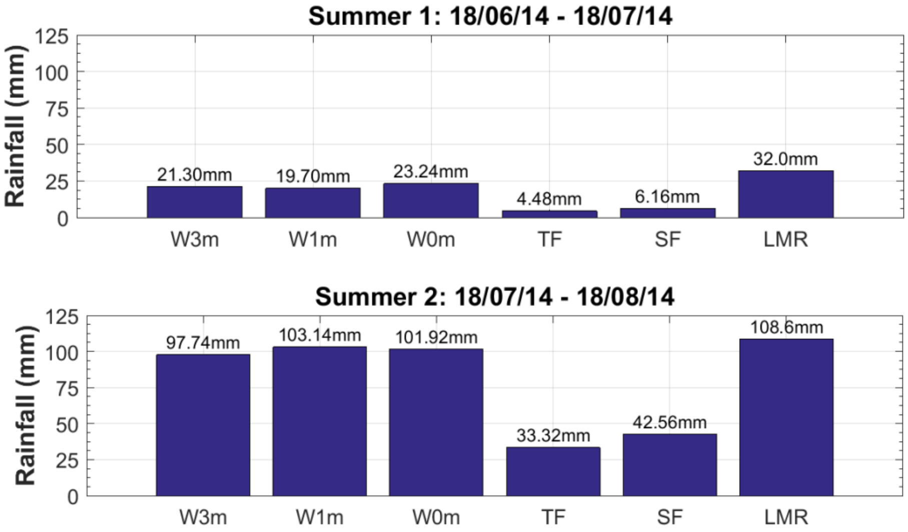

Figure 6.13: Total quantity of rainfall observed at the Hedgerow, summer 2014. SF=Stemflow, TF=Throughfall, LMR=Lumley Moor Reservoir.

In the two winter periods (Figure 6.14) the hedgerow was leafless. The GR from 1 November to 1 December 2014 was 35.03mm and the total quantity of throughfall (21.56mm) was 62%. The GR from 1 December to 1 January 2015 was 31.59mm and throughfall was 45% (17.31mm). This means that the hedgerow intercepted a lower percentage (38-55%) of GR than in the summer. There were similar amounts of rainfall in both periods but the results show there was more variability (17%) in the two winter periods than in the summer periods.

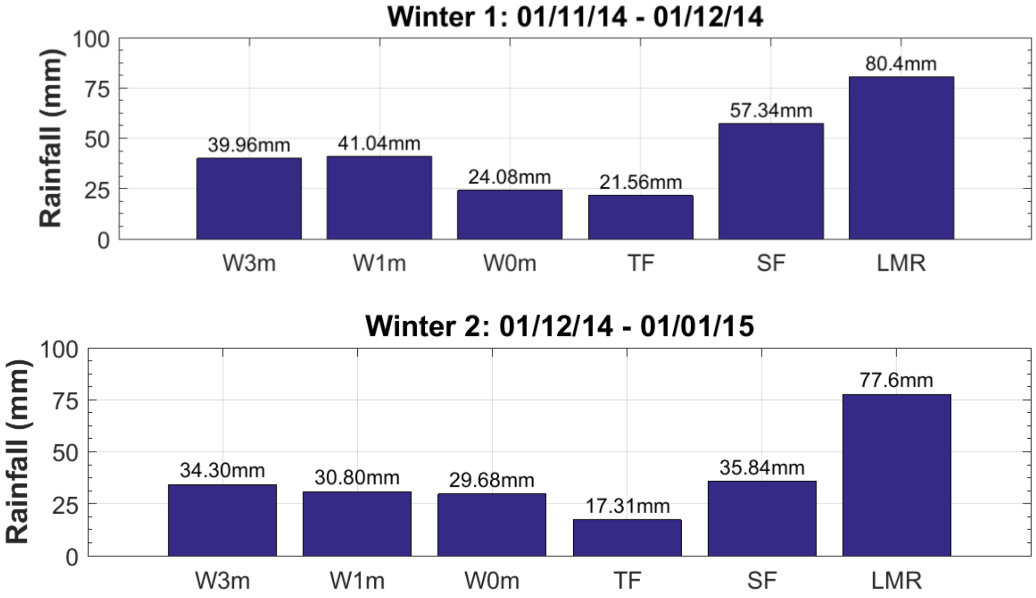

Figure 6.14: Total quantity of rainfall observed at the Hedgerow. SF=Stemflow, TF=Throughfall, LMR=Lumley Moor Reservoir.

To increase the robustness of the throughfall results, two experiments were run to quantify throughfall variability, based on the density of the canopy. In the first experiment (28 September-26 October 2015) the hedgerow was leafed and in the second experiment (27 October-10 November 2015) it was semi-leafless. The GR was taken from the LMR gauge.

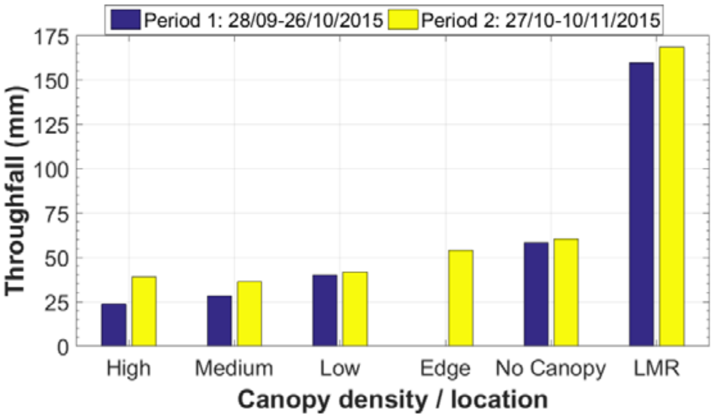

Figure 6.15: Throughfall at five hedgerow locations and the LMR gauge.

In the first experiment, throughfall at the Clotherholme hedgerow ranged from 15-36% of GR (160.6mm) depending on the location and intercepted 64-85%

of rainfall. In the second experiment it ranged from 27-40% of GR (134.2mm) and intercepted 60-73% of rainfall even in this semi- leafed period. In both experiments the highest amount of throughfall occurred at the ‘No Canopy’ gauge and the lowest at the ‘High density’ gauge (Figure 6.15).

In conclusion, the quantities of throughfall from the summer periods show good agreement by the two methods that were used. The TBR gauges provided a narrower range in throughfall (21-33%) than the experiments which had a wider range (15-36%). This is probably because the experiments were conducted under different parts of the canopy to also look at the differences under different canopy densities whereas the TBR gauge was set in one position. The second experiment showed that throughfall increased (27-40%) as the leaves began to fall and the TBR gauges from the winter period showed that throughfall was significantly greater (45-62%) in the leafless period.

The quantity of throughfall in summer (15-36%) was considerably lower than at a hedgerow shelterbelt in Pontbren (Wheater et al., 2008) where 46-56% of GR was observed as throughfall however, the quantity of throughfall in winter (45-62%) was similar. The reason for the differences between the two studies could be that the trees in the Pontbren study were at least five metres tall and more widely spaced, so significantly more permeable than the study hedgerow.

6.3.3 Stemflow Losses

Stemflow was compared to gross rainfall (GR), classed as the average of the W3, W1 and W0 gauges. The GR in the two summer periods was 21.41mm and 100.93mm and the quantity of stemflow (Figure 6.13) was 29% (6.16mm) and 42% (42.56mm) of GR. The results show that stemflow varied by 13% in the two summer periods. Stemflow was 27% and 22% higher than the quantity of throughfall in the same periods.

The GR in the two winter periods was 35.03mm and 31.59mm and the quantity of stemflow (Figure 6.14) was 39% (57.34mm) and 12% (35.84mm) higher than GR suggesting that no rainfall was being intercepted, or that there was a problem with the collar. These results would mean that stemflow was 63% and 52% higher than the quantity of throughfall that was recorded in the two winter periods.

In conclusion, these results suggest that stemflow contributes a significant portion (29-100%) to the hedgerow hydrological cycle depending on the season and the canopy cover. In previous studies it has been reported as negligible, for example it was 0.3% (David et al., 2006), 2% (Guevara-Escobar et al., 2007) and 0.2-0.5% of GR in the Swindon study (Herbst et al., 2006). There are a number of reasons why this might be the case. In comparison to the Swindon study, the hedgerow in this study was shorter in height, with a denser network of stems and branches. Also, the canopy area above the stemflow collar in this study is a lot larger than the collection area of the gauge and therefore, the contributing area may be a lot larger than in the Swindon study. Further tests would be required to confirm this finding, as only one stemflow collar was built and monitored in this study.

6.3.4 Interception Losses

The simple interception loss model was used to calculate the interception losses at the hedgerow (Equation 6.1). The equation showed 33-70% of GR, was lost as interception on the hedgerow in this summer leafed period and 68-98% were lost in the winter leafless period. The average summer losses are similar than the losses (57% of GR) reported by (Herbst et al., 2006) for the leafed period however, in the Swindon study the losses were dominated by a higher quantity of throughfall and a much lower quantity of stemflow than in this study.

To increase the robustness of the results, the LWS data was also analysed. In the two summer periods, the Top Sensor wetted up 44-52% of the time and the Inside Sensor only wetted up 16-22% of the time. This showed that the structure intercepted 28-30% of rainfall. In the winter period, the Top Sensor wetted up most of the time (96%) and the Inside Sensor also wetted up for the majority (92%) of the time. This showed that the structure intercepted 8% of rainfall.

Table 6.5: Interception loss calculated using the simple equation.

Period	GR (mm)	TF (mm)	SF (mm)	Interception loss (mm) / (%)
Summer 1	**32.0**	**4.48**	**6.16**	**21.36 / 33**
Summer 2	**108.6**	**33.32**	**42.56**	**32.72 / 70**
Winter 1	**80.4**	**21.56**	**57.34**	**1.5 / 98**
Winter 2	**77.6**	**17.31**	**35.84**	**24.45 / 68**

Table 6.6: Percentage of time (%) the Leaf Wetness Sensors were wet.

	Inside (shade) (LWS2)	Top (sunlit) (LWS3)
Summer 14	**16**	**52**
Winter 14/15	**92**	**96**
Summer 15	**22**	**44**

The summer interception losses calculated with the interception model were substantially higher than those determined using the LWS which suggests that the stemflow collar may have overestimated the amount of stemflow, especially in the second summer period. The interception losses calculated with the LWS' are similar to the losses in (Ghazavi et al., 2008) where 28% of rainfall was intercepted by the oak hedgerow in the leafed period. It is also similar to (David et al., 2006) where 22% of rainfall was intercepted by individual oak trees and (Gomez et al., 2000) where up to 25% of rainfall was intercepted by olive trees. The winter interception losses calculated with the interception model (68-98%) were a lot higher than those calculated using the LWS (8%) and again suggest some problem with the stemflow collar during the winter period in this study.

In conclusion, this study has shown that interception values differ greatly due to the season, the canopy density and leaf area index, as well as the intensity and duration of rainfall events. They also differ depending on the method used to calculate them. The interception losses calculated from the TBR gauges and those observed by the LWS’ in this study are comparable with previous research on hedgerows and lines of trees. However, the fraction of throughfall and stemflow were different.

The quantity of throughfall was lower than had been reported in other studies which may be due to the smaller and denser structure of the Clotherholme hedgerow. The quantity of stemflow was considerably higher than in other studies and it is possible that the stemflow collar overestimated the amount of stemflow that occurred. It is suggested that further monitoring of small stems within hedgerows would be required to clarify the stemflow component of the hedgerow water balance.

6.4 Quantifying the Impact of the Hedgerow on Subsurface Soil Moisture

This section will discuss and quantify how the Clotherholme hedgerow had an impact on the root zone hydrology focusing on the soil moisture content. This will be done by examining three questions:

1. Is the hedgerow sheltering effect observed in other studies, also present in this study?
2. If, the sheltering effect is present, how does it influence the soil moisture content at the hedgerow and further away from it?
3. Is the effect the same in summer and winter?

All three questions were examined by analysing the Volumetric Water Content (VWC) of the soil next to the hedgerow (zero metres) and up to ten metres away from it. This was done using two methods; the first was the continuous Time Domain Reflectrometry (TDR) system. The E1010cm and E1030cm TDR probes were not reliable and were not used in the analysis. The second method was the discrete measurements taken at twenty centimetres depth with the HydroSense II probe. Questions one and two are discussed in Section 6.5.1 and question three is discussed in Section 6.5.2.

6.4.1 Soil Moisture Distribution

The TDR probes showed that during the year (May 2014-April 2015) at zero metres from the hedgerow the VWC of the soil (Figure 6.16) was significantly lower on the east-side than the west-side at 10cm and 30cm depth (21% and 8%). There are a number of reasons for why the east-side is drier than the west-side, even though the structure creates a high evaporative capacity on the west-side (windward) due to the enhanced turbulent air exchange (Ryszkowski and Kedziora, 1987). The shade created by the hedgerow structure on the east-side (leeward) reduces wind speeds, which keeps temperatures and evaporation rates low (Pollard et al., 1974).

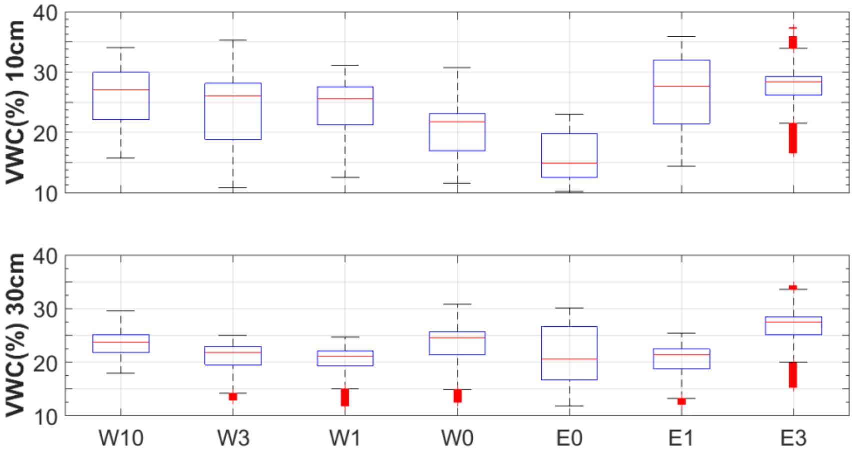

Figure 6.16: VWC measured at seven locations May 2014-April 2015.

It could also be because the east-side had slightly better soil properties than the west-side, including a higher percentage of sand, higher organic matter content and a higher saturated hydraulic conductivity rate (Section 6.3.3). This allows water to drain quicker through the topsoil than the west-side. However, both sides had reasonably good soil structure and drainage potential. Finally, it could also be because the east-side had substantially less rainfall than the west-side which was shown in Section 6.4.1.

Further from the hedgerow (one metre and greater), the benefits to the soil structure and drainage diminish and the open field is affected by other factors such as soil compaction. The VWC at the one metre locations, were significantly lower (10%) on the west-side than the east-side at 10cm depth but practically the same at 30cm depth (VWC: 20%). Also, at three metres from the hedgerow, VWCs were significantly lower on the west side than the east side at both depths (13% and 20%).

The range of VWCs recorded at zero metres, was substantially larger on the west-side (11.5-30.7%) than east-side (10.1-23.0%) at 10cm depth but at 30cm depth the west-side (12.5-30.8%) was similar to the east-side (11.9-30.2%) suggesting that different processes (soil evaporation, groundwater) are at work at greater depth.

To increase the robustness of the TDR results, the soil VWC, was also measured every 50cm along transects using the HydroSense II. This was done at Clotherholme (CHF), Hedge Nook (HNF) and Holme Farm (HF) (see Chapter 5 – Section 5.6.3.1) on 28 September 2015. The data showed that the east-side transects (CHF3, HNF4 and HF2) were drier, 25-75% and 12-38% respectively, at the zero and one metre locations, than on the west-side transects (Figure 6.17).

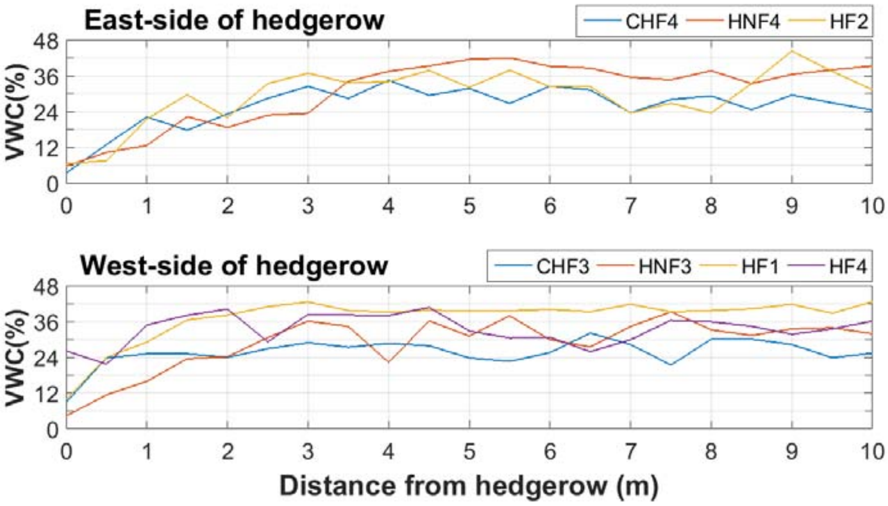

Figure 6.17: VWC measured with the HydroSense II on 28 September 2015. CHF=Clotherholme Farm, HNF=Hedge Nook Farm, HF=Holme Farm.

At the three metre locations, the east-side transects were drier (4-13%) than the west-side transects except at the CHF4 which was 11% wetter than the west-side. At all transects, the soil VWC increased with distance from the hedgerow out to 0.5-3m on the west-side and out to 1.5-2.5m on the east-side. These results suggest that the sheltering affect does not extend out further than three metres from the hedgerow.

In conclusion, the two methods used to assess the sheltering effect of the hedgerow on soil VWC show different results. The TDR data showed that the sheltering affect did have an influence on soil VWC at zero metres from the structure but did not extend out to one metre or greater from it. In comparison, the discrete measurements taken at other hedgerows showed that the soil VWC was lower on the east-side than the west-side up to 2.5

metres from the hedgerow. These results suggest that further monitoring of the soil VWC at and around hedgerows is needed but that the sheltering effect can potentially extend out 2.5m from the structure, or approximately two times the height of the hedgerow. This is a lot lower than was hypothesised by Pollard et al., 1974 in their research who thought that the sheltering affect had an influence of twelve times the height of the hedgerow.

6.4.2 Seasonality of Soil Moisture

The TDR probes showed that the mean soil VWC at all locations was wetter in winter than in summer (Figure 6.19) as would be expected due to the higher rainfall totals in winter and the lack of hedgerow transpiration between November and April when the plant lost its leaves. The summer also had more sunshine hours (540 vs 225), lower relative humidity (88% vs 95%), higher air and soil temperatures (Figure 6.19) and lower soil water potential. Therefore, it is assumed that the transpiration rates were higher (Hopkins and Huner, 2008) and the roots removed more water from the soil than in winter.

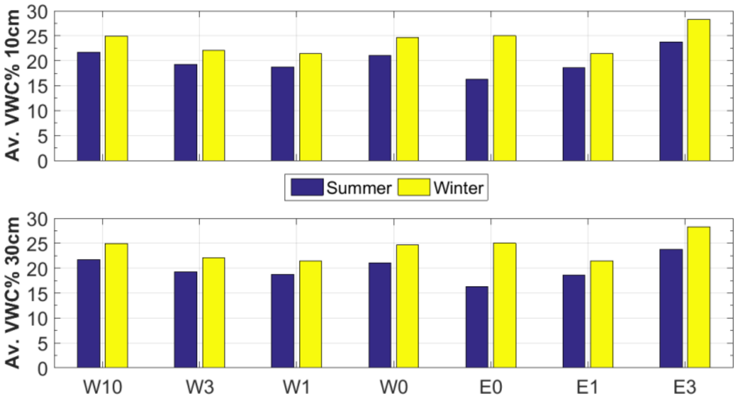

Figure 6.18: Average VWC at each location in summer and winter.

The highest VWC in summer was at E310cm and in winter it was at E110cm. This may be because these two locations had lower porosities (56% and 61%) than the other locations so the drainage potential was lower. The lowest VWC in summer and winter was at E010cm which is due to the sheltering affect causing a lack of rainfall here. The largest difference between the two seasons was at E030cm and E010cm where the mean

VWCs were 35% and 32% higher in winter than summer which shows that the sheltering effect is evident in summer, but less dominant in winter when the hedgerow is leafless. The smallest difference between the two seasons was at W130cm, W330cm and W1030cm where the mean VWCs were only 13% higher in winter than in summer showing a lack of sheltering effect in either season.

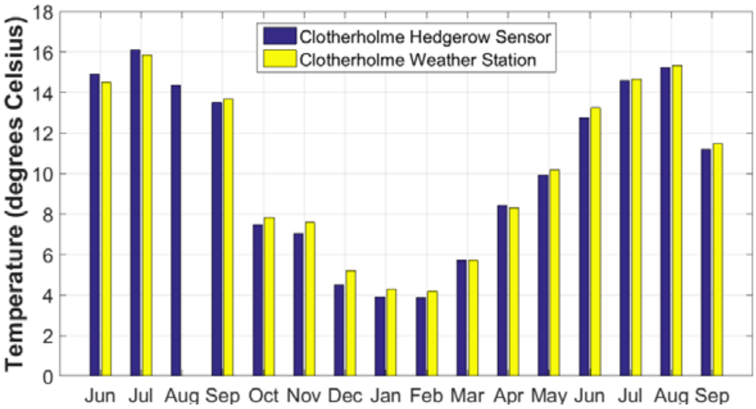

Figure 6.19: Average monthly temperatures during monitoring period.

Section 6.4.1 determined that the mean VWC at zero metres was significantly lower on the east-side than the west-side. The TDR probes also showed this trend at 10cm depth (Figure 6.20) in the summer and winter seasons (30% and 13%) but at 30cm depth, this trend was only evident in the summer (23%). The reason for the different result at 0-30cm between the two seasons could be due to higher groundwater levels in winter, or because the sheltering affect is not as strong in winter, when the hedgerow is leafless.

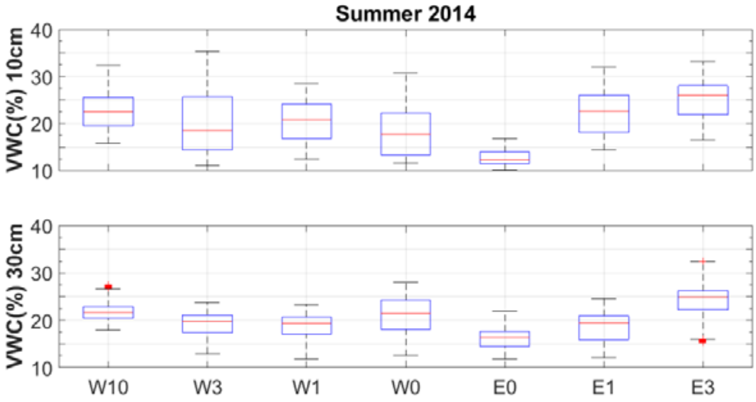

Figure 6.20: VWC at seven locations.

At the one metre locations, the VWCs were significantly lower on the west-side than the east-side at 10cm depth in the summer and winter (8% and 12%) but VWCs were very similar at 30cm depth in both seasons. Also, at three metres from the hedgerow, the VWCs were significantly lower on the west side than the east side at both depths in summer (20% and 19%) and winter (9% and 22%). This again shows a lack of sheltering effect on the soil at a distance greater than zero metres from the hedgerow.

In conclusion, VWCs were lower in winter than in summer at all locations. The E010cm probe had the lowest VWCs in both seasons which is thought to be due to the sheltering affect and the largest difference between the seasons was at E0m which is thought to be due to the diminished sheltering affect in the winter when the hedgerow is leafless. The smallest difference between the seasons was on at 30cm depth at W1, W3 and W10 which is believed to be due to the lack of any sheltering affect in either season.

At the zero metre locations, the east-side was significantly drier than the west at 10cm in both seasons showing a sheltering affect at this depth, but at 30cm it was only significantly drier on the east-side in the summer. This may mean that another process such as groundwater influences or the lack of shelter increased drainage in the winter. At one and three metres from the hedgerow, at 10cm depth the west-side was drier than the east in both seasons which suggests that these locations are not influenced by the sheltering effect of the hedgerow.

6.5 Chapter Summary

In summary, this chapter has looked at the soil-hedgerow-atmosphere continuum. A conceptual model was designed that was based on previous literature and fieldwork. This model defined how hedgerows could have an impact on specific hydrological processes including rainfall, stemflow, throughfall, interception and on soil moisture levels. From this initial model a number of research questions were planned with the aim of creating new data sets and adding to previous knowledge of the hydrology of hedgerows. Firstly the physical hedgerow characteristics were assessed, secondly the impact of the hedgerow on the spatial rainfall distribution was analysed and thirdly the impact of the hedgerow on the soil moisture was examined. Using the rainfall and soil moisture results from this study, the original conceptual model has been revised (Figure 6.212).

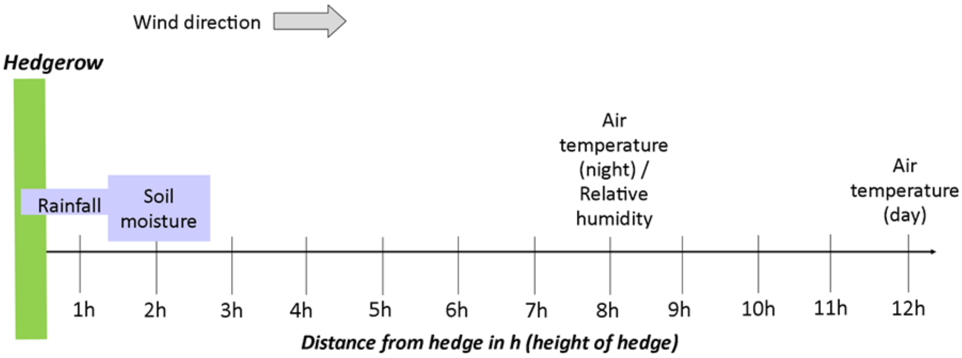

Figure 6.21: The shelter effect of a hedgerow on climatic factors. (Redrawn from Pollard et al., 1974 to include other research).

The hedgerow characteristics for a hawthorn hedgerow in Northern England, UK were determined. This study has shown that the horizontal roots only extend out one to three metres from the structure. It has calculated the leaf area index which was 2.50cm^2 +/-1.24. This is lower than has been observed in previous studies, but can be explained by the short height of the hedgerow. It has confirmed that the soil properties (organic matter content, bulk density and saturated hydraulic conductivity rates) next to the hedgerow are better than further away from it (out to ten metres).

This study has shown that the sheltering effect of the hedgerow on the spatial rainfall distribution was present on the leeward (east-side) of the structure. This was confirmed by the TBR gauge and LWS results that showed that there was up to 56% less rainfall on the leeward than windward side. The LWS results suggested that the sheltering affect at the hedge was greatest in winter than in summer. The TBR results also showed that the sheltering affect had an influence on rainfall out to at least one metre, which is one times the height of the structure which is similar to previous studies.

This study determined the portion of gross rainfall was transported as throughfall and stemflow at the hedgerow from the TBR gauge results and bucket experiments. The results showed that in summer throughfall ranged from 15-37% and in winter it ranged from 27-62% depending on the canopy density and rainfall event type. These figures are slightly lower than in other comparable studies. The results showed that stemflow ranged from 29-100% gross rainfall which was significantly higher than in other comparable studies. This suggests that the collar over-estimated the amount of stemflow, or that there was a problem with the gauge.

This study calculated the amount of interception loss at the hedgerow using the simple interception model and the LWS. The results ranged from 28-70% of gross rainfall in summer and 8-98% in winter. Interception calculated by the LWS results was much lower (Summer: 28-30%, Winter: 8%) than the simple interception model which again suggested an overestimation with the stemflow, or throughfall results.

This study has shown that the sheltering effect of the hedgerow on the soil moisture content is present on the leeward side of the structure. This was confirmed by the TDR continuous monitoring and the Hydrosense II discrete measurements which showed that the soil VWC was up to 75% drier on the leeward than the windward side. The TDR results showed that the sheltering affect had an influence on VWC at the zero metre locations but not further out, however the Hydrosense results which surveyed a number of other hedgerows showed that the influence was evident up to 2.5m from the structure. Further monitoring is necessary to confirm these results.

Some of the results showed that the effect on VWCs was different in summer and winter for example VWCs were higher at all locations in winter due to higher rainfall and lower transpiration. The largest difference in VWC was at the E0m location which showed that the lack of shelter affect in winter. However, a number of things were the same in both seasons including that the E0m had the lowest VWC and the W1-W10m locations were the driest in both season and had the smallest difference in VWC between seasons, suggesting no sheltering affect.

Chapter 7 - Conclusion

7.1 Chapter Scope

This chapter summarises the main findings of this thesis and revisits the aims and objectives from Chapter one. The aim of this thesis was ‘To determine the impact of rural land management on soil hydrology and river flows’ by studying two things, firstly the process-based relationship between soil compaction and soil hydrology which is discussed in Section 7.2 and secondly the soil-vegetation-atmosphere interaction around English hedgerows which is discussed in Section 7.3.

To accomplish the thesis aim and objectives, a case study approach was used which included fieldwork, laboratory work and a mapping campaign to assess how landscape features affect hydrological connectivity at the catchment scale. Previous research in other countries has shown that specific land management practices have a significant influence on soil properties and soil water movement. The question now is how sub-field features are having an impact on soil hydrology and catchment scale response.

Section 7.4 will make recommendations about the role of sub-field features on soil hydrology and catchment response for use in natural flood management intervention schemes and in future numerical modelling studies. Section 7.5 will provide a critical evaluation of the methodologies and the results that have been produced in this thesis. Finally, Section 7.6 will make some concluding remarks.

7.2 Complexity in Soil Compaction

The complexity in the process-based relationship between soil compaction and soil hydrology was tested in Chapters three and four.

1. To develop a holistic methodology to study the process-based relationship between soil compaction and soil hydrology:

Chapter three answered this question. An experimental methodology was designed at the field-scale to assess soil compaction and soil hydrology. Firstly, four catchment-wide types of agricultural land management were identified including arable farming, cattle grazing, horse grazing and sheep grazing. Then four sub-field features were identified where machinery and animals congregate within the fields including tramlines, feeding troughs, field gates and tree shelters. A final sub-field feature, open areas were identified where animals and machinery were less likely to congregate. Two main fieldwork periods were identified in October and April, which are seen as key times for crop and grass growth and that had high potential for trafficking and animal poaching.

A fieldwork campaign was designed that used a stratified random sampling strategy to capture the site specific soil characteristics as well as providing information on the level of soil compaction, soil structure and aggregate stability, soil water content and soil water movement. Appropriate testing equipment was investigated, purchased and then used at site. The fieldwork concentrated on the collection of data in the field through on-site experiments and also the collection of numerous soil samples that were brought back to the laboratory to test and analyse. The experimental data was then analysed using descriptive statistics in the first instance and then the ANOVA test to determine if there were significant differences between samples.

2. To assess the problem of complexity in the relationship between soil compaction and soil hydrology at different spatial scales:

Chapter four answered this question. The problem of complexity was assessed at the plot scale by implementing a fieldwork campaign that collected soil samples and undertook experiments in the field. A set of observations were collected at the end of summer 2014 and again at the end of winter 2014/15.

Firstly the potential for compaction at each field site was assessed by analysing the natural characteristics of the soil and site location. Secondly, the level of compaction was assessed by quantifying characteristics about soil strength, structure and drainage potential. Thirdly, the potential and actual levels of compaction observed at site were compared to determine any correlations. Fourthly, the difference between the inter-site (sub-areas of individual fields) and intra-site (between fields under four different types of land management) were quantified. Finally, the difference between the sites at the end of summer and end of winter was quantified.

The data showed that there was great variability in soil compaction and soil hydrology but in general two of the Open Field areas had the lowest levels of compaction and three of the ‘compacted’ areas had the highest levels of compaction. The data showed that in general there were low levels of correlation between the natural soil characteristics and levels of compaction based on the factors that were used to assume compaction. The only strong correlation was between soil structure and organic matter content which showed a negative correlation which has also been observed in previous studies.

The inter-site section showed that at all four management sites, the ‘compacted’ areas had poorest soil quality, based on strength, structure and drainage in comparison to the ‘open field’ areas which were all ranked in the top six sites. The intra-sites showed that the Feeding Trough and Field Gate Sites had the highest levels of compaction based on the strength, structure and drainage characteristics and the Open Field Sites had the lowest levels of compaction.

The data showed that there was no improvement in subsurface soil compaction between the October and April fieldwork periods at the most compacted and least compacted sites which may be due to the short period of rest over winter. However, there was strong improvement in soil quality at some sites which may be due to natural recovery over winter when there was no trafficking by machinery or animals. On the other hand, there was a strong deterioration in soil quality at other sites which may be due to some use of the field at the start or end of the winter period.

7.3 Hedgerow Hydrology

The relationship between hedgerows and hydrology and the impact of hedgerows on the soil-vegetation-atmosphere interactions was tested in Chapters five and six. This was done through objectives three and four.

3. To develop a conceptual model to assess how the presence of a hedgerow modifies the hydrological cycle locally:

Chapter five answered this question. A literature review was undertaken to develop a conceptual hypothesis regarding the effects of linear woody features, including hedgerows on soil hydrology. This identified three main areas of the hydrological cycle which are thought to be affected by the presence of hedgerows. Firstly, the hedgerow characteristics, secondly the subsurface water balance and thirdly, the root zone water balance. A conceptual model was built that focused on these three areas which showed the potential positive and negative impacts that hedgerow may have on these aspects of hydrology.

4. To test and revise the conceptual model through an intensive monitoring programme of the holistic hydrological cycle and assessment of soil-hedgerow-atmosphere interactions:

Chapter five answered this question. Once the conceptual model had been created, a main hedgerow study site and two secondary sites were identified in the Skell catchment. A monitoring plan was developed to capture observations of the hedgerow characteristics, the processes of rainfall, throughfall, stemflow and interception, air temperature and soil moisture content. Appropriate monitoring equipment was investigated, purchased and then installed at the site and monitoring continued at site for a period of eighteen months. A weather station was also set up nearby to provide a control for the data being collected.

The data showed that the horizontal extent of the hedgerow roots was relatively narrow, only extending out up to three metres from the structure. The leaf area index of the hedgerow was 2.50m^2 which is lower than in other studies but may be due to the smaller height of this hedgerow. The data showed that the hedgerow did affect the sub-surface characteristics by increasing organic matter content and saturated hydraulic conductivity and reducing bulk density next to the hedgerow. These improvements only extended out one-three metres from the hedgerow.

The rainfall data showed that the sheltering effect of the hedgerow caused up to 56% less rainfall on the leeward side of the structure. This effect was shown to be stronger in winter than summer and that the effect extended out to at least one metre from the structure. The throughfall and stemflow data showed that the quantity varied depending on the canopy density and rainfall event type. The total quantity observed in this study is less than previous studies which may be due to the dense nature of the hedgerow structure in this study. The percentage of gross rainfall that fell as throughfall was lower than previous studies but the quantity of stemflow was a lot higher. It is thought that the stemflow collar may have produced unrealistic quantities due to its set up. Further monitoring is needed of stemflow at hedgerows.

The interception data showed that interception losses differed depending on the method used to calculate them. The LWS method showed lower levels of interception than the simple interception model although it is thought that the error with the stemflow results affected the model results. The LWS method showed that there was more interception in summer, when the hedgerow was leafed and less in winter.

The soil moisture data showed that the sheltering effect of the hedgerow was present on the leeward side of the structure and that the effect extended out up to 2.5m from the hedgerow. The lack of leaves in winter was shown to create a large difference in soil moisture content on the leeward side, compared to summer when the leaves were present.

7.4 Recommendations

The final objective was as follows and is answered through a discussion below.

5. To make recommendations about the role of sub-field features on soil hydrology and catchment response for natural flood management intervention schemes and for use in future numerical modelling studies.

7.4.1 Natural Flood Management Schemes

First, this section discusses the role of sub-field features and soil compaction in soil and land management NFM intervention schemes. In England and Wales the cost of soil compaction is very high (£0.5 billion per year). The primary cost is the loss of agricultural productivity due to poor soil structure, high water contents and poor soil drainage and the stress and loss of reputation to the farmer. The secondary costs are associated with runoff from areas of compaction. They include flood damage to properties, the effects of increased greenhouse gas emissions due to loss of soil carbon, loss of nutrients and build-up of pollutants and the loss of land for recreational walking (Graves et al., 2015).

This thesis has shown that higher levels of compaction occur in specific sub-field areas (TL, FT, FG and TS) than in more open field areas. To reduce compaction in these areas it is recommended that in arable fields, the number of tractor passes needs to be reduced and the tyre pressures should be as low as possible to reduce the impact of the weight of the tractor and machinery. This can be done by improving the operational efficiency of tractors, using larger and more tyres, using low tyre inflation pressures and limiting axle loads. Reducing compaction also means that there is less need to undertake sub-soiling to aerate and improve the soil structure.

In pastoral fields, it is recommended that stock traffic should be spread out across the field and not encouraged to congregate. This can be done by not placing feeding troughs and field gates in high risk areas, such as those at the bottom of the slope, in areas with high soil water content and with poor drainage (such as near watercourses). This may mean re-siting these features, moving feeders during the season or having additional entrances to fields. This allows stock to walk over different areas of the field and walk a different route in and out of the field. In problem areas hard standing (concrete or rubber flooring) may also be useful.

The removal of stock at some sites over winter did show an improvement in the soil conditions. Therefore, it is recommended that stock be removed from the land at the start of winter, in cooler periods and when the soil is saturated, such as in periods of very heavy rain and placed on purpose built stand-off facilities/yards. It is also recommended that stock graze wetter fields before the start of the wet season and then use the drier fields. To save farmer's time and money it is recommended that when they are looking to make improvements that they prioritise specific areas of the field which are known to be associated with/at risk of high levels of compaction (TL, FT, FG and TS).

Second, this section discusses the role of hedgerow features in soil and land management NFM intervention schemes. In England and Wales hedgerows are declining in length and structural condition due to lack of rejuvenation management, neglect and over-frequent trimming (Staley et al., 2015). This thesis has shown that hedgerows modify the sub-surface flow paths, the surface water balance and the local micro-climate. It has shown that the leeward side of hedgerows have more soil storage for rainfall and reduce soil water content compared to the open field. To maximum the benefits of these improvements, it is recommended that the condition of current hedgerows are improved. This includes careful management of hedgerows such as reducing or filling gaps, increasing the density of woody material at the base and trimming hedgerows at appropriate times of the year to allow for positive root die back.

It is also recommended that more new hedgerows be planted to increase the potential benefits that they can make on a larger scale and across the whole catchment. This idea is supported by the Hedgerows and Boundaries grant, 2017, which is part of the Countryside Stewardship scheme. The grants can be used for hedgerow laying, coppicing, gapping-up, casting-up, top binding and staking and hedgerow tree planting (ranging from £3-9.40 per metre). As well as being used for flood control hedgerows deliver multiple ecosystem services for wildlife, water quality, climate, water and erosion regulation, pest control, pollination, protection of livestock, cultural and provisioning services.

However, from speaking to land owners there are barriers to planting hedgerows. One of the main reasons for hedgerow removal, prior to the 1997 Hedgerow Regulations was to increase field size and the productivity of agricultural processes due to less tractor turns and use of a larger area of the field. Also, hedgerows require a reasonable amount of management including trimming which takes time away from other tasks.

Finally, to successfully implement natural flood management schemes all the key stakeholders from the local area must be involved in the project and there needs to be real interest and willingness to try something different. Due to the lack of past case studies that have tested soil and land management measures such as those listed above these techniques will still need to be implemented in conjunction with traditional hard engineered defences and proven techniques.

7.4.2 Catchment Modelling

Numerical modelling is a useful technique due to the limitations of measurement practices, the limited number of observations in space and time and for developing knowledge about past, present and future scenarios and potential impacts of change. However, modelling is underpinned by data and knowledge of scientific processes which have been collected in this study.

First, this section discusses the representation of sub-field features and soil compaction at the catchment scale. There are currently very few data sources available to assess how the level of compaction varies by soil conditions. This thesis has provided data sets on a wide range of conditions/processes including, soil characteristics, levels of soil compaction, soil structure, soil water content and movement as well as the interactions between them. It is recommended that soil properties (soil texture, bulk density/porosity, soil moisture content and saturated hydraulic conductivity) are represented in catchment models.

There is also a lack of data regarding the complexity of soil compaction around sub-field scale features and between fields under different types of management. This thesis has provided information of the process-based relationship between compaction and hydrology. However, this complexity is not currently represented in numerical models. It is recommended that sub-field variability is included in future catchment models to help to improve the representation of real world soil conditions, runoff and flood risk. The outputs of modelling could be used to prioritise which areas of high compaction need to be modified first to make the most impact, improve the soil and reduce the risk of runoff and flooding. It is recommended that land managers and stakeholders represent sub-field features in catchment models, to identify which areas are most at risk of compaction and to ascertain ideal places to locate sub-field features.

Second, this section discusses the representation of hedgerow features and soil hydrology at the catchment scale. There have been no UK studies that represent hedgerows, or woody linear features at the catchment scale. This thesis has provided validation data on the hydrological processes surrounding a hedgerow which are essential for future modelling of these features. The key processes to represent would be the interception of rainfall by the physical structure and the reduction in soil moisture beneath and one the leeward side of the hedgerow network.

It is recommended that land managers and stakeholders represent hedgerows in catchment models, to identify hydrological connectivity across the catchment, identify which areas have the most potential to deliver benefits for water and flood risk regulation. This could be done by burning the hedgerow network into a fine resolution DTM and analysing changes in the hydrological connectivity. Modelling could help to show where water naturally ponds to determine the best location to plant new hedgerows, or be used to determine if planting new hedgerows perpendicular to the river channel would create a physical barrier that prevents runoff being transported to the channel.

However, there are barriers to upscaling sub-field features and small-scale processes to the catchment scale due to the complexity of catchment systems. Catchments are unique and at the field scale the effects of sub-field features are spatially and temporally variable depending on topography, soil characteristics and on the individual rainfall event (Beven, 2000). At larger scales these effects become diffuse due to the cumulative impact of other land management and climatic signals (Blöschl et al., 2007). This does not mean that there is no influence on river flows just that it is not discernible (Wheater & Evans, 2009; Fiener et al., 2011). The spatial location and extent of land management features, the effect of them on the local river reach and the relative flow timings from the sub-field areas adds to the complexity as do disturbances caused by travel time in the reach (hydrodynamic dispersion) and the shape of the river network (geomorphological dispersion) (Rinaldo et al., 1991; Pattison et al., 2014).

7.5 Critical Evaluation of Method and Results

This section will review the problems associated with the methods used in this thesis. Large quantities of primary field and laboratory data were collected in this project and analysed using statistics which are associated with two type of error. The first type of error is random error which is inevitable and unpredictable and which create unknown uncertainty, but do not create bias. This includes errors due to faulty instruments, misreading, tiredness and the complexity of the natural system being studied.

Potential random errors in the field experiments included not using the equipment properly, keeping the equipment parallel during use, not fully inserting equipment into the depth required, the presence of stones and roots affecting the readings and differences in weather conditions on sampling days. These errors were reduced by practicing the techniques prior to undertaking them at site, being aware of factors that may have a negative influence on the results, repeating experiments when necessary, carrying out experiments at all sites on the same day where possible,

Potential random errors in the monitoring set-up included bad spacing and misalignment of probes, grass growth around pieces of equipment particularly the rain gauges, throughfall devices and stemflow collar, the deposit of debris creating clogging of funnels, wires becoming loose or being chewed by animals. Readings may also be affected by animals moving or landing on the equipment. These errors were reduced by again practicing the set-up of monitoring equipment for trial periods prior to installation at site, visiting the site regularly to trim vegetation and clear debris from equipment, burying the wires beneath the ground to shelter them from the weather and from animals.

Potential random errors in the laboratory work included handling errors, the position of the crucibles in the furnaces and ovens, cooling times, reabsorption of moisture, the loss of material during soaking and cracks in the core cutters. These errors were reduced by practicing the laboratory techniques on test samples prior to working on the real samples. The British Standard methods and guidance were followed on the use of laboratory equipment, how to handle and prepare samples as carefully as possible and when to remove samples which did not meet the standards required. All these errors are therefore not believed to have distorted the results gained from the data.

The second type of error is systematic errors which include sampling bias which leads to samples that are unrepresentative of the target population of interest. This can include sampling of an unrepresentative geographical site or sampling during an unrepresentative time of the year. It can also be affected by the sampling method or by a small sample size that does not represent the underlying variability in the population. Other systematic errors are caused by imperfect calibration of instruments, incorrect zeroing and drift. Systematic error was reduced by calibrating the instruments in the laboratory before installation and at the end of the monitoring period, correcting for temperature dependence in equipment using standard corrections. All these errors are therefore not believed to have distorted the results gained from the data.

There are a number of assumptions that have been made in this project. The stratified random sampling technique assumed that the visual identification of bare soils and ponded water is an indicator of soil compaction, which may, or may not have been true. The quadrat method used to assess the hedgerow roots assumed that the samples were representative of the study area as a whole. The TPS-2 device used to assess transpiration assumed that the leaf characteristics are homogeneous and that the leaf is exposed on the upper and lower surface. The ANOVA tests assumed that the populations measured had the same level of variance, that they were sampled from a normal distribution and that each data point is independent of the others.

Secondary data were also used to compare the results with other climatic datasets locally. These datasets included the Met Office MIDAS data, EDINA digimap data and NEXTmap data which are collected using calibrated instruments with a level of accuracy, that are based at sites that generally use well documented protocols and that have metadata.

7.6 Concluding Remarks

This thesis has quantified the impact of rural land management on soil hydrology and catchment response. It has provided new, good quality field scale data for an English catchment that is vital for representing sub-field scale variability in hydrological models and in improving the prediction of fluvial flood inundation. It is one of the first studies to measure the high spatial and temporal variability in soil conditions, compaction, runoff and drainage potential between inter-sites and intra-sites. It has also completed one of the first analyses of the impact of hedgerow features on soil hydrology and provided new knowledge of sub-surface and surface processes.

A future research aim would be to use the field data collected in this study to parameterise a hydrological model. A number of different scenarios could be tested including:

Soil compaction:

- The representation of the whole catchment under different levels of compaction (high, moderate and low levels)
- The representation of different levels of soil compaction based on the land use type in individual fields (arable and cattle, horse and sheep grazing)
- The representation of soil compaction around different sub-field features (tramlines, feeding troughs, field gates, tree shelters and open fields) across the catchment

Hedgerow hydrology

- The sensitivity of runoff to variations in the soil input parameters (bulk density, soil moisture content, saturated hydraulic conductivity).
- The representation of the past and current extents of hedgerows based on information from Ordnance Survey mapping
- The representation of different network densities of hedgerow features (very dense-less dense-none)

- The sensitivity of runoff to variations in the input parameters (soil moisture content, interception, evapotranspiration).

Other future work may include fieldwork to gather data that can be used to progress the science of soil hydrology and to parameterise numerical models including:

Soil compaction:

- Measuring soil compaction and soil properties following trafficking with different sized tyres and under different levels of inflation
- Monitoring stock within fields and determining the proportion of time that they spend in different parts of the field

Hedgerow hydrology

- Planting a new hedgerow and monitoring changes to soil properties and hydrological process as the hedgerow becomes more established
- Monitoring different species of hedgerows in the UK, or in other countries
- Monitoring hedgerows that are associated with ditches or banks to determine the effects on hydrology
- Determining how the density of other field boundaries (such as stone walls, ditch networks, grips) has changed over time, due to the increase in field size and how this change may have had an impact on local soil hydrology.

Appendix 1- Soil Tests

Table A-1: Ten master soil horizons and layers.

(Food and Agriculture Organisation of the United Nations, 2006).

Horizon	Colour	Composition
H	Dark brown/black	Dominated by organic matter (OM)
O	Dark brown/black	>20% OM, partially decomposed leaves, needles, twigs, moss, lichens
A	Darker than lower horizons, browns	Topsoil, mineral, rich in OM
E	Often lighter than A or B, maybe bleached	Mineral, concentration of sand/silt (coarser than B), lack of clay, iron
B	Stronger than A, browns/reds	Mineral, accumulation of clay, salts, silicon, iron, humus, carbonates from above, or removal of carbonates
C	Reduction = Grays, blues Oxidization = Yellows, browns, reds	Mineral, but can contain shells/coral, contains lumps of rock, unconsolidated
R	Depends on rock type	Bedrock strongly cemented together
I	Ice	Ice lenses/wedges >75% ice by volume
L		Limnic materials composed of organic & inorganic materials, deposited in water
W		Water layers in soils (lakes, tidal flats)

Table A-2: Particle shape, form and texture of coarse particles (>gravel sized).

(The British Standards Institution, 2015).

Shape	Very Angular	Sub-rounded
	Angular	Rounded
	Sub-angular	Well rounded
Form	Cubic	
	Flat / Tabular	
	Elongate	
Surface texture	Rough	
	Smooth	

Table A-3: Principle soil types - Particle size ranges.

(The British Standards Institution, 2015).

Name				Size range (mm)
Coarse soil	Gravel	Coarse gravel	CGr	20–63
		Medium gravel	MGr	6.3–20
		Fine gravel	FGr	2.0–6.3
	Sand	Coarse sand	CSa	0.63–2.0
		Medium sand	MSa	0.2–0.63
		Fine sand	FSa	0.063–0.2
Fine soil	Silt	Coarse silt	CSi	0.02–0.063
		Medium silt	MSi	0.0063–0.02
		Fine silt	FSi	0.002–0.0063
	Clay		Cl	≤0.002

Table A-4: Terms for mixtures of soil types.
(The British Standards Institution, 2015).

Secondary constituent term	Principle soil type	% secondary constituent
Slightly clay, Slightly silty AND/OR Slightly sandy, Slightly gravelly	GRAVEL and/or SAND	< 5
Clayey, Silty AND/OR Sandy, Gravelly	GRAVEL and/or SAND	5-20
Very clayey, Very silty AND/OR Very sandy, Very gravelly	GRAVEL and/or SAND	> 20
Slightly sandy or Slightly gravelly	GRAVEL or SAND	< 5
Sandy or Gravelly	GRAVEL or SAND	5-20
Very sandy, Very gravelly	GRAVEL or SAND	> 20
	GRAVEL / SAND	Equal portions
	CLAY / SILT	Equal portions
Very sandy, Very gravelly	CLAY or SILT	>65
Sandy, Gravelly	CLAY or SILT	35-65
Slightly sandy AND/OR Slightly gravelly	CLAY or SILT	<35

Table A-5: Soil structure terms – ped shape, face and orientation.

Term	Unit shape	Faces	Orientation
Granular/Crumb	Spherical	Curved, irregular	None
Blocky	Square/blocky	Flat-rounded	Both
Prismatic/Columnar	Longer faces vertically	Flat-rounded	Vertical
Platy	Flat/plate-like	Flat	Horizontal
Structure-less: Massive	Bonded mass		None
Structure-less: Single Grain	Individual particles	Curved	None

Table A-6: Mottled colours caused by drainage conditions in the soil.

Colours	Drainage	Water table depth (m)
No mottles – very bright soil colours	Very good	
Warm browns, reds, yellows and oranges	Good	>1.20
Pale & dark yellows, greys and rusty oranges	Seasonally poor	0.25-1.20
Pale & dark bluish greys, brownish yellows and rusty oranges	Seasonally swampy soil	<0.25

Table A-7: Abundance of mottles.
(Food and Agriculture Organisation of the United Nations, 2006).

Term	% Mottles
None	0
Very few	0-2
Few	2-5
Common	5-15
Many	15-40
Abundant	>40

Figure A-1: Chart to estimate proportions of mottles.

(1, 3, 5, 10, 15, 20, 25, 30, 40, 50, 75 and 90%).

(Food and Agriculture Organisation of the United Nations, 2006) .

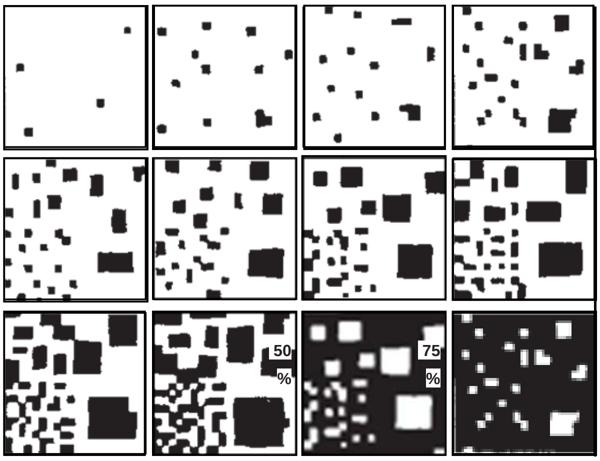

Table A-8: Terminology for calcium carbonate content in the soil and reaction due to hydrochloric acid.

(British Standards Institution, 2013).

Term	Reaction
Carbonate free	No reaction from HCI
Slightly calcareous	Weak/sporadic effervescence from HCI
Calcareous	Clear, but not sustained effervescence
Highly calcareous	Strong, sustained effervescence from HCI

Table A-9: Organic matter content of the soil.

(The British Standards Institution, 2015).

Term	Colour	OMC	Weight % of dry mass	Soil type
Slightly organic	Grey	Low	2-6	Mineral
Organic	Dark grey	Medium	6-20	Organic/mineral
Very organic	Black	High	20-35	Peaty loam/sand

Appendix 2 – Hedgerow Fieldwork

Table A-10: Dates when equipment was installed at Hedgerow Site (February 2014-October 2015).

			Winter 2013		*Summer 2014*						*Winter 2014*						*Summer 2015*						*Winter 2015*
		Equipment	**Feb-14**	**Mar-14**	**Apr-14**	**May-14**	**Jun-14**	**Jul-14**	**Aug-14**	**Sep-14**	**Oct-14**	**Nov-14**	**Dec-14**	**Jan-15**	**Feb-15**	**Mar-15**	**Apr-15**	**May-15**	**Jun-15**	**Jul-15**	**Aug-15**	**Sep-15**	**Oct-15**
Hydrological process	Climate	**Weather station**					17-30	1-15	30-31	✓	✓	✓	✓	✓	×	✓	✓	✓	×	×	×	×	
	Precipitation	**West side 0m**			28-30	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	1-28
		West side 1m			28-30	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	1-28
		West side 3m			28-30	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	1-28
		West side 10m			28-30	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	1-11	28-31	✓	✓	✓	✓	1-28
		East-side 0m			28-30	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		East-side 1m			28-30	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	×	×	×	17-31	✓	1-28
		East-side 3m			28-30	✓	✓	15-31	✓	×	×	×	×	×	×	×	×	×	×	×	×	×	×
		East-side 10m					10-30	✓	1-30	×	×	×	11-12	×	×	×	×	×	×	×	×	×	×
		Stemflow					17-30	✓	✓	✓	✓	✓	✓	✓	×	×	1-11	28-31	✓	✓	✓	1-29	
		Throughflow 1				28	1-10,17-30	✓	✓	✓	✓	×	×	✓	✓	✓	1-11	28-31	✓	✓	✓	1-29	
		Throughflow 2				28	1-10,17-30	✓	✓	✓	✓	×	✓	×	×	✓	1-11	28-31	✓	✓	✓	1-29	
	Temp.	**Top of hedge**									25-31	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	1-28
		Bottom of hedge				✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	1-28
	Trans.	**Sap flow meter**					17	15	23-26	12-14	15,16,17,18	25	6,7,8,9,30	2,3,4,7,10,11,12,13				19	4-18		17,18,19	28	
	Interception	**LWS 1 - East-side**						1-15	14-26	6-18	13-25	×	×	3-15	8-20	9-31	×	7-19,19-31	✓	1-13,14-31	✓	1-3	
		LWS 2 - Inside						1-15	14-26	6-18	13-25	×	×	3-15	8-20	9-31	×	7-19,19-31	✓	1-13,14-31	✓	1-3	
		LWS 3 - Top						1-15	14-26	6-18	13-25	×	×	3-15	8-20	9-31	×	7-19,19-31	✓	1-13,14-31	✓	1-3	
		LWS 4 - West-side						1-15	14-26	6-18	13-25	×	×	3-15	8-20	9-31	×	7-19,19-31	✓	1-13,14-31	✓	1-3	
	Soil moisture	**TDR - E0m 10cm**	26-28	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	26-31
		TDR - E1m 10cm	26-28	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	26-31
		TDR - E3m 10cm	26-28	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	26-31
		TDR - E10m 10cm	26-28	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	26-31
		TDR - E0m 30cm	26-28	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	26-31
		TDR - E1m 30cm	26-28	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	26-31
		TDR - E3m 30cm	26-28	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	26-31
		TDR - E10m 30cm	26-28	✓	✓	✓	1-17	×	×	18-30	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	26-31
		TDR - W0m 10cm	26-28	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	26-31
		TDR - W1m 10cm	26-28	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	26-31
		TDR - W3m 10cm	26-28	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	26-31
		TDR - W10m 10cm	26-28	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	26-31
		TDR - W0m 30cm	26-28	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	26-31
		TDR - W1m 30cm	26-28	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	26-31
		TDR - W3m 30cm	26-28	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	26-31
		TDR - W10m 30cm	26-28	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	26-31

Key							
✓	Installed for whole month	×	Equipment failure	1-28	Working within dates	▨	Equipment not installed

Table A-11: Experiment dates at the Hedgerow Site (April 2014-November 2015).

The grey boxes indicate that no experiments were undertaken.

	Experiments	**Apr-14**	**May-14**	**Jun-14**	**Jul-14**	**Aug-14**	**Sep-14**	**Oct-14**	**Nov-14**	**Dec-14**	**Jan-15**	**Feb-15**	**Mar-15**	**Apr-15**	**May-15**	**Jun-15**	**Jul-15**	**Aug-15**	**Sep-15**	**Oct-15**	**Nov-15**
Climate	**TPS-2 Unit - Transpiration**																		28	25	
Interception	**LAI application**																				10
	Throughfall																		28	25	
	Leaf litter																			26	
Soil properties	**Augering for bulk density, porosity & Ksat**			17	15	26	18	25			15	20	31		19	17	13				
	1m Cores - Soil horizons, drainage														28	18			28		
	Root density pits																			26	
	Hydrosense - Soil moisture	28			15		18	25			15	20	31			19			28	26	

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