Reduction of rainfall reaching the ground by deciduous trees on the edge of stands - a study into incremental wet canopy evaporation through storm events

Louise Emma Gill BSc. (Hons)

A thesis submitted for the degree of Master by Research in Environmental Science at Lancaster University, United Kingdom

December 2019

Centre for Global Eco-Innovation

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Abstract

Can deciduous trees be used to reduce hydrograph peaks? This is an intriguing question to scientists, charities, and the public alike and the answer is yes. It is beneficial to understand how hydrological processes are influenced by edge effects and differs from other studies that are 100+m into woodlands, due to the planting of narrow belts for natural flood management.

This research quantifies the WCE (Wet Canopy Evaporation) of a mature Chestnut tree through storms between May 2018 and April 2019, combined with manual weekly volumetric data from three Beech and two Oak trees in a narrow woodland on the Lancaster University campus. From the six trees studied, the WCE% during the measurement period was 41.97% of gross-rainfall, while the remainder of the gross-rainfall was partitioned into throughfall (54.39%) and stemflow (3.65%). The WCE% of the tree species (excluding the chestnut tree) are significantly higher than that found in other studies where measurements are taken 100s of metres into woodlands away from edge effects; but this data agrees with Herbst et al.'s (2006) findings relating to WCE of hedges. In part this is due to the greater ventilation of the canopy and stems. Although lower than during the leafed periods, WCE remained high from leafless branches and stems. It was also found that the WCE% decreases as storm size increases. The Frumau horizontal and vertical rain gauges (Frumau et al., 2011. Hydrological Processes 25: 499-509) found that horizontal rainfall caused under-estimation of gross rainfall collected by the tree, which was influenced by wind speed and direction. Negative WCE (i.e. larger throughfall than rainfall) was seen as the tree collected rainfall from a larger area. If corrected rainfall was known the WCE would be larger.

The Penman equation showed a poor fit, overestimating evaporation as it shows potential WCE. With little improvement in the utilisation of stores, the Rutter original underestimates evaporation that occurs. The Rutter Sparse model provided the best fit, but was still poor, underestimating evaporation. The Rutter Sparse parameters were altered showing the best fit altering the aerodynamic resistance to 5s/m rather than converting Hazelrigg weather stations wind speed. Alternatively, the canopy capacity was increased and throughfall coefficient decreased to produce a good fit, however these were calculated using the data collected suggesting the best alterations to the model account for the edge effect better by altering the aerodynamic resistance. The research highlights how model parameters representative of conditions at the centre of large woodland blocks should not be used to estimate WCE for narrow belts of trees. Indeed, narrow tree belts could be considered as potential 'hot spots' of evaporation requiring more direct measurements to understand their significance as a tool for removing net-rainfall from catchment systems during flood peaks.

Keywords:
Interception; Wet Canopy Evaporation and Change in Storage; Throughfall; Deciduous; Stemflow; Edge Effects; Modelling; Rutter Original; Sparse; Penman.

Declaration

I hereby declare that this thesis consists of original work undertaken solely by myself at Lancaster University; where the work of other researchers is properly acknowledged and referenced. The work reported in this thesis has not been previously submitted for a higher degree or other qualification in this or any other form at this or any other institution.

Signed: L.E.Gill Date: 18th December 2019

Name (Capitals): LOUISE GILL

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Alongside this I would like to thank the Lune Valley Rivers Trust especially Sarah James (nee Littlefield) and Louisa Blundall in supporting this project. Also, to the Woodland Trust for financial support and Pete Leeson for further support.

A huge thank you to the support and guidance from the Centre for Global Eco-Innovation staff and the ERDF funding for the project, which without this project would not have been possible.

Thanks go to Lancaster University for allowing the research to be undertaken on campus particularly the support of Ian Sturzaker from the Estates department.

On a personal note I would like to thank my husband, Ben Gill and two girls, Annabel and Lucy, for their support, especially when dashing out to collect data after a storm. Finally, a big thanks to those that helped look after my girls while I collected data, undertook research and wrote my thesis particularly Alison Gill and Jill Phillips and especially the whole team at Lancaster University Pre-school whom without this would not have been possible (including Tasha, Sammy, Amy, Helen, Chris, and Gina).

This is in memory of my father, Frank Phillips who died during my analysis and write up of my Thesis. You will be missed.

Preface

This project was undertaken as part of a collaboration between the Lune Rivers Trust, Woodland Trust and Centre for Global Eco-Innovation (CGE). This was supported financially by the Woodland Trust and the European Regional Development Fund (ERDF). This project was supervised by Dr Nick A. Chappell and Professor (Emeritus) Keith Beven of Lancaster Environment Centre.

The aim of the research is to gain scientific evidence into the importance/effectiveness of trees at reducing flood peaks and therefore the benefit to planting trees. This will allow the companies above to provide evidence for tree planting to stakeholders such as farmers and other landowners to encourage, as part of the Woodland Trust upland tree planting scheme, and the Rivers Trust natural flood management schemes to reduce downstream flood peaks. The data will also be utilised in parameterisation for the Cumbria Flood model (Chappell et al., 2017). This research and implementation are particularly important due to the numerous flooding events which have occurred downstream in the Lune Catchment including Storm Desmond and November 2017.

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Abbreviation	Meaning
C	Canopy storage i.e. how much is stored in the canopy
D	Drainage from the canopy
DTF	Direct throughfall
E	Evaporation from Penman Equation
GHG	Greenhouse Gas
NFM	Natural Flood Management
nRF	Net Rainfall
p	Throughfall coefficient
RF	Gross Rainfall
rWCE	Rutter predicted wet canopy evaporation
S	Canopy capacity i.e. what it can hold
SF	Stemflow
TF	Throughfall
TS	Trunk store
WCE	Wet canopy evaporation
WCE%	Wet Canopy Evaporation as a % of gross rainfall
WCEΔS	Wet Canopy Evaporation and Change in Storage

1. Introduction

1.1 Context

During the wettest winter in almost 250 years (winter of 2017/8 (LEC, 2018)), February 2020 storms, and Storm Desmond in 2015, there were major flooding events throughout Lancashire and Cumbria causing large economic and emotional damages. The economic damages from storm Desmond alone were estimated by KPMG and BBC News (2015) to exceed £5bn, with 2500 homes flooded at 229 separate communities across Lancashire, and power lost to thousands of residences. The local damages of storm Desmond, Eva and Frank were estimated as £1.3bn by the Association of British Insurers. To gain further investment in Lancashire to ensure stability and economic growth relies on a resilient network where flooding is minimised to ensure the community can built on and maintain a skilled workforce.

Flooding events regularly renew the interest of the nation (with the most recent being Storms Ciara, Dennis and Jorge in February 2020) in the methods used for flood mitigation; in particular the benefit that natural flood management (NFM) can provide in relation to reducing flooding along with the other benefits these methods can bring. The growing use of NFM measures can be seen with their increasing use in Government papers and Environment Agency's strategies to reduce flooding. The necessary wide-scale implementation of these measures is, however, hampered by the lack of credible scientific studies to quantify the magnitude of the hydrological benefits.

The proposal's focus was on the Lune catchment after it recorded the largest flood discharge of an English river during Storm Desmond in December 2015. This resulted in severe flooding in Lancaster with thousands of residents without electricity. The project focused on deciduous trees as the form of NFM that can be used to mitigate flooding. Here the edge effects of trees on the edge of woodlands for wet canopy evaporation and storage (WCE&S) were quantified. Models were used to look at the processes occurring and determine if edge effects can be modelled.

Initial projects involving planting of native woodland indicate that the benefits outweigh the initial costs of planting (Pilkington et al., 2015). However, the person(s) gaining the benefit and putting in the measures are often not the same. Therefore, implementing planting schemes requires Rivers Trusts and other stakeholders to work with farmers and landowners. The actual benefit of trees is also still to be quantified at a process scale and analysis of species preferences is required, to ensure scientifically factual arguments can be put forward in favour of NFM and provide evidence to the benefit of tree planting for funders. Therefore, this collaborative Masters project was supported and funded by the Lune Rivers Trust and the Woodland Trust to ensure they have access to vital data required in their day-to-day work, working with Lancaster University and the Centre for Global Eco-Innovation.

The Woodland Trust are now working with Lancaster City Council, who have declared a Climate Emergency, to plant a million trees across North Lancashire as part of the Northern Forest Project (Lakin, 2019). This research will allow these bodies to persuade more landowners of the importance of planting trees and gain further funding. Increased planting will also increase carbon sequestration in the Lune Catchment and hence support Lancaster City Council with their declared climate emergency.

This project also supports the Environment Agency's Working with Natural Processes research programme to develop an evidence base for NFM benefits to show that investment in green infrastructure can have a cost saving and carbon capture role in infrastructure planning and management and, rather than building more carbon intensive concrete flood defences downstream, can provide a sustainable approach to protecting infrastructure.

Below is information on the businesses with input into the project:

1.1.1 Centre for Global Eco-Innovation

This is a Centre for Global Eco-Innovation (CGE) project. CGE are a low carbon innovation hub for Lancashire based within Lancaster Environment Centre at Lancaster University. They aim to deliver new products and services, which support a transition towards a "low carbon economy" and therefore can demonstrate a measurable environmental benefit, and economical value. Their aim is to address the pressing regional need for reducing costs of flooding while helping to deliver GHG capture, which led to this project on the Lune Catchment.

1.1.2 The Woodland Trust

The Woodland Trust are a woodland conservation charity who aim to increase the tree cover in England through the creation, protection and restoration of native trees. This project will provide data that can be used to gain funding for tree planting and evidence for their funders.

The Woodland Trust have 6 key principles, one of which is "We take account of ecosystems, landscape and catchments", which encompasses the trees' ability to affect water catchments through slowing the rate of runoff, increasing infiltration, and roots binding the soil together decreasing sediment loss. Trees improve the water quality and reduce flood risk, but by how much?

The Charter for Trees, Woods and People was created in November 2017 due to an outcry from the public in relation to the public bodies bill in 2010. This is a follow on from the Charter of the Forest and Magna Carta in 1297. One of the 10 principles of the Charter is to "Strengthen our landscape with trees". Within this principle is the following statement "Rising water swells and floods, so strong riverbanks with roots… to slow the flow of nature's deluge". This research is following the charters' principles and proving the importance of trees in relation to water.

The Woodland Trust have already planted trees/woodlands in several locations in Cumbria as well as 66,000 trees on Tebay Common in the headwaters of the Lune. The 123ha was formerly heavily grazed (McEwan et al., 2016). This open scrubby wood provides shelter for stock and wildlife, increase water percolation and reduces high flows.

1.1.3 The Lune Rivers Trust

The Lune Rivers Trust is the small-medium sized enterprise that works with CGE. They are dedicated to the conservation, protection, rehabilitation and improvement of the River Lune and its tributaries (**Error! Reference source not found.**). The catchment's sources are in Cumbria, Yorkshire and Lancashire and enters the sea at Morecombe Bay. The Lune Rivers Trust are committed to working with landowners and farmers to plant trees and utilise other NFM methods to reduce flooding and deliver carbon capture.

The Lune Rivers Trust has catchment maps indicating the response time of sub-catchments and areas where the realistic amounts/type of NFM can be implemented. This is to ensure the Rivers Trust can improve the land, rivers and wetlands at a catchment or river basin scale.

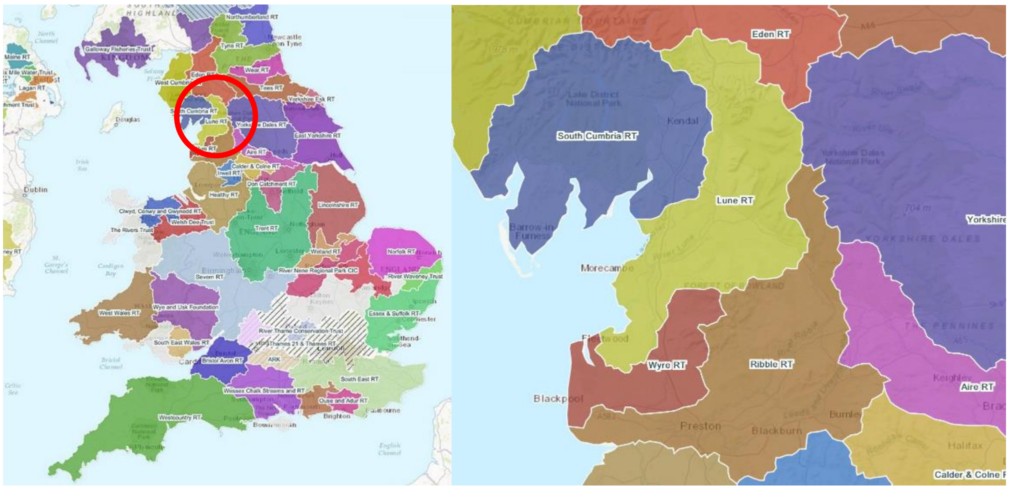


Figure 1-1:Map of the location of the Lune Catchment (The Rivers Trust, 2019)

1.2 Current knowledge

Studies of wet canopy evaporation (WCE), i.e. evaporation during wet canopy conditions, are limited within the UK, especially for deciduous trees (Law, 1956; Chappell and Kennedy, 2009), and specifically for those on the edge of stands. This study therefore examines the collection of high frequency throughfall (TF) and rainfall (RF) data to determine WCE&S, unique to the UK (Hankin et al., 2016). The project gathered data relating to the importance of WCE on narrow tree belt. These types of tree belts are more frequently utilised as part of NFM, to reduce rainfall entering the catchment system; and hence reducing flood peaks. Such NFM measures are being put in place locally to reduce flood peaks and mitigate future flooding.

It is thought that native tree planting has a positive impact on flood mitigation (e.g. enhanced interception/evaporation even in winter, reduced overland flow, and enhanced infiltration (Bonell et al., 2010)). Trees have a higher evaporation rate than other vegetation (e.g. grass) as ventilation is larger than other vegetation. Trees have a greater interception and the increased ventilation causes more water to be evaporated from the leaves and branches, hence removing more water from the catchment. On a large enough scale, trees could reduce hydrograph peaks.

Unlike this study that focuses on trees at the edge, previous studies specifically looked at trees within a woodland. Law's (1956) coniferous tree WCE experiment was located 24km to the East of here. Law found higher WCE than others due to being located closer to the edge of the woodland than other studies. The magnitude of the benefit trees planted in belts can provide is currently unknown, and therefore the parameterisation of models is based on assumption rather than measurements.

1.2.1 Overview

From a water management perspective, the way water flows on hillslopes is of interest in controlling:

- water yield (flood protection, drought mitigation, and agricultural land drainage),
- water quality,
- soil water status (trees which produce drier antecedent conditions).

It is also perceived that science at the hillslope scale can help engineers in the prediction of river flow and greater reliability of data used in models (Beven, 2006). Modelling has been used to determine the best model fit allowing for processes that occur to be considered and provide data for model parameterisation of local scenarios on whether and where to plant trees to reduce flooding.

The modern river landscape is different from what nature intended. There are fewer wetlands and a greater area of hard surfaces increasing surface runoff and the speed the water reaches the river, as well as straightening of rivers causing increased speed water travels through the river. This leaves rivers less able to cope with the rainfall we experience and will see in the future leading to more flooding. Flooding is a natural process, which is important for healthy rivers creating habitats for wildlife, which move nutrients and cleans gravel, but can be devasting for communities.

Equation 1-1 determines the amount of water that enters the river; therefore, altering the storage and evaporation will affect the potential for flooding.

Equation 1-1 Amount of water that enters rivers

$$Runoff = precipitation - evaporation \pm \Delta Storage \qquad (Jones, 1997)$$

The water can be stored in the canopy, depressions, surface detention, groundwater, litter, pipes, and soil moisture. The speed at which runoff enters the rivers is altered by changing the processes by which water enters the river. Processes and flow by which rainfall enters the rivers includes: drip, groundwater, infiltration, litter flow, melt water, overland flow, precipitation, channel precipitation, pipe flow, return flow, stream flow, saturation overland flow, spring flow, stemflow, and throughfall (Jones, 1997). Rainfall is removed from the system by evaporation of intercepted water and transpiration.

Pilkington et al. (2015), suggests that NFM can have a significant effect on reducing flood peaks by 4 % or more for a 1 in 25-year flood occurrence. Forest cover lowers and delays flood peaks but this is mostly limited to small and moderate rainfall events. However, the effect on the hydrograph is less well understood at catchment scale (Rogger et al., 2017).

Methods of NFM include:

- strategic planting of trees and reforestation,
- installation of leaky barriers upstream by man or beavers, although the latter can lead to unpredictable damming,
- Paludiculture-improving, restoring and increasing wetlands/marshlands, peatlands, and moorlands to increase habitats and wildlife and reduce pollutants,
- River Restoration-creating their natural forms/reprofiling including re-meandering and removing concrete barriers to allow flooding into flood plains. This cannot be undertaken to the length of the river but can be to sections.
- Increase and protect flood plain and buffer zones,
- Changing farming techniques to improve soil conditions (deep cultivations and decreasing compaction),
- Decreasing connectivity by adding buffer zones, ponds, swales and rock horseshoes to slow the flow
- Maintaining gullies and channels by removing vegetation and debris to increase their capacity

Law (1957) concluded that at an annual scale the forests had substantially higher rainfall interception and, therefore, produced less drainage and streamflow (van Dijk et al., 2015). This shows the larger potential trees could have to reduce a flood peak over grasslands if this translates to all event sizes (Hankin et al., 2016). Evaporation from trees being higher than grasslands was also agreed by Muzylo et al. (2009). Trees have multiple benefits including altering hydrological pathways to reduce flooding but can also:

- benefit water quality by reducing sediment and pollutant input from farmland, which reduces chemical application to fields,
- more sustainable management of water resources through reducing surface water runoff, increasing infiltration rates (Rogger et al., 2017), recharging groundwater resources (Environment Agency, 2017),
- provide income for farmers,
- shelter for sheep (cool in summer and warm in winter),
- reduce soil loss (Carroll et al., 2004),
- Levia and Frost (2006) stated that wooded areas are also a sink for global carbon while also affecting the distribution of solar radiation, surface albedo, sensible and latent heat flux, and the hydrologic cycle.

It was determined at Pontbren catchment in Wales that planting tree shelterbelts on sheep pasture can increase infiltration by 60 times (Keenleyside, 2013). Forested slopes can also delay rainfall by as much as 11 minutes and reduce discharge rate to only 16% of the rainfall rate (Brookes et al., 1994 in Armson et al., 2013). It has also been stated (McEwin et al., 2016) that tree planting is required now to ensure that the landscape can offer these benefits by the time greater climate change occurs in 20-30 years. However, the location of flood management methods needs to be carefully planned to ensure slowing of one sub-catchment does not lead to peaks coinciding downstream causing an increased risk of flooding.

Isolated trees and farm-coppices provide a significant proportion of the UK tree-cover (Brown and Fisher, 2009) in addition to forests. It has also been noted by Armson et al. (2013) that single trees in Urban areas also reduce surface runoff (by 62% in asphalt due to interception and infiltration into the tree pit) and hence flood peaks and should not be overlooked.

Trees and wooded areas are extremely important in relation to water dynamics as they:

- Increase infiltration via the roots horizontally and vertically, (Liang et al., 2011; Beven and Germann, 1982) which were removed through agri-intensification (Rogger et al., 2017).
- Reduce overland flow,
- Reduce connectivity and conveyance on the surface,
- Increase evapotranspiration of water and storage in the canopy compared to other vegetation types
- Reduce antecedent soil moisture (Rogger et al., 2017)

The importance of NFM has been reiterated further by the Environment Agency within their Draft National Flood and Coastal Risk Management Strategy for England (Environment Agency, 2017). This requires the Lead Local Flood Authorities to 'update their local flood risk strategies, use NFM to mitigate flooding, to enhance the resilience of our environment to future flooding, work with farmers/landowners to identify opportunities to manage agricultural practices, develop guidance setting out best practice on local flood infrastructure management and record keeping'.

Rivers trusts are trying to expand the use of NFM as advised by the Environment Agency (2017), while, the Woodland Trust and Lancaster City Council are expanding the Northern Forest Project by planting 1 million trees in North Lancashire (Lakin, 2019). However, this requires scientific reasoning to back up the assumptions to encourage farmers and landowners to work cooperatively to benefit those downstream. This scientific data will be able to influence changes in land management practices, which are required as part of the draft strategy (Environment Agency, 2017).

1.2.2 Wet Canopy Evaporation and Storage

A tree can partition rainfall into throughfall and stemflow, causing water to be funnelled around a tree base, and can preferentially divert rainwater in soil layers, causing water to be funnelled around tree roots (Liang et al., 2011).

Only sparse data has been collected in the UK and little data has been gathered in the Lune Basin (Chandler and Chappell, 2008), where major flooding has occurred and requires mitigation. Available data is also limited by sampling and methods used. In particular, the flow pathways during high rainfall events need to be looked at in more detail (Helvey and Patric, 1965).

Definitions of terms utilised within this document:

- *Gross Rainfall (RF) is the total amount of rainfall that reaches the ground in the open.*

- *Net rainfall (nRF) is the amount of water that reaches the ground through the tree canopy. This falls through the canopy (direct throughfall) and includes drip from the branches and leaves (indirect throughfall), and stemflow from the trunk.*
- *Throughfall (TF) is the "precipitation that falls directly through vegetation to the ground surface below, and falls off the leaves after interception (Park, 2012), i.e. drip".*
- *Stemflow (SF) is the component of gross rainfall that reaches the ground via flowing down the tree trunk/stems to the ground. Stemflow has been overlooked in the past in relation to its importance to both hydrology and biogeochemistry; However, scientists are now becoming more aware of its importance (Levia and Germer, 2015). Germer et al. (2010) believes that stemflow should not be discounted as has been in many studies as trees are a concentrated point source of water.*
- *WCE is defined as the component of gross rainfall that never reaches the ground beneath the woodland canopy; stored within the canopy for short time periods then evaporated. When measured over longer integration periods it equated to that returned to the atmosphere as WCE (Hankin et al., 2016; Chappell et al., 2006).*

Interception loss cannot be directly measured therefore is calculated as follows (Helvey and Patric, 1965):

Equation 1-2:Interception loss/WCE

$$Interception\ loss = Gross\ Rainfall - (Stemflow + Throughfall)$$

Van Dijk (2015) states up to half of gross rainfall returns to the atmosphere via WCE and is a major cause of the difference in water use between forests and short vegetation, the process of which is still poorly understood. Throughfall is affected by numerous factors included meteorological conditions, canopy structure and season (Levia and Frost, 2006). Throughfall is also important for investigations into soil erosion, soil moisture on the forest floor, solute input and runoff generation (Ziegler et al., 2009).

Initially it was believed that deciduous trees had limited effect on reducing rainfall during the winter. Although there is a measurable reduction in interception loss in winter due to leaf fall, the effect is commonly surprisingly small (Reynolds and Henderson, 1967). In winter WCE can be 10-20% of gross rainfall for prevailing conditions in the UK (Hankin et al., 2016).

There are varying opinions in previous work carried out as to whether stemflow is insignificant or not; with most suggesting stemflow is usually 1-2% (Chappell et al., 2001; Sinun et al., 1992) of gross rainfall especially in coniferous and tropical stands. Temperate deciduous stands usually have 3-6% stemflow (Price and Carlyle-Moses, 2003; Chappell et al., 1990); except for beech which is higher and fir that is negligible (Hewlett and Nutter, 1982). Stemflow is affected by tree size and shape (branch cover, angle, number and foliage (Levia and Germer, 2015), species, crown area, epiphyte cover (Oyarzun et al., 2011), and climate. Sinun et al. (1992) found that one tree produced more stemflow when it lost its leaves, making this a potentially important mechanism in deciduous woodlands. Levia and Germer (2015) reviewed stemflow studies from 2003 to 2015 and concluded that stemflow is increased with branch cover, branch angle, branch number and less foliage, supporting Sinun et al.'s (1992) assumption.

Oyarzun et al. (2011) found throughfall is correlated with mean quadratic diameter and varies due to canopy density and drip (Navar, 2011). The difference in proportion of throughfall and WCE was found to be significant only in winter by Oyarzun et al. (2011).

Looking at previous studies Jones (1997) found that WCE, stemflow and throughfall vary considerably between evergreen and deciduous woodlands, with WCE higher in coniferous woodlands, whereas stemflow is higher in deciduous woodlands. Loss of water to WCE has been reported to be up to 30-40% of the gross rainfall where there are frequently wetted dense canopies in windy environments (Calder, 1990 in Shaw et al., 2011). There are varying opinions on the effect of season on throughfall and stemflow between the types of woodland.

Horton's (1919) study was the start of interception studies. There are few studies into the magnitude of stemflow, throughfall and WCE within deciduous forest in the UK. Studies into the effect of trees in the UK includes the Coalburn catchment study, which looked at the effects of planting coniferous trees on moorland (Institute of hydrology, 1994). Coniferous trees were also looked at in the Plynlimon catchment study (Institute of Hydrology, 1977 and Kirby et al., 1991), which looked at the stemflow and throughfall and was the longest running investigations into flooding and trees. At the Pontbren catchment study, mixed deciduous trees were strategically planted in shelter belts. The project found significant results when comparing woodlands to grassland but is irrelevant at a large scale. Studies looking at the interception of deciduous trees in the UK are summarised by Hankin et al. (2016) in table 1.1. Other notable studies in the UK looking at the hydrological impact of trees include:

- Beech and Ash in Hampshire in the 1980s (Neal et al., 1993)
- Ash in Northamptonshire comparing woodland to grassland drainage in the late 1980s to early 90s (Neal, 2013)
- Clipstone Forest relating to the recharge of the ground water aquifer (Calder et al., 2002)

This is the only deciduous tree interception study in the UK with high frequency data of edge effects that has been collected. Many more studies have been undertaken within rainforests in Asia and South America, which look at the effect of logging on the ecosystem (Chappell et al., 2001; Juvik et al., 2011).

Stemflow has also been studied for many reasons from chemistry and water quality to determining water fluxes such as interception loss. Even where stemflow is small it can still have a significant effect on the soil moisture (Lei et al., 2016). Navar (2011) also found that in large rainfall events stemflow contributes to the flow pathways that allow for recharge of the aquifers and replenishes soil moisture 4.5 times more than incident rainfall while replenishing the soil water around roots for transpiration.

Other international studies of throughfall, stemflow and WCE for varying tree type vary considerably and can be seen in Figure 1-2 and with wet canopy evaporation being between 6-50% but mainly between 11-30% of gross rainfall .

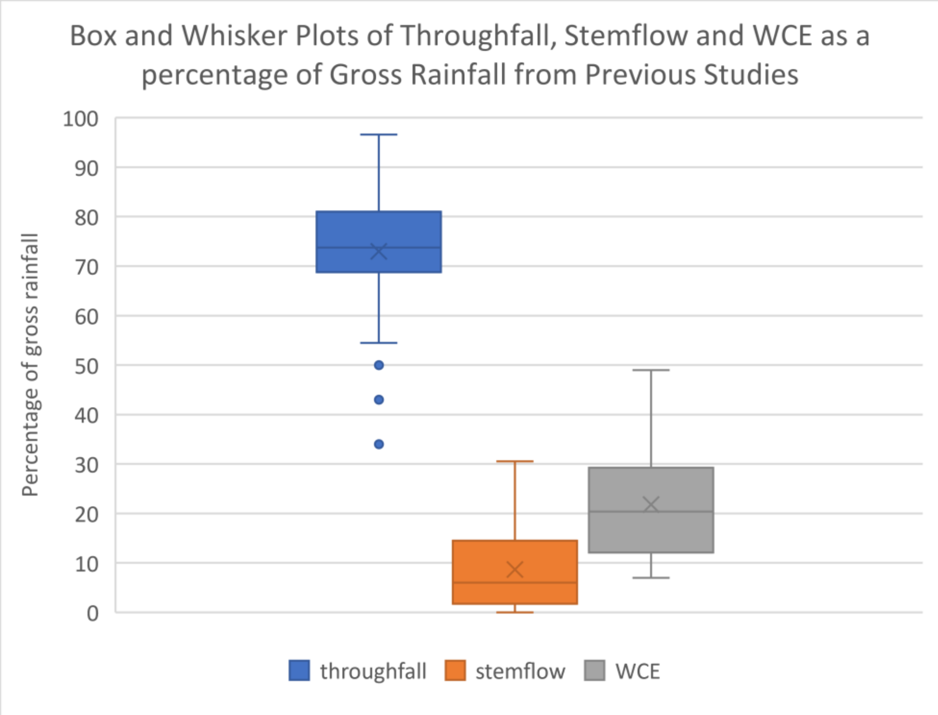


Figure 1-2:Box and whisker plots of throughfall, stemflow and WCE in previous international studies from 1948-2017 of deciduous and coniferous trees. shows this data in more detail.

Table 1-1:Stemflow, throughfall and interception loss published in papers

Paper	**Throughfall** (% of RF unless stated)	**Stemflow** (% of RF unless stated)	**Interception loss** (% RF unless stated)	**Other Information**
Kettridge (1948)	-	-	6-48% gross rainfall intercepted	Hardwoods
Helvey and Patric (1965)	-	-	-	5% uncertainty
Ford and Dean (1978)	43%/57% (Dec-Mar)	27%	30 / 15% in Dec-Mar	Greskine Forest, SF measured on 10 trees; TF measured at greater density
Peterson and Rolfe (1979) (in Levia and Frost (2006))	80-96.1%	-	-	Oak Hickory Forest
Hewlett and Nutter (1982)	-	1-2% except in beech forests where it may be 5-8%. It is hydrologically	-	Various forest types

		hydrologically negligible in spruce and Fir		
Anderson and Pyatt, (1986) in Johnson (1990)	82% of net precipitation	18% of net precipitation	29% of gross precipitation	Kielder
Anderson and Pyatt (1986) in Johnson (1990)	98% of net precipitation	2% of net precipitation	49% of gross precipitation	Kielder Sitka Spruce
Hudson (1988) in Johnson (1990)	82% of net precipitation	18% of net precipitation	25% of gross precipitation	Plynlimon
Chappell et al. (1990)	-	5%	Interception and transpiration loss from the canopy is 35%. This has been noted by others to be 5-17%,	Coniferous UK Forest
Johnson (1990)	96% of net precipitation	4% of net precipitation	28% (varies throughout the year with largest in summer up to 79% and lowest in winter down to 0%)	Balquhidder
Masukata et al. (1990) (in Levia and Frost (2006))	64.9-73.1 %	-	-	Evergreen Broadleaved Forest
Kirby et al. (1991)	81%	19%	29-32% mainly interception and less transpiration	Coniferous, UK <2% uncertainty The study showed that coniferous forests evaporate more water than grasslands (15-17% from transpiration).
Cape et al. (1991) in	Scots Pine 58% ±7% for 1st year	-	-	Devilla Forest, in northern Britain. *Pinus sylvestris* L. (Scots

Levia and Frost (2006)	51% ±6% for 2nd year Larch 81% ±10% for the 1st year and 73% ±9% for the 2nd year			pine) and *Larix decidua* L. (larch) over two successive years of measurement using a series of fixed gauges
Sinun et al. (1992)	80.7%	1.7%	17.4%	Danum Valley Borneo – rainforest
Soulsby and Reynolds, (1994)	79%	8%	13%	Oak stand with some birch and rowan
Jones (1997) Based on data from Geiger (1957)	Temperate Mid-Latitude Coniferous (Fir): • Summer– 70% • Winter - 73% Beech: • Summer- 67% • Winter – 73% Subtropical primeval Forest, Brazil • Annual- 34%	Temperate Mid-Latitude Coniferous (Fir): • Summer- 1% • Winter – 1% Beech: • Summer– 17% • Winter – 17% Subtropical primeval Forest, Brazil • Annual – 20%	Temperate Mid-Latitude Coniferous (Fir): • Summer- 32% • Winter- 26% Beech: • Summer-16% • Winter -10% Subtropical primeval Forest, Brazil • Annual- 25% intercepted and 18% wetting bark	Various Forest types
Price et al. (1997) (in Levia and Frost (2006))	75.8 %	-	-	Black Spruce forest
Burghouts et al. (1998) (in Levia and Frost (2006))	81%	-	-	Bornean Rainforest
Lin et al. (2000) (in Levia and	91.6%	-5	-	Subtropical rainforest

Frost (2006))				
Huber and Iroume (2000)	62-80%	1-7%	19-37%	Broadleaved
Huber and Iroume (2000)	74%	4%	22%	Evergreen
Chappell et al. (2001)	91% These rates were, however, reduced to between 80%–86% beneath representative plots of moderately impacted to creeper-covered, highly damaged patches of forest.	<1%	8%	lowland dipterocarp forest
Rodrigo and Avila (2001) (in Levia and Frost (2006))	72.1-75.5 %	-	-	Mediterranean Holm Oak Forest
Iroume and Huber (2002)	79%	7%	14%	Broadleaved Native, Southern Chile
Iroume and Huber (2002)	72%	6%	22%	Douglas Fir, Southern Chile
Bidin et al. (2003)	-	-	7%	Undisturbed stand (rainforest)
Price and Carlyle-Moses (2003)	77.5 ± 1.0 %	3.7 ± 1.3 %	18.8 ± 3.8 % (found larger in storms)	Natural Temperate Deciduous Stand, Ontario Canada
Chuyong et al. (2004) (in Levia and Frost (2006))	96.6%	-	-	African Rainforest

Lilienfein and wilcke (2004) (in Levia and Frost (2006))	75-85%	-	-	Pinus caribaea plantation
Chappell et al. (2006)	86%	-	-	Baru, Malaysia, rainforest
Levia and Frost (2006)	*Pinus* spp 69% ±5% *Betula papyrifera* Marsh. (white birch) was 83% ±5%	-	-	forested plot in central New Brunswick, Canada
Staelens et al. (2006)	Annual 71% Dormant 81% Growing 63%	Annual 8% Dormant 10% Growing 6%	Annual 21% Dormant 9% Growing 31%	Deciduous Stand- 1 beech tree
Herbst et al. (2008)				WCE study in Grimsbury Wood, Berkshire, UK of leafed and leafless Oak and Birch
Ziegler et al. (2009)	82% with variations due to drip in the canopy (near tree bases of large trees and canopy edges) but no obvious spatial structure	-	-	Thailand - rainforest
Germer et al. (2010)	-	8 ± 1.8%	-	Tropical rainforest – palm trees
Juvik et al. (2011)		< 1 %	-	Hawaii - rainforest
Oyarzun et al. (2011)	64-80%	0.3-3.4%	11-36%	Chilean Temperate Rainforest of old growth evergreen and secondary deciduous native forests
Safeeq and fares (2014)	43.3-56.5%	33.9-3.6% (high value due to smooth bark, steep branches and	23-45%	Hawaii Rainforest

		stem density		
González-Martínez et al. (2017)	-	4.5% of which 70.1% was the understory, 10.6% small trees and upper canopy trees 19.3%	-	Humid Tropical Rainforest

Of the limited number of WCE studies undertaken in the UK, very few were for deciduous trees. Rainfall interception in the winter was thought to be insignificant e.g. Staelens et al., (2006) found 9% during leafless compared to 31% during the leafed period. However, more recently the leafless periods have been shown to be important (***Error! Reference source not found.***). Jones (1997) found a small difference of 26% to 32% between the leafless and leafed periods. Neal and Rosier et al., (1990) suggest anywhere from 5 to 50% can account for all extremes in leafless trees, which is likely to be magnified where a woody understory is present. This variation is agreed by Hankin et al. (2016) and can be seen in **Error! Reference source not found.** and **Error! Reference source not found.**. These measurements were collected in the middle of the woodland apart from Law (1956) and Herbst et al. (2006) study on hedges, which were closer to the edge/on the edge. The largest value (40-50%) belongs to open hedges, due to their interception of horizontal rainfall. Wet canopy evaporation of deciduous trees is found to be lower than that of coniferous trees likewise in the dormant phase than growing season.

Table 1-2:WCE rates for leafless deciduous trees in winter (Hankin et al., 2016).

Table 6-3: Wet-canopy evaporation: rates for leafless deciduous trees plus shrubs in winter

% P (by rank)	Dominant species	Reference	UK/Europe
40-50%	hawthorn (hedge)	Herbst et al (2006)	UK
36%	oak/birch	Noirfalise (1959)	Continental Europe
29%	hornbeam	Leyton et al (1967)	UK
22.5%	oak	Vinke et al (2005)	Continental Europe
19.8%	oak/birch	Herbst et al (2008)	UK
15.1%	beech/hornbeam	Aussenac (1968)	Continental Europe
14%	beech	Reynolds & Henderson (1967)	UK
12.1%	mixed	White and Carlisle (1967)	UK (Cumbria)
12%	oak coppice	Thompson (1972)	UK
11%	oak	Dolman (1987)	Continental Europe
10.5%	hornbeam/oak	Schnock (1969)	Continental Europe
10%	oak/beech	Staelens et al (2008)	Continental Europe
9.9%	oak	Carlisle et al (1965)	UK
7%	beech	Gerrits (2010)	Continental Europe

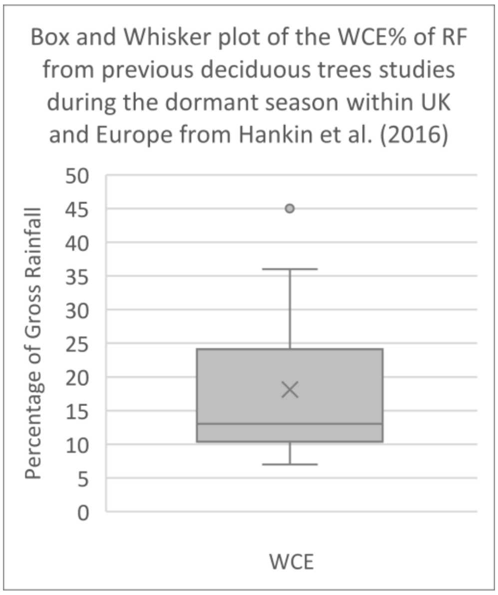


Figure 1-3:Box and whisker plot of the WCE% of gross rainfall for deciduous trees within the UK and Europe during the dormant season according to Hankin et al., (2016).

Table 1-3:WCE in European and UK Studies for leafed and non-leafed periods. Non-leafed periods are found in Hankin et al. (2016).

Reference	Species	Location	Rainfall Vol. (mm)	Leafed WCE (%)	Leafless WCE (%)
Gerrits (2010)	Beech	Luxembourg	792	15	7
Carlisle et al. (1965)	Oak	UK (Bogle Crag Wood, Cumbria)	1714	16.9	9.9
Staelens et al. (2008)	Oak/Beech	Belgium	755	31	10
Schnock (1969)	Hornbeam/Oak	Belgium	966	22.3	10.5
Thompson (1972)	Oak Coppice	UK (Oxfordshire)	673	24	12
White and Carlisle (1967)	Mixed	UK (Meathop Wood, Cumbria)	1200	16.7	12.1
Reynolds and Henderson (1967)	Beech	UK (Oxfordshire)	unknown	18	14
Aussenac (1968)	Beech/Hornbeam	France	719	18.6	15.1
Doman (1987)	Oak	Netherlands	Unknown	Unknown	15.6
Herbst et al. (2008)	Oak/Birch	UK (Berkshire)	773.1	29.3	19.8
Vinke et al. (2005)	Oak	Belgium	960	30.6	22.6
Leyton et al. (1967)	Hornbeam	UK (Oxfordshire)	447	57	31
Noirfalise (1959)	Oak/Birch	Belgium	877	23	36
Herbst et al. (2006)	Hawthorn (Hedge)	UK (Berkshire)	1350	57	49

There is a gap in research in relation to meteorological effects on throughfall (Levia and Frost, 2006).

Many scientists believe stemflow to be insignificant, whereas others are of the conclusion stemflow can be significant is some environments and is particularly important in relation to the input of rainfall to the ground.

Iida et al. (2012) believe RF, TF and SF have been underestimated and hence interception overestimated due to the use of tipping buckets, which requires correction with calibration regression equations. WCE (i.e. the rainfall that is caught by the tree canopy or branches and evaporated) is one of the most underestimated processes in rainfall runoff analysis where WCE often gets ignored or lumped with evapotranspiration (Safeeq and Fares, 2014). Evapotranspiration is the evaporation of the water intercepted by the leaves and branches as well as the water lost from within the tree that is collected by the root through the trees leaves (transpiration). This, along with the relatively few studies conducted within the UK and the potential of utilising trees to mitigate flooding led to this project, looking at the interception of trees on the edge.

1.2.3 Measurement Methods Used

There are several methods of measuring the benefit of trees include:

- Using gauging structures (e.g. V-notch weirs) to measure discharge/time (hydrograph) before, during and after an intervention. This infers the change in streamflow produced by the trees.
- Measuring surface water runoff before and after planting by measuring the input (gross rainfall) and output in controlled boundary experiments where water is prevented escaping. Beven (2006) determined that these were not accurate, as an impermeable bedrock cannot be assumed. This would not be an applicable method to the Lune Basin which lies on Limestone and Sandstone (British Geological Survey, 2018) meaning the water could enter the bedrock and hence not be measured.
- Soil infiltration rates between grassed and woodland areas using ring permeameters
- Soil moisture content in grassed and woodland areas using theta probes
- Fixed point photography of before and after an intervention. This only provides limited data on their true benefit and requires storm conditions to test.
- Interception of the tree canopy of already mature trees by measuring throughfall, stemflow and rainfall

Some of these methods require a large amount of time between implementation and measurement to gain the data to show a change as the trees mature; therefore, these methods were excluded. As the time scale only allowed measurements to be collated over a year, mature deciduous trees were monitored opposed to before- after planting of shelter belts. This project looked at the partitioning of rainfall by edge trees into throughfall, WCE, and stemflow, to allow for successful watershed management and flood protection as little data has been gathered for trees on the edge.

Gross Rainfall

Gross rainfall must be collected in the open or above the canopy (Juvik et al. 2011); with a tipping bucket rain gauge and data logger (Chappell et al. 1999). The gauge will be far enough away from obstacles to ensure no more than a 45° angle from the top of the obstacles (Hewlett and Nutter, 1982) to prevent turbulence affecting the measurement. Chappell et al. (1990) utilised 1 volumetric and 2 tipping bucket rain gauges. However, Helvey and Patric (1965) found one gross rainfall gauge is adequate for comparisons with throughfall and stemflow.

Stemflow

Stemflow requires a certain amount of previous rainfall before it occurs (Sinun et al., 1992; Lei et al., 2016). The most commonly used and accurate method to measure stemflows is randomly selecting trees within the plot and fitting a collar or spiral (Levia and Germer, 2015) to them, which drains into a tipping bucket mechanism with data logger (Kirby et al, 1991; Shaw et al., 2011). Others including Oyarzun et al. (2011) collected the data in a container and manually recorded these results. Staelens et al. (2006) also used another method of stemflow collection by using a spiral collector around the trunk that emptied into a 0.2l automated tipping bucket and then into a jar and manually measured each weekly.

Collars are made of flexible Neoprene/rubber, tarpaulin, urethane mats, aluminium or plastic foil.

Another method was used by Jukik et al. (2011) where they sampled 10cm wide areas of the bark covering around 16-20% of the tree trunk. This method provided insignificant results and does not take account of the tree structure.

Some researchers selected the trees randomly (Sinun et al. (1992) using a grid map and collecting from the nearest tree) and others (Kirby et al., 1991; Oyarzun et al., 2011) have selected these taking account of the girth of the tree to gain a variety of sizes and species. Others sampled areas of the forest (González-Martínez et al., 2017 and Levia and Germer, 2015) to gain representative data on the species and size/diameter.

González-Martínez et al. (2017) found that the understory wooded plant makes up a large proportion of the forest (96%) so therefore should not be overlooked in data collection to prevent underestimation. It is important to select a variety of sized trees as Sinun et al. (1992) found that smaller trees generally produced more stemflow than larger trees except in large rainfall events.

Safeeq and Fares (2014) collected stemflow from a larger number of trees in a selected area due to the high variability of stemflow ensuring it was representative of diameter breast height and species through previous categorisation and random selection. Multiple collars drained into 1 tipping bucket mechanism to provide a more representative result of the wooded area. Others have used a variety of numbers from 2-3 up to 40 collectors with an average of 18 gauges.

Throughfall

There is no consensus on the standard measurement protocol for throughfall (Levia and Frost, 2006) with a variety of methods being used. However, funnels and troughs are the most common. Methods cover roving (i.e. moving gauges between measurements) and stationary use. The funnel volumetric storage collectors (Chappell et al., 1990; Kirby et al., 1991; Sinun, et al., 1992) and funnelled tipping bucket gauges (Chappell et al., 1990; Chappell et al., 2006; Shaw et al., 2011) with and without troughs (Shaw et al., 2011; Ziegler et al., 2009; Safeeq and Fares, 2014; USGS, 2018) are most common.

Trough gauges are stationary piece of equipment that measure a larger area at once, whereas volumetric storage collectors with funnels can be moved regularly to provide a more spatially accurate result and are cheaper. Tipping bucket gauges with troughs extend the surface area that the tipping bucket collects from, and are better than jar methods as higher resolution data is provided due to the data logger. Staelens et al. (2006) found that throughfall is spatially variable due to canopy cover and branch cover during the growing season; therefore, covering a larger area provides a more accurate result of actual throughfall. However, due to cost and the large number of collectors required, as well as the ability to easily move them around for spatial variability volumetric storage collectors are often utilised

Ziegler et al. (2009) study looked at 3 different methods (rover, stationary and point). Their study concluded that stationary methods when not looking at spatial variability are the best with low standard uncertainty and coefficient of variance. This involves troughs collecting the water and draining into a tipping bucket mechanism with data logger.

Another method is to cover the area in a plastic sheet and drain this into gauges to collect the total throughfall (Calder and Rosier, 1976) under a tree or partial area of woodland. This also ensures a large surface area is measured reducing spatial uncertainty. This is much more time consuming, expensive and requires whole areas without public access.

Dunkerley (2010) suggests that an alternative method of collecting throughfall is through using plaster of Paris blocks beneath a traditional funnel, which dissolve through contact with water. This, however, requires manual weighing so does not provide the high resolution required, but does allow for measurements where there isn't room/height for traditional methods.

Stationary reinforced plastic or metal trough collectors (Ziegler et al., 2009) collect from a larger area taking account of spatial variability under the canopy and draining into a tipping bucket rain gauge. The tipping bucket capacity of 0.2mm per tip was found by Iida et al. (2012) to have the same uncertainty up to this capacity (increasing with larger capacity). This method is favoured by many including Kirby et al. (1991). Troughs are tilted downwards to ensure rapid drainage into the tipping bucket gauge. The trough area can vary but is often around 4m in length, 0.1m width and 0.3m depth.

To prevent splash back from the throughfall collectors a depth of 0.23m is required (Chappell et al., 2001). Sinun et al. (1992) extended the sides of their collection jars vertically to also prevent splash. They need to be deep enough to prevent blockages of leaf litter and for snow; these must be kept clean to prevent evaporation from leaf litter (Kirby et al., 1991; Juvik et al., 2011). Johnson (1990) managed to measure the snowfall by using larger collectors; however, this is less relevant for the Lune Basin where snowfall is less frequent.

1.2.4 Number of Instruments

Throughfall and Stemflow are spatially variable and can be determined only at discrete points so it is difficult to gain enough measurements for accurate data collection. This is done through either the use of many individual funnel gauges to produce a larger total area covered or using fewer trough gauges that individually cover a greater area.

The number of measurements required is less than the 345 throughfall measurements collected in Chappell et al. (2001) or 450 randomly placed storage gauges and 5 tipping bucket gauges over a 4km^2 area (Bidin et al., 2003 and Chappell et al., 2006) in Baru experimental catchment as spatial variability in rainfall and canopy cover were studied. The Plynlimon catchment has been widely studied and has a lower quantity of throughfall gauges. Chappell et al.'s (1990) study consisted of 12 volumetric and 3 tipping bucket collectors and 1 volumetric and 2 tipping-bucket precipitation collectors, whereas the Institute of Hydrology studied a larger area with 39 volumetric and 12 tipping bucket rain gauges over the Severn and Wye catchments with it being found that 49 would be required for both catchments to be within a 10% error. 48 throughfall troughs over 6 sites were used by Kirby et al., 1991. The number of gauges used by Chappell et al. (1990) was less due to the size of the site being measured and likely due to affordability of equipment. Kirby et al. (1991) showed fewer gauges are required indicating that the spatial variability of frontal weather systems in the UK is less pronounced than in the convectional systems in tropics of Chappell et al. (2001).

The number of standard gauges required has been suggested by many to be 6 (Helvey and Patric, 1965) to 50 (Price and Carlyle-Moses, 2003; Shaw et al., 2011), with Levia and Frost (2006) suggesting that as 30 is reached the benefit becomes small when weighed up against time and cost. Significantly more gauges are required for the smallest events e.g. up to 46 for events <0.2mm rainfall but as low as 6 for larger events during the dormant phase (Helvey and Patric, 1965) up to 21 (Price and Carlyle-Moses, 1965).

Due to the temperate site location and the fact the larger events are the focus of the study it is acceptable to assume < 30 standard gauges would be required if not as few as 6. Where trough gauges are used this can be further reduced by 20% while providing a 5% accuracy (Helvey and Patric, 1965 and Shaw et al., 2011). 30 standard gauges (where funnel diameter is 350mm) would cover an area of 2.88m^2.

Troughs are utilised in the study with the five gauges with two troughs having an area of 0.89m2 each and the gauge with 6 troughs having an area of 2.64m2. This provides a total area measured of 7.09m^2, which gives an area 2.4 times larger than 30 standard funnel gauges.

The larger surface area of trough gauges also ensure variability under the tree canopy (e.g. due to drip from the trees causing larger collection in certain locations (Sinun et al., 1992)) is taken account of, negating the requirement to relocate the gauges unlike standard funnel gauges. and

shows the frequency/number of collectors used in various studies.

Table 1-4:*Frequency of stemflow collectors used in other studies.*

Paper	Number of Stemflow collectors	Other information
Ford and Dean, 1978	10	Originally collected at 23. Trees in low rainfall week but reduced to 10
Johnson (1990)	9	9 of the 87 trees were measured
Kirby et al. (1991)	35 collectors	5 at each of the 6 sites at Plynlimon
Kirby et al. (1991)	18 trees	The Hafren experiment saw data collected over the 9 subplots with an uncertainty of less than 2%.

Sinun et al. (1992)	20 collectors	Stemflow varies tree to tree (Sinun et al., 1992) therefore, it is important to collect samples for several trees of varying size, location, and species
Soulsby and Reynolds (1994)	8 collectors	Within the dominant oak stand with some birch and rowan
Bidin et al. (2003)	40 gauges	44-hectare Baru experimental catchment
Price and Carlyle (2003)	20 trees	4 trees at each of the 5 plots
Germer et al. (2010)	40 with an additional 8 for Babassu palm	24 various sized over 5 cm DBH; 16 juveniles. 1 tipping bucket for 5-minute intervals; these covered varying DBH. It is important to collect from various DBH and species.
Oyarzun et al. (2011)	10 trees per plot	Representative of the diameter distribution and dominant tree species
Iida et al. (2012)	10 or more trees per plot	Calibration study of tipping bucket rain gauges and flow meters in tropical coniferous and deciduous forests.
Safeeq and Fares (2014	2/3 gauges at each plot each with 2-7 trees draining into them. (6-21 trees at each plot)	collected data at 15-minute intervals and cumulative data which was collected every 4-5 weeks. They selected rectangular plots of 12 x 14 or 12 x 12 m which contained 2 or 3 gauges. Each gauge had 2 – 7 trees draining into each. The plots were surveyed for trees species and DBH and trees were categorised into DBH. The trees were then selected randomly taking account of the groups to get a representative sample. This reduced costs as less tipping buckets were required.
Siegert and Levia (2015)	-	recorded data from tree collars at 5-minute intervals for high resolution data. They also noted the limitations with tipping buckets and accounted for this
Lei et al. (2016)	20 trees	5 from each of the 4 most dominant species. These trees were not covered by other trees. These were split into 5 DBH groups with 1 of each species in each group. Tubing was wrapped 2/3 times around the trunk and attached with nails and silicone sealant. This was collected in a jar. They also covered the stemflow equipment with plastic to prevent throughfall entering and litter blocking it. Checked and emptied prior to each rainfall event. Samples were measured 2 hours or next morning after a rainfall event.
González-Martínez et al. (2017)	-	recorded stemflow using spiral collars on trees with a diameter greater than 10cm and funnels on smaller trees. The water was collected and manually measured every 1-2 days.

Table 1-5:Frequency of throughfall collectors used in other studies

Paper	Throughfall Collector Frequency	Other Information
Wilm (1943) from Helvey and Patric (1965)	12	Uneven throughfall can be overcome by moving 12 gauges randomly
Black (1957) from Helvey and Patric (1965)	9	With 9 roving gauges equalling the accuracy of 1 gross rainfall gauge
Helvey and Patric (1965)	6 in winter and 15 in summer (20% less of trough gauges)	adequate to sample throughfall in storms of all sizes.
Hewlett and Nutter (1982)	10	10 throughfall gauges are required for the same accuracy of 1 gross rainfall gauge
Chappell et al. (1990)	12 volumetric and 3 tipping bucket collectors	Along with gross precipitation. Plynlimon catchment Wales
Johnson (1990)	6	randomly positioned throughfall collectors used by coordinates
Kirby et al. (1991)	18 troughs and 48 throughfall collectors.	Plynlimon used 6 sites and at each site in the catchment with one main collection site just outside the catchment. At each site, a tree was chosen as the focal point and had 6 troughs around a gauge at random bearing.
Kirby et al. (1991)	36 troughs	The Hafren experiment over 9 subplots with an uncertainty of less than 2%
Sinun et al. (1992)	40 collectors	used 4 transects with 101 sampling points on each 1 m apart. Each transect is 50m from each other. 40 collectors were located randomly and relocated each week to

<table>
<tr><td></td><td></td><td>minimise the standard uncertainty.</td></tr>
<tr><td>Chappell et al. (2001)</td><td>345</td><td>with 0.15 m diameter orifice, 0.56 m above ground and a drop of 0.23 m preventing out splash. Evaporation loss was reduced by directing the flow through narrow diameter holes and painting white to reduce radiation absorption. 80 gauges in 4 vegetation category areas and 20 in category 5. Each plot is randomly selected. They compared standard and non-standard gauges gaining an uncertainty of 1.04% and evaporation loss was negligible.</td></tr>
<tr><td>Bidin et al. (2003) Chappell et al. (2006)</td><td>450 storage gauges and 5 tipping bucket gauges</td><td>Randomly placed over a 4 km^2 area in Baru Experimental Catchment</td></tr>
<tr><td>Price and Carlyle-Moses (2003) suggests</td><td>Table 4
Number of gauges required to estimate mean event throughfall within ±5 and ±10% at the 95% confidence level within the study plot during the 1995 growing-season
<table>
<tr><th>Incident precipitation depth (mm)</th><th>Mean number of gauges and range for ±5% of mean throughfall</th><th>Mean number of gauges and range for ±10% of mean throughfall</th></tr>
<tr><td><2.0</td><td>855 (66–3294)</td><td>215 (17–824)</td></tr>
<tr><td>2.0–3.9</td><td>87 (46–174)</td><td>22 (12–44)</td></tr>
<tr><td>4.0–7.9</td><td>39 (26–66)</td><td>11 (7–11)</td></tr>
<tr><td>8.0–9.9</td><td>50 (20–81)</td><td>13 (5–21)</td></tr>
<tr><td>10.0–19.9</td><td>25 (17–35)</td><td>7 (5–9)</td></tr>
<tr><td>>20.0</td><td>21 (18–23)</td><td>6 (5–6)</td></tr>
</table></td><td>This shows the number of gauges required for both 5 and 10 % confidence levels.</td></tr>
<tr><td>Levia and Frost (2006)</td><td>30 Collectors</td><td>Review of literature. The use of trough and funnel is less significant than the number required. They found that more than 30 and the benefits were not seen.

The use of roving/stationary gauges depends on the objective with stationary required if meteorological measurements are being</td></tr>
</table>

		looked at as the canopy cover must stay the same.
Staelens et al. (2006)	48 collectors	20 tipping bucket, and 28 manual collectors
Ziegler et al. (2009)	4 stationary trough collectors and 20 mobile standard gauge collectors	Agreement between them was gained after 35 sampling occasions. He determined the stationary method was better when spatial distribution is not required as they do not need to be moved and sample a larger area. Stationary method used a fabricated galvanised steel tipping bucket gauge measured the water captured in the toughs (tipping mechanism is a larger version of a commercial tipping bucket rain gauge with a solid-state reed switch monitored by a Campbell CR10x data logger). 150 cm^3 (0.2 mm) of throughfall was required for 1 tip. Each gauge had 3 troughs. The troughs were 43 mm wide and had a triangular shape channel (120 degrees angle) and 25 mm vertical risers to reduce rain splash. The trough was 6 m long giving 0.77 m^2 sampling area (after correcting for trough angle). Each trough was 0.5-1 m above ground to reduce interference from vegetation on the ground. Standard uncertainty was less than 2% and coefficient of variance less than 10%. Measurements Should be separated from half

		a crown to 40 m to be spatially independent.
Shaw et al. (2011).	50	due to the spatial variability. Alternatively, a smaller number of troughs can be used as they cover a larger area
Juvik et al. (2011)	Covered whole of base with sheet to collect 100% of throughfall providing result within 4% of gauge method. Also used trough and tipping bucket gauge method	3 sites were used to account for summit, middle and upper of the hillslope. He looked at the throughfall spatially under a trees canopy covering over 1% of the area with gauges from the conical canopy and perimeter. Juvik used a lot less as he assumed heterogeneity. measuring equipment included four 15.2 cm diameter recording rain gauges with a tipping bucket capacity of 3.65 ml; with v shaped trough expansion of the collection area (446.8 cm^2 per trough). Troughs were place randomly and rotated monthly by 45˚, 90˚ or 135˚ to the canopy midpoint. This trough method was found to have significant splash back causing underestimation.
Iida et al. (2012)	Area covering at least $1m^2$ to scale to forest scale	calibration study of tipping bucket rain gauges and flow meters in tropical coniferous and deciduous forests.
Safeeq and Fares (2014)	8 trough gauges	With tipping bucket mechanisms over 3 sites. Collecting cumulative and 15-minute intervals. Troughs were maintained every 4-5 weeks
USGS Science for a Changing World (2018)		Throughfall collectors consist of three 6-meter long stainless-steel troughs that drain into a large-capacity tipping bucket gauge. The gauge enclosures are 46.5 cm

		in diameter and 72 cm tall. The bucket tips at approximately 0.15 litres of water, which represents 0.2 to 0.25 mm of throughfall,

Davison and Leigh (2004) found that the rainfall recorded at Hazelrigg weather station and one 10km further south was the same; however, a weather station at Over Kellet (21km North) recorded zero and Morecombe (12km North-West) recorded a much lower intensity during August 2004. The distance between the throughfall/stemflow collectors and the gross rainfall gauge as well as Hazelrigg weather station (500m away) is small enough that it will not be affected by the spatial variability. Due to weather systems being less spatially variable (except for extreme convective events) in the UK and spatial variability not being studied, fewer rainfall gauges are required for this experiment. Shaw et al. (2011), suggest 1 rain gauge per 600-900km^2 for temperate regions.

1.2.5 Uncertainty

Where tipping bucket rain gauges and flow meters are used to collect data per event, Iida et al. (2012) determined that calibration equations were required to prevent underestimation and hence overestimation of interception. This is because the tips lead to water not being collected by the bucket when it is tipping. However, the gauges show the character of the rain. Underestimation is increased for tipping buckets with higher rainfall intensity as more water is lost during each tip. Iida et al. (2012) produced regression equations for 5 different tipping buckets; some produce linear equations, but others did not, due to smaller buckets producing lower tipping uncertainty from greater kinetic energy as intensity of flow increased. The equations provided an uncertainty of 3%.

The accurate measurement of rainfall is important. Pollock et al. (2018a) suggest that wind induced undercatch is the major source of uncertainty in rain gauges, with undercatch being compounded by poor siting, and variation in gauge height. It was found that the design shape is significant in terms of the measured rainfall, as well as the rainfall event type with typical English west-coast upland events being more susceptible to wind effects than the east coast convective events. Pollock concluded that pit gauges were the most accurate at collecting rainfall as those above ground change the trajectories of precipitation especially when windy causing undercatch. The difference in undercatch between a standard 30cm and a ground-level gauge were also noted at Plynlimon, this difference was up to 16% at higher sites (Rodda and Dixon, 2012).

The undercatch is significant for a rain gauge 1m above ground, which only catch 83-4% of the rainfall, whereas gauges at ground level catch 91-93% (Pollock et al., 2018). Kurtyka (1953) found that rain gauge uncertainty (evaporation, adhesion, colour, inclination and splash) was 1.5% rising to between 5-80% as a function of wind exposure. However, it is generally considered that between 2-10% of rainfall is not captured by the gauges at wind speeds of more the 4m/s (Pollock, 2012). Larson and Peck (1974) reported that the under-catch percentages for an unshielded gauge increase at 2.24% for every m/s of wind. This agrees with Guo et al. (2001) who stated that under catch ranges from 10 to 15% for wind speeds under 6.71m/s and can increase to 56% for 22.36m/s wind speeds.

According to Sevruk (2006) precipitation corrections are readily applied in many parts of Europe; however, they are not in the UK. Input data includes wind speed, precipitation intensity and weather situation (different drop-size distributions exist for different types of rain with the same intensity), temperature, rain/snow amounts, frequency of events (Sevruk, 2006).

Chang and Harrison (2005 in Pollock, 2012) found that rainfall gauges collect vertical rainfall however, rainfall is often horizontal as the air is not calm. Wilkinson (2009, in Pollock et al., 2018) agreed with this and found that gauges in Cumbria were not collecting any rainfall/drizzle when it was clearly raining and could be seen by an increase in the catchment discharge. However, this study is less concerned about the effects of small events as they do not cause flooding.

Rodda and Smith (1986) found that rainfall is underestimated by 5-20% for the wetter parts of the country, which is on the higher end for wetter parts of the country (Rodda and Dixon, 2012). In some of the UK's wetter catchments (e.g. Eden), the estimated percentage under catch by standard rain gauges is approximately equal to the annual average evaporative loss (Hannaford and Marsh, 2008).

Specific uncertainties to the throughfall gauge, which also relate to the throughfall tipping bucket (Pollock et al., 2018) are:

- Instrumental uncertainty, which can be reduced by using quality equipment with regular maintenance:
    - Mechanical uncertainty at different intensities
    - Repeatability of the tipping bucket mechanism
    - Gauge blockage
    - Electronic and data logging uncertainty
- Discrete sampling mechanism of the results, which can be significant during light rainfall
- Environmental uncertainty:
    - Evaporation of rainfall not yet accounted for within the equipment
    - Splash in/out of equipment
    - Adhesion/wetting
    - Wind-induced uncertainty (dependant on gauge shape and mounted height).

1.2.6 Modelling

Many hydrological models do not take account of stemflow or throughfall (Beven, 2006); therefore, collecting and analysing stemflow and throughfall data will provide a more accurate representation of what really happens in the field allowing model parameters to be altered for more accurate modelling. Modelling is important in determining where potential flood events could happen, as well as mitigation measures that could be implemented and where, to reduce flood peaks. This along with the importance of the WCE from tree canopies in the hydrological cycle, is why it is important to have a model that can predict the evaporation that will occur. The WCE model can then be used within the NFM model. This data will also allow the parameterisation of these larger models to ensure the modelling is as realistic as possible and based on real local data.

Trees could also reduce flood peaks through the combined effect of overland flow, and transmissivity, which needs to be accounted for in modelling as well as WCE. The amount trees reduce water entering the catchment/slow water down is larger when taken account of separately. The WCE of trees removes a consistent proportion of flow and to a lesser extent the trees cause a delayed flow due to decreasing of overland flow velocity. In some cases, trees can also reduce the hydrograph peak by a small amount (Hankin et al., 2016).

Stratford et al. (2018) gained observational and modelled data from various papers looking at countries like the UK in climate, with 36/53 studies showing increasing tree cover decreases flood risk (with 5 studies having no influence). When tree cover is decreased, 32/53 saw an increase in flood risk (with 0 decreases and 11 studies with no influence). When the storm size is small, flooding is decreased when increasing tree cover; however, Stratford found large events are not influenced by tree cover. However, the statement 'Tree planting reduces flood peaks' is founded on model outputs (Stratford et al., 2018), which do not take account of evaporation that occurs for trees on the edge. It is of great importance to quantify the effect of WCE with real data from established edge trees and model the collected data to prove if the statement is correct.

Hankin et al. (2016) suggest that for their study, "realistic changes were made to parameter values based on scientific literature, but there are large gaps in our knowledge", including how edge trees affect hydrology. The EA 'Evidence Base' project is seeking to address this, along with a NERC Funded call to fill more gaps (Dec 2016). This needs to be done with new monitoring of implementations in tandem with more modelling to help model scale effects.

A temporal dataset of throughfall on the edge of tree belts and gross rainfall has been collected, which is unique in the UK for deciduous trees. This data will be used to model interception and the findings will be used to influence catchment modelling to parameterise the WCE variable within the Cumbria model (a NFM model being created as part of the NERC's Q-NFM project (Hankin et al., 2016)).

WCE Models

The first modelling of evaporation was undertaken by Horton in 1919. Until 1970 WCE was predicted using empirical-derived relationships with gross rainfall, but these cannot be applied to other conditions. The Rutter model in the early 1970s was the first model to describe interception as a process then Gash later in the 70s. Now well over 15 models exist (Muzylo et al., 2009).

The review written by Muzylo et al. (2009) revealed the requirement for more modelling of deciduous trees particularly more sparse forests, areas with intensive storms, and high rainfall rates. Models are derived from relatively few events so are approximate when applied to extreme events as they are outside the calibration range (Wei, et al., 2008).

The Penman equation (Beven, 2012) is utilised to calculate the potential evaporation. The model is based on a combination of simplified energy balance equations for the surface and transport of sensible and latent heat away from the surface. The Penman equation assumes the ‘big leaf’ concept (i.e. the canopy is assumed to be completely covered as if one big leaf) so does not model sparse canopies well or take account of evaporation from splash droplets. The equation requires a lot of data including temperature, net radiation, wind speed and humidity. The equation is dependent on the canopy roughness and wind speed i.e. rougher the canopy and higher the wind speed, lower the values of aerodynamic resistance, which results in more efficient mixing of the air and faster rates of transport (Beven, 2012).

There are many variations of evaporation models utilised worldwide. The Gash or Rutter type models are most commonly used. These types of models have various models that sit under these categories including (Muzylo et al., 2009):

- Rutter type models:
    - Rutter original (Rutter et al., 1971, and Rutter et al., 1975)
    - Rutter sparse (Valente et al., 1997)
    - Massman (Massman 1983)
    - Sellers and Lockwood (Sellers and Lockwood, 1981)
    - Liu J (Liu, 1988)
    - Liu S (Liu, 1997)
    - Xiao (Xiao, et al., 2000)
- Gash type models:
    - Gash original (Gash, 1979)
    - Improved Gash sparse (Gash et al., 1995)
    - Mulder (Mulder, 1985)
    - Zeng (Zeng et al., 2000)
    - Van Dijk and Bruijnzeel (Van Dijk and Bruijnzeel, 2001)
    - Murakami (Murakami, 2007)
    - Calder Stochastic (Calder, 1986)
    - Calder two-layer (Calder, 1996)

The Rutter type models are more commonly used in the UK with 6/9 different UK studies using this model. However, the Gash model is more commonly used in European studies (excluding the UK) with 6/8 (Muzylo et al., 2009). Over the whole of Europe, they are similarly chosen, with the Mulder model also being used but to a lesser extent. The temperate environment of the UK is simiar to Europe so likely the difference in model usage is choice rather than scientific reason. Hardwood trees have mainly been modelled by the Gash model in most cases with only a few using the Rutter Model. Both model types are utilised in temperate environments (Muzylo et al., 2009). Globally the most commonly used is Gash Sparse (which has a simpler analytical approach) (69 cases) then the Rutter (42 cases), Gash, then Rutter Sparse than Mulder. The other models are used less frequently.

Rutter Models

The Rutter model (Rutter et al., 1971 and 1975, Calder, 1977, and Gash and Morton, 1978) uses the Penman equation for evaporation of intercepted rain. The model itself is easier to use than some but has been found to underestimate. The Rutter model splits the rainfall into direct throughfall, canopy interception and stemflow storage. The Rutter model treats drainage over time allowing drainage to continue after rainfall ceases. The Rutter model also assumes a closed canopy i.e. no gaps (Muzylo et al., 2009).

The Rutter model was adjusted to the Rutter Sparse model to accommodate forest stands with significant open spaces in the canopy. The canopy area is used to calculate the evaporation rate and assumes that the canopy does not totally cover the ground. It treats drainage as an integral part of a closed water balance therefore drainage stops as rainfall stops. The model assumes the canopy is completely dry at the start of the storm.

The Massman model drainage depends directly on rainfall intensity. The model is easier and quicker to use than some but is not suited to varying temperatures as in the UK. The advantage of the Massman model was that its input at a temporal scale is of 10-minute time steps (Muzylo et al., 2009); whereas the other Rutter type models and the Gash type models use hourly or daily data

Gash Models

The Gash analytics model (Gash, 1979) simulates rainfall interception loss. The model assumes it is completely dry at the start of a storm. The Gash model was modified (Gash, 1995) to the Gash Sparse to account for significant open space in the canopy. It assumes that rainfall occurs in a series of discrete events. Three rainfall phases are differentiated within the model: canopy wetting phase, saturation phase, and drying phase. It uses two climatic parameters (mean evaporation from Penman and mean rainfall intensity) and four canopy parameters are used:

- canopy storage capacity (S), the amount of water left in a saturated canopy in absence of evaporation after the drainage and rainfall has ceased
- the free throughfall coefficient (p), the fraction of incident rainfall that reaches the forest floor without touching the forest canopy
- the coefficient (pt), the fraction of rain diverted to the trunks as SF
- stem storage (St), the amount of water that can be stored on the stems

It has a low data demand but is known to overestimate evaporation (Muzylo et al., 2009). However, Motachari et al. (2013) found the model to predict interception, over an annual time scale, well. The Gash model is limited by (1) rainfall is represented by a series of discrete storms separated by periods long enough to allow the canopy to completely dry up; (2) the meteorological conditions are constant throughout the storm; and (3) there is no drip from the canopy during wet-up (Gash (1979).

The Mulder model maintains the 3 storm phases with modifications and assumes a moist canopy between storms; it doesn’t assume total drying. The Murakami Gash type model does not distinguish between different storms and derives evaporation from the rainfall. Unlike Penman, Murakami deals with splash droplet evaporation (Muzylo et al., 2009). It uses the observed data for WCE and is good for intense storms with high rainfall rates.

The Calder Stochastic model uses Penman equation and employs Poisson probability distribution to determine the number of raindrops that strike the canopy and are retained. It assumes water is removed by evaporation or when the storage canopy is reached it drains to the ground (Muzylo et al., 2009). It accounts for secondary drops. The Calder stochastic model requires more parameters than other models, and some detailed measurements during wetting experiments including drop sizes (Calder et al., 1996); therefore, is not utilised.

1.3 What Requires Further Investigation?

Many scientists and the general population agree that trees can potentially be beneficial to reducing flood peaks; however, the magnitude of flood peak reduction, where to plant them and scale of planting to reducing downstream flooding is still unclear. This leads to the subject producing some controversy within the scientific community.

A primary focus of the project is to provide the Evidence Base (a scienctific database on NFM collated by the Environment Agency (Hankin et al., 2016)) with scientifically credible high resolution and quality data on WCE to quantify the magnitude of hydrological benefits edge trees have on mitigating flooding.

There is very little scientific data on WCE in the UK especially for deciduous trees and none looking at WCE and processes through a storm or the effect of leafed and non-leafed periods on this.

1.4 Project Aims and Hypotheses

It is thought that native tree planting has a positive impact on flood mitigation (e.g. enhanced interception loss even in winter, reduced overland flow, enhanced infiltration and drier soils) (Bonell et al., 2010), but the magnitude of these changes is unknown or the how to parameterise in catchment flood models. New observations through storms were required specific to the Lune catchment and conditions. The data collected provided a unique dataset of international significance due to the absence of throughfall/rainfall data through a storm and edge effects in others' WCE studies (Hankin et al., 2016).

The project gathered local evidence in relation to the importance of trees in reducing rainfall entering the catchment systems, hence reducing flood peaks. It has been seen by others that trees on the edge of woodlands, whether single or in small belts, do not follow previously measured evaporation within the middle of woodlands. Therefore, it is important to determine the effect edge trees can have on WCE as trees planted as part of NFM are often planted in small belts. It is important to determine if models can be used to predict, with or without alterations, the effect being on the edge has on WCE. The data and models are needed to determine whether trees can be used as NFM and reduce flooding.

The aim of the project was:

"To determine the benefit deciduous tree canopies, on the edge of narrow woodland (often shelter) belts, can provide in relation to reducing the water reaching the ground through wet canopy evaporation during a range of storm conditions within the temperate environment of Lancashire, UK."

This aim was supported by the following objectives:

- To undertake a literature review of WCE studies
- To create a methodology taking account of the literature review
- To find a suitable site and determine the trees to measure
- To design and purchase equipment
- To undertake calibration tests on the tipping bucket equipment
- To build the equipment in the workshop and put up on site
- To undertake calibration of equipment once in place, test the data loggers, and measurements on site (e.g. tree canopy area, and area of throughfall equipment).
- To collect data weekly for stemflow, manual throughfall collectors, and check/clean out equipment, and collect data loggers monthly.
- To collate data into an excel spreadsheet, convert tips and total volumes into depth, calculate WCE from TF, SF and gross RF,
- To undertake statistical analysis on the data and create graphs of the WCE, TF and RF through events, and graphs of WCE according to various categories such as storm size, leafed/non-leafed periods, and wind direction.
- To calculate the uncertainty in the data
- To critically analyse the data and discuss findings
- To undertake a literature review of interception models
- To determine which models to test on the data
- To test the models on the 5-min time step gross rainfall, throughfall and WCE data from the Horse Chestnut tree
- To alter parameters to create a best fit of the model that fits the data best
- To critically analyse the models and discuss findings in relation to edge effects

The project looked at the WCE of 6 mature deciduous edge trees (1 Horse Chestnut, 2 Sessile Oak and 3 Common Beech trees) where gross rainfall was collected nearby the site in the open. The throughfall was measured manually on a weekly basis for 5 trees, and the Horse Chestnut was measured using a tipping bucket to collect data through storms. The number of instruments to be used is discussed in more detail in Section 1.2.4 above. The location (Lancaster University Campus) was chosen as mature deciduous trees were used to undertake the measurements. This site was the only local site with mature deciduous trees with easy access for data collection. More information on the site can be seen in Section 2.1. The project looked at the processes through events not just longer-term scale e.g. weekly or annually, as well as variation between the dormant and growing seasons, and rainfall events size. Penman Equation, Rutter Model (Rutter, 1971), and Rutter Sparse Model (Valente et al., 1997) were compared.

These objectives allowed the aim to be answered by determining how much WCE occurs on the edge of narrow tree belts, how WCE is affected by other conditions, and whether WCE could be modelled. The modelling tests the reproducibility and reasons behind the processes that occur. The data collected also allows for parameterisation of NFM catchment models (e.g. the NERC Q-NFM Cumbria Model (Chappell et al., 2017).

It is hypothesized that:

- The tree canopies will intercept, store and evaporate larger amounts of rainfall than found in other studies within the middle of stands due to the edge effects on these trees.
- WCE is significant for the deciduous trees even during the non-leafed period.
- The larger the storm, the smaller the WCE percentage to gross rainfall.
- Horizontal rainfall affects WCE for trees on the edge.
- The models will not be able to predict the evaporation due to the edge effects on the trees.
- The models will need to be altered to allow them to fit trees situated on the edge of stands

Work written and published in English was looked at in this thesis.

2 Methodology

2.1 Study Area

2.1.1 Lune Valley

The Lune Basin has hilly uplands and a maritime environment. The maritime environment plays an important role in the local weather causing it to be particularly mild. Lancashire is also wet with a predominant south-westerly wind.

Autumn has an average temperature of around 10°C, winters drop to 0°C, which rises through Spring to Summer where temperatures are often mid-20s °C (Met Office, 2018).

Lancashire is exposed to westerly maritime air masses, which along with having some of the highest ground within the country means it has some of the wettest places in the UK (Met Office, 2016). Lancaster is relatively close to the Irish Sea and exposed to south/south-westerly winds, which typically moves to west/northwest winds as storms move away. Spring has a maximum frequency of north-east winds and summer can have a greater incidence of north-west/westerly winds due to sea breeze (Met Office, 2016).

Rain is fairly common throughout the year. Summer can be fairly dry but can also be wet when large events occur. Weather gets stormier in autumn which persists into winter with highest winds due to Atlantic depressions being their most vigorous. However, some winters can be colder and calmer with more fog, and frost. As Lancaster is close to the coast, winters are often slightly warmer than inland. Spring is usually calm and drier (Met Office, 2018). Lancaster's average rainfall is 1096mm (Climate Lancaster, 2019). Prolonged rainfall in late winter and early spring when the ground is the most saturated can often lead to flooding. Snowfall is rare due to Lancaster's lower level and proximity to the coast.

The source of the River Lune is located in Cumbria with tributaries starting in Lancashire and Yorkshire (Figure 2-1). The river is 53 miles in length starting at 238m above sea-level with westward draining rivers. The River Conder is one of the tributaries to the River Lune with a 28.5km^2 (Davison and Leigh, 2005) catchment and joins the Lune Estuary prior to it entering Morecombe Bay. Ou Beck is a tributary to the River Conder with a 2km^2 catchment (Free Map Tools, 2018), which is where the data was collected.

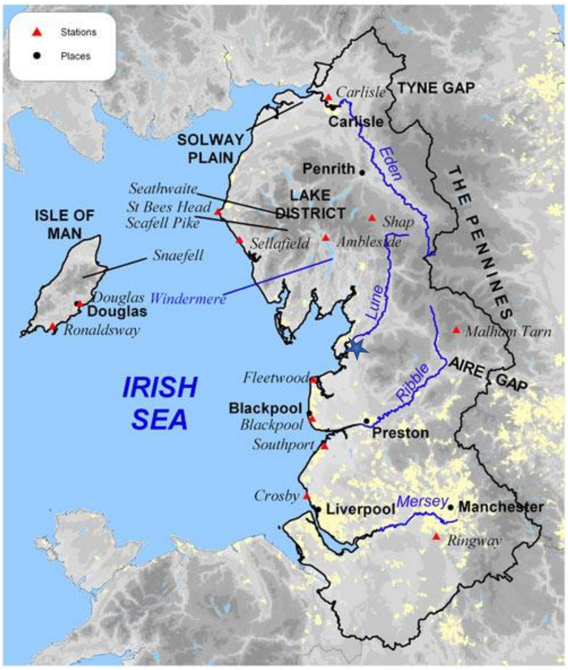


Figure 2-1:Location of the River Lune and extent of its catchment (Met Office, 2016). Blue star is the measurement location and red triangles weather stations.

Trees cover 7% of England (British Geological Survey, 2018). Isolated trees and farm-coppices provide a significant proportion of UK tree-cover (Brown and Fisher, 2009) which is no different in the Lune Catchment. This project focuses on the benefit that trees in belts can provide to mitigating flooding by taking account of boundary affects.

The land is traditionally used as grassland (due to their low fertility) with some arable and forestry. The soils are freely or imperfectly drained.

Little scientific data has been collected in the Lune catchment (Chandler and Chappell, 2008), where major flooding has occurred and requires mitigation. Studies close by include Law (1956) experimental site (24km away to the East), and Eggerslack Forest in Cumbria (Chappell and Kennedy, 2009).

2.1.2 Site Specifics

The data was collected from the deciduous woods on Lancaster University Campus, which has large mature trees with complex canopies and lower branches to attach equipment to. Many other woodlands around Galgate/South Lancaster were discounted as they lacked mature edge trees. Campus provided easy access for data collection/installation and several trees had restricted access while others were away from the woodland path where they wouldn't be tampered with.

The trees that were monitored are described in detail in *Table 2.1* and location in ***Error! Reference source not found.***. The chestnut tree is located on the edge of a strip of woodland (Natural England, 2018) to the North-West of campus, just North of the Sports Centre and South of the Health Innovation campus. The Chestnut tree was chosen due to its size (i.e. a mature tree) which also had lower branches to allow for attaching of the throughfall gauge troughs. It was conveniently fenced off from the public. The chestnut tree is open from the East through to the West with the woodland around the remainder of the tree.

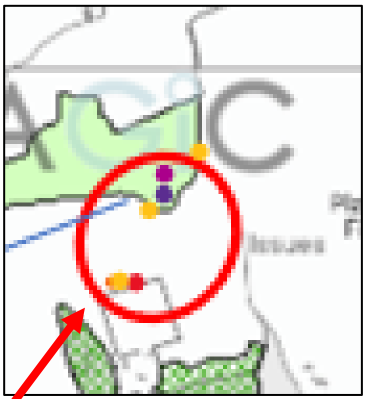
Table 2-1:*Details on each tree utilised within the experiment.*

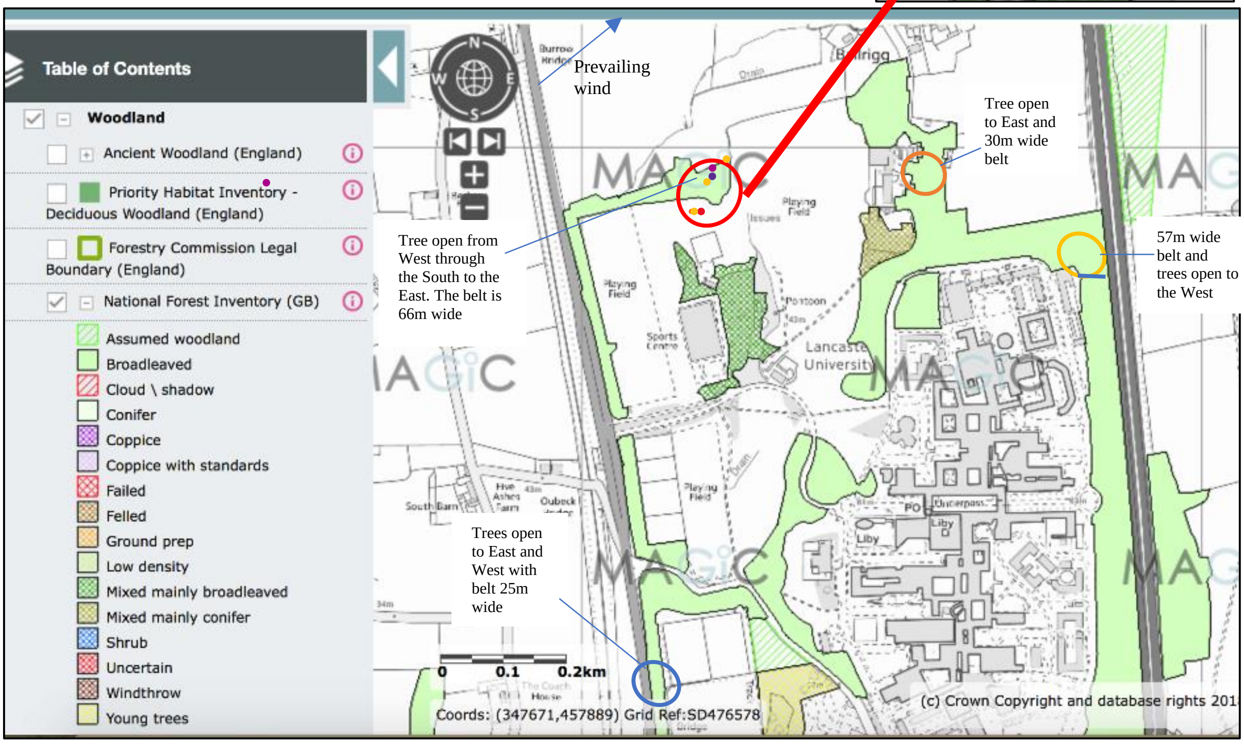
Tree and Species	**Location**	**GPS**	**Measurements**	**Basal diameter for stemflow calculations**	**Circumference (m)**	**DBH (m)**	**Height (m)**
Horse Chestnut (Aesculus hippocastanum)	NW Campus, Bowling Green	N 54°00'52.2 W 002°47'12.2	Stemflow, throughfall tipping bucket, Frumau gauges and rainfall (nearby)	16 X 17	3.6	1.1459	28
	The Horse Chestnut has a dense canopy with very large branches. Its branches point towards the trunk with others pointing towards the ground from the trunk. It has lots of drip points. It is open from East around to West    						
Common Beech (Fagus sylvatica)	Cycle Path, NW Campus	N 54°00'49.2 W 002°46'57.2	Throughfall manual	-	3.96	1.2605	35-40
	The Beech has a dense canopy with lots of smaller branches. The branches all point down towards the stem.						

	 						
Sessile Oak (Quercus petraea)	NE Campus	N 52°37'22.4 W 003°59'47.4	Throughfall manual and stemflow	12 x 5	2.18	0.6939	30-35
	The Oak has quite a sparse canopy and branches point in towards the trunk. It is surrounded by trees except to the West.  						
Common Beech (Fagus sylvatica)	NE Campus	N 52°37'22.4 W 003°59'47.4	Throughfall manual	-	4.4	1.4006	30
	This is a very tall tree with a high canopy. This tree is surrounded by other trees but is taller than these surrounding trees. This tree has two smaller trees within the crown area.  						
Sessile Oak (Quercus petraea)	SW Campus	N 54°00'52.6 W 002°47'29.8	Throughfall manual	-	4.74	1.5088	25

	This oak is the smallest in height but is a mature tree. It is open to both the East and West with trees to the North and South. It has a few main large branches with an open canopy. The branches point to the trunk.  						
Common Beech (Fagus sylvatica)	SW Campus	N 54°00'52.6 W 002°47'29.8	Throughfall manual and stemflow	10 x 12	2.19	0.6971	30 - 35
	This Beech is similar sized with lower branches at head height. It has a higher canopy than the SW Oak with a dense canopy. It is open to both the East and West with trees to the North and South   						

One Oak and Beech are located to the South West of campus parallel to the A6 and are open to their east and west, and the Beech is also open to the north. The Beech to the West of the North cycle path exiting the campus is open to the east but is still close to other trees after the opening. The other beech and oak are open to their west and are located to the North East of Campus between the M6 motorway and CEH building.





Key

Red circle – Chestnut tree – throughfall bucket (purple dot), stemflow collector (blue dot), rainfall gauge (red dot), and 3 Frumau gauges (orange dots).
Blue circle – SW Oak and Beech
Orange circle – Cycle path Beech
Yellow circle - NE Oak and Beech

Figure 2-2:Measurement and gauge locations. The chestnut tree belt is 66x281m, the southwest belt is 25x780m, the cycle path beech is 30x200m, and the north east shelter belt is 57x900m.

Gross rainfall was collected at the Bowling Green, south of the Chestnut tree. Rainfall collected using the Frumau gauges (described below) was collected in 3 locations: adjacent to the rain gauge, to the north-east of the Chestnut tree and to the south-west of the Chestnut tree, to determine why negative WCE was being seen (i.e. if the trees rainfall capture was higher or if there was wind induced undercatch at the rain gauge). Other meteorological data was also collected from Hazelrigg Weather station 1km to the east of the campus on the opposite side of the M6 motorway (Figure 2-3).

Figure 2-3:Distance between the site and the closest weather station (Hazelrigg) as 1.121km (Bing Maps, 2018).

Kirby et al. (1991) state that a forest needs to be a certain size to ensure that edge effects don't account for the results obtained. However, the project is directly looking at the edge effects on trees. The woodland is ~21,000m² but is long and thin. It is important to quantify the edge effects as trees are being planted in small groups, singly and in belts not in large woodlands.

The campus woodland is old broadleaved trees representative of the local forest type with mixed age, species, size (National Library of Scotland, 2018) and non-ancient (but over 100 years old (National Library of Scotland, 2018)) (Figure 2-2:Measurement and gauge locations. The chestnut tree belt is 66x281m, the southwest belt is 25x780m, the cycle path beech is 30x200m, and the north east shelter belt is 57x900m. to Figure 2-4). It is important that the woodland is representative of the species and local woodlands as throughfall varies according to species (Levia and Frost, 2006). The University sites are on the border between lowland Oak-Birch with bluebell/wild hyacinth and Beech-Oak with bramble (British Geological Survey, 2018). The University grounds are maintained regularly meaning there are few sapling/young trees within the woodland (i.e. little natural succession). The trees on the boundary of the University campus are large mature trees of various species including the native Sessile Oak (*Quercus Petraea*), non-native Horse Chestnut (*Aesculus hippocastanum*), Common Beech (*Fagus Sylvatica*) and Birch.

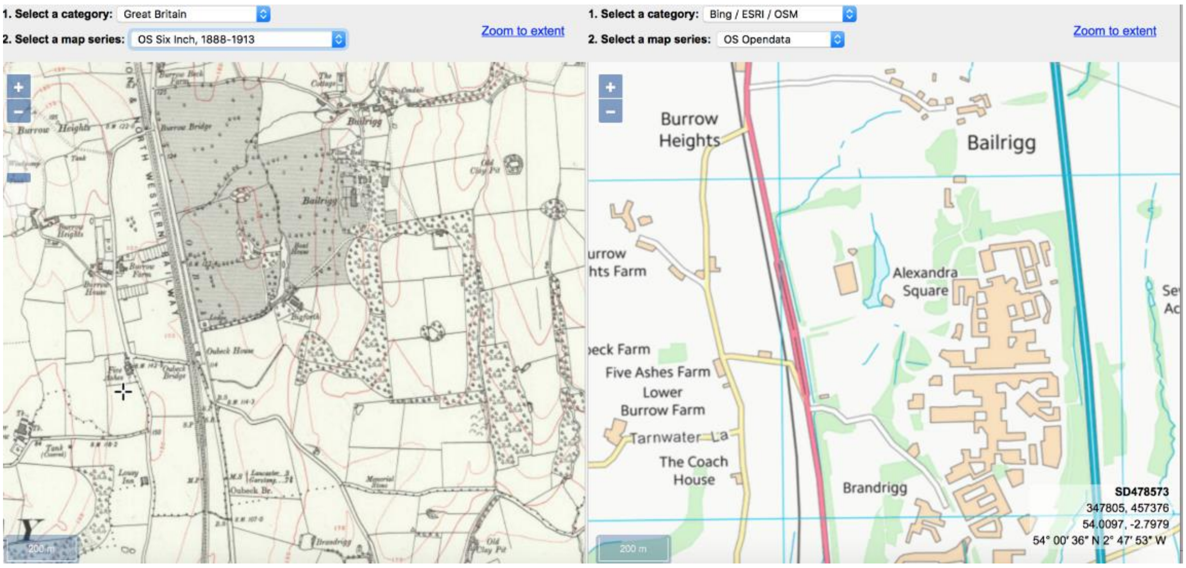


Figure 2-4:The woodland is not classified as ancient woodland but is shown on the maps from 1888-1913 (National Library of Scotland, 2018) so is over 100 years old.

The Galgate/South Lancaster area is important for Curlews (whose habitat consists of wetlands, farmlands, heathland and moorland), Lapwings (who prefer farming that produces short vegetation for nesting), and Tree Sparrows who have declined by 93% between 1970 and 1995 (RSPB, 2018). Curlews produce unsuccessful nests when nesting near Woodlands, therefore the planting of woodlands/trees in Lancashire will need to be considered carefully so as not to be the detriment of this species. Tree sparrow habitat consists of farmland, hedgerows, and woodland edges and nests in hedge/tree/building holes (Natural England, 2018). The measurement site has the ideal habitat for Tree Sparrows. Therefore, the locations of equipment were carefully selected to not disturb these species. Deer are also found here.

2.2 Method/Experimental Design

WCE was measured, to allow the importance of the hydrological pathway of WCE in both slowing and reducing the water entering a catchment during events of various sizes to be quantified. To calculate WCE, measurements of throughfall, stemflow and gross rainfall need to be collated (a flow diagram can be seen in Figure 2-5) for mature trees to determine the benefit of newly planted NFM trees as they mature.

Data was collected between 10/05/2018-30/04/2019 for the rain and throughfall tipping buckets at the chestnut tree. Data from the manual collectors was collected between 05/08/2018-30/04/2019.

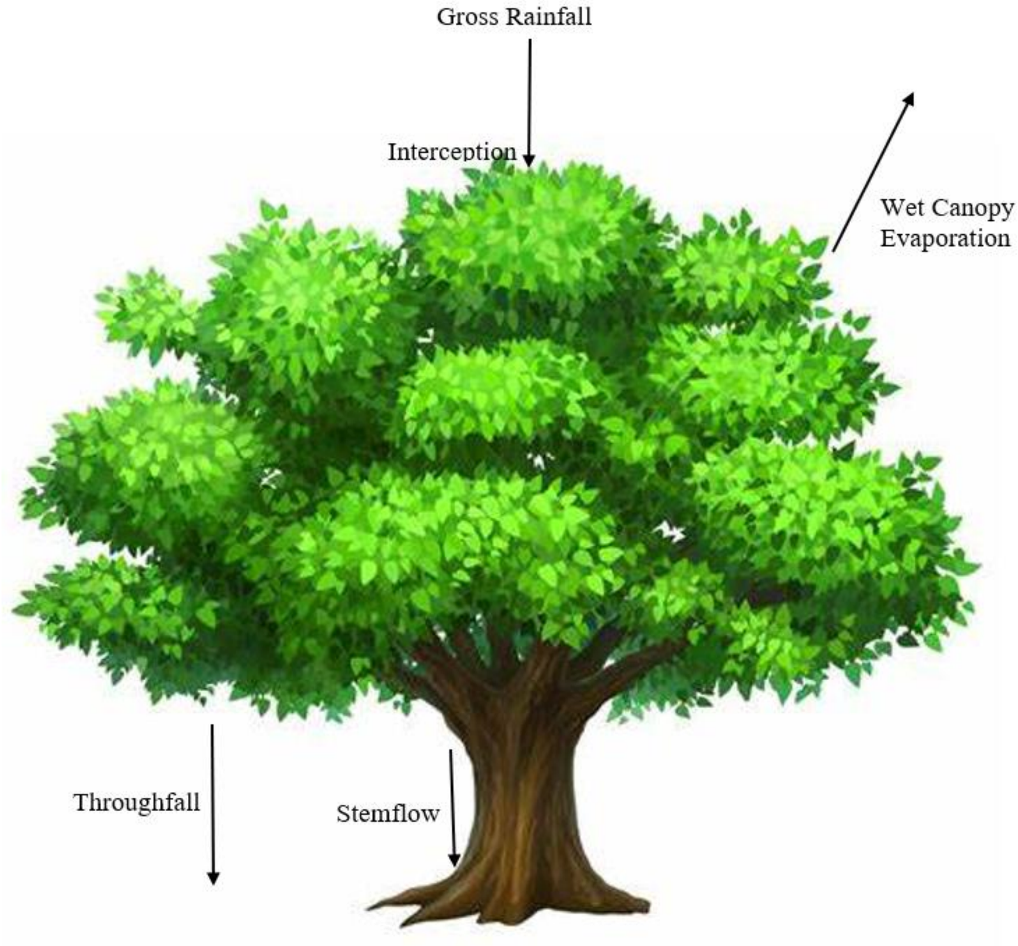


Figure 2-5:Flow diagram of the process occurring when gross rainfall hits a tree canopy

1 Chestnut, 3 Beech and 2 Oak trees on Lancaster University Campus were chosen as they were on the edge and representative of the local woodlands. The trees span 4 locations with varying directions of open canopy (sections 2.1.2). The width and location of the tree belts can be seen in **Error! Reference source not found.**.

Measuring throughfall was undertaken manually weekly to provide a WCE for weekly and annually timescales. However, the chestnut tree had a tipping bucket fitted to allow for WCE to be calculated from throughfall through a storm at 5-min timesteps, determining the processes taking place. This allowed the data to be split into event size to determine the effect for the largest events. The tipping buckets were not implemented on other trees due to project finances. The number of throughfall gauges used and the area covered provides an accuracy of 5% for the larger events, however a larger area would be needed for the same accuracy of small events (Section 2.2.6). Time-series graphs were produced, and data collated at various intervals e.g. 5min, event and annually.

1 tree from each species had a stemflow collector, as it varies according to species, which was collected manually each week. The specific design and set up of the equipment is described in sections 2.2.1 - 2.2.7.

The rainfall, throughfall, stemflow and WCE were calculated as follows:

- The depth of rainfall (mm) is calculated by multiplying each tip by resolution per tip (0.198mm), which was calculated by measuring the volume of water per tip (ml) converting to litres and dividing it by the measurement area (0.0127m^2)
- The throughfall depth was calculated by multiplying each tip by the tip resolution (0.03777mm), which was calculated by measuring the volume per tip (ml) converting to litres and diving it by the measurement area (2.6396m^2).
- Manual collectors (Stemflow and throughfall) are calculated via the same method. The volume measured (ml) is converted to litres, then divided by the basal area of the tree (calculated by measuring the longest and shortest diameter and assumed to be a circle). This provides the depth of throughfall and stemflow in mm.
- The throughfall and stemflow depths (mm) are converted to a percentage of rainfall by dividing by the depth of rainfall and multiplying by 100.
- The WCE is calculated by adding the throughfall and stemflow depth and taking away from the rainfall depth. This provides a WCE (mm), which is also converted to a percentage of rainfall.

The weekly manual collection data and chestnut tree data was used to calculate:

- average WCE values,
- compare non-leafed, transitional, and leafed periods,
- separate according to species,
- Basic statistics were applied including mean, range, median, and percentages,
- Graphs e.g. box and whisker plots were used,
- Bar charts of the spatial throughfall data,
- Mann-Whitney Test of significance and the Kruskal-Wallis Test (one-way ANOVA on ranks) from Socsci Statistics (2019) to determine whether there is a significant difference in non-normal data (Staelens et al., 2006).

The tipping bucket rainfall and throughfall data was used to:

- compare against Hazelrigg data e.g. comparing gross rainfall from the EML gauge to Hazelrigg's rainfall gauge, and compare wind speed, direction, temperature, and humidity to WCE,
- calculate wetting up and drying out periods,
- time-series graphs showing the volume of gross rainfall, throughfall and WCE&storage through events, and compare against wind speed and direction,
- create cumulative graphs over the events.

An alternative method would have been 5 transects of 10 trees 300m into the woodland and repeat this for woodlands facing different directions. This would provide control trees in the middle of woodlands where trees are not affected by edge effects allowing edge to be determined. This experimental design was not utilised because the amount of monitoring required and budget for the method was beyond the scope of the project.

Matlab was used to create models of Penman equation, Rutter Original and Rutter Sparse models which run for every 5-min time-step of the data. Totals and time against volume graphs are then plotted with lines for the measured WCE, Penman's evaporation, Rutter Original and Sparse evaporations. The equations/models are explained below (section 2.4).

2.2.1 WCE

WCE can be measured via several methods. In this study the gross rainfall (nearby) and throughfall (under the Chestnut tree) were measured at high frequency using tipping buckets. Frumau gauges (Frumau et al., 2011 and explained in section 2.2.4) were also placed around the Chestnut tree to measure vertical and horizontal rainfall. Five other trees (2 Oak and 3 Beech) had throughfall measured manually weekly (or before and after a large storm) with stemflow measured manually each week at 1 of the Oaks and 1 Beech weekly. The location of this equipment in respect to the tree can be seen in Figure 2-6 and the tree locations can be seen in **Error! Reference source not found.**.

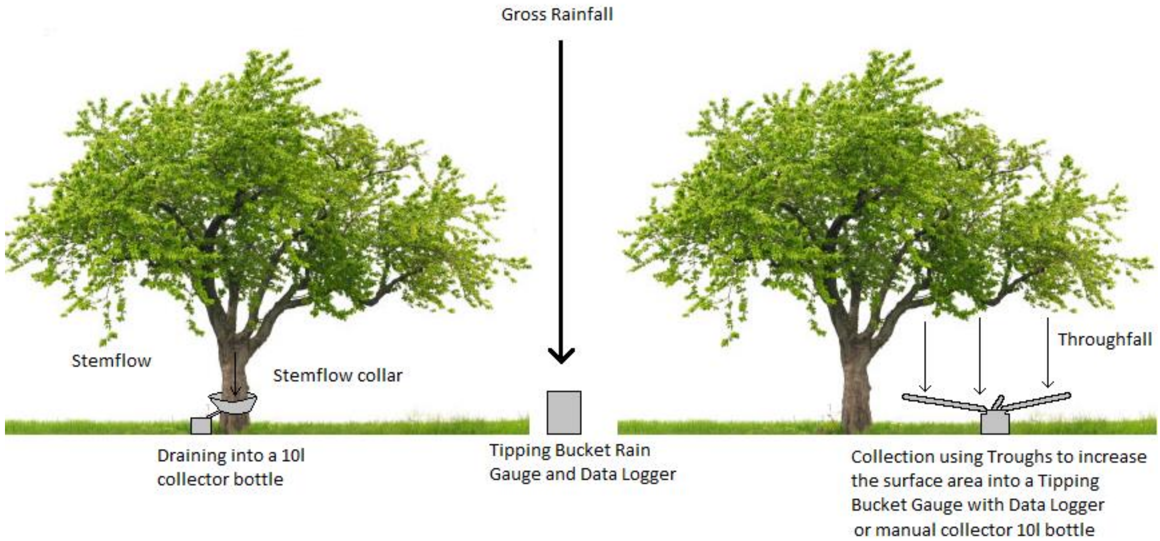


*Figure 2-6:L*ocation of the stemflow, throughfall and rainfall collectors in respect to the tree.

The WCE was calculated by Equation 1-2 (Oyarzun et al., 2011) for event and annual scale. WCE at a 5-min timestep scale is evaporation+ΔStorage i.e. water is stored on the leaves during and immediately after rainfall events. Stored water can be lost as drip or evaporation over time. Therefore, at a 5-min time-step, change in storage is included.

2.2.2 Rainfall

As stated by Shaw et al. (2011), one rainfall gauge is required to cover a 600-900km^2 temperate area. The rain gauge is located near to the woodland sites to reduce the error in spatial distribution of rainfall events (i.e. the rain gauge and throughfall gauges are recording the same event). Hazelrigg Weather Station is also nearby. Levia and Germer (2015) state that rainfall can vary significantly in volume and intensity over small areas. However, in Lancashire the rainfall has been found to be localised (distributed the same spatially and temporally) to a few square miles (Davison and Leigh, 2004).

Rainfall measurements are most accurate with pit gauges or gauges at canopy height (Juvik et al., 2011); however, this is impractical (price and siting). Therefore, gauges with improved aerodynamic properties to minimise wind-induced under-catch are preferable (Pollock et al., 2018). Aerodynamic gauges are important as uncertainty can range from 5-20% (Rodda and Smith, 1986). Pollock et al.'s (2018) study found that rainfall measurements collect vertical rainfall whereas most rainfall is not vertical as the air is not calm. Rainfall in Cumbria has been underestimated due to this and could indicate issues for trees on the edge. Rain gauges have increased underestimation with high rainfall intensity as more water is lost during each tip. Precipitation correction equations are applied in many parts of Europe but not within the UK (Sevruk, 2006). The rainfall collection is affected by rainfall intensity, temperature, drop size, event frequency and wind speed.

The gross rainfall was collected nearby the Chestnut tree on the bowling green. The gauge is located on open grassland with uniformed scattered obstacles that aren't too large to cause eddying. This is to reduce exposure to high wind speeds, which are present on large flat areas. The distance between the gauge and the obstacle e.g. a tree is at least two times the height of the obstacle.

Rain is collected in the funnel of a rain gauge and runs down to a filter that removes debris. Then into the tipping bucket mechanism, which when full tips and the other bucket positions itself under the nozzle to catch the drips. The moving arm forces the magnet past the reed at each tip causing contact for a few milliseconds. The outgoing water is then drained away through an outlet.

An EML Kalyx aerodynamic rain gauge with integrated limpet logger was used, which is based on the physical size of the 5" (127cm^2) Met Office rain gauge. The EML gauge improves accuracy for high winds, which without wind induced undercatch can be up to 20% due to the accelerating wind speed around the orifice. The gauge is raised to 72cm above ground to allow for the gauge to be above surrounding vegetation (Figure 2-7). Its accuracy, according to EML (2019), is 99% for up to 120ml/hour of rainfall and calibrated to 2% of the 0.2mm tipping volume. The gauge was cleaned regularly and at least every month to prevent blockages to the tipping buckets and filter. The logger records the time of the tip allowing the data to be converted to any time-step.

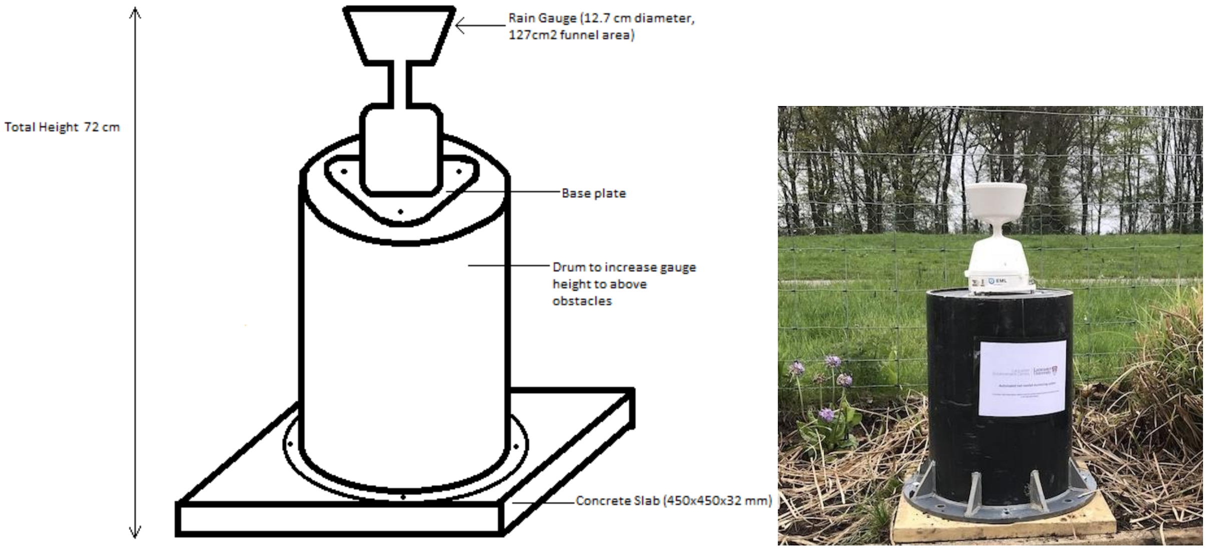


Figure 2-7:Kalyx Rainfall gauge with 5" collecting funnel and 0.2mm tip resolution. 72cm height ensures the gauge is above vegetation

The rain gauge was assembled as per the diagram by:

- Set up gauge-detach lid, remove foam and replace tipping bucket,
- Download limpet logger software on computer,
- Connect limpet logger and configure settings,
- detach logger from computer,
- Test the bucket tips and records before reattaching and downloading data. Wipe the logger and detach logger from the computer,
- Drill holes in slab and securely fasten stand for stability,
- Attach the logger to the stand via the 3 holes in the base of the gauge,
- Carefully transport to site and level in place using a spirit level,
- Log time in place as the logger can tip during transportation,
- Take laptop and cable to site to download data as required,
- Check/clean/inspect for damage the gauge and filter to prevent blockages every month.

2.2.3 Hazelrigg Weather Station Data

Certain data was required to determine any meteorological influences on WCE. Meteorological data was gained from Lancaster University's weather station, Hazelrigg, which is located within the few square miles suggested by Davidson and Leigh (2004) for the localisation of weather systems. The weather station site is to the east of the Chestnut tree and the M6 motorway at the top of a hill. The weather station is 1121m from the wood and 10 km East of the Irish Sea. Weather observations have been collected on this site since 1976. The data at Hazelrigg weather station is collected at 0900 GMT time every day and is also collected by the automatic weather station every 10 minutes.

There are two sites where data is collected. Temperature, wind direction, total radiation, relative humidity and rainfall volume were from the main site (Grid Reference 493 578) at 95m above sea level; and wind speed is used from the site B (Grid Ref 490 579) which at 85m above sea level is more sheltered and therefore more like campus conditions. The rainfall data is collected using an EML ARG100 tipping bucket rain gauge sited on the ground with a 0.2mm tip. Nearby objects include a 100m tall wind turbine 150m WSW, meteorological mast 10m NW, road and trees 30m East. This data is 10-minute averages. The data was then aligned with the high frequency data collected to 5-minute time-steps, by assuming the same value for the two 5-minute time-steps from each 10-minute time-step.

2.2.4 Frumau Rainfall Gauge

Three Frumau rain gauges have been strategically installed around the chestnut tree (stars in Figure 2-8) with one on the prevailing wind side, one to the leeward side and one next to the rain gauge in the bowling green grounds nearby.

Figure 2-8:Map depicting the location of the Frumau gauges relative to the Chestnut.

Frumau rain gauges were built and borrowed from Dr Mark Mulligan from Kings College London. These gauges are described in Frumau et al. (2011). Each gauge has 2 data loggers: one for the vertical rainfall collection and one for the horizontal collection. These data loggers are kept inside a cylinder container to protect them from the rain. The vertical rainfall is collected in a funnel at the top of the gauge and is channelled to a tipping bucket at the bottom (seen in Figure 2-9). The horizontal rainfall is collected through a mesh screen, which surrounds the gauge like a cylinder. The rain hits the screen and is directed down to the second lower funnel and is then channelled to the other tipping bucket for recording.

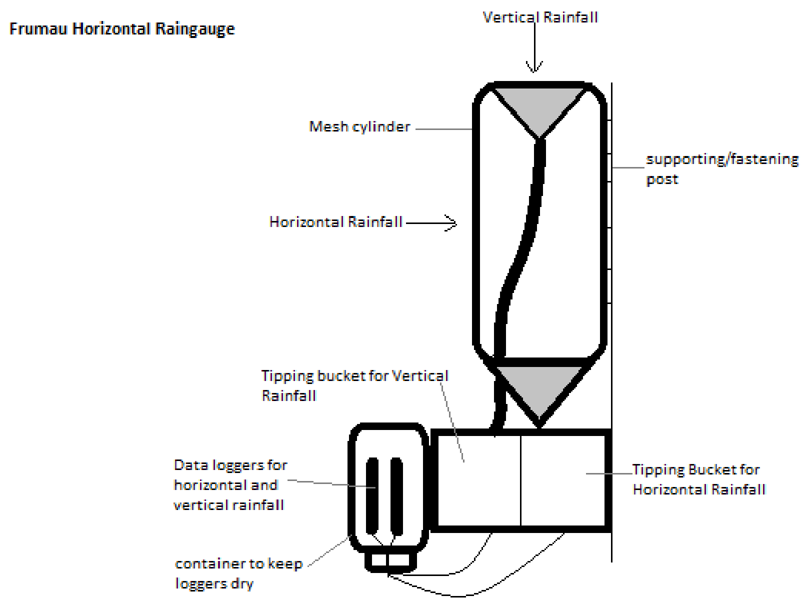


Figure 2-9:Pictures of the Frumau gauge in situ next to the gross rainfall gauge and a diagram of how the Frumau vertical and horizontal gauge works.

2.2.5 Stemflow

The stemflow collectors are located on the Chestnut tree, NE Oak and SW Beech, as stemflow varies between species and girth (Germer et al., 2010). The water flows down the stems to the trunk and is concentrated into the ground surrounding the tree, to its roots. The stemflow collector intercepts the water flowing down the trunk and collects and stores the water in a large container using a spiral neoprene collar. The water is captured in the tubing through holes and prevented from being lost over the edge by silicone sealant beading on the outside of the holes, as per Levia and Germer (2015) installation. The collar is no more than 2.5cm from the trunk to ensure drip is not intercepted (Oyarzun et al., 2011). Stemflow is then collected manually every week when equipment is checked and cleaned.

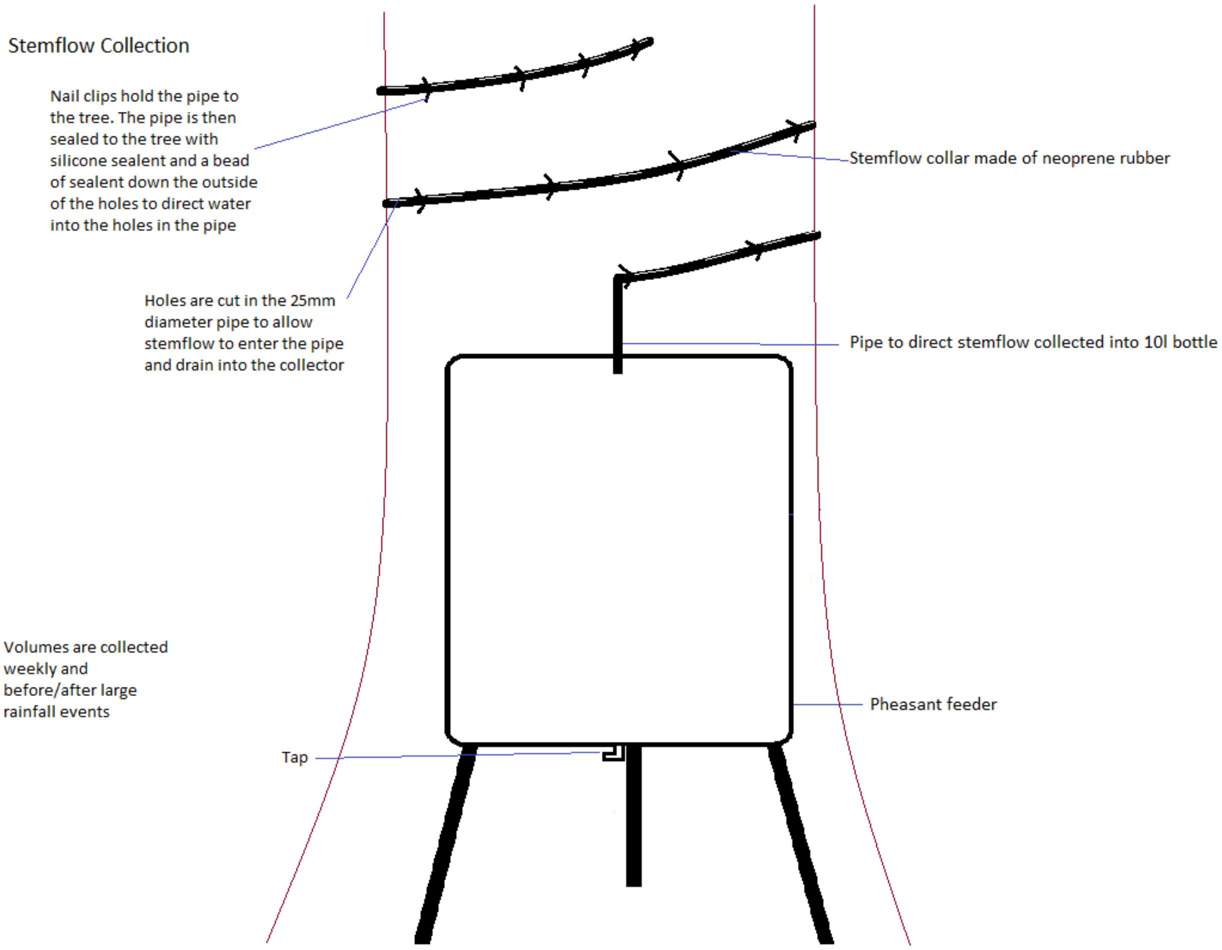
Stemflow volume is transformed into depth (mm) by using surface area of the horizontal canopy area. As the stemflow as a % of gross rainfall is small (although volume can be large (Chappell et al., 2001; Sinun et al., 1992)), it is less significant in relation to this experiment, therefore was not completed on every tree due to cost.

The equipment is assembled:

- In the workshop:
  - drill holes in containers for the pipe to enter at the top and overflow pipe,
  - add the taps at the bottom and seal,
  - cut pipe for overflow and stemflow pipe to required length.
- In the field:
  - Place the container where it is the most sheltered from wind around the tree,
  - Put the pipe in the container and spiral around the tree,
  - Fasten the pipe in place on the tree using pipe clips,
  - Using the electric cutter and wire cutters cut slits in the pipe for water to enter the pipe,

- In dry weather seal the pipe to the tree with silicone sealant; where there is a big gap use roof flashing to connect the stem to the pipe and seal this,
- Put a line of silicone sealant at the top outside of the pipe to prevent the water running off of the pipe and directing it into the holes,
- Once dry ensure taps are closed and measure once a week,
- An overflow was added with a tap at the top of the water butt into the overflow container.

The diagrams (Figure 2-10) show the stemflow installation for the smaller volume (i and ii) of the chestnut tree and higher volume (iii) for the oak and beech trees:



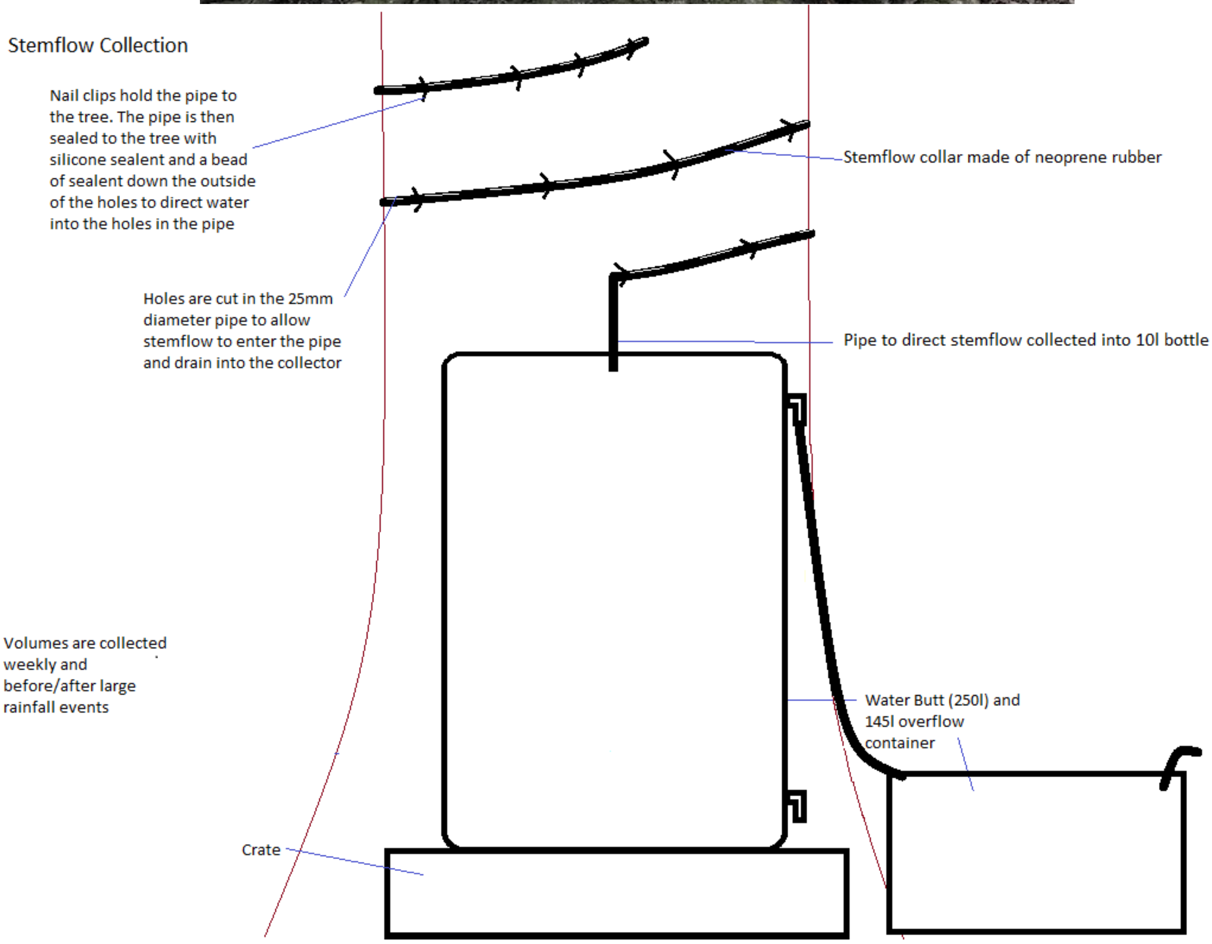


Figure 2-10:Diagram of stemflow equipment for (i and ii) smaller (Chestnut) and (iii) larger volumes of input (beech and oak trees)

The stemflow depth (mm) was calculated using Equation 2-1.

Equation 2-1:Stemflow calculation using Price and Carlyle-Moses (2003) and Siegert and Levia (2015) method.

$$SF = \frac{SFtotal/1000}{FA}$$

SF = Stemflow (mm)
SFtotal (ml) = average stemflow from sampled trees
FA = given area of forest/canopy area of the tree (m^2)

Staelens et al. (2006) converts stemflow collected into stemflow (mm) collected per horizontal canopy area while Lei et al. (2016) assumed the canopy area made an ellipse and calculated:

Equation 2-2:Canopy area using Lei et al. (2016) method

$$FA = \pi * d_1 * d_2 / 4$$

d_1 and d_2 are the longest and shortest diameters through the centre, as per **Error! Reference source not found.**. The table also shows circumference, DBH and height of the tree.

Table 2-2:Measurements of each tree including canopy area, diameter breast height (DBH), and height.

Location / Tree	Canopy diameter (m)	Canopy diameter (m)	Canopy Area (m2)	Circumference (m)	DBH (m)	Estimated Height (m) (and Max. species height)
NW Campus - Tipping Bucket – Horse Chestnut	16	17	213.628	3.6	1.146	28 (40m)
Cycle path – Common Beech	Not required as not stemflow present			3.96	1.261	35-40 (40m)
NE campus – Sessile Oak	12	5	47.124	2.18	0.694	30-35 (20-40m)
NE Campus – Common Beech	Not required as stemflow not present			4.4	1.401	~30 (40m)
SW Campus – Sessile Oak	Not required as stemflow not present			4.74	1.509	~25 (20-40m)
SW Campus – Common Beech	10	12	94.248	2.19	0.697	30-35 (40m)

Stemflow rate as a % of rainfall (Germer et al., 2010) is defined:

Equation 2-3:Stemflow rate (Germer et al., 2010).

$$S_{F\%} = S_F/R * 100$$

R is the rainfall depth.

$S_{F\%}$ = volume of stemflow water collected

2.2.6 Throughfall Tipping Bucket

Throughfall is the water/rainfall that falls to the ground either directly through a tree canopy or indirectly after being intercepted by the leaves. Throughfall data can be collected by roving and static methods and using either small gauges or trough gauges. These varying methods have their positives and negatives and their use depends on the area of study. For example spatial variability requires lots of small roaming gauges (Ziegler et al., 2009); whereas trough gauges with a larger collection area account for the variability, while the static factor ensures other factors affecting WCE can be studied, instead of the tree's variability potentially, which causes changes when using roaming gauges. Tipping bucket gauges data through events to allow for processes through a storm to be studied. For these reasons, static trough collectors were used to ensure the spatial variability is accounted for while the WCE variations can be measured. A high frequency tipping bucket is used to collect the throughfall data to see the variations through a storm.

The throughfall tipping bucket collector was a KIPP 100 tipping counter (Labcell Ltd.), which is made to accurately measure high intensity rainfall and large flows. The bucket has a volume of 99.7ml per tip and was logged on an EML Limpet logger XL (same logger as the rain gauge in more robust casing). The gauge records each time-stamped tip; this is then converted to 5-minute intervals once collected. The larger capacity of the troughs allows collection of throughfall from a larger area ensuring the data represents the woodland more accurately (10 times that of rainfall). The logger sat within a pheasant feeder with a funnel (350mm diameter) directing the water captured in the troughs into the tipping bucket (Figure 2-11). The 6 troughs were made of guttering of 4x0.114m with a depth of 0.06m to prevent splash back. The troughs were held up using large cable ties around lower branches. The troughs are angled to ensure water drains quickly and does not pool in the troughs, which did occur in Plynlimon (Institute of Hydrology, 1977). A mesh in the funnel prevents debris from entering the equipment. The equipment is emptied frequently (weekly with daily emptying during leaf fall) to prevent leaf litter build up causing pooling and increased evaporation (Kirby et al., 1991; Juvik et al., 2011).

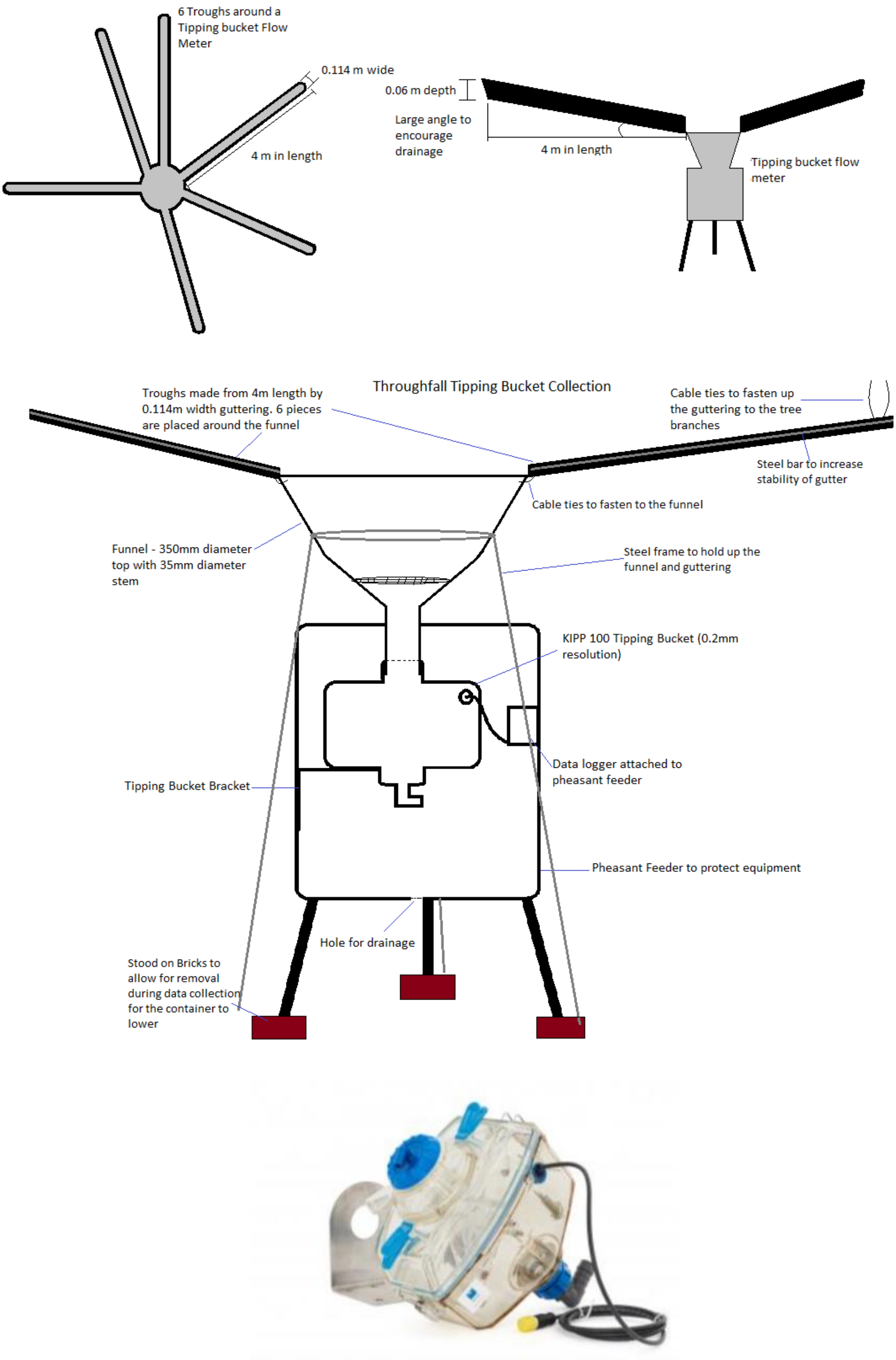


Figure 2-11:Tipping bucket (KIPP100) throughfall collector.

The localisation of rainfall events covers a large enough area that the spatial variability in rainfall does not affect the throughfall/rainfall collection locations due to the distance between the locations. Hazelrigg weather station is 500m away and therefore also allows the data to be compared without spatial variability in rainfall causing uncertainty in the results.

Throughfall measurements are spatially variable so require a large area to be measured (Chappell et al., 2001). The weather systems' spatial variability in the UK's temperate environment is lower than the tropics where many of these experiments have been undertaken. The lower spatial variability of rainfall and the fact this isn't being studied means less gauges are required for this experiment. The number of TF gauges required is into the 800s for a small event size in a woodland with 5% accuracy but with larger events this is significantly smaller around 6-50 depending on the uncertainty and size of storm (Price and Carlyle Moses, 2003; and Helvey and Patric, 1965). As large events are being studied an accuracy of 10% requires less than 13 standard gauges. Trough gauges were used as they require a further 20% smaller area (Helvey and Patric, 1965) as they ensure spatial variability is taken account of, are less time consuming for collection and do not require moving. One gauge with six troughs was used covering an area of 2.64m^2 (**Error! Reference source not found.**), which is much larger than that required for 13 standard gauges that covers an area of 1.25m^2 and Iida et al's suggestion of 1m^2 for trough gauges to allow for accurate scaling up to a forest stand and reduce the uncertainty in the spatial variability.

Table 2-3:Throughfall gauge area for the Chestnut 6-trough tipping bucket gauge located (corrected area is 2.64 m^2 when flat was 2.74 m^2)

Troughs	Height (height off ground - height of funnel) (a)	Angle X (degrees)	Corrected length (b) (mm)	Area
1	196-124 = 72 cm = 720 mm	10.37	3935	0.448 m^2
2	198 – 124 =74 cm = 740 mm	10.6	3930.95 = 3931	448134 mm^2 0.448m^2
3	(220+45) – 124 = 141 cm = 1410 mm	20.64	3743	426702 mm^2 = 0.4267 m^2
4	198 – 124 = 74 cm = 740 mm	10.6	3931	0.448 m^2
5	248 – 124 = 124cm = 1240mm	18.06	3803	433,542mm^2 = 0.4335m^2
6	(258-15) – 124 = 119 cm = 1190mm	17.31	3819	435366mm^2 = 0.4354 m^2
Total Corrected Area (if flat is 2.736m2)				=2.6396 m^2

The throughfall tipping bucket is assembled (Figure 2-11) by:

- Attach limpet logger (two wires) to the tipping bucket (remove 4 pin plug). Use a multi meter on resistance range to check the tipping bucket,
- Test tipping bucket/limpet logger and download data onto computer,
- Attach legs to pheasant feeder drum,
- Attach tipping bucket to inside of pheasant feeder using supplied bracket, ensure it is level with clearance off the bottom of the feeder,
- Cut the pheasant feeder lid to fit the stem of the funnel at its larger part,
- Cut ~1/2cm off the base of the funnel so it sits with the wide part of the stem within the lid for extra support. Cut a rectangle out of the bottom of the funnel stem so it sits in the tipping bucket better,
- Drill 2 holes in the side of the peasant feeder opposite the tipping bucket for the data logger to be attached using a cable tie,
- Drill 2 holes in the guttering at each end for attaching to the funnel and the branches, sides near the end to fit a cable tie through (about 5 cm from end),
- Attach steel pipe to the outside edges of the guttering to increase stability,
- Drill holes around the top of the funnel with 5cm gap to attach to gutter,
- Produce a support for the funnel to sit securely on pheasant feeder,
- Reduce height of pheasant feeder legs and sit on bricks (to allow for them to be removed to allow the feeder to be lowered away from the funnel/guttering for access to the data logger)
- Attach in the field using cable ties and attach funnel to pheasant feeder handles to increase stability

2.2.7 Manual Throughfall

The five manual collectors supplemented the tipping bucket gauge to measure WCE over a longer period. These collectors are below the Oak and Beech trees. These gauges were manually measured weekly or immediately before and after a large event. They have the same design as the tipping bucket collector but collect the water in a pheasant feeder and overflow container. They had 2 troughs instead of 6. The number of troughs were limited due to the frequency of collection required for a greater number of troughs. Figure 2-12 shows the design of the manual throughfall collector and one in-situ.

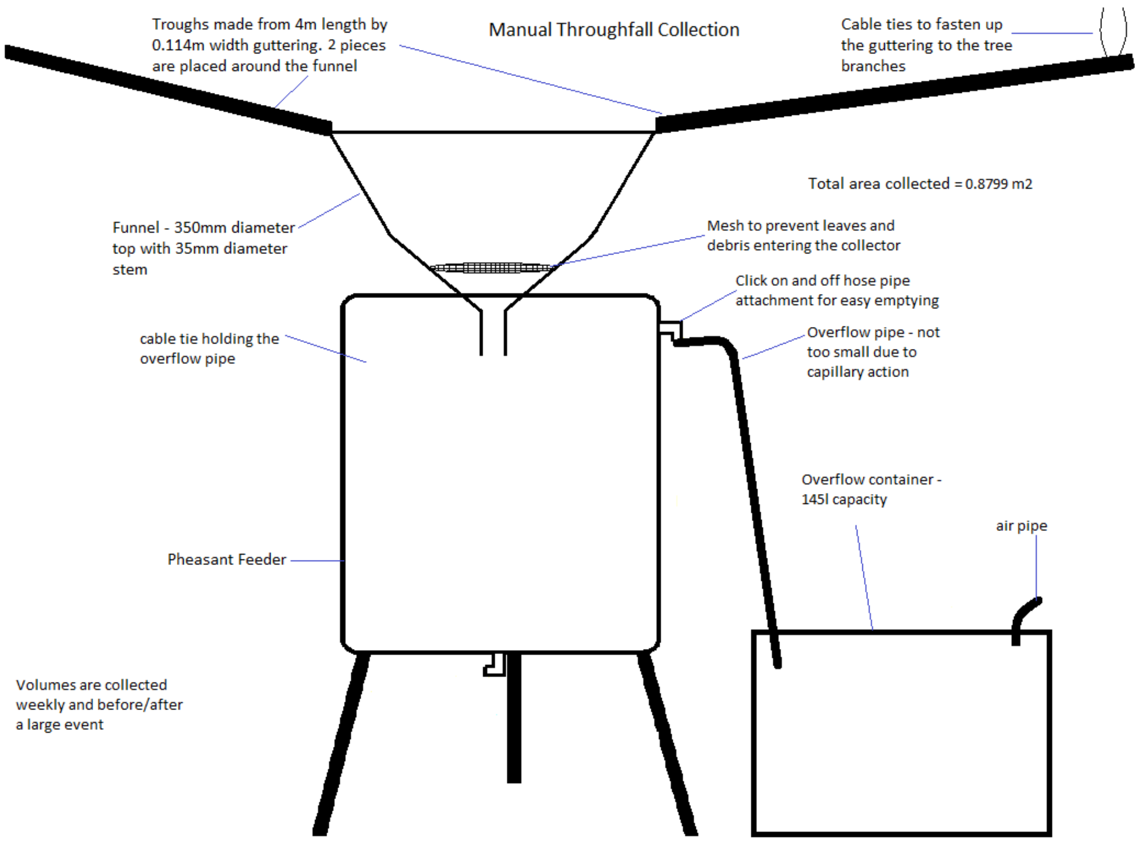


Figure 2-12:Picture and diagram of the manual throughfall collector.

Each manual collector had an area of around 0.9m^2 (varies slightly according to trough angle), which is similar to that required for the 20% smaller area of the 13 standard gauges (1m^2). This ensures that a large enough area has been sampled for a 10% accuracy with larger events. The trough areas for the manual collectors was calculated as per **Error! Reference source not found.**.

Table 2-4:Throughfall gauge area for the 2-trough manual collectors located at the cycle path, NE campus and SW campus

Trough 1						
	Height at trough centre	Height at edge of trough	height change (mm)	Corrected Length (mm)	Angle (degrees)	Area (mm^2)
NE OAK	1m 15cm	2 m 44cm	1290	3786.28	18.8	431635.92
NE BEECH	1m 17cm	2m 28cm	1110	3842.9	16.1	438090.6
SE OAK	1m 22cm	2m 20cm	980	3878.09	14.2	442102.26
SE BEECH	1m 10cm	3m 18cm	2080	3416.67	31.1	389500.38
CYCLE	1m 23cm	2m 66cm	1430	3735.65	20.9	425864.1

Trough 2						
	Height at trough at centre	Height at edge of trough	height change (mm)	Corrected Length (mm)	Angle (degrees)	Area (mm^2)
NE OAK	1m 15cm	2m 87cm	1720	3611.32	25.5	411690.48
NE BEECH	1m 17cm	2m 08cm	910	3895.11	13.1	444042.54
SE OAK	1m 22cm	2m 56cm	1340	3768.87	19.6	429651.18
SE BEECH	1m 10cm	3m 5cm	1950	3492.49	29.2	398143.86
CYCLE	1m 23cm	2m 37cm	1140	3830	16.6	436620

Troughs	Total		Average Angle at each tree (degrees)
	Total Area of troughs for Collector (mm^2)	Total in m^2	
NE OAK	843326	0.8433	22.15
NE BEECH	882133	0.8821	14.6
SE OAK	871753	0.8718	16.9
SE BEECH	787644	0.7876	30.15
CYCLE BEECH	862484	0.8624	18.75
CHESTNUT	2639600	2.6396	14.6

The manual throughfall equipment is assembled as per the tipping bucket throughfall without the tipping bucket. The base of the pheasant feeder had a tap attached and sealed. An overflow tap is attached near the top of the feeder and pipe attached to the tap and into another container through a hole at the top.

2.2.8 Spatial Variability under the Chestnut Tree

The spatial variability of the throughfall under the Chestnut was investigated due to negative WCE. To measure this, a grid was created (***Error! Reference source not found.Error! Reference source not found.***), which surrounded the throughfall collector. 30 1litre collectors were randomly given a random number and placed out by measuring out the grid. These were collected on 4 occasions (22nd-26th March, 01st-02nd, 03rd, and 27-28th April).

Table 2-5:Grid locations for spatial variability in throughfall under the Chestnut (outside means not covered by the canopy).

	0	1	2	3	4	5	6	7	8	9	10	11
0	edge	Tree	Tree	Tree	Tree	Tree	Tree	X1	Tree	Outside	outside	outside
1	Tree	X2	Tree	Tree	Tree	Tree	Tree	Tree	Tree	Tree	outside	outside
2	Tree	Tree	Tree	Tree	Tree	Tree	Tree	Tree	Tree	X3	outside	outside
3	Tree	Tree	X4	Tree	Tree	Tree	Tree	Tree	X5	Tree	outside	outside
4	Tree	Tree	Tree	Tree	Tree	Tree	Tree	X6	Tree	Tree	tree	outside
5	Tree	Tree	Tree	X7	X8	Tree	X9	Tree	Tree	Tree	Tree	outside
6	Tree	Tree	Tree	Tree	Tree	Tree	Tree	Tree	Tree	X10	outside	outside
7	X11	Tree	Tree	Tree	Tree	X12	X13	X14	Tree	X15	outside	outside
8	X16	Tree	Tree	Tree	X17	X18	Tree	Tree	Tree	X19	outside	outside
9	trunk	ST Collector	X20	Tree	X21	TF Collector	Tree	Tree	Tree	Tree	Tree	Tree
10	trunk	Tree	**X40**	Tree	Tree	X22	Tree	X23	Tree	Tree	X24	Tree
11	Tree	X25	Tree	Tree	Tree	Tree	Tree	Tree	Tree	Tree	Tree	Tree
12	Tree	Tree	Tree	X26	X27	X28	Tree	Tree	Tree	Tree	Tree	Tree
13	Tree	Tree	X29	Tree	Tree	Tree	Tree	X30	Tree	Tree	Tree	outside
14	Tree	X31	Tree	Tree	X32	Tree	X33	Tree	Tree	outside	outside	outside
15	Tree	Tree	Tree	Tree	X34	Tree	Tree	Tree	outside	outside	outside	outside
16	X35	X36	X37	Tree	Tree	Tree	Tree	X38	outside	outside	outside	outside
17	Tree	Tree	Tree	Tree	X39	Tree	Tree	outside	outside	outside	outside	outside
18	outside	outside	outside	outside	outside	outside	outside	outside	outside	outside	outside	outside

2.3 Field Techniques

2.3.1 Systematic Uncertainty Analysis

The location of the meteorological station is a site uncertainty as it is not immediately next to the chestnut tree. This data is not representative of the whole of the Lune catchment as there is varying landscape, meteorology and species. Therefore, evaporation estimates will be uncertain if scaled up to catchment scale (Beven, 1979). Beven (1979) also suggests that site uncertainty may exhibit bias as well as a random component and may show correlation in both space and time.

For the smallest events, the throughfall data collected suggests equivalent to 140 standard gauges would be required for a 10% uncertainty using the method in Price and Carlyle-Moses (2003); this would increase to 802 for a 5% uncertainty. This high value agreed with Price and Carlyle-Moses (2003) who found similar for a 5% uncertainty for small events. The number of gauges used (6) suggests a 40% uncertainty for these small events, however the 6 gauge (section 1.2.4)) covers 7.09m^2 which is 2.4 times larger than the 30 standard gauge area needed to provide a 5% uncertainty for the largest events. Price and Carlyle-Moses also found a small number of standard gauges were required for the larger events which are being studied here (6-25).

Measurement uncertainty is due to both instrument uncertainty and uncertainty in calculations (Beven, 1979). The measured rainfall (using a standard aerodynamic rain gauge at 1m height) has an uncertainty of 12.2% according to Pollock (2018), Kurtyka (1953), and EML (2019). The rain gauge is located just under 1m above ground level (0.72m) providing an added uncertainty to the wind uncertainty. Other uncertainty includes systematic uncertainty and actual manufacturer uncertainty of the equipment (**Error! Reference source not found.**). A similar uncertainty was also found by Rodda and Smith (1986) in Lancaster between a pit gauge and gauges with a height between 30cm-2m in height.

The throughfall measurement uncertainty is 7.74% and 7.86% for the tipping and manual collectors (Table 2-6:Uncertainty of rainfall and throughfall measurements). Uncertainty in the stemflow is introduced over time as the stemflow collector becomes loose and moves away from the tree.

Table 2-6:Uncertainty of rainfall and throughfall measurements

	Error (%)	Reference
Manufacturer rain gauge error (Kalyx-RG)	1	EML (2019)
Systematic error (included within the 1% manufacturer error)	1.5	Kurtyka (1953) and Pollock (2018)
Wind Induced Error	11.2	Pollock (2018)
Total Systematic error for rain gauge	**12.2%**	
Tipping bucket error	1	
Trough wetting up error	2.24	Section 2.2.4
Standard throughfall collection error	4.5	Holwerda et al. (2012)
Total error for throughfall tipping bucket	**7.74**	
Measurement/precision error	1.12	
Standard throughfall collector error	4.5	Holwerda et al. (2012)
Trough wetting up error	2.24	
Total error for manual collector	**7.86**	

Kurtyka, 1953	Systematic Error
Evaporation	-1
Adhesion	-0.5
Colour	-0.5
Inclination	-0.5
Splash	1
Total	**-1.5**
Exposure to Wind	-5 to -80

2.3.2 Gauge Calibration

The rain gauge has a manufacturer tip volume of 0.2mm. The rain gauge was calibrated on site to 0.198mm/tip. The rain gauge was calibrated by using an input only volumetric method (Santana et al., 2015). This is where a set volume is poured into the gauge slowly (ensuring overfilling or splash does not occur) and compared to the number of tips; allowing a volume per tip to be calculated. The gauge is fully wetted prior to calibration to ensure all water flows through the gauge for the calibration. The gauge has an uncertainty of ±5% (Omega, 2018). Its calibration was checked again at the end of October to the same value.

The Throughfall tipping bucket was calibrated using the same method. The tipping bucket had a 100ml tip according to the manufacturer and in the field was found to be 99.7ml.

The overall uncertainty has been calculated as 14.44% for the rain gauge.

On arrival at Lancaster University, from Prof. Mark Mulligan (Kings College London), three of the 6 gauges were erected in the field. It was noticed that one gauge was providing unusual readings. On trial it was leaking so the spare three were checked in the laboratory where one gave a value of 0.192mm/tip; however, the other 2 leaked. The working and leaking gauge were swopped.

2.3.3 Uncertainty in wetting up – actual vs measured

The uncertainty in throughfall gauges is caused by wetting up, evaporation, splash, inclination and colour. This was calculated by putting a known volume down the troughs and collecting it at the end (i.e. where the gauge collects/measures the water). This showed an average uncertainty of -2.24% (**Error! Reference source not found.**) due to adhesion and evaporation of water, which Kurtyka (1958) calculated as -1.5% for a rain gauge. Due to the larger area of the troughs the uncertainty is realistic. The uncertainty varied largely depending on the tree/throughfall gauge.

The Chestnut and NE Oak have the largest uncertainty in throughfall calculation. Throughfall collection uncertainty in Plynlimon was found to be caused by lack of angle of the troughs and clumping of pine needles in the equipment allowing for pooling of water. There is not a link between trough angle and uncertainty although as can be seen the troughs have large angles to ensure draining and not pooling. The troughs were also regularly cleaned out to prevent pooling (weekly and more frequently when leaves were falling. The uncertainty could vary through the year/events as the evaporation will varying depending on temperature, net radiation and wind speed. These measurements were undertaken on a sunny September morning with low wind speed.

The overall uncertainty has been calculated as 13.7% for the throughfall gauge.

Table 2-7:Percentage of water lost between hitting the equipment surface and collection

	Input (equal over number of troughs)	Output	Percentage lost
Chestnut (6 troughs)	1200	• 1130 • 1150 • 1150	• 5.83 • 4.17 • 4.17 Average: 4.72 %
SW Beech (2 troughs)	800	• 800 • 790 • 790	• 0 • 1.25 • 1.25 Average: 0.83
SW Oak (2 troughs)	800	• 790 • 800 • 790	• 1.25 • 0 • 1.25 Average: 0.83
Cycle path Beech (2 troughs)	800	• 780 • 780 • 780	• 2.5 • 2.5 • 2.5 Average: 2.5
NE Beech (2 troughs)	800	• 790 • 800 • 790	• 1.25 • 0 • 1.25 Average: 0.83
NE Oak (2 troughs)	800	• 760 • 780 • 770	• 5 • 2.5 • 3.75 Average: 3.75
All trees			Average: 2.24%

2.4 Modelling

The measured data was modelled to look at the system processes that occur through the events in more detail. The Rutter models (original and sparse) were utilised as they have been used the most frequently in the UK. The data will allow for WCE to be parameterised correctly for edge trees, rather than those in the middle of woodlands, in NFM models (e.g. the Cumbria Flood Model (Chappell et al., 2017)). Model parameters were adjusted to fit the data better.

Due to the high usage within the UK, the Rutter Original model was looked at, to determine if this is an accurate model to use in this environment and for trees affected by the edge. The Penman equation is required as part of the Rutter model therefore this equation was calculated first. Finally, the Rutter Sparse model was used to model the data as it accounted for a sparse canopy unlike the original which assumed a 'big leaf' effect (i.e. no gaps in the canopy) assuming the Rutter sparse may model the edge trees better.

2.4.1 Penman Equation

The potential evaporation (with unlimited access to water) that occurs (E) is calculated using the Penman Equation (Equation 2-4 (Beven, 2012, Rutter and Morton, 1977, and Gash and Morton, 1978)). The Penman equation is used as the Penman-Monteith equation contains the additional term for stomata resistance (to measure transpiration), which is reduced to zero in the Penman equation.

Equation 2-4:Penman Equation

$$E = \frac{\Delta R_n + \rho cp(VPD)/r_a}{\lambda(\Delta + \gamma)}$$

Where:
R_n = net radiational energy,
ρ = density of air
cp = specific heat of air and constant pressure
VPD = vapour pressure deficit
r_a = aerodynamic resistance, which can be sufficiently accurately measured from wind speed and stand height
λ = latent heat of vaporisation of water
Δ = Slope of saturation vapour pressure
γ = psychometric constant

Evaporation is affected by temperature, humidity and wind speed, which have been gained from Hazelrigg Weather Station (section 2.2.3). Hazelrigg data was converted to 5-min timestep from its recorded 10-min timestep to align with the rainfall and throughfall.

The E was then plotted against the measured evaporation calculated from Equation 2-1. Stemflow was very small so therefore discounted. The equation requires the time-step, relative humidity (Hazelrigg), air temperature (Hazelrigg), net radiation (below), aerodynamic resistance (below), canopy resistance (assumed to be 0), and additional energy (assumed to be 0). The variables required are in

.

Table 2-8:Variables and values used within the Penman equation

Parameter	Symbol	Unit	Value	Where it is from
Parameter	**Symbol**	**Unit**	**Value**	**Where it is from**
Time-step	TS	seconds		Hazelrigg data
Time-step	TSs	5-min	5*60	
Rainfall	RF	mm		Measured
Throughfall	TF	mm		Measured
Wet canopy evaporation from my data	WCE	mm		Calculated using measured data
Air Temperature	TZ	°C		Hazelrigg data
Relative Humidity	RH	%		Hazelrigg data
Aerodynamic Resistance	Ra	s/m	below	Gash and Morton (1978) and Calder (1977)
Wind speed at Hazelrigg	wind	m/s		Hazelrigg data
Height of mast at Hazelrigg	z	m	10	
Height of Chestnut tree	Ht	m	28	
Roughness length of observational surface assumed to be grass	Zg		0.1*0.1	Gash and Morton (1978) and Calder (1977)
Wind speed at corrected height	RU	m/s	Calculated below	Gash and Morton (1978) and Calder (1977)
Von Karman Wind Constant	k		0.41	Gash and Morton (1978), Calder (1977), Beven (1979)
Zero-plane displacement	d	m	0.75*z	Gash and Morton (1978) and Calder (1977)
Roughness length	Z0	m	0.05*z	Gash and Morton (1978) and Calder (1977)
Net Radiation	Rn	MJ/m²/s	Rns-Rnl	FAO (2019)
Total Radiation	Rt	MJ/m²/s		Hazelrigg data
Net shortwave radiation	Rns	MJ/m²/s	(1-α)*Rtz	FAO (2019)

Soil surface albedo range	Alpha α		(0.15+0.18) /2	Average for range for deciduous trees from Climate Data Information (2019)
Net longwave radiation	Rnl	MJ/m²/s	sigma*(TZk ^4)*(0.34-0.14*(sqrt(Eo)))*(ac*(Rt /Rso)+bc)	FAO (2019)
Pi	Pi π	-	3.14159265	An et al. (2017) and FAO (2019)
Stefan Boltzmann Constant	Sigma	MJ/m2/s	5.6748e-14	An et al. (2017) and FAO (2019)
Julian Day of Year	J	Julian day	((((TSz-12009600)/60)/60)/24) +135	This converts seconds data to Julian days
Temperature in Kelvin	TZk	K	TZ+273.15	
Relative Distance between Earth and the Sun	dr		1+0.033*cos((J*(2*π))/365)	Kalogirou (2014) and FAO (2019)
Latitude	phi	radians	(π/180)*54.05	FAO (2019)
Solar Declination	deta	radians	asin(0.39779*cos(0.98565*(J+10)+1.914*sin(0.98565*J-2))	ATACA (2019) and FAO (2019)
Solar constant	Gr	MJ m-2 min-1	0.08202	FAO (2019)
Seasonal Correction for Solar Time	bsc		((2*pi)*(J-81))/364	FAO (2019)
Seasonal Correction for Solar Time	Sc		0.1645*sin(2*bsc)-0.1255*cos(bsc)-0.025*sin(bsc)	FAO (2019)
Local Longitude	LL	deg	2.8007	Longitude difference from Lancaster to Greenwich
Standard Longitude	SL	deg	0	Longitude of time zone (Greenwich)
Solar time angle	w		(pi/12)*(((J) +0.06667*(LL-SL)+Sc)-12)	ATACA (2019) and FAO (2019)

Solar time period at start of time period	w1		w-((pi*(0.0833))/24)	An et al. (2017) and FAO (2019)
Solar time period at end of time period	w2		W+((pi*(0.0833))/24)	An et al. (2017) and FAO (2019)
Extra-terrestrial solar radiation	Rsa		((12*60)/(pi))*dr*0.0820*((w2-w1)*sin(phi)*sin(deta)+cos(phi)*cos(deta)*(sin(w2)-sin(w1)))	An et al. (2017) and FAO (2019)
Relative shortwave radiation (i.e. cloudiness of the atmosphere)	Rso		Rsa*(0.75+0.00002*ELmsl)	An et al. (2017) and FAO (2019)
Elevation above sea level	ELmsl	m	48	An et al. (2017)
Mean daily dew point temperature parameter	Td		TZ-((100-RH)/5)	An et al. (2017)
Actual Vapour Pressure	E_0	kPa	(0.6108*exp((Td*17.27)/(Td+237.3)))*(RH/100)	FAO (2019)
Cloud factor	ac		1.35	An et al. (2017) and FAO (2019)
Cloud factor	bc		-0.35	An et al. (2017) and FAO (2019)
Emissivity factor in Rnl	a1		0.34	Evett et al. (2011) from An et al. (2017) and FAO (2019)
Emissivity factor in Rnl	b1		0.14	Evett et al. (2011) from An et al. (2017) and FAO (2019)
Penman				Page (2019)
Additional Energy	Ca	MJ/m²/s	0	
Canopy Resistance	Rc	s m-1	0 potential evaporation rate	Singh (1995)
Specific heat capacity of air at constant pressure	cp	MJ/KG/K	$0.01E^{-03}$	

Constant	gamma γ	KPa/K	66/1000	
Latent heat of vaporisation	lambda λ	MJ/KG	2.47	
Specific Gas constant of air	R	-	287.05	
Density of air	rho	Kg/m^3	le5/(R*(TZ+273.3)	
Saturation vapour pressure at TZ	esTZ	kPa	Calculation is below	
Actual Vapour Pressure	E_0	kPa	esTZ*RH/100	
slope of saturation vapour pressure curve at TZ	delta	KPa/K	(4098*(0.607*exp(17.27*TZ/(TZ+237.3))))/((TZ+273.3)^2)	
Evaporative latent heat flux	LamdaE	MJ m-2 TS-1	(Delta*(Rn-Ca)+(cp*rho*(esTZ-e0)/Ra))/(Delta+gamma*(1+Rc/Ra))*TSs	
Potential evaporation rate	E	Kg m-2 d-1 or mm TS-1	LamdaE/lambda	Penman Equation (Beven, (2012))

The **aerodynamic resistance** can be calculated (Calder, 1977) using the collected WCE data and rearranging the Penman equation but can produce significant uncertainty (Beven, 1979). Modelled aerodynamic resistance is around 5-14 s/m for singular trees (Gromke and Ruck, 2008)), which agrees with <10s/m for deciduous trees. It was calculated using the wind speed, which is corrected to tree canopy height (RU), as follows:

Equation 2-5:Wind speed corrected to tree canopy height

$$RU = {windspeed} \Big/ \frac{\log \frac{z}{Zg}}{\log \frac{Ht}{Zg}}$$

The variables are defined in

above. The aerodynamic resistance is then calculated using the corrected height of wind speed as follows:

Equation 2-6:The aerodynamic resistance calculation with windspeed's corrected height

$$Ra = log^{(\frac{z-d+Ht-z}{Z0})^2} / _{(RU*K)^2}$$

Some meteorological parameters are easy to measure unlike the **net radiation** (Equation 2-7), which involves other energy fluxes which are more difficult to quantify (Beven, 1979).

Equation 2-7:Net Radiation calculation

$$R_n = R_{ns} - R_{nl}$$

This is net shortwave radiation (R_{ns}) minus longwave radiation (R_{nl}) (incoming-outgoing). The parameters and their origins are in

. R_{ns} is calculated as follows, when R_t is the total radiation measured at Hazelrigg:

Equation 2-8:Net shortwave Radiation

$$R_{ns} = (1-\alpha) * R_t$$

Equation 2-9:Soil surface albedo

$$\alpha = (0.15 + 0.18)/2$$

And R_{nl} is calculated as follows from Hazelrigg temperature:

Equation 2-10:Net Longwave Radiation

$$R_{nl} = sigma * TZk^4 * \left(a1 - b1 * \sqrt{E_0}\right) * \left[ac * \left(\frac{Rt}{Rso}\right) + bc\right]$$

Where Relative shortwave radiation/cloudiness of the atmosphere:

Equation 2-11:Relative Shortwave Radiation

$$R_{so} = R_{sa} * (0.75 + 0.00002 * Emsl)$$

Extra-terrestrial solar radiation:

Equation 2-12:Extra-terrestrial solar radiation

$$R_{sa} = \left(\frac{12*60}{\pi}\right) * dr * Gr * ((w2 - w1) * \sin(phi) * \sin(deta) + \cos(phi) * \cos(deta) * (\sin(w2) - \sin(w1)))$$

When dr is the relative distance from the sun:

Equation 2-13:Reverse relative distance from the sun

$$d_r = 1 + 0.033cos\left(\frac{2*Pi}{365} * J\right)$$

With Julian day (J) is calculated in Equation 2-14, with 135 being the Julian day of 0 seconds when starting on 15th May 2018 (start of the measurements) in TS:

Equation 2-14:Julian Day

$$J = (((\frac{(TZ-1209600)}{60})/60)/24) + 135$$

Deta is the solar declination calculated using the Julian days:

Equation 2-15:Solar Declination in Julian Days

$$Deta = 0.409\sin(\frac{2\pi}{365}J - 1.39)$$

The solar time angle at the start (w1) and end (w2) of the measurement period is calculated using Equation 2-16 with minus and plus respectively:

Equation 2-16:Solar Time Angle

$$W_{1/2} = w \ \pm (\frac{\pi * (0.0833)}{24})$$

Solar time angle at the mid-point of the measurement period:

Equation 2-17Solar time angle at the mid-point of measurement period

$$W = \left(\frac{\pi}{12}\right) * ((J + 0.06667 * (LL - SL) + Sc) - 12)$$

Sc is the seasonal correction of solar time where:

Equation 2-18:Seasonal correction of solar time

$$Sc = 0.1645 * \sin(2 * bsc) - 0.1255 * \cos(bsc) - 0.025 * \sin(bsc)$$

Equation 2-19:Seasonal Correction for Solar Time

$$bsc = \frac{(2 * \pi) * (j - 81)}{364}$$

The **saturation vapour pressure** (esTZ) is also required, which uses the temperature from Hazelrigg:

Equation 2-20:Saturation vapour pressure

$$esTZ = 0.6108 * \exp(\frac{17.27 * TZ}{TZ + 237.3})$$

The **actual vapour pressure (E_0)** is then calculated using esTZ and the relative humidity also collected at Hazelrigg:

Equation 2-21:Actual Vapour Pressure

$$E_0 = esTZ * RH/100$$

The slope of saturation vapour pressure curve at TZ is calculated by:

Equation 2-22:Slope of saturation vapour pressure curve

$$Delta = {(4098 * (0.607 * \exp\left(\frac{17.27*TZ}{TZ+237.3}\right)} \Big/ {(TZ + 273.3)^2}$$

The density of air (rho) is calculated:

Equation 2-23:Density of air where R is the specific gas constant of air

$$rho = \frac{1e^5}{R * (TZ + 273.3)}$$

The Evaporative latent heat flux (LamdaE) can then be calculated as follows, with parameters defined in

and where TS is the time-step:

Equation 2-24:Evaporative latent heat flux

$$LamdaE = TS * \left[\frac{delta*(R_n - C_a) + (C_p*rho*(esTZ - E_0 \big/ R_a}{Delta + gamma*(1 + R_c \big/ R_a)}\right]$$

The mass water evapotranspiration rate is calculated as follows, where E is negative it is assumed to be zero:

Equation 2-25:Mass water evapotranspiration rate

$$E = LamdaE/Lambda$$

E=(E<0)=0

2.4.2 Physically-based Model – Rutter Models

The process equation for WCE is:

Equation 2-26:WCE process equation

$$RF = TF + WCE \& \Delta S + SF$$

The stemflow section is highlighted in blue and is excluded from this equation as it has a small volume, which sits within the data collection/model systematic uncertainty and was recorded at a different time interval. The following flow chart shows the inputs, pathways and outputs of this process and that used of the Rutter Model (Gash and Morton 1978):

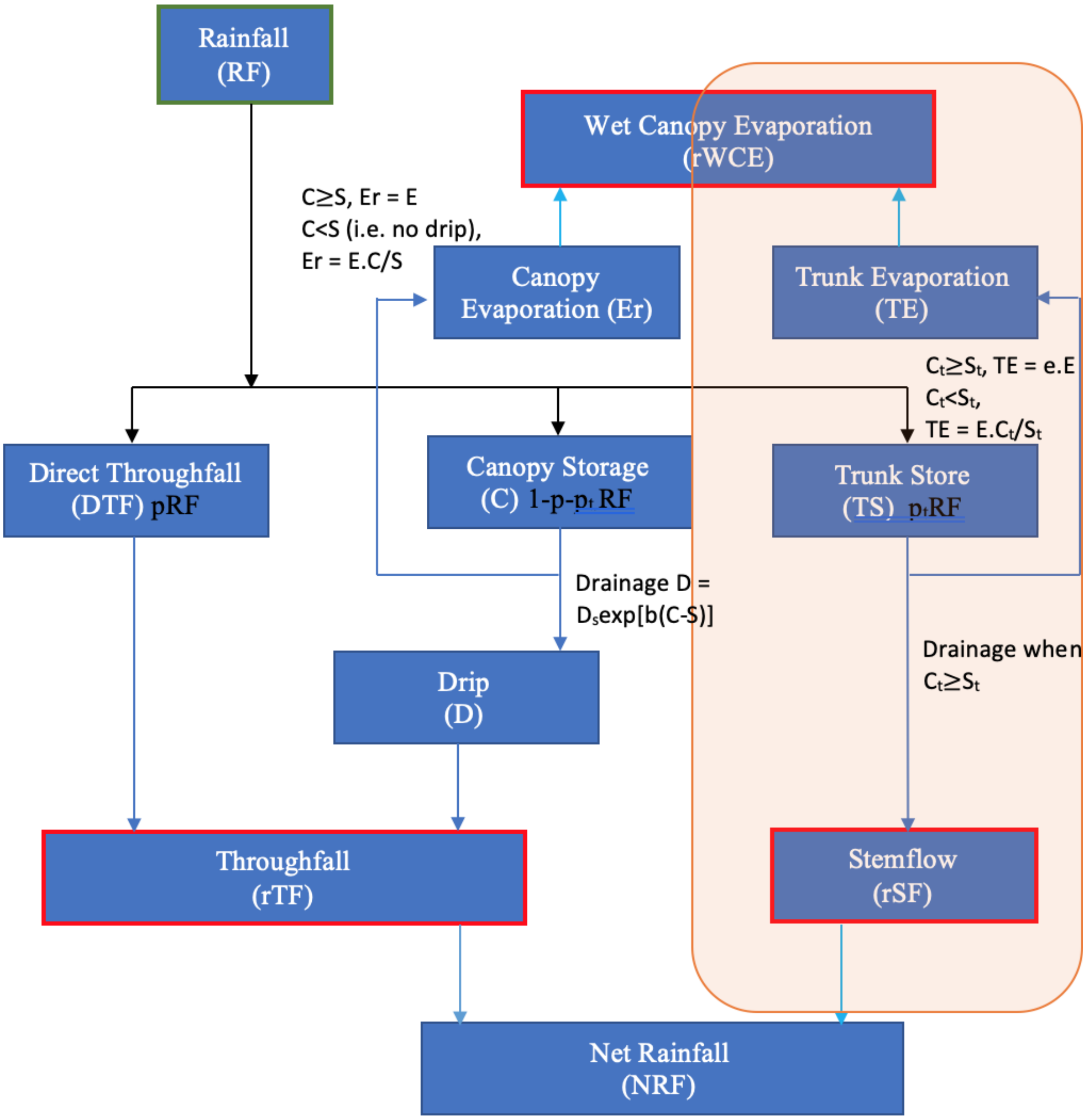


Figure 2-13:Input, output and pathways involved in the process from rainfall to WCE (Gash, 1978). The orange highlights the excluded stemflow process.

The Rutter model uses the Penman equation to calculate potential evaporation prior to utilising it within the model to calculate the 'Rutter' evaporation. The initial variables and inputs that are required are available in Table 2-9.

Table 2-9:Rutter Model input data

Parameter	Symbol	Unit	Value	Where it is from
Rainfall	RF	mm	-	Measured
Time of rainfall	tRF	Julian day	-	Measured
Time in seconds	tnrs	seconds	-	
Time of throughfall	tTF	Julian day	-	Measured
Throughfall	TF	mm	-	Measured
Throughfall (from Rutter Model)	rTF	mm	-	Rutter Model output
Stemflow from Rutter Model	rSF	mm	-	Rutter Model output
Direct Throughfall	DTF	mm		Rutter Model output
Potential evaporation	E	mm	-	Penman Equation (Beven, (2012), Gash and Morton (1978) and FAO (2019))
Drainage coefficient	b	-	3.7	Gash and Morton (1978), Rutter et al. (1975) and Rutter et al. (1971) varied between 3 and 4.6
Free throughfall coefficient - proportion of rainfall to touch the floor without touching the canopy	p	-	-	Calculated using measured data, shown in the results section
Proportion of rainfall diverted to stemflow	P_t	-	N/A	Is not required as excluding stemflow
Proportion of evaporation in relation to stemflow	e	-	N/A	Is not required as excluding stemflow
Drip	D	mm	If C<S D=0	Gash and Morton (1978)
Drainage rate when C=S	Ds	mm	If C=S, Ds=0.0038 mm/min If C<S Ds=0	Calculated and Graph in Rutter et al. (1971) And utilised in Rutter et al. (1975) and Gash and Morton (1978)
Trunk water capacity	S_t	-	N/A	Not required as SF not calculated
Trunk Store	TS	mm	-	
Total wet canopy evaporation calculated by Rutter Model	rWCE	mm	For each 5-minute time step	Rutter Model output
Canopy evaporation	Er	mm	For each 5-minute time step	Gash and Morton (1978)
Trunk evaporation	TE	mm	For each 5-minute time step	
Water in the Canopy	C	mm		Gash and Morton (1978)
Canopy capacity – minimum quantity of water to wet the canopy (wetting up)	S	mm	Please see results section below	Calculated using graph of throughfall vs rainfall (volume)

Unlike the Penman equation, Rutter predicts the evaporation according to the intercepted rainfall. The Rutter model uses rainfall as the input and from there predicts the rWCE, rSF and rTF. The RF falls on the tree canopy where a proportion falls directly through the tree (DTF):

Equation 2-27:Direct throughfall

$$DTF = p.RF$$

The rest of the rainfall hits the canopy (C) and trunk (TS) where it is initially stored until it reaches its capacity:

Equation 2-28:Water stored in the canopy

$$C = (1 - p - p_t)RF$$

The free throughfall coefficient (p) is calculated by plotting rainfall vs throughfall for events <1mm (Gash and Morton, 1978). A regression line is plotted and the coefficient of regression of throughfall against rainfall is p.

The canopy capacity (S) (i.e. amount of water held in the canopy before drip occurs) is calculated from the sum of the rainfall volume at throughfall time zero. This is calculated by plotting throughfall volume against rainfall. Where the straight line crosses the x axis when y = 0 provides the canopy capacity.

Equation 2-29:Canopy Capacity

$$S = \Sigma RF_{TF0}$$

Once the capacity (S) is reached in the canopy, drip (D) occurs, which along with DTR makes up throughfall (TF). The drainage of the canopy is expressed as, when C<S:

Equation 2-30:Drip when C<S

$$D=0$$

To ensure it avoids mathematical absurdity (Calder, 1977) of a small but infinite drainage rate when C=0, and consistent with deriving S, when C=>S

Equation 2-31:Drip when C=>S

$$D = D_s \exp[b(C - S)]$$

Where b is a drainage parameter of 3.7. This drainage parameter was used as the average of that calculated from 4 storms by Rutter et al. (1971). The range, which was 3-4.6, was found to have a negligible effect on the final model. The storms covered a fair range of seasonal and climatic variation.

The drainage rate (D_s) of 0.002mm/min was determined in Rutter et al. (1971) and utilised in Rutter et al. (1975). Gash and Morton (1978) suggested it should take account of the specific tree therefore 0.002*(2.0048/1.05) gives 0.0038mm/min, where 2.0048mm is the calculated value of S and 1.05mm is the calculated value of S for the tree where Ds is 0.002mm/min.

Throughfall is calculated from:

Equation 2-32:Rutter Model Throughfall Calculation

$$rTF = D + DTF$$

The water in the canopy (C) that is not lost to D, is evaporated from the canopy.

rWCE is made up from the proportion evaporated from the canopy (Er) and trunk (TE). The Er is calculated as follows:

Equation 2-33:Water Evaporated from the Canopy

If C< S

$$Er = E.\frac{C}{S}$$

Or when C≥S

$$Er = E$$

The proportion of RF that reaches the trunk store (TS) is shown in Equation 2-34. However, this part is excluded from the model as it is below the measurement uncertainty.

Equation 2-34:Trunk Store

$$TS = p_t.RF$$

The water is either evaporated (TE, Equation 2-35-Equation 2-36) or drained as stemflow (SF, Equation 2-36). The stemflow along with D and DTF makes up net throughfall. The parameter 'e' is the proportion of evaporation in relation to stemflow.

Equation 2-35:Trunk Evaporation

Where $C_t \geq S_t$,

$$TE = e.E$$

Or if $C_t < S_t$,

$$TE = E.\frac{C_t}{S_t}$$

Equation 2-36:Stemflow

$$rSF = TS - TE$$

The total evaporation from the tree (rWCE) is calculated by totalling the TE and Er. As stemflow section is not being calculated, rWCE = Er.

rWCE, and rTF were plotted against measured throughfall and WCE.

The Rutter Original had some shortcomings which were improved within the Rutter Sparse model. The problems were linked to the canopy store when the rainfall is high (explained in Valente et al., 1997). The Sparse model has a simplified drainage function with drainage for each time-step calculated by:

Equation 2-37:Rutter Sparse simplified drainage function

If $C \geq S$: $$D = C - S$$

$C < S$: $$D = 0$$

The simplified drainage of the Rutter Sparse model prevents the excessive build-up of water on the canopy over the canopy capacity. Any storage above the canopy storage level is converted immediately to drainage, therefore drainage is assumed to stop when rainfall does. Omitting the drainage function of the original Rutter model removes the requirement of Ds and b to be calculated which are not know and estimated by extrapolating original values calculated by Rutter. Valente et al. (1997) found that this was also agreed by Aston (1979) and Lloyd et al. (1988).

3 Results

3.1 Rainfall

The total rainfall volume measured from the EML rain gauge (10/05/18-30/04/19) was 803.54mm (Table). The average annual rainfall total for Lancaster was 1048.8mm (Met Office, 2019). Only 15 days less than the year was measured by the EML gauge suggesting a drier year than average.

Pollock (2016) found that at upland sites, a pit EML ARG100 aerodynamic rain gauge underestimated rainfall by 8% whereas at 1m height it underestimated by 16.5%. Pollock et al., (2018) found that the lowland gauge at 0.5m height reduced catch by 3.4% compared to the pit gauge. Therefore, when this 0.7m high EML rain gauge was corrected by 3.4%, it measured 830.54mm. These estimates are still much drier than the Lancaster average rainfall.

The Frumau vertical gauge installed next to the EML gauge, shows an overestimation of 39.5% and 23.4% of rainfall compared to the EML (corrected by 3.4%) and Hazelrigg rain gauges, respectively (Table).

When the rainfall from the EML gauge was corrected by the 3.4% to account for wind induced underestimation, the volume was only 71% of that recorded by the Frumau vertical gauge. This did not include the volume that fell horizontally (additional 98% of the vertical rainfall) and was caught by the horizontal gauge. The Frumau horizontal gauge shows that the EML gauge experiences higher horizontal rainfall than would be expected at a lowland site suggesting that the underestimation is greater than the 3.4% suggested by Pollock (2018) suggesting greater wind speeds to produce the underestimation. This also implies that the true rainfall volume captured by the tree should be so the WCE% would be larger than calculated.

*The average annual Lancaster (**Error! Reference source not found.**), Hazelrigg, and EML (corrected by 3.4%) rainfalls suggests the year was drier than average. The data shows that each month (excluding September, December and March) was drier than average with some months significantly drier. The number of days of rainfall was 70 days more than the average while the volume was less indicating more smaller events over the year apart from the 3 months where larger events occurred (*

).

Table 3-1:(1)recorded rainfall, (2)rainfall volume for the events where Chestnut throughfall was recorded, (3) rainfall for data collection period from all 6 trees, and (4)rainfall when the Frumau gauge is installed.

	EML Data (mm) (Bracketed value is corrected according to Pollock (2018) by 3.4%)	**Hazelrigg (ground level) (mm)**	**Frumau Gauge (next to the EML gauge) Vertical RF (mm)**
1. Annual Rainfall (15/05/18 – 30/04/19)	803.54 (830.86)	924.00	-
2. Rainfall data without events with missing throughfall data (15/05/18 – 30/04/19)	651.26 (673.4)	742.61	-
3. Rainfall over manual measured period (5/8/18 – 30/4/19)	742.05 (767.28)	854.21	-
4. Installation dates for the Frumau Gauge (8/3/19 – 30/4/19)	142.22 (147.06)	160.80	205.09

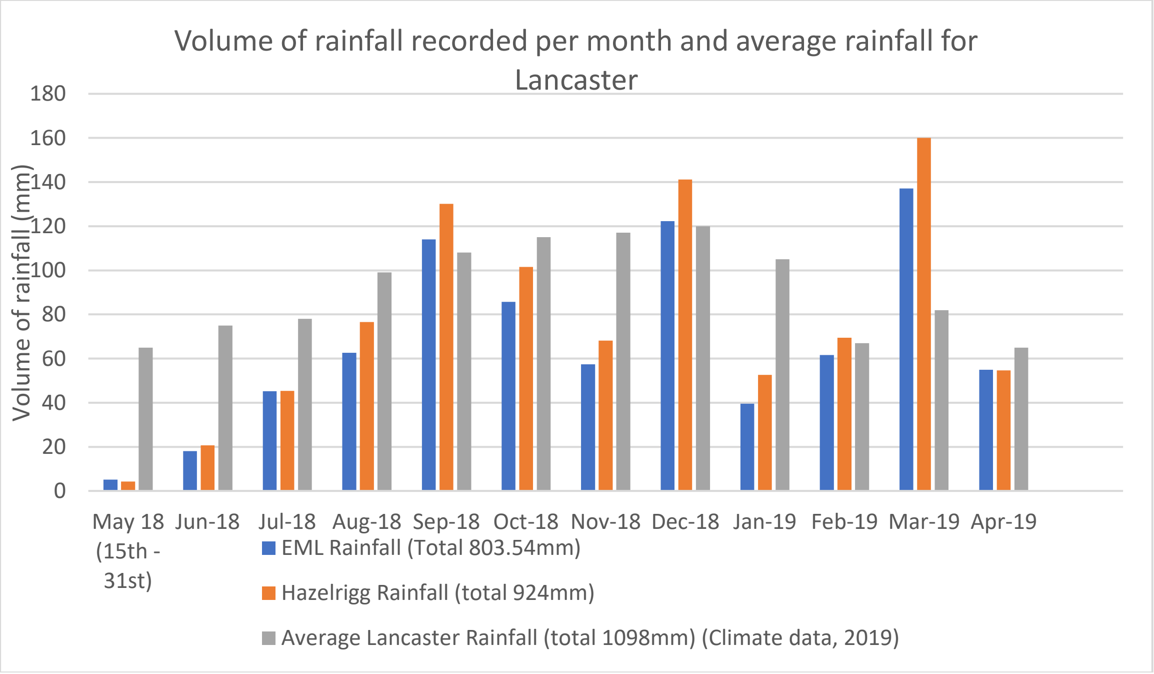


Figure 3-1:Volume of rainfall recorded each month by the EML gauge, Hazelrigg gauge and average monthly rainfall for Lancashire

*Table 3-2:*Rainfall days measured against average for Lancaster and difference.

(Holiday Weather, 2019)	**Average Lancashire days of rain**	**Measured days of rain**	**Difference**
May 2018 (15th -31st)	14	3	-11
June 2018	11	8	-3
July 2018	14	8	-6
August 2018	11	18	7
September 2018	10	20	10
October 2018	7	23	16
November 2018	9	22	13
December 2018	10	21	11
January 2019	9	25	16
February 2019	10	17	7
March 2019	8	20	12
April 2019	12	10	-2
Total	**125**	**195**	**70**

When the Frumau gauge (at the rain gauge site) is used to calculate WCE, the WCE% for the measurement period was 69.4% whereas the EML rain gauge in the same period gives 17.6%. (**Error! Reference source not found.**).

However, where the Frumau gauges have been sited (one at the open tree canopy, one at the closed canopy and one at the rain gauge) and the area of open canopy (East through to West), the data cannot be used to accurately determine a true value of horizontal rainfall taken up by all the open side of the canopy to add this to the vertical rainfall. This is because the open canopy spans a large part of the chestnut tree that one gauge is not sufficient to determine the horizontal water collected as some will be in the prevailing wind and other at the leeward side meaning rainfall collected by various parts of the canopy would be very different. This could be overcome by placing more Frumau gauges around the open canopy to determine the rainfall hitting varying segments of the open canopy.

Negative WCE occurred at the event and weekly scale. Only 4 negative WCE events were recorded when using the Frumau gauges. When the WCE for these events was recalculated using the Frumau vertical and horizontal data, the recalculation produced all positive WCE values suggesting that the horizontal rainfall is the cause for this. The largest negative WCE during this period was -56% suggesting that horizontal rainfall is the cause of the majority of negative WCE values. However, some negative WCE events reached over -100%; it is therefore still unknown if horizontal rainfall accounts fully for these events but is likely to also be the case as these occurred during light rainfall events.

Where negative WCE is measured using the EML gauge, the Frumau gauge at the rain gauge recorded more horizontal than vertical rainfall and more than when the WCE is positive. 22.8, (when negative) compared to 3.4 (when positive) times greater than vertical rainfall when hitting the open canopy. This is similar when hitting the non-prevailing wind side of the tree with horizontal rainfall 13.6 times larger than vertical when negative WCE occurs compared to 2.1 times larger when WCE is positive. This shows an underestimation of rainfall by the EML gauge that is intercepted by the tree requiring adjustments of total rainfall, increasing WCE. For negative WCE more rainfall hits the windward side of the canopy, which is the open side, suggesting wind direction and speed are important to create horizontal rainfall towards the open canopy for increased collection. The Frumau gauges show the prevailing wind direction towards the open canopy where more horizontal rainfall occurs.

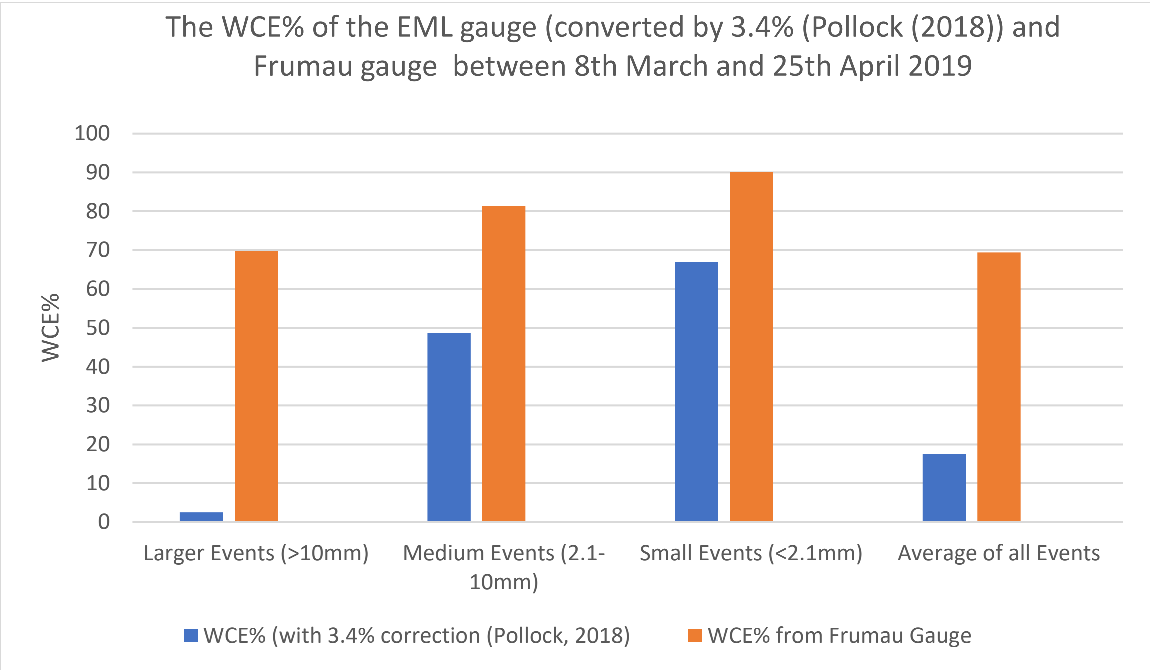


Figure 3-2:WCE percentages when calculated using the Frumau gauge and calculated WCE (using Pollock (2018) 3.4% rainfall correction) between 8/3/19-25/4/19

Figure 3-3 shows that during events where WCE is negative less water reaches the leeward gauge as vertical or horizontal rainfall showing a rain shadow. The positive WCE graph also indicates that there is more wind to the open canopy than the leeward side as greater amounts of horizontal rainfall are detected, indicating WCE is underestimated as the collected rainfall received by the canopy is larger than measured.

It has been found the EML rain gauge underestimates the intercepted rainfall due to the horizontal rainfall increasing the canopy collection of rainfall. The rainfall measurement method around an edge tree needs to account for horizontal rainfall using multiple gauges (e.g. Frumau gauge) around the tree to determine the horizontal rainfall received by the tree.

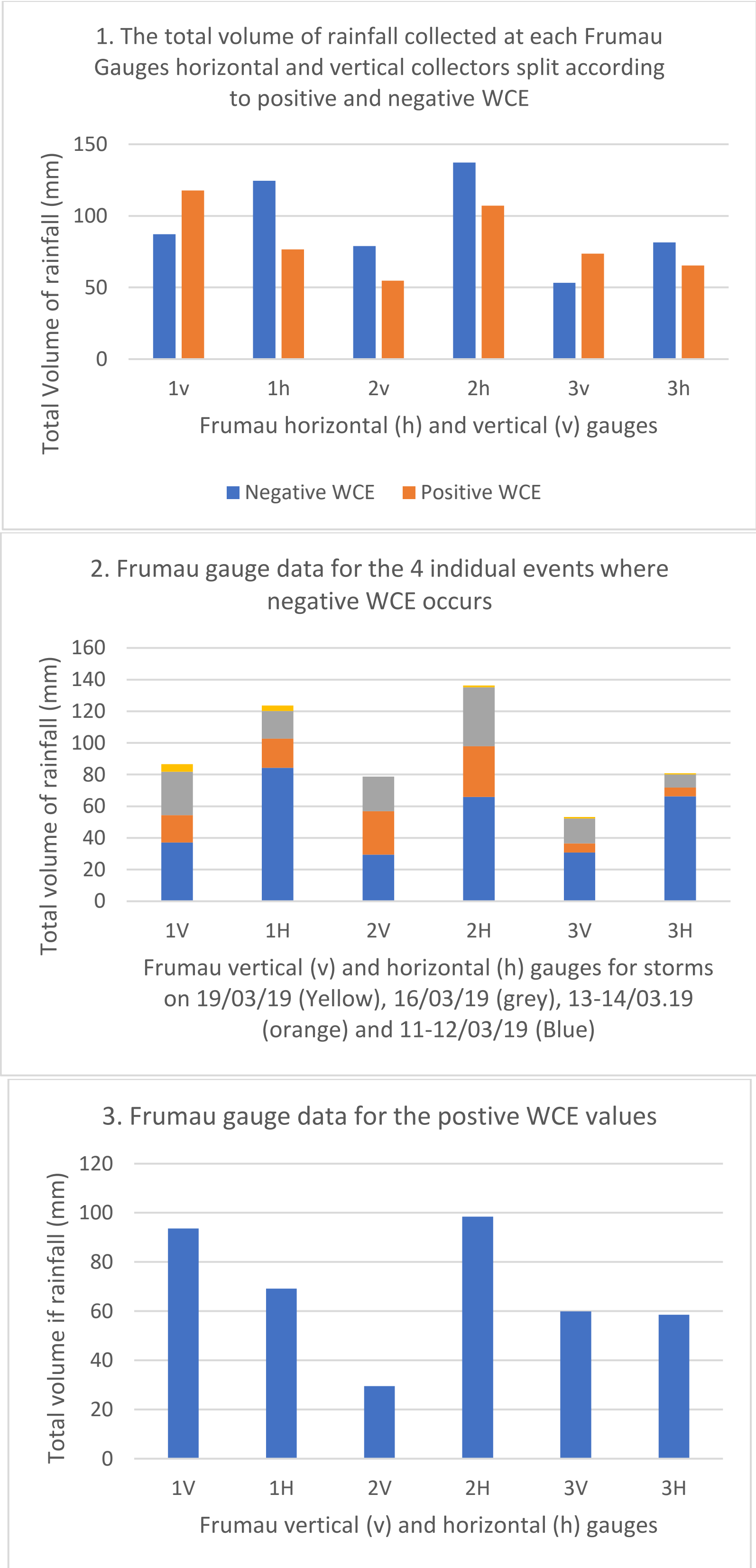


Figure 3-3:(1)total rainfall volume collected between *8/3/19-25/4/19* at each Frumau gauge (1 next to EML rain, 2 open side, and 3 closed side of canopy) for the vertical and horizontal collection split, (2)separate for the negative WCE events, and (3)data for positive WCE events

3.2 Annual, Leafed and Non-leafed Data, and Storm Data

The TF%, WCE% and SF% against rainfall were calculated using the rainfall measured (UCR in) and corrected according to Pollock (2018) (CR in) for lowland undercatch. Although the Frumau rainfall data suggests Pollock (2018) correction is too low, the true undercatch due to horizontal rainfall is not known for these trees as horizontal rainfall was only measured for a small number of events and is highly dependent on wind speed and direction.

Equipment fell over more frequently for the Chestnut tree than the others. However, collecting the Chestnut data using the tipping bucket allowed for all events without missing data to be used to calculate the percentage unlike the manual collectors where a whole week of data would be lost.

When weekly data was used, this led to the Chestnut gaining a lower WCE (22.08% uncorrected between Aug 2018-April 2019) than would have been the case when data was used per event (i.e. only lost once it fell over instead of the whole week (equipment fell over between 8-15 Nov, 27/11-24/12 on several occasions)). The WCE% was calculated using the event data to 22.36%. This was more pronounced when taken account of the extra months where only the tipping bucket was used (i.e. May18-April19), which saw a WCE% of 26.9% () and 29.31% with Pollock's (2018) correction. Therefore, the Chestnut data was calculated per event rather than weekly to decrease data loss with the rainfall correction.

The higher WCE% for the chestnut (May18-April19) indicates that the WCE for the other trees could also potentially be higher if more of the leafed period had been measured (measurements started August18). The higher WCE during May to Aug suggests there were more smaller events as these have a higher WCE.

When the Chestnut event data is used to calculate the average for all the trees, the values change to **41.97% WCE, 54.39% TF and 3.65% SF for the corrected rainfall (Pollock, 2018)).**

The all trees average of TF% increases in the non-leafed period and transition lies in-between. This variation is the same for all species (and **Error! Reference source not found.**). All but the Chestnut are significantly different in TF between non-leafed and leafed period. As meteorology was the same between the trees this has been attributed to the Chestnut canopy which is denser with branches so collects more rainfall in the non-leafed period and also has larger branches pointing towards the ground away from the trunk hence channelling more rainfall into throughfall rather than stemflow in the leafed period.

The average stemflow is small at 3.65% annually. Stemflow was found to be larger during the non-leafed period for all trees except the Chestnut (*and* ***Error! Reference source not found.***).

The WCE% for all trees is large at 41.97%. When segregated by species, it is also high for Oak and Beech with the Chestnut being lower (*and* ***Error! Reference source not found.***). The WCE is highest during the leafed period but also shows that a large amount of water is evaporated during the non-leafed period. The WCE% for the leafed period of the chestnut is a lot lower than the other trees. All except the Chestnut are significantly different in WCE between non-leafed and leafed period. The Chestnut and Oak tree sit within the range of WCE seen within

Europe (7-36% (Gerritts, 2010; Noirfalise, 1959; Hankin et al., 2016)) with the Beech being higher than this. However, these studies use trees in the middle of woodlands without edge effects, which when accounted for would see higher WCE% suggesting these values are realistic. The Chestnut is affected more by edge effects than the other trees with a larger collection of rainfall due to horizontal rainfall as seen by the negative WCE; therefore, if the true intercepted rainfall was collected the WCE would be higher.

Table 3-3:Annual, leafed, non-leafed and transitional periods TF%, WCE% and SF%. Calculated from uncorrected measured rainfall (UCR) and corrected rainfall (CR) according to Pollock (2018). Utilised data in bold.

		Species	Throughfall%		WCE%		Stemflow%	
			UCR	CR	UCR	CR	UCR	CR
Annual	**(05.08.18-30.04.19)**	All Trees	56.58	54.72	39.57	41.56	3.84	3.72
		All Trees (using Chestnut event data)	56.23	**54.39**	39.99	**41.97**	3.77	**3.65**
		Chestnut (using weekly data)	77.71	**75.15**	22.08	**24.64**	0.21	**0.2**
		Chestnut (from event data)		70.45		29.35		0.2
		Oak	61.03	**59.02**	33.09	**35.29**	5.88	**5.68**
		Beech	48.18	**46.6**	48.46	**52.28**	3.51	**1.12**
	(15.05.18-30.04.19)	**Chestnut (from event data)**	72.8	**70.45**	26.9	**29.31**	0.25	**0.24**
Leafed	**(5.08.18 – 30.09.18 & 21.04.19-30.04.19)**	**All Trees**	44.04	**42.59**	54.24	**55.75**	1.72	**1.66**
		Chestnut (using weekly data)	75.36	72.88	25.42	26.81	0.32	0.31
		Oak	46.37	**44.84**	50.67	**52.29**	2.96	**2.86**
		Beech	32.93	**31.85**	65.72	**66.84**	1.35	**1.31**
	(15.05.18 – 30.09.18 & 21.04.19-30.04.19)	**Chestnut (from event data)**	66.99	**64.79**	32.69	**34.9**	0.32	**0.31**
Non-Leafed	**(14.11.18-26.03.19)**	**All Trees**	65.31	**63.71**	29.43	**31.07**	5.39	**5.21**
		Chestnut (using weekly data)	76.77	74.24	23.09	25.61	0.15	0.14
		Oak	72.12	**69.75**	19.40	**22.05**	8.48	**8.2**
		Beech	57.92	**56.01**	37.34	**39.43**	4.71	**4.55**
		Chestnut (from event data)	71.96	**69.59**	27.87	**30.24**	0.17	**0.17**
Transitional	**(01.10.18-13.11.18 & 27.03.19-20.04.19)**	**All Trees**	49.02	**47.41**	48.65	**50.34**	2.32	**2.25**
		Chestnut (using weekly data)	72.72	70.33	27.12	29.51	0.16	0.16
		Oak	46.90	**45.36**	51.69	**53.28**	1.41	**1.36**
		Beech	42.16	**40.78**	54.35	**55.85**	3.49	**3.38**
		Chestnut (from event data)	85.75	**82.93**	14.06	**16.89**	0.19	**0.18**

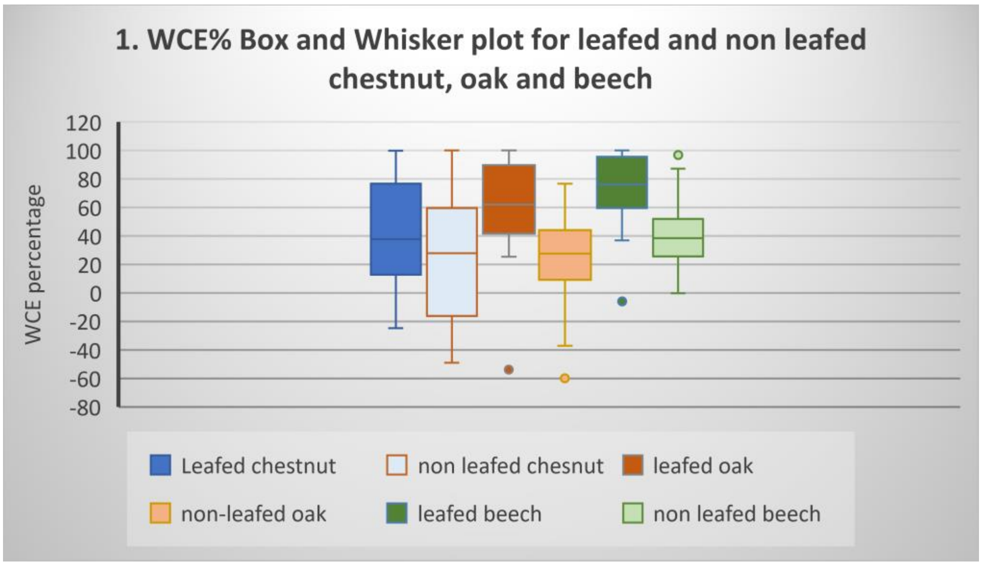
Figure 3-4:Throughfall% (1), WCE% (2), and Stemflow% (3) during the leafed, non-leafed, transitional and annual periods.

Figure 3-5 shows the Chestnut has the largest variation in WCE% particularly during the non-leafed period. All trees have lower WCE% values for the non-leafed period. All trees during the non-leafed period record high WCE% during some events with the Chestnut reaching 100% in some events showing WCE is still an important process during the non-leafed period.

The individual tree plots (Figure 3-5 graph 2) show negative WCE mainly occurs on selected trees (i.e. Chestnut and NE Oak), however, it is also seen to a lesser extent on the NE and SW Beech Trees. The fact other trees also have negative WCE suggests edge effects are at play. The median value of the WCE% is high for all tree species therefore the higher WCE% is seen through the majority of events.

The Box and Whisker plots (Figure 3-5) of the Chestnut data indicates that the data for WCE mainly sits between 5-65% of the rainfall but can be found anywhere between -10-100% with outliers producing highly negative values bringing down the mean value. The Throughfall data (

Figure 3-6) shows the opposite, with the majority sitting within the 0-50% range and outliers having a throughfall of 430% of rainfall due to the greater collection of horizontal rainfall.



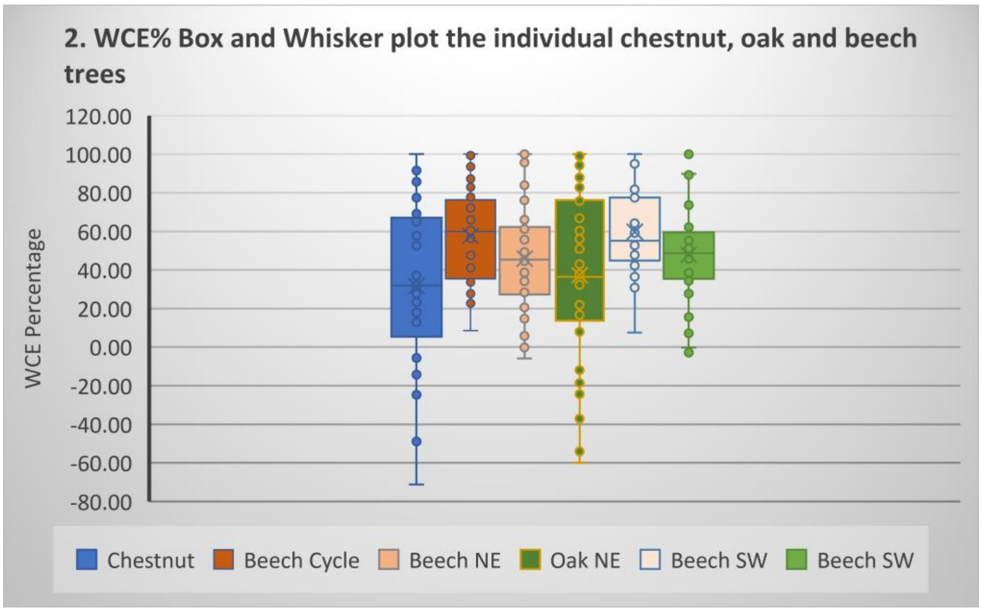


Figure 3-5:WCE% Box and whisker plots each week per tree species and individual trees during leafed and non-leafed periods

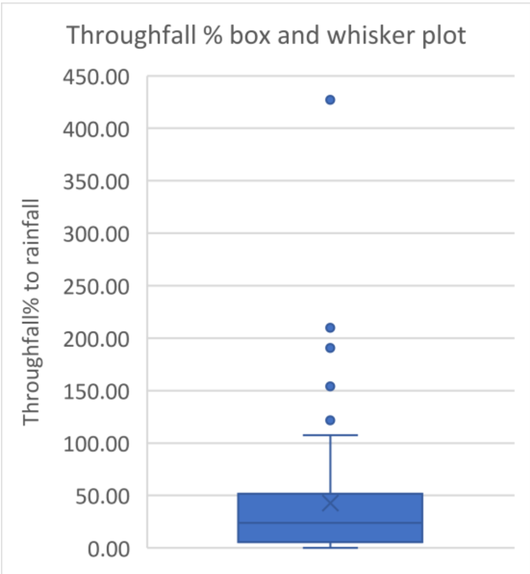


Figure 3-6:Throughfall box and whisker plot

The trees can provide a large impact at reducing the water reaching the ground for events of small and medium size (≤10mm of rainfall). However, they have a much smaller effect with a low WCE% for the larger events (>10mm) (Figure 3-7). The annual average duration of an event was 11hr02min55sec with the rainfall intensity of 2.28mm/hr.

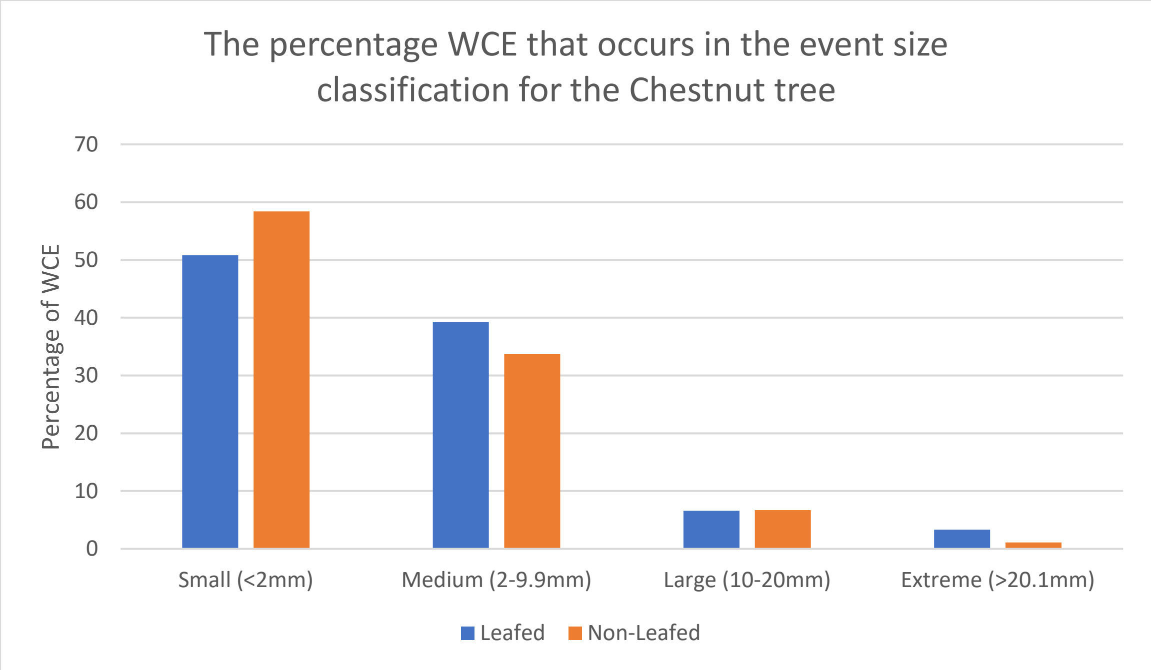


Figure 3-7:WCE% that occurs according to event size for the Chestnut.

The Chestnut's canopy required 0.346mm of rainfall to wet the canopy (i.e. average rainfall volume prior to TF commencing) and took an average of 01hr02min12sec. The canopy drain down took 1hour00min05sec. The RF sometimes finished after the TF (average drain down of -0.0635mm), indicating that there is either a pause in the events or the rainfall turned to drizzle at the end of events, which allowed evaporation to occur allowing the canopy to hold more water. The other issue could be that water has sat within the TF tipping bucket without tipping at the end of events as its volume is larger than that of the RF gauge.

3.3 Event Data

The storm intensity (
Figure 3-8) has no significant effect on the stemflow. However, it does have a significant effect on throughfall volume and percentage and WCE%. The smallest intensity events have a medium TF with the largest intensity events having the smallest. The WCE is largest at the highest intensity events and medium intensity being the lowest. These very high intensity events are often very short whereas medium intensity events are longer duration meaning the short high intensity events lead to high WCE whereas the medium intensity events usually last for a longer period saturating the canopy storage leading to higher TF.

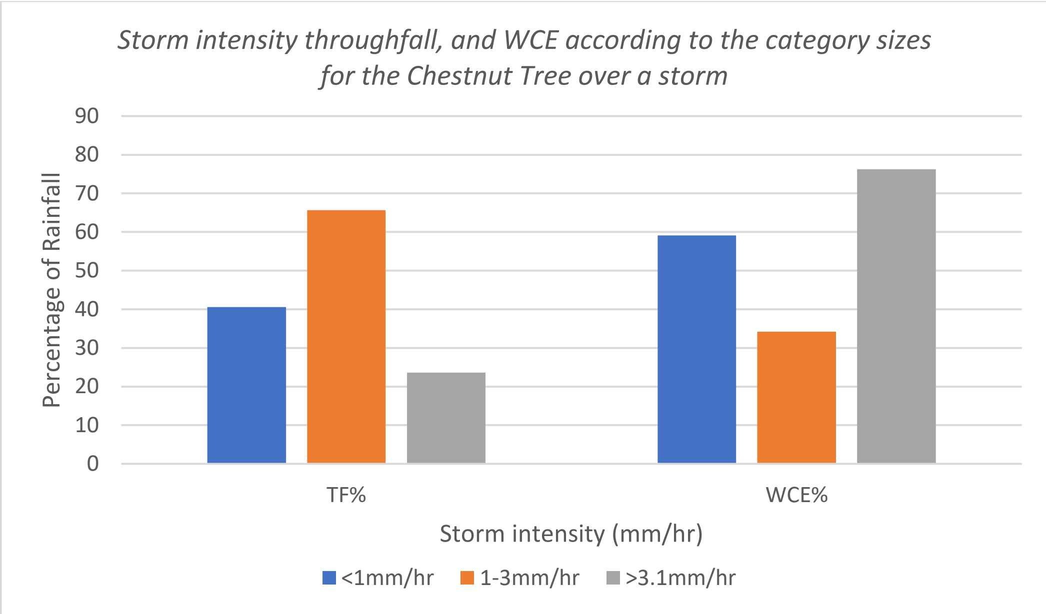


*Figure 3-8:*TF% and WCE% for Storm intensity for the Chestnut

The length of events significantly affects throughfall% and WCE% and volumes but not stemflow. The WCE% decreases from short to long events and throughfall% increases (

Figure *3-9*). As expected throughfall and WCE volumes increases from small to medium event as there is more rainfall available to evaporate.

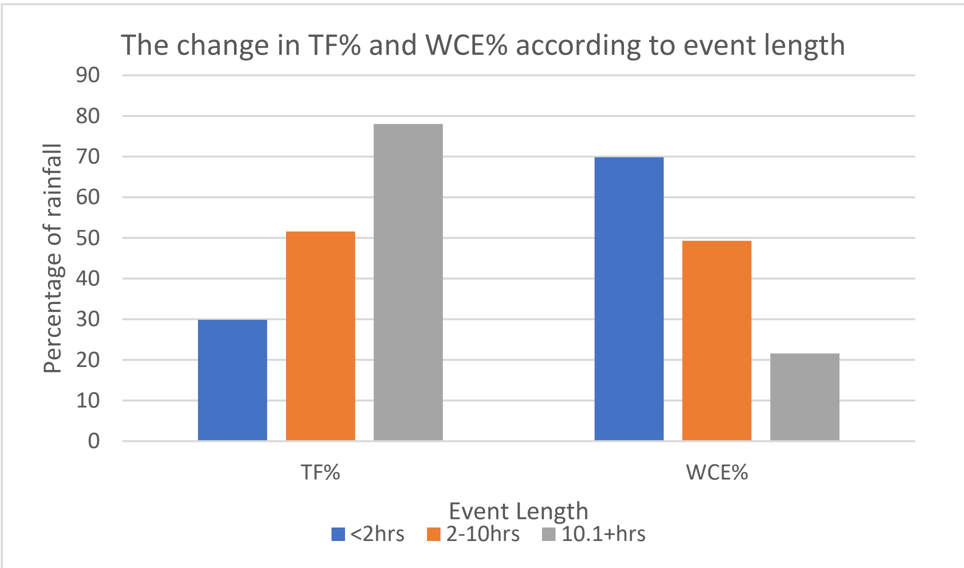


Figure 3-9:Event length on throughfall, and WCE for the Chestnut tree

The most rainfall falls at the medium events. However, the majority of events are small. The 4 extreme events account for over 20% of the rainfall for the year (**Error! Reference source not found.**).

Table 3-4:Average event size (volume) per storm size.

Storm size (mm)	Small (<2)	Medium (2.1-9.9)	Large (10-20)	Extreme (>20.1)
Total rainfall (mm)	82.77	293.47	140.97	134.04
Number of Events	110	62	10	4
Average rainfall volume per event (mm)	0.75	4.73	14.1	33.51

The storm size is significant for throughfall% and WCE% and volumes but is not significant for stemflow. Throughfall volume and percentage increase with increasing storm size, likewise WCE percentage decreases (**Error! Reference source not found.**). The throughfall% is 38.83% for the smallest event size but at the largest events collects more throughfall than rainfall at 107.72%. The average volume of WCE per event is 0.4484mm for the smallest events and increases to 2.01mm for the medium events showing the canopy storage capacity is above 2 as water is available to fill the canopy store. The WCE volume then decreases in the large and extreme events to a negative volume (-2.66mm) showing the throughfall is greater than rainfall.

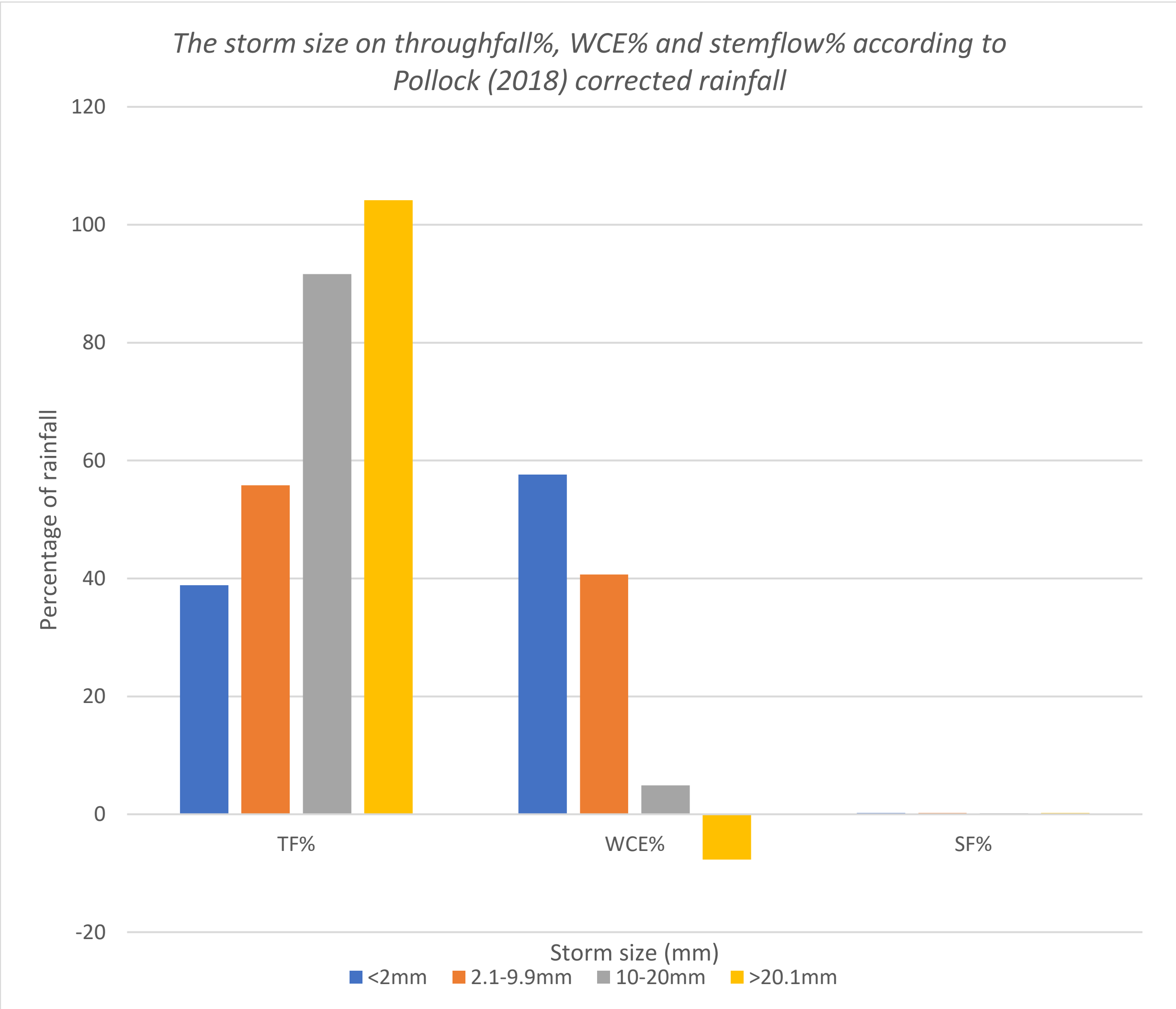


Figure 3-10:WCE% and TF% against storm size

3.4 Weather Data

The weather conditions affect WCE (**Error! Reference source not found.**). The effect of temperature on the evaporation cannot be detected, which shows that the effects of other variables (e.g. storm size) are more important than temperature.

Error! Reference source not found. shows wind speed is the most variable in the non-leafed period but is highest during the negative WCE events and similar in the non-leafed period. The range is the same for negative WCE as the leafed period but the mean is higher suggesting these events have a higher wind speed than events that have positive WCE values. **Error! Reference source not found.** shows most events occur in the prevailing wind direction.

Table 3-5:Variations in temperature, wind speed and direction during leafed, non-leafed and transitional for the Chestnut

WCE (%)	**Temp (°C)**	**Wind speed (Beaufont scale)**	**Wind direction (Degrees)**
Annual Observed: 36.55 % (75.39 % without negative WCE)			
Non leaf Observed: *47.1%* *(65.8 % without negative WCE)*	Mean 6.09 Range min 0.7 Range max 10.27	Mean 4.59 Range min 0.4 Range max 10.2	Mean: 202.8 SSW
Leafed Observed: *24.32 %* *(low due to negative WCE, 70% if negatives ignored)*	Mean 13.5C Range min 6.8 Range max 18.35	Mean 3.8 Range min 1.35 Range max 7.93	Mean 207 SSW
Negative WCE Observed: -49.5 % 25 times	Mean 9.79 Range min 1.38 Range max 18.35	Mean4.6 Range min 1.48 Range max 7.49	Mean 196 SSW

It can be seen in **Error! Reference source not found.** that for the smallest wind speed events, the WCE% is the highest as water can sit in the canopy. Between medium and larger wind speeds events, WCE increases **Error! Reference source not found.** indicating that during the largest wind speed events more ventilation of the canopy occurs. However, this is most likely due to the medium wind events having the majority of negative WCE events (18/27), which would artificially decrease the WCE suggesting as wind speed increased WCE decreased. Also, the larger wind speeds saw the trees intercept rainfall from a larger area due to horizontal rainfall producing lower WCE. This meant the effect of ventilation on the canopy was not seen in this data. The highest wind speed events did not cause negative WCE showing more is at play than just wind speed (0/27 negative WCE events).

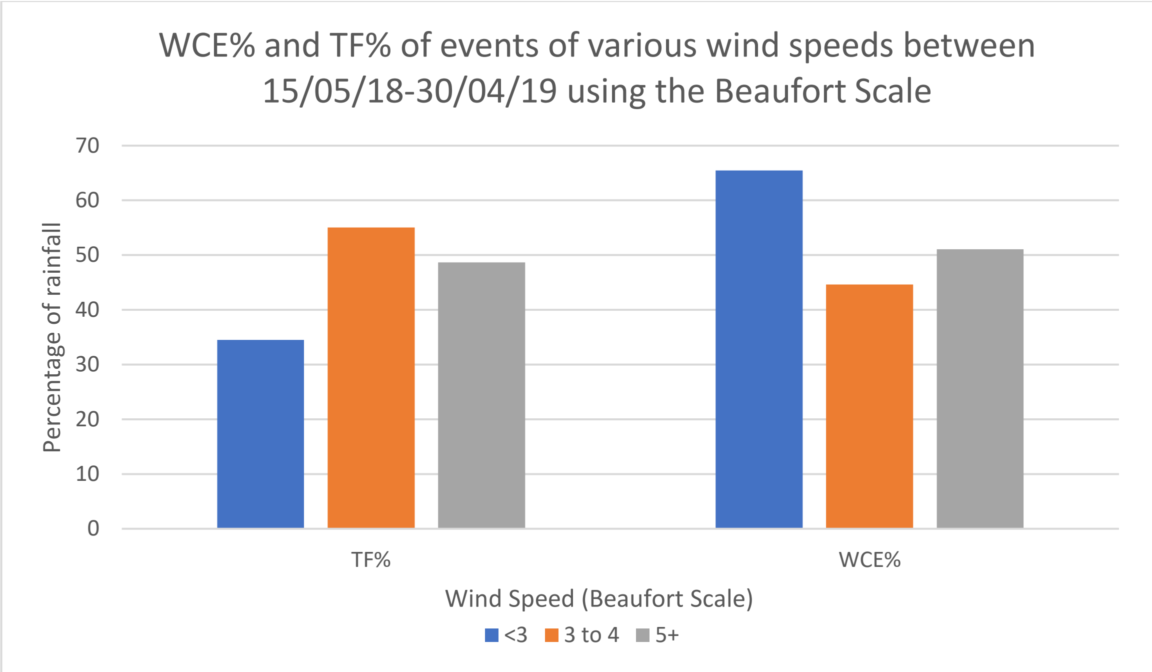


Figure 3-11:WCE% and TF% of events with various wind speeds (Beaufort Scale) between 15/05/18-30/04/19. The Beaufort Scale is in the table below.

*Table 3-6:*Beaufort Scale

Wind speed		
m/s	**Classification**	**Beaufort scale**
<0.5	Calm	0
0.5-1.5	Light Air	1
1.6- 3.3	Light Breeze	2
3.4-5.5	Gentle Breeze	3
5.5-7.9	Moderate Breeze	4
8-10.7	Fresh Breeze	5
10.8 - 13.8	Strong breeze	6
13.9-17.1	High wind, moderate gale to near gale	7
17.2-20.7	Gale to fresh gale	8
20.8-24.4	Strong to severe gale	9
24.5 - 28.4	Storm	10
28.5-32.6	Violent storm	11
≥32.7	Hurricane	12

Looking at the RF, TF and WCE through an event at the Chestnut tree (Figure 3-12 to Figure 3-15), it can be seen that an increase in wind speed leads to greater throughfall and hence reduced, and on some occasions negative, WCE due to increased collection of rainfall from horizontal rain. The negative WCE has been seen when wind speed is consistently high, which saw too large a throughfall to be solely due to shaking of leaves and branches. The high wind speeds need to coincide with the wind direction towards the open canopy to cause a negative WCE event due to the increased rainfall collected by the tree. During events where negative WCE occurs wind speed in relation to throughfall was shown to be significant.

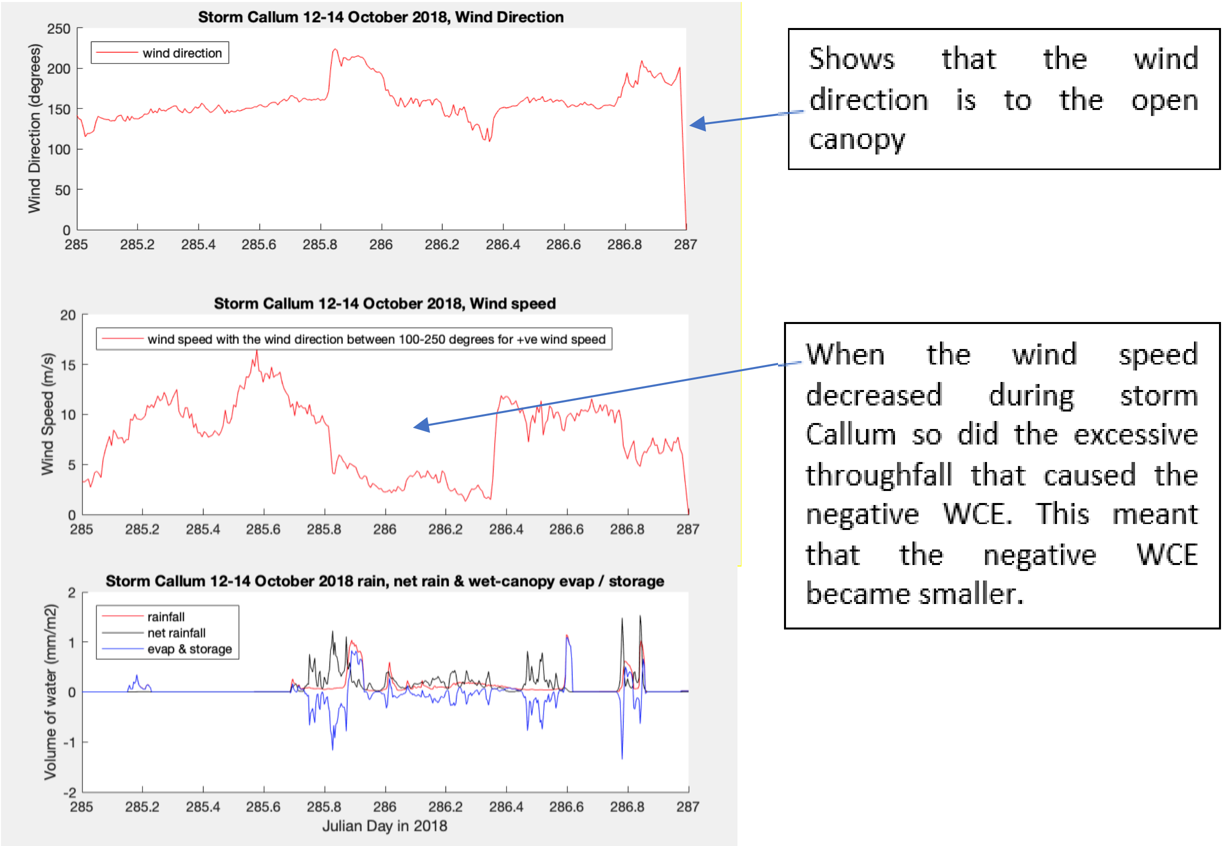


Figure 3-12:Wind direction and speed for Storm Callum

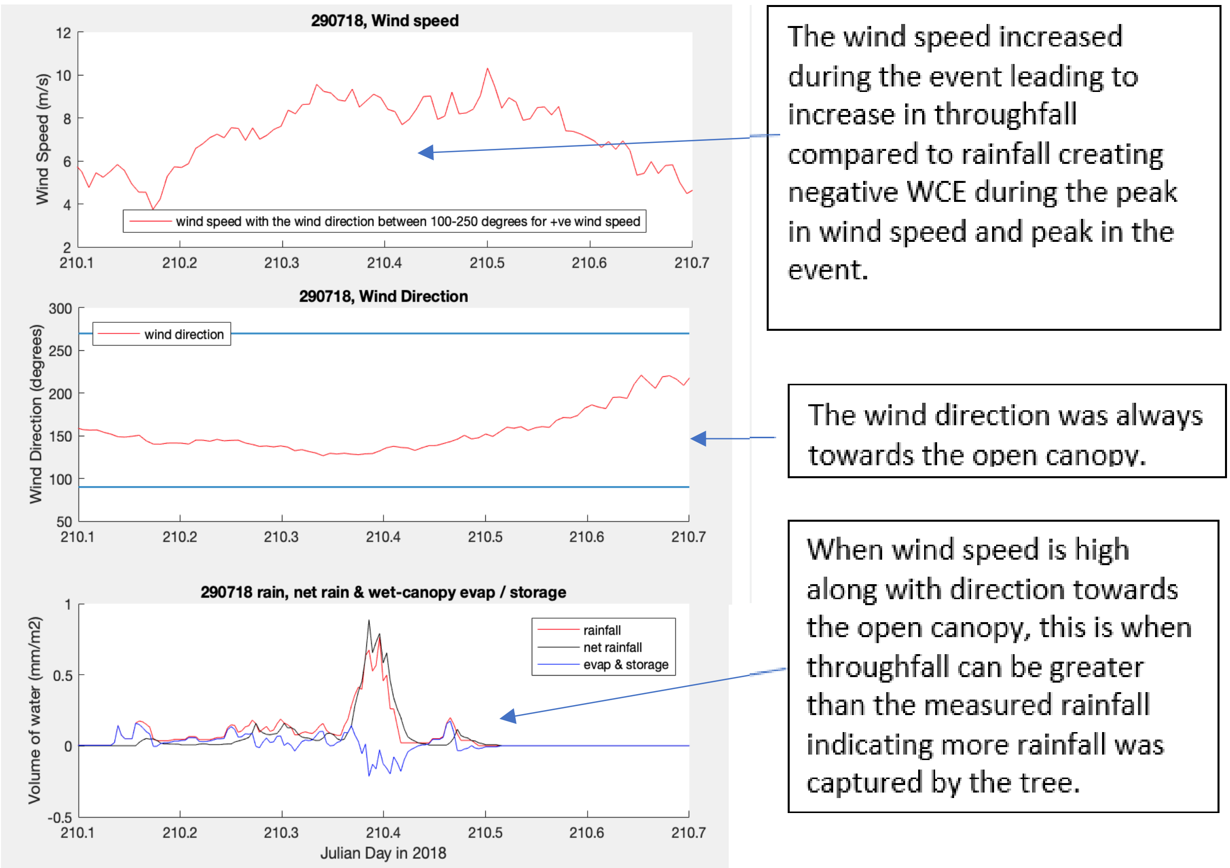


Figure 3-13:Wind speed and direction during event 29/07/18

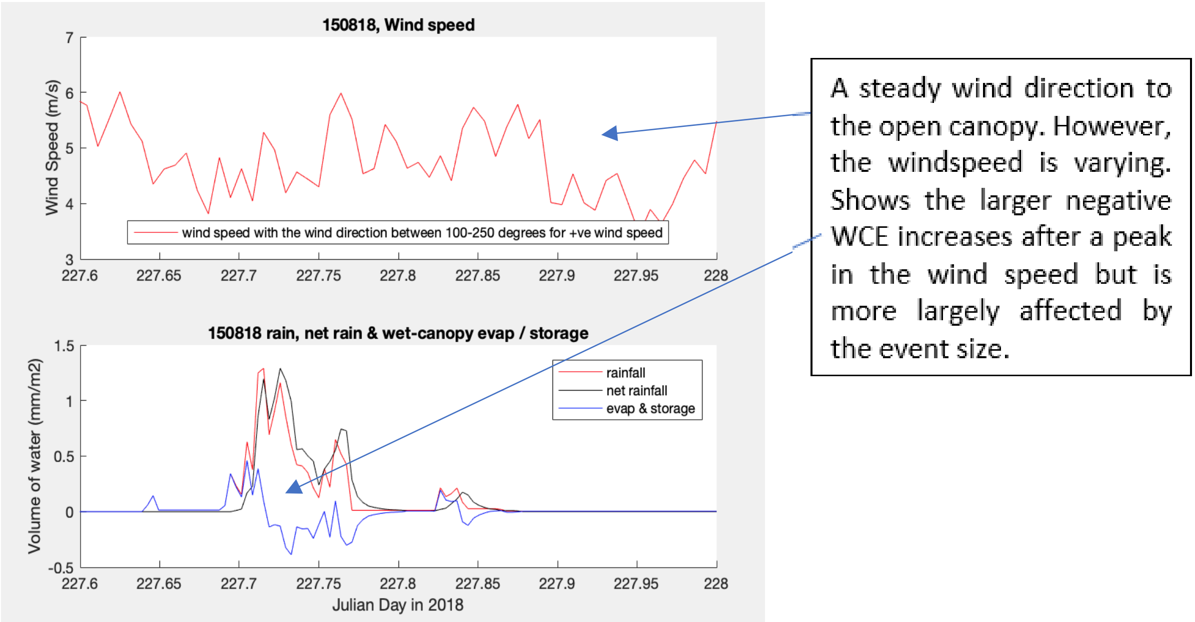


Figure 3-14: Wind speed during event 15.08.18

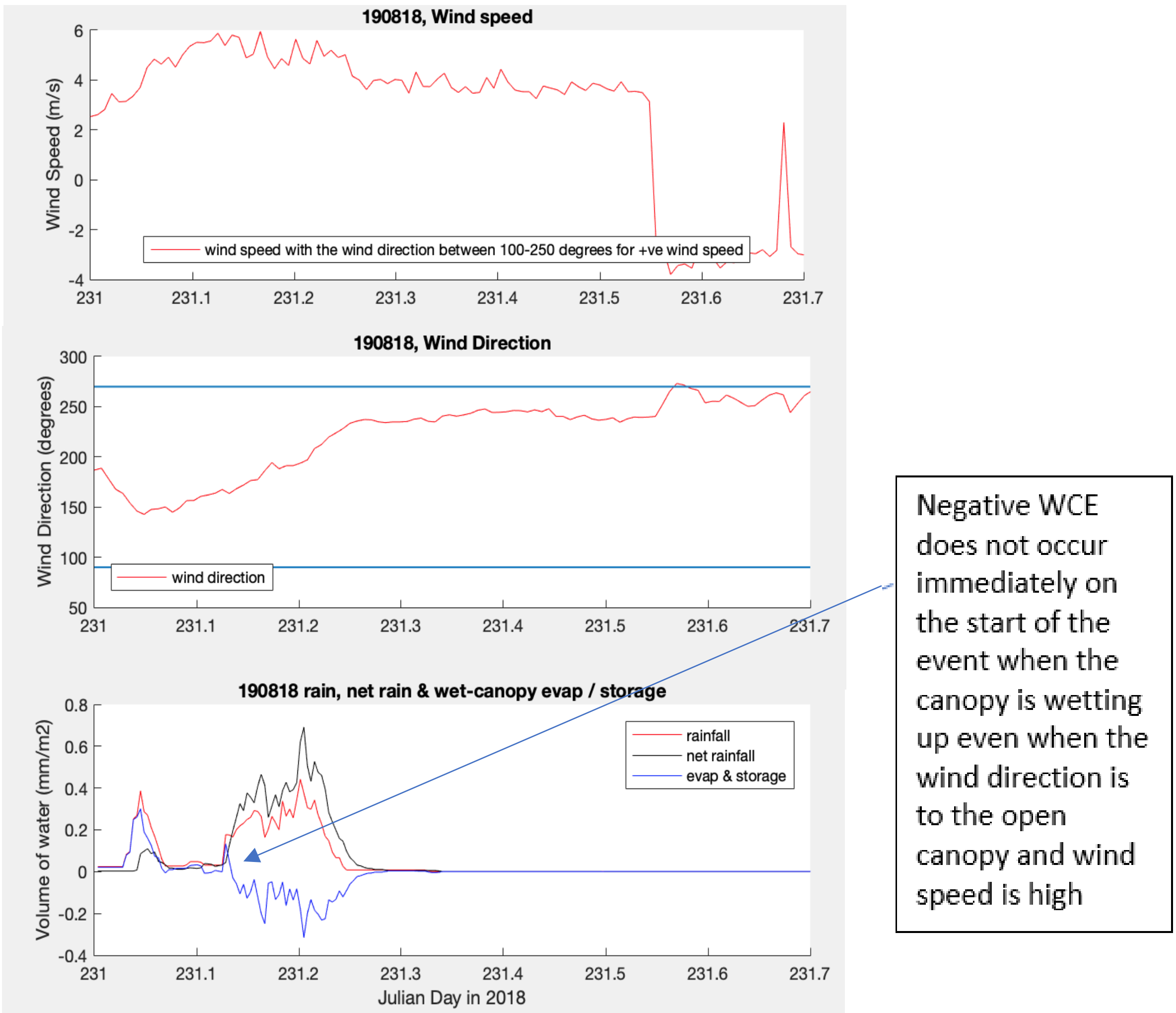


Figure 3-15: Wind speed and direction during event 19.08.18

The open canopy (no trees next to the canopy) was found to have a higher WCE% than the closed canopy (trees immediately next to the canopy) and was significantly different according to Mann-Whitney test (Figure 3-16). This was attributed to most smaller events hitting the open canopy with a higher WCE as it was in the prevailing wind.

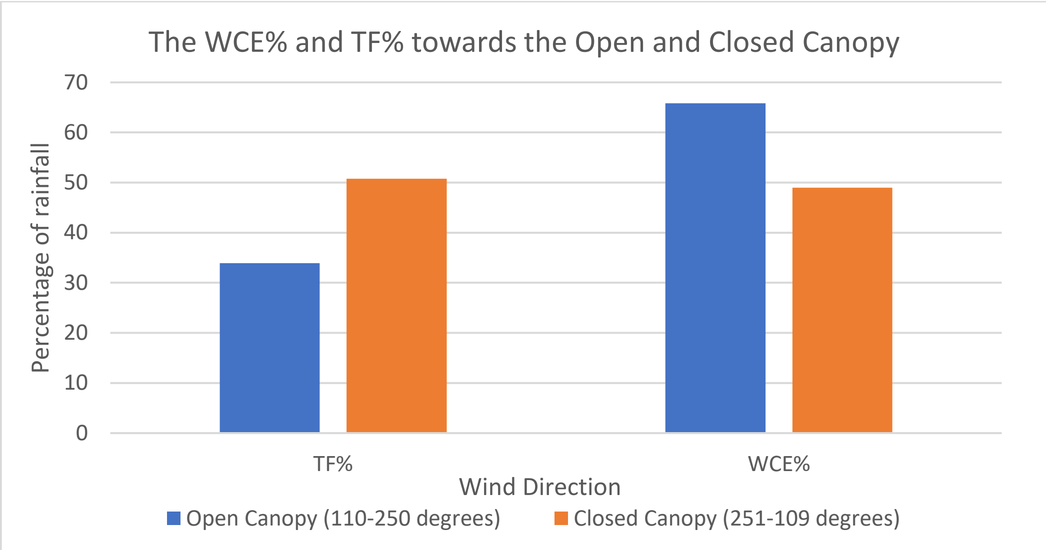


Figure 3-16:TF% and WCE% towards the open and closed canopy of the chestnut (15/05/18-30/04/19)

The open and closed canopy on its own tells little to its effect on WCE for some events (particularly negative WCE) and requires other factors including wind speed, type of rainfall, and wind direction to be taken account of. Where the wind speed during events is consistently high and a change in direction occurs, it can be seen that as the direction change occurs negative WCE occurs (Figure 3-17-

Figure 3-19). The direction needs to be towards the open canopy for the tree to capture greater throughfall than rainfall values (negative events).

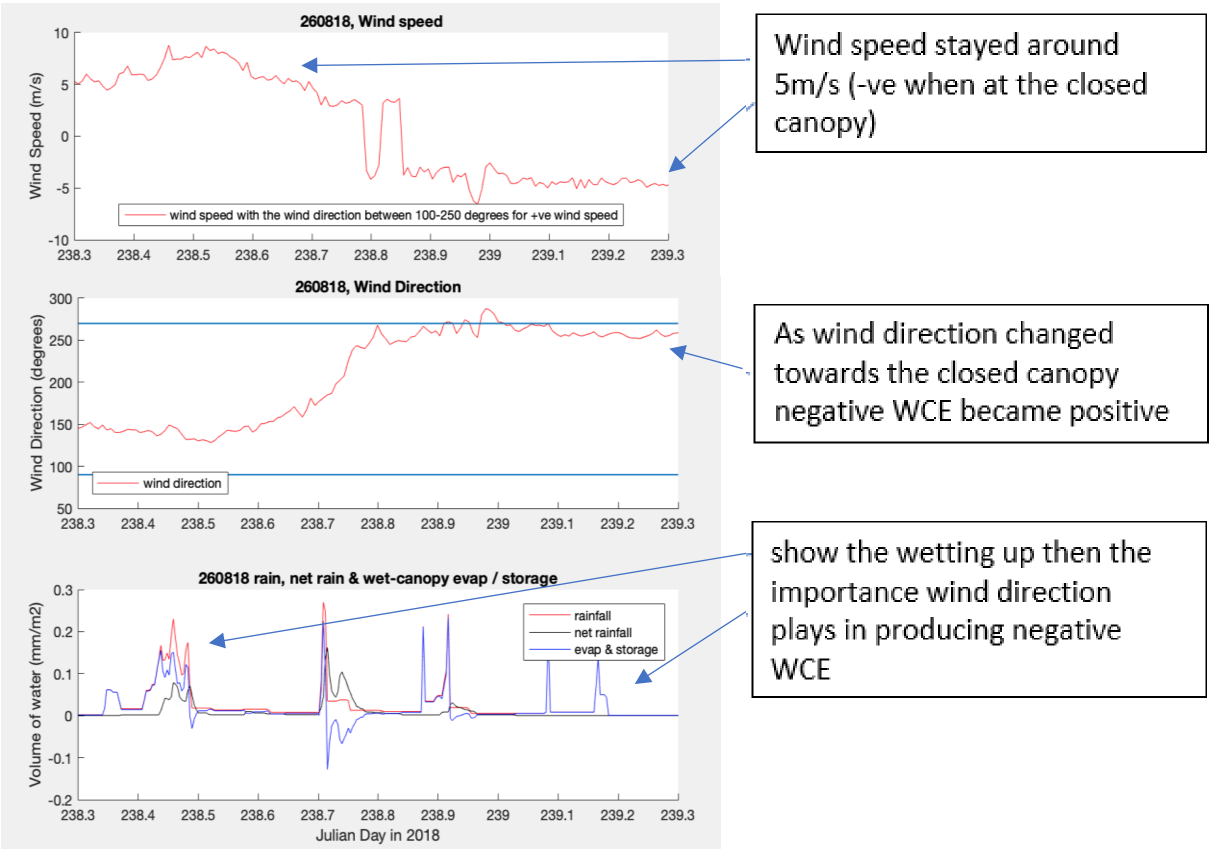


Figure 3-17: Wind speed and direction during event 26.08.18

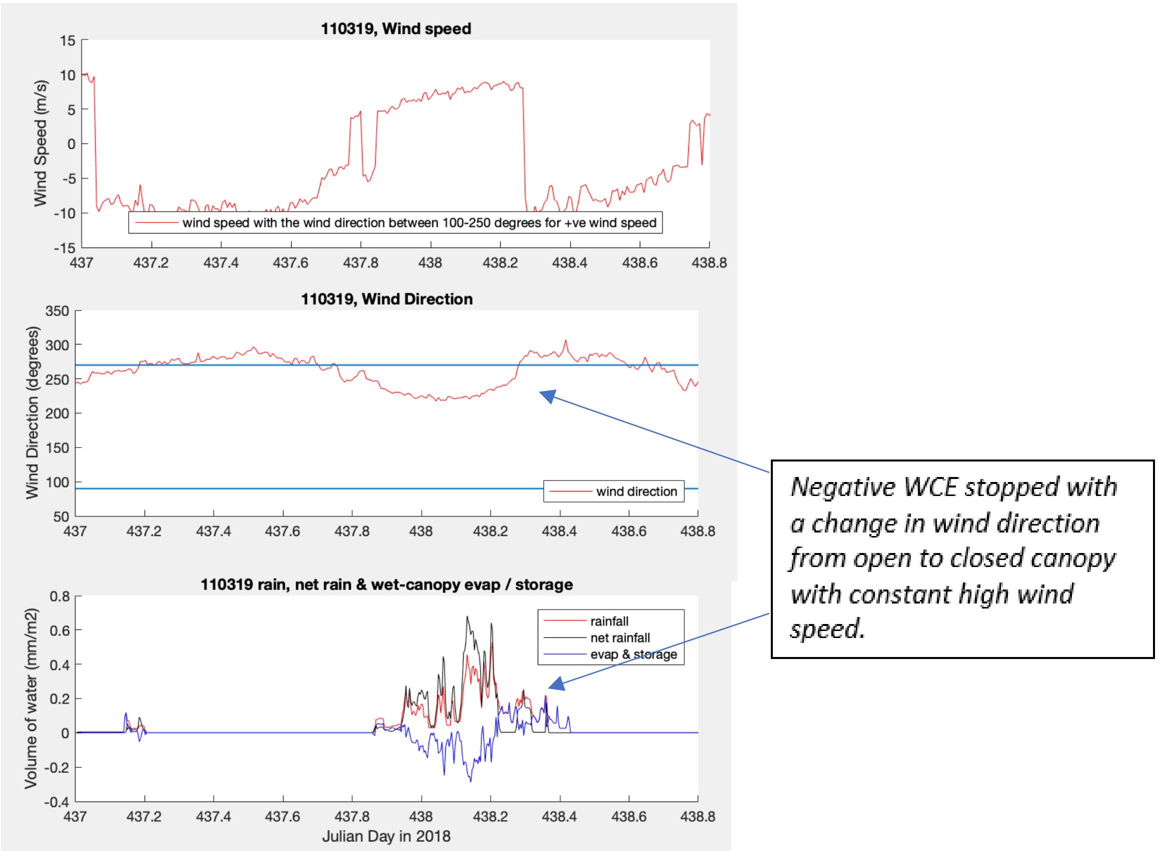


Figure 3-18: Event on 11.03.19-12.01.19 where negative WCE occurred with a change in wind direction from closed to open canopy.

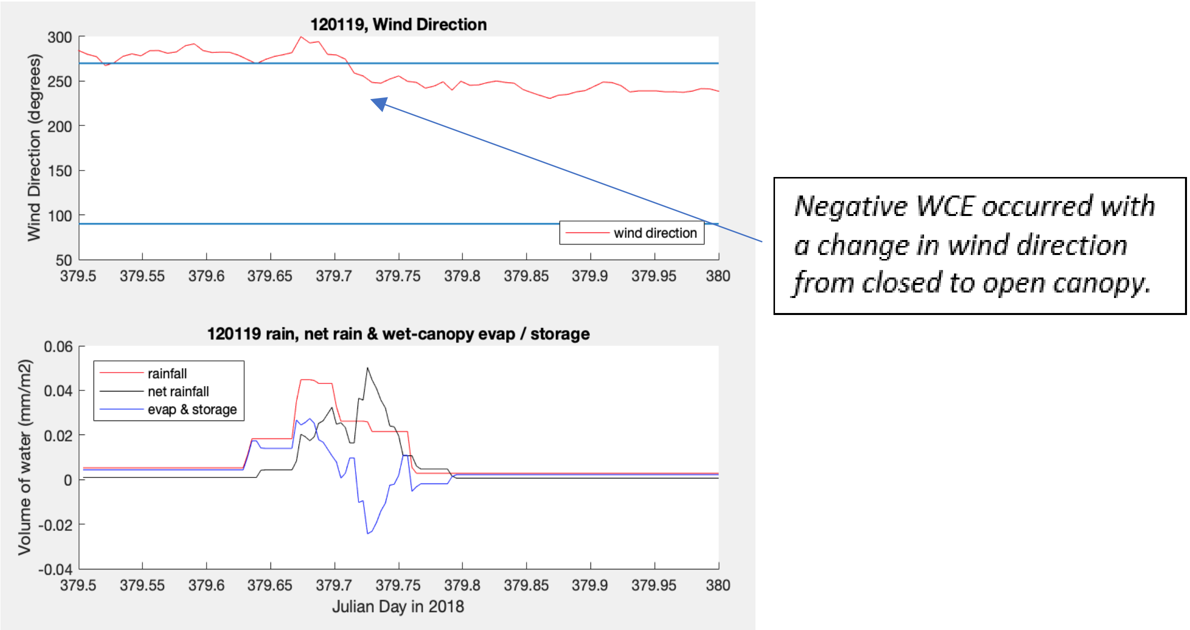


*Figure 3-19:*Event on 12.01.19

This is not always the case; the event on 06.01.19 (Figure 3-20) shows that the wind speed is low and direction to the closed canopy yet negative WCE still occurred suggesting not only wind speed and direction are important but also the rainfall characteristics (e.g. size and intensity).

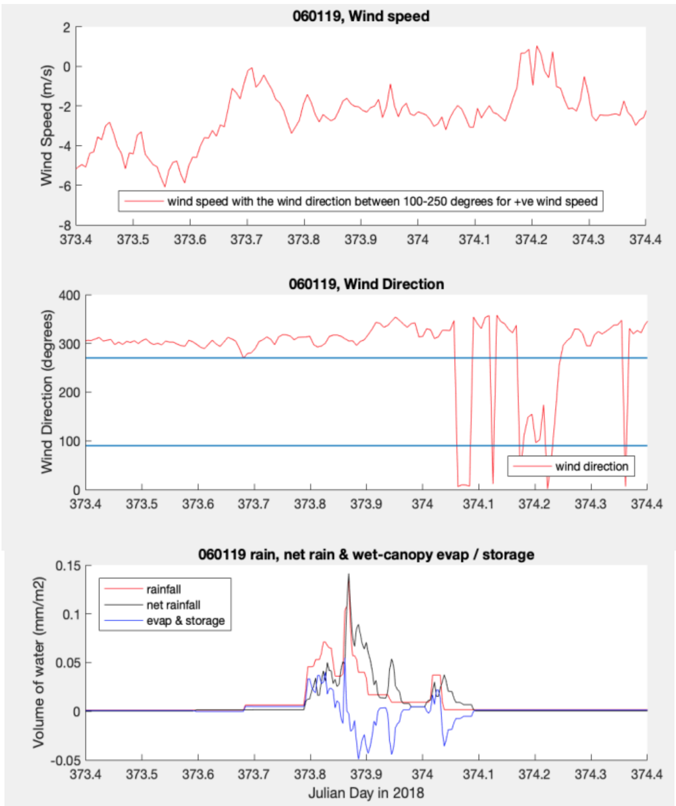


*Figure 3-20:*06.01.19 event against wind speed and direction

Wind speed and direction play a part in influencing how the tree behaves being on the edge. Trees on the edge pick up more rainwater on its open canopy side (not just the top). The wind direction is vital to determine if the rainfall will be coming in the direction of the open canopy (which has been shown by the Frumau gauges to collect more horizontal rainfall). The wind speed determines how much horizontal rainfall occurs and how much hits the canopy. The wind speed and direction effect are complex and rely on the size of event (large gives large negative WCE) but is also influenced by how wet the canopy is.

The wind direction is generally required to be to the open canopy, which is the prevailing wind direction, for negative WCE to occur. Wind speed is dependent on the wind direction towards the open canopy to produce negative WCE.

3.5 Spatial Variability

The spatial variability of throughfall at the Chestnut tree was looked at to determine why throughfall at the gauge was higher than rainfall for three events (the first 2 during transition and 3rd is leafed with little difference). Figure 3-21 shows that throughfall increases slightly to the outside edges of the tree and is highly variable under the canopy. The throughfall collector has a large surface area to take account of this variability under the canopy. The data also shows that the drip points change between events with one point being large within all events, which was below an overhanging branch. The throughfall collector is sited where the throughfall recorded for the spatial variability produce average values with one drip point. This indicates that the collector takes account of the average throughfall and drip points. The collector is not collecting a large amount of drip points to skew the data.

Figure 3-21 indicates that the throughfall readings vary depending on the rainfall event/meteorological conditions. This was clarified by the Frumau Gauges, which saw the rainfall direction for the event on 02.04.19 hitting the canopy of the tree to the East (and agreed by Hazelrigg) where the throughfall is significantly higher than in the other two events.

The high value for the 3.4.19 is on the edge of the canopy during the non-leafed/transitional period therefore more similar to actual rainfall. The Frumau gauge, however, recorded increased horizontal rainfall to the open SW side of the tree i.e. not where the yellow collector is located.

During the 28.4.19 event both large collections are located at the side of large branches indicating these are drip points. Mostly vertical rainfall was seen during this event and rainfall direction changed.

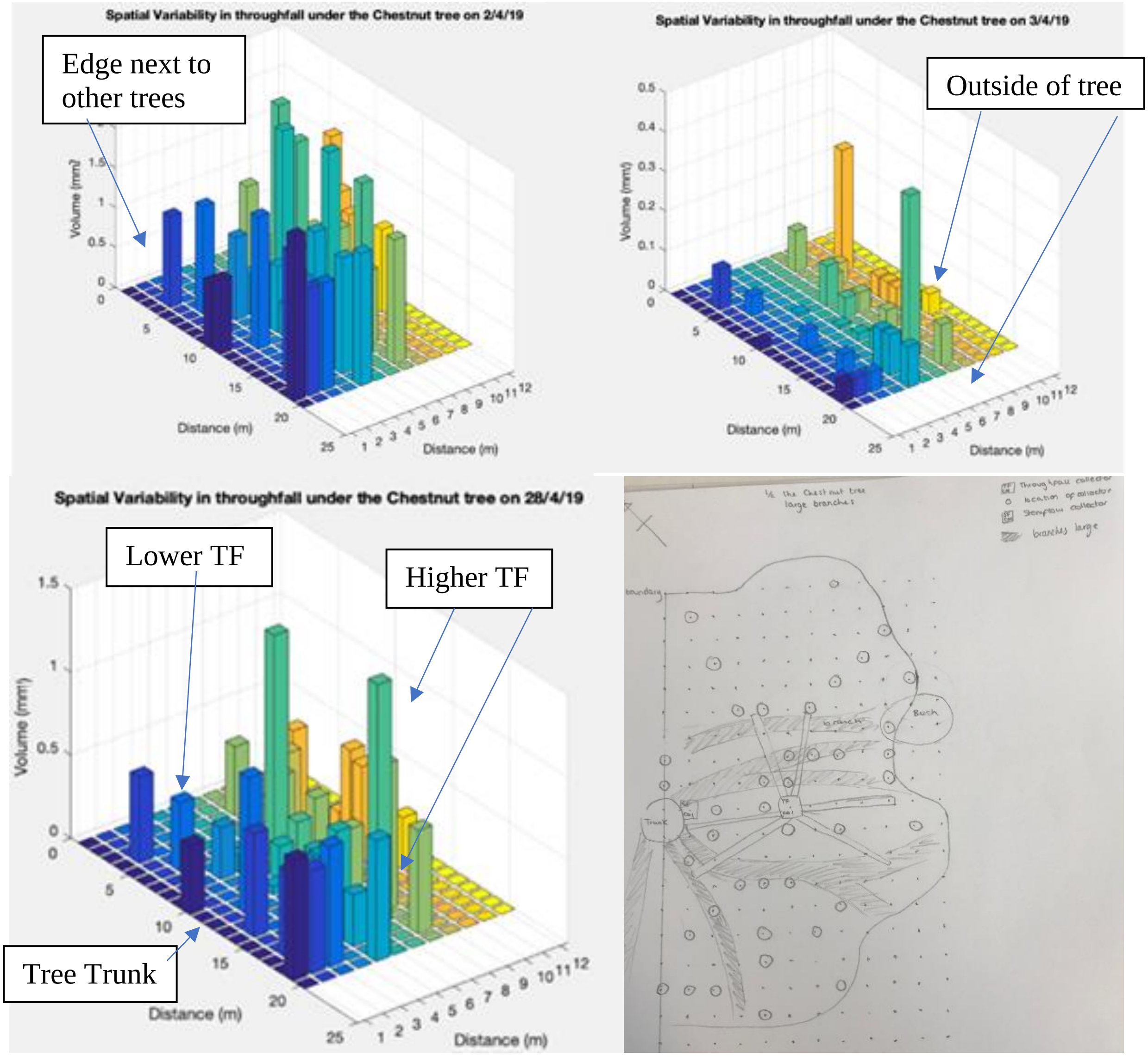


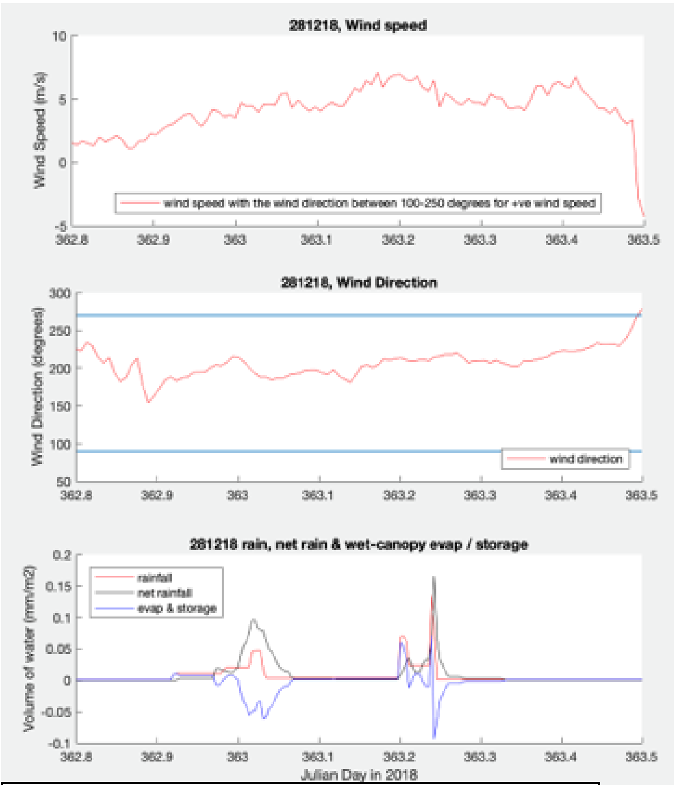
*Figure 3-21:*Spatial variability of throughfall under the chestnut for 3 events and schematic canopy. The trunk sits on the graph at (1,11) and (1,12) (i.e. next to the dark blue column.

3.6 Time-series graphs

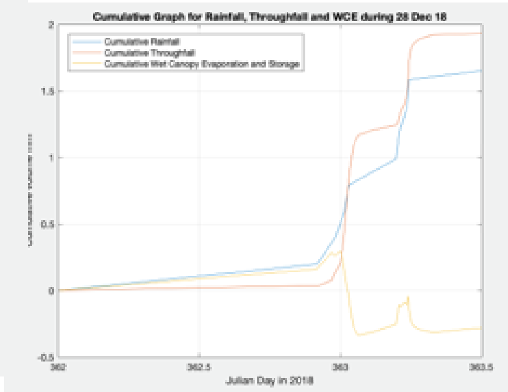
Time-series graphs of WCE, TF and RF were created using data through events collected from the Chestnut. Stemflow was assumed to be insignificant. The blue line in the time-series graphs (below) shows the WCE&storage within the tree canopy not just the evaporation so provides volumes higher than would be expected of just WCE in some time-steps.

The amount of throughfall and the time it takes to occur is dependent on volume of rainfall and storm characteristics. It has been found that the wetting up varies depending on storm event duration, intensity and size. The time it takes throughfall to occur varies significantly from a few minutes-5 hours for low intensity events. It is often around 30 minutes. The higher the intensity the quicker the throughfall occurs (Figure 3-26-Figure 3-43).

The throughfall is small in small events (<2mm) with high WCE. The events generally require between 0.2-0.5mm (Figure 3-22-Figure 3-23) of rainfall before throughfall occurs but some events it does not occur. Throughfall is delayed at the start from a few minutes (Figure 3-22)-1/2hr (Figure 3-24) according to size and intensity of event and if previously wet/dry (Figure 3-22). WCE and storage usually accounts for the start of events, regardless of how much throughfall occurs, due to the wetting up of the canopy. Negative WCE can occur even in small events (Figure 3-22), when the wind direction is towards the open canopy with a high wind speed. Negative events also require a certain volume before TF can occur (i.e. wetting up). WCE is still important even in previously wet events (Figure 3-22). A decrease in WCE and continued throughfall after the rainfall has finished suggests some stored canopy water is removed via drip (Figure 3-25 and Figure 3-26).



Event 28.12.18 – non-leafed
Previously wet before the event – shows antecedent weather conditions are important in
Low rainfall volume and intensity
High TF% and low WCE%
Negative WCE event
WCE played important part initially for both mini events
Rainfall is concentrated under the canopy



Cumulative Graph

See both mini events with a plateau in the rainfall between events and increases (before the decrease) in WCE. Indicating a drying of the canopy between the two events but reaches its storage capacity quickly.

TF occurs when 0.2mm of rainfall has occurred for the first event and immediately for the second
Shows a negative WCE event
High wind speed towards open canopy throughout event

Figure 3-22:Time-series graphs of TF, WCE and RF (28.12.18)

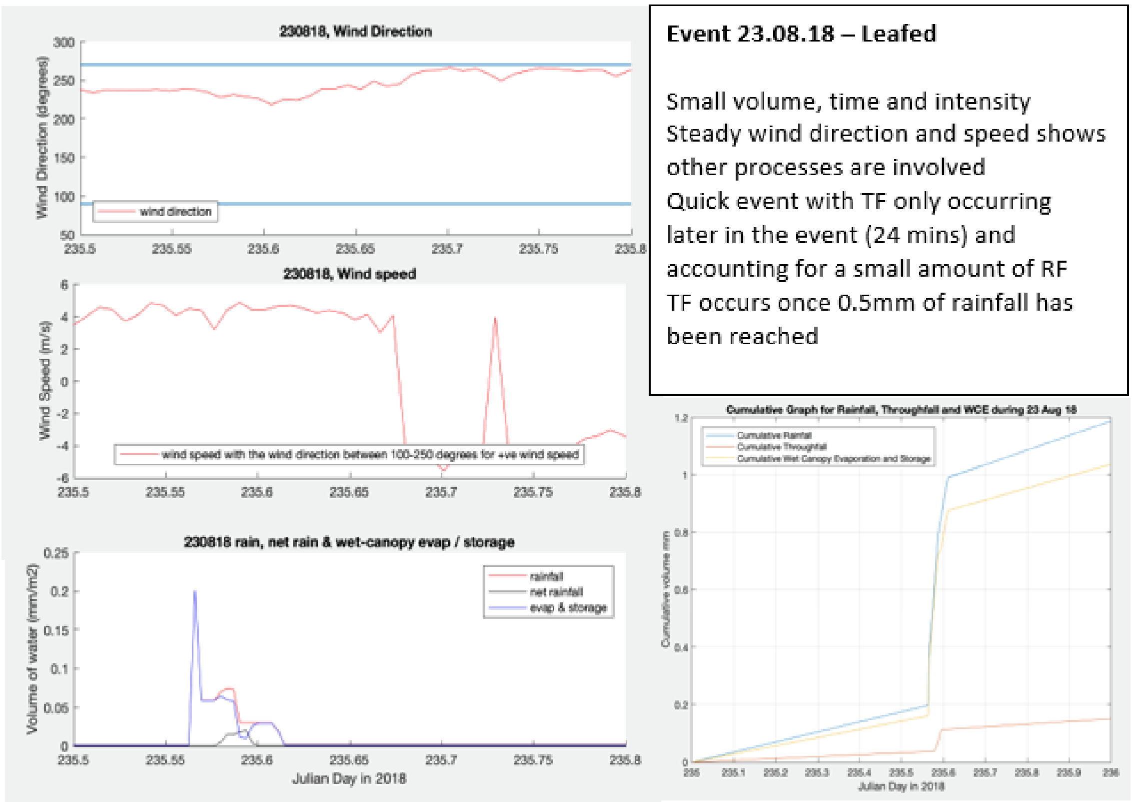


Figure 3-23:Time series graphs of TF, WCE and RF (23.08.18)

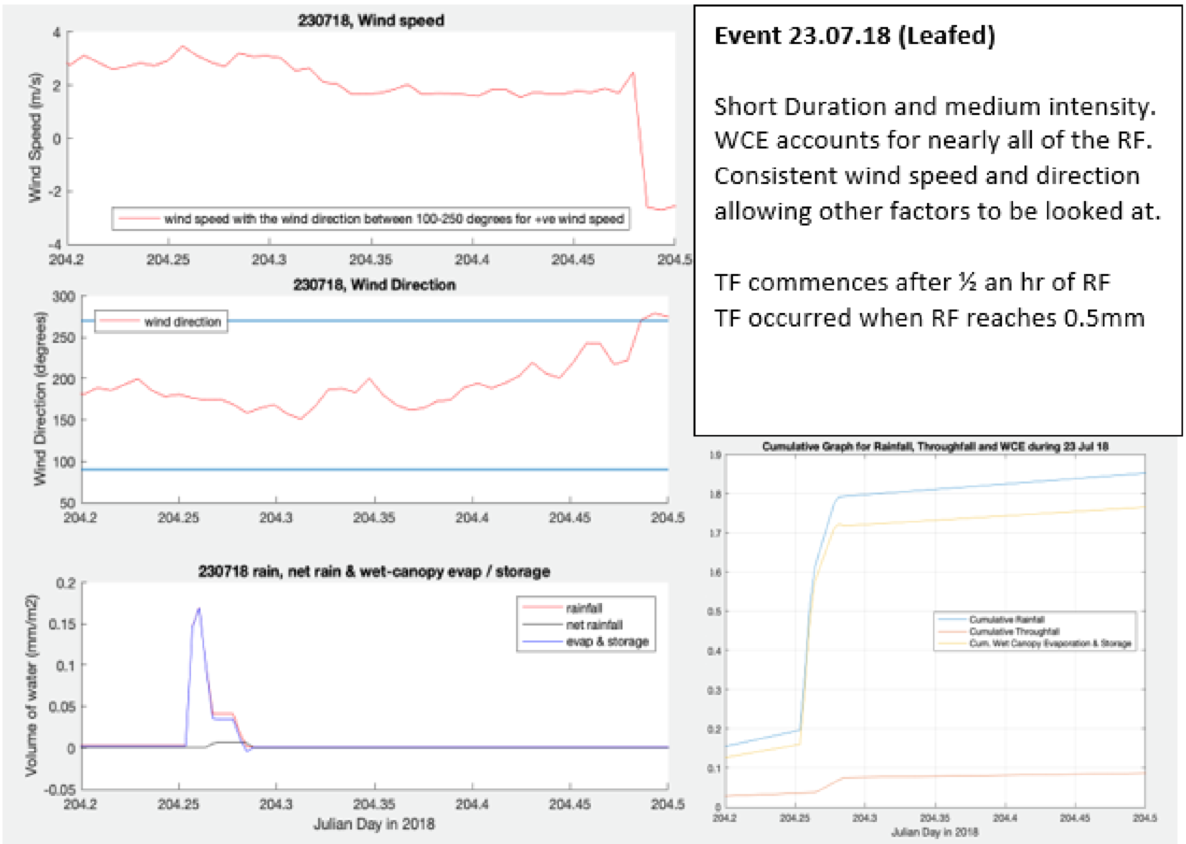
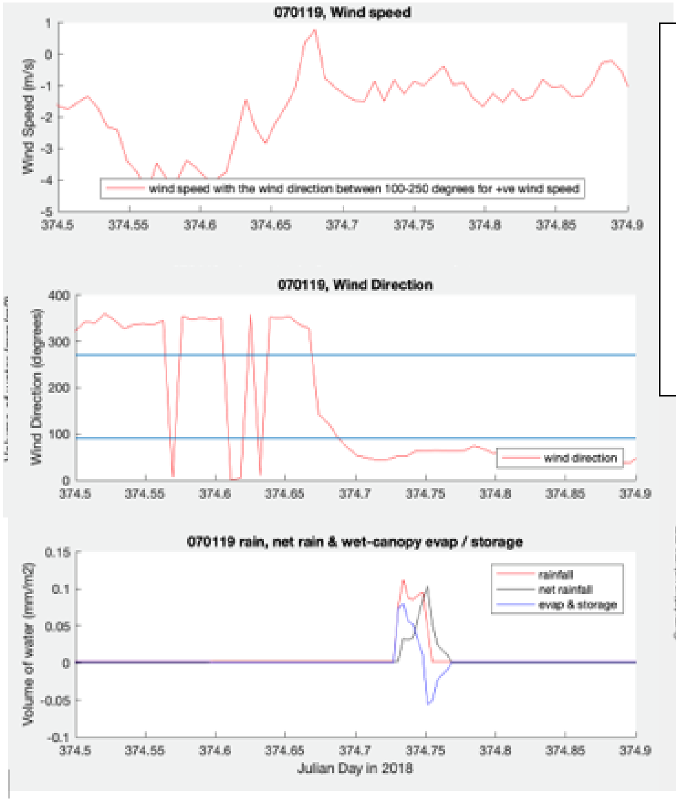


Figure 3-24:Time series graphs of TF, WCE and RF (23/07/18)



Event 01.01.19 – Non-leafed

Short duration wit medium intensity
Wind direction – towards the closed canopy with low wind speed
TF% is high and WCE% low
TF occurs after a few minutes when 0.2mm of rainfall is reached
TF is delayed after the rainfall showing it is held in the canopy before it drains.

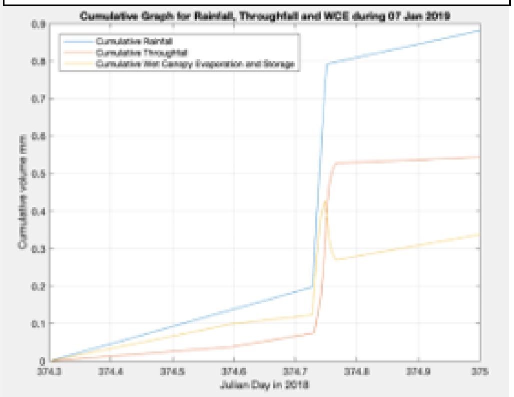
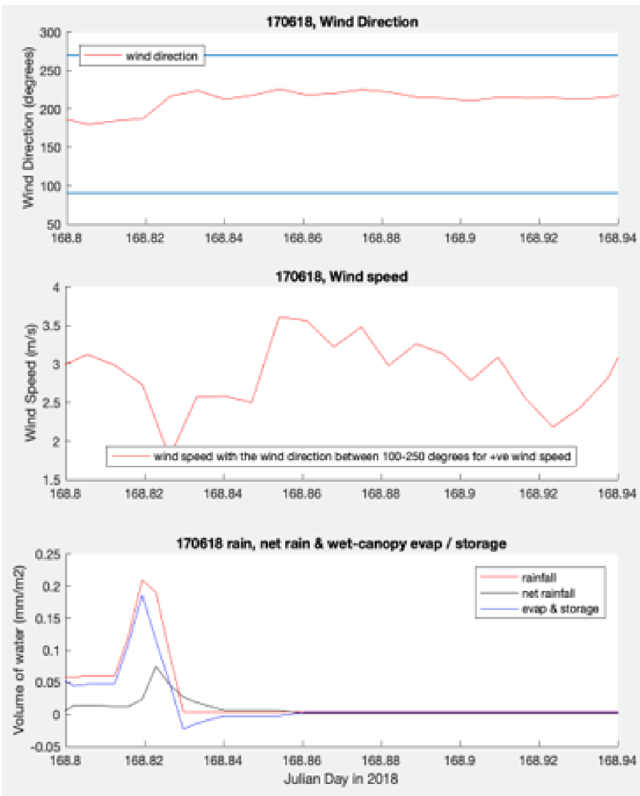


Figure 3-25:Time series graphs of TF, WCE and RF (07.01.19)



Event 17.06.18 (Leafed)
Wind direction – towards open canopy
Wind Speed – decreases through event
TF delayed at start of event (i.e. wetting up) by 15 mins

Cumulative graph - TF starts when RF reaches 0.75mm and increases further when rainfall reaches 1mm. The slight decrease in WCE and storage suggests that water is removed from the tree as drip after the rainfall event has finished.

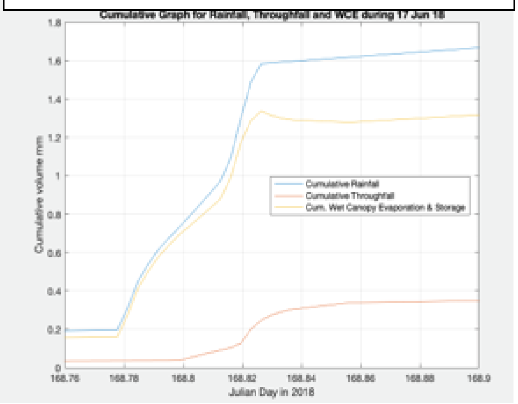
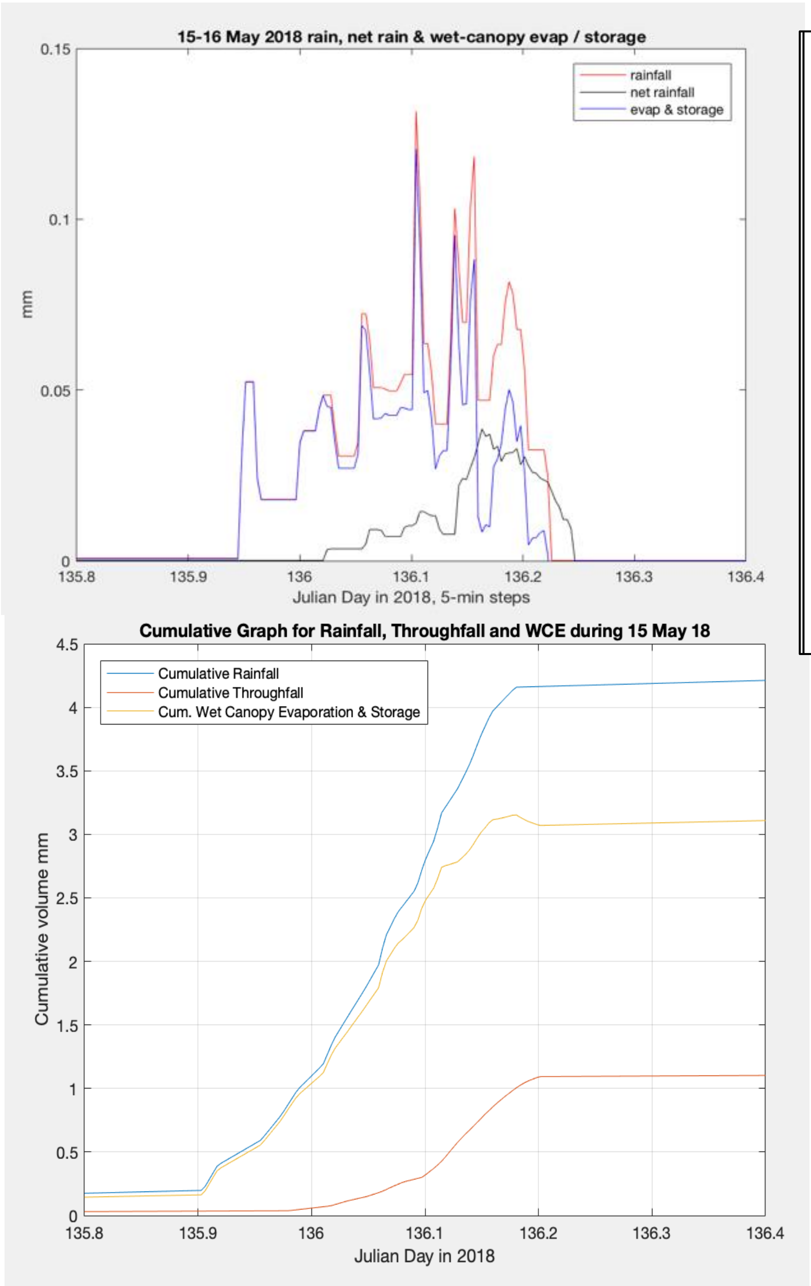


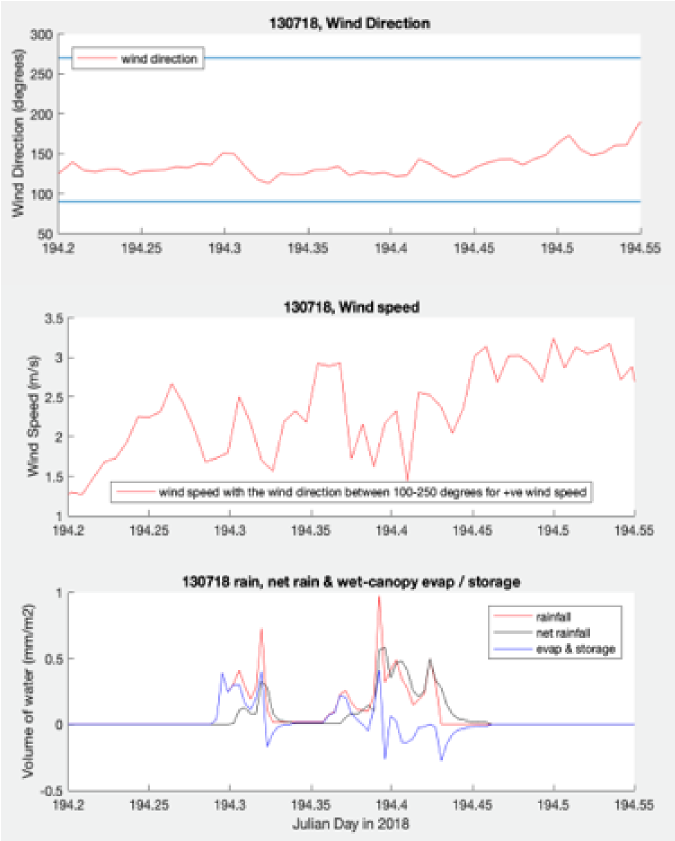
Figure 3-26:Time series graphs of TF, WCE and RF (17/06/18)

The longer duration of the medium volume (2.1-9.9mm) events where rainfall is steadier, throughfall may not occur until 1-2mm (Figure 3-27, Figure 3-28 and **Error! Reference source not found.**) of rainfall has occurred over >3hrs (Figure 3-27). Others with a higher initial intensity can mean throughfall occurs at 0.2mm (Figure 3-30) of rainfall within anything from a few-30mins (Figure 3-31). This indicates that WCE occurs during longer events allowing for the storage in the canopy to be reduced and more restored (Figure 3-32). Throughfall can account for anything from a small percentage up to >100% of rainfall, although more often WCE is higher than TF (Figure 3-32 and Figure 3-33). A high wind speed and direction towards the open canopy is generally required to produce a negative WCE event however this does not always produce negative WCE (Figure 3-33).



Event 15-16.05.18 -leafed
Medium event Previously dry
Medium duration of 6hrs 40min
TF occurs after 2 hours and 1mm of rainfall
Indicating a low intensity event allowing evaporation during the event.
WCE accounts for the majority of the RF but decreases as the event progresses when RF becomes larger
TF carried on during the canopy drain down for 25 mins after rainfall ceased

Figure 3-27:Time series graphs of TF, WCE and RF (15.05.18)



Event 13.07.18 – Leafed

Medium event towards the open canopy
Wind speed is variable through the event
TF starts when 1mm of RF has been reached
TF makes up 2/3 of RF
TF is delayed suggesting it is temporarily stored in the canopy and removed through drip

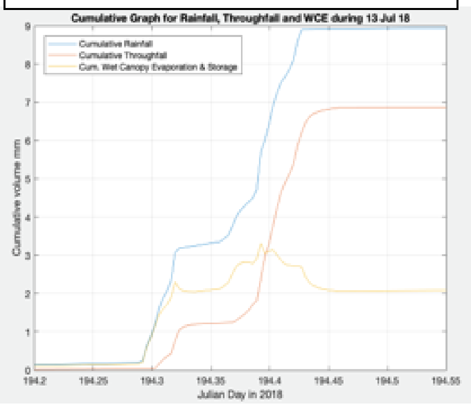
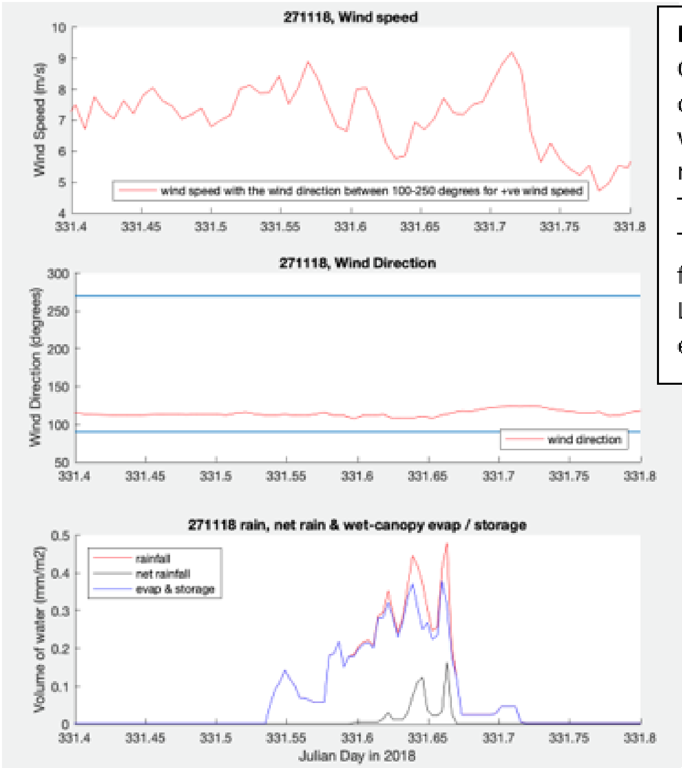


Figure 3-28:Time series graphs of TF, WCE and RF (13.07.18)



Event 27.11.18 – non-leafed

Consistent wind direction (ESE near the closed to open boundary)
varying high wind speed
medium duration and intensity
TF after 1hr 20min and 2mm of RF
TF decreased rapidly as RF did and finished before RF suggesting light rain
Low TF suggests water is being evaporated through the event

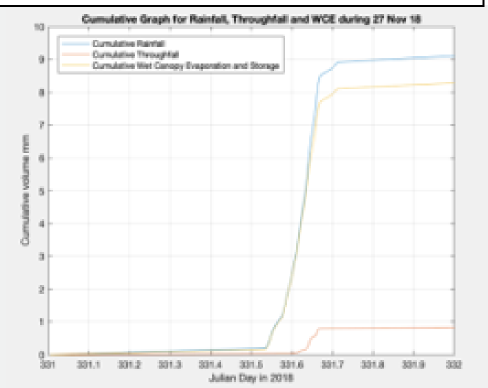
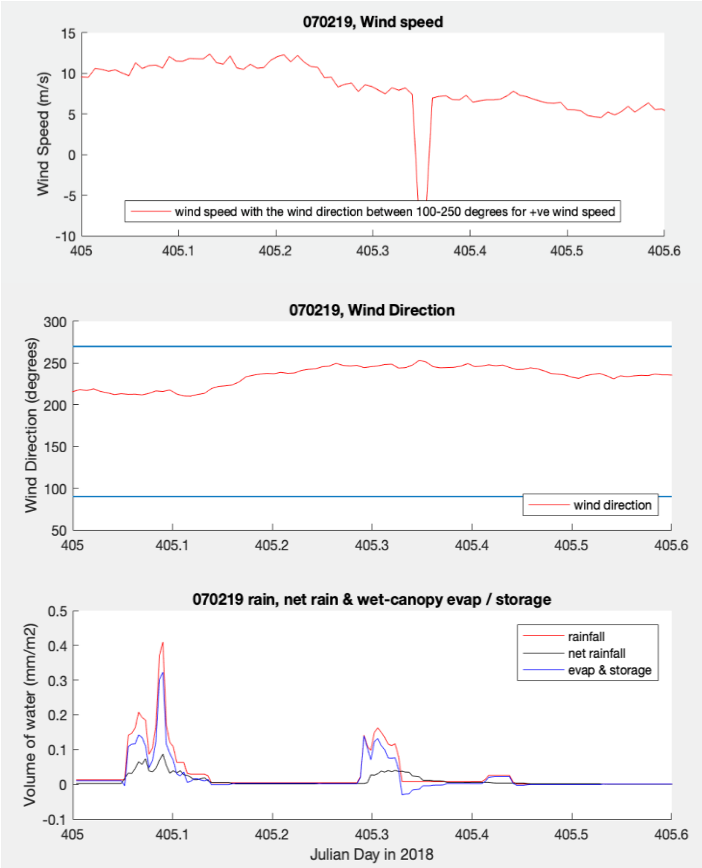


Figure 3-29:Time series graphs of TF, WCE and RF (27.11.18)



Event 07.02.19 – non-leafed
Medium duration and low intensity
TF is about 1/3 of RF
High wind speed throughout
Direction towards open canopy but close to the closed canopy
TF is delayed by 15min at each peak
TF occurs after 0.2mm of RF

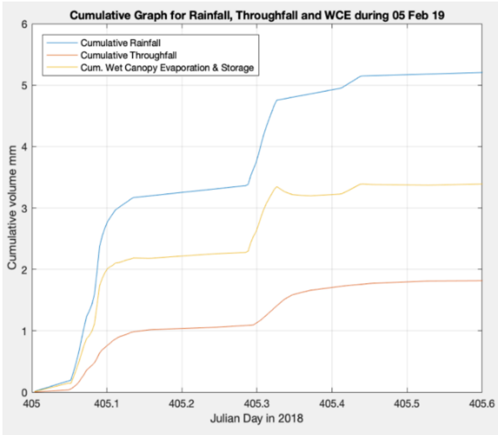
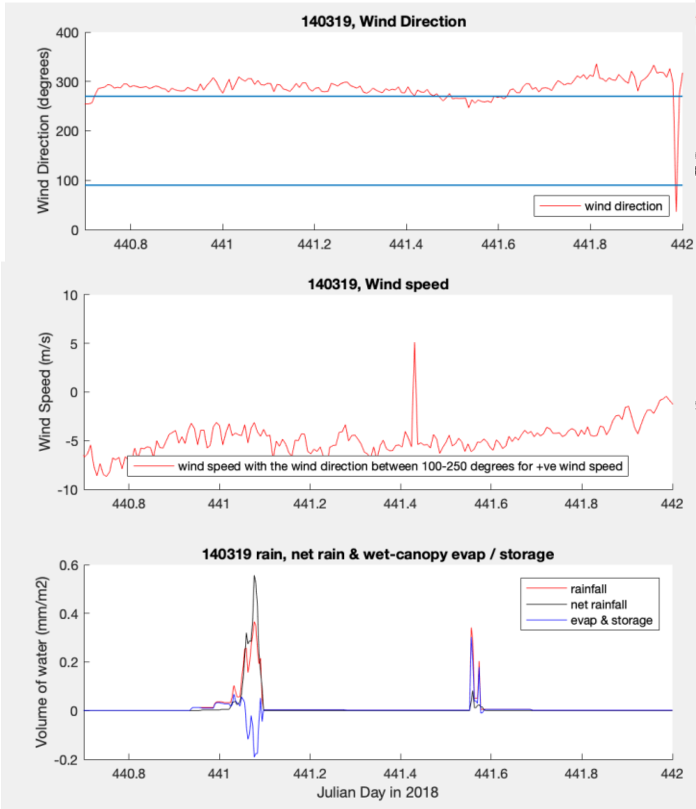


Figure 3-30:Time series graphs of TF, WCE and RF (07.02.19)



Event 14-15.03.19 – non-leafed
2 fast events making 1 medium event.
Peak 1 medium intensity and peak 2 low intensity
Wind direction – border of closed to open and wind speed is medium allowing some horizontal rainfall ot hit some open canopy
TF is around ¾ of RF
TF starts 30 mins (peak 1) and 1-2 mins after rainfall (peak 2)
TF stops within a few minutes after RF (peak 1) and 2.5hr before RF (peak 2)
Frumau gauges showed peak 1 RF towards open canopy and horizontal but peak 2 has lower TF as horizontal RF is lower

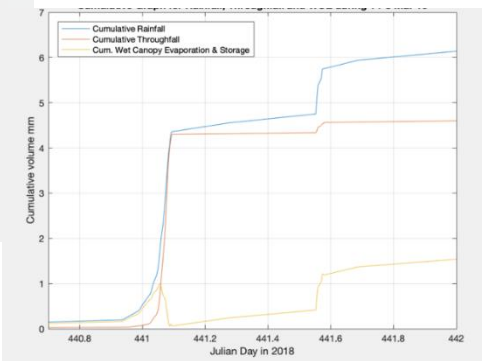


Figure 3-31:Time series graphs of TF, WCE and RF (14-15.03.19)

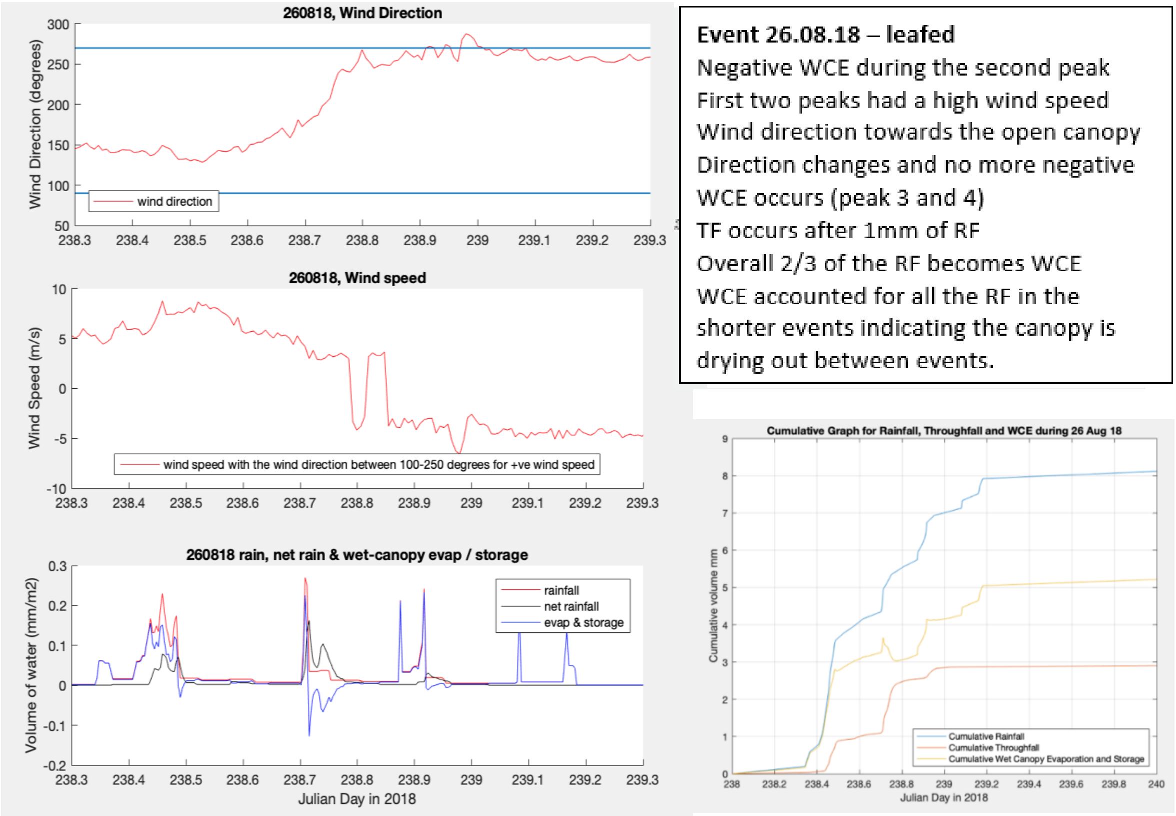


Figure 3-32:Time series graphs of TF, WCE and RF (26.08.18)

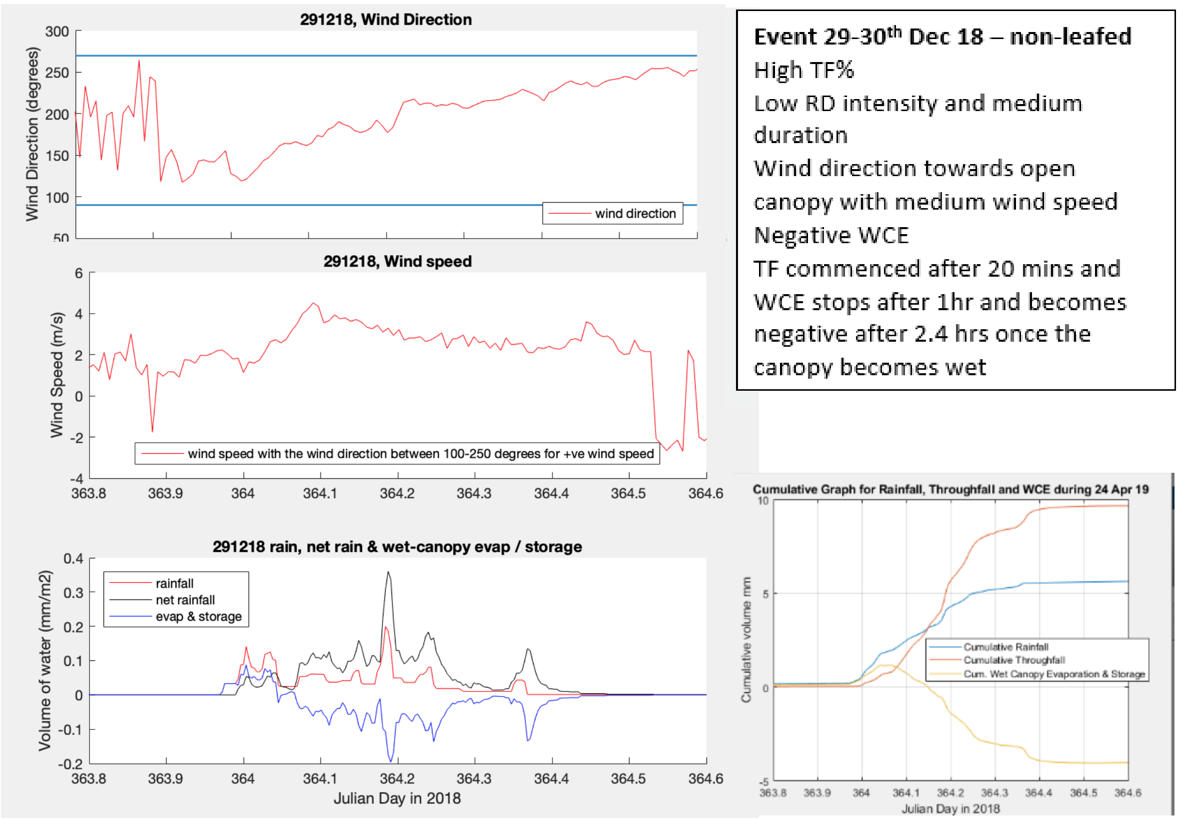
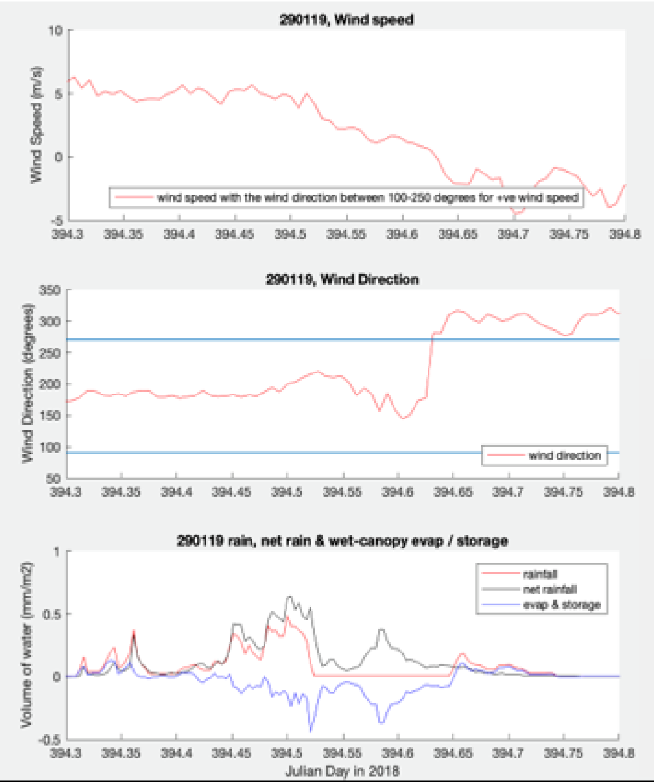


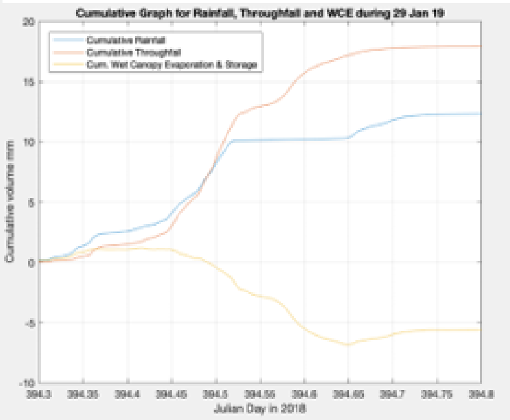
Figure 3-33:Time series graphs of TF, WCE and RF (29.012.18)

Large events (10-20mm) show that throughfall can vary similarly to medium events from 0.2-1.3mm (Figure 3-34-Figure 3-35) depending on the event duration/intensity. The duration before throughfall occurs can be anything from immediate-1/2hr as events are larger and often more intense (Figure 3-36). More negative WCE events occur during this sized event (Figure 3-34, Figure 3-37 and Figure 3-38). The time series show the importance of wind direction to the open canopy and higher wind speed in the occurrence of negative WCE. However, this is not always the case (Figure 3-35 and Figure 3-39).



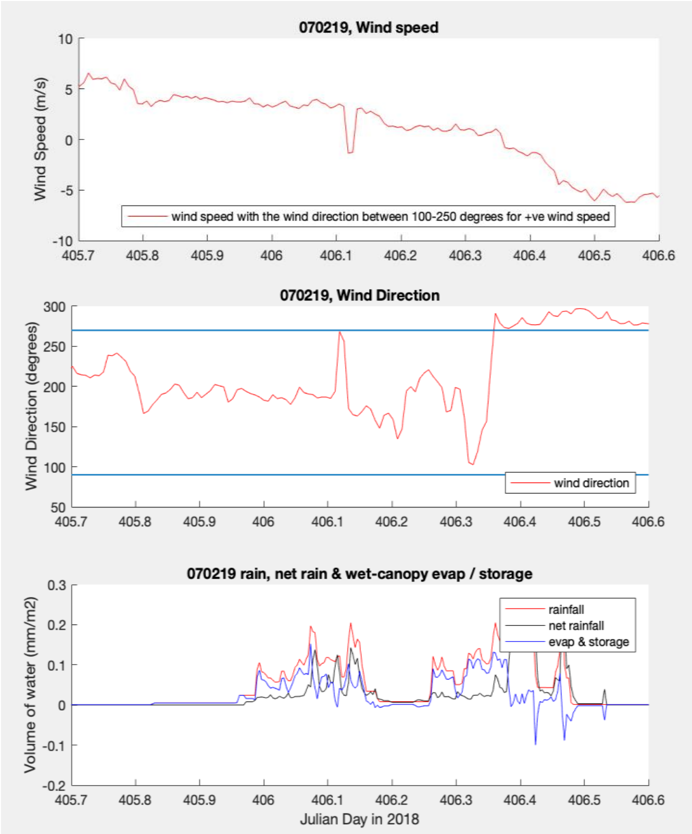
Event 29.01.19 – non-leafed

Long duration and medium intensity
Wind direction towards open canopy
TF% high producing negative WCE
TF occurred when RF reached 0.2mm
negative WCE



Halfway through this event the RF turned to sleet/snow (1230-mid afternoon) which is seen in the sudden decrease in RF
During melting at 1530 a delayed TF peak can be seen
The rain gauge massively underestimated RF as it could not measure the snow, however this occurred after the initial negative WCE

Figure 3-34:Time series graphs of TF, WCE and RF (29.01.19)



Event 07.03.19 – non-leafed
RF >13mm
Low intensity and long duration
WCE% and TF% medium
TF delayed by 15 mins with no delay for second peak indicating not drying out of the canopy in the 2hour gap
TF commences at 1.3mm of RF
Wind direction towards open canopy then closed canopy when TF is greater than RF

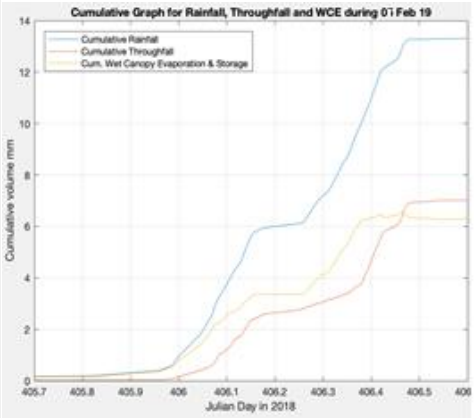
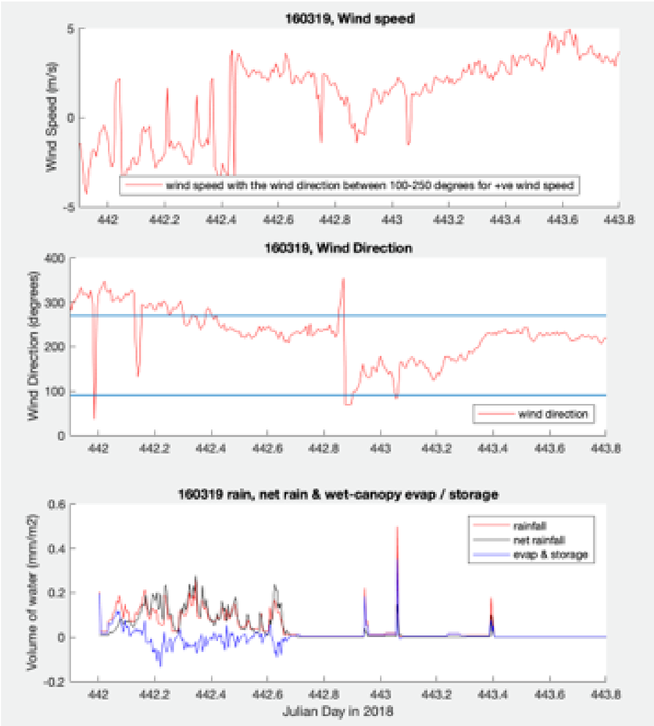
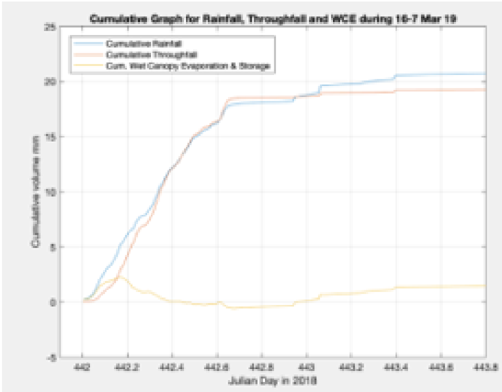


Figure 3-35:Time series graphs of TF, WCE and RF (07-08.02.19)

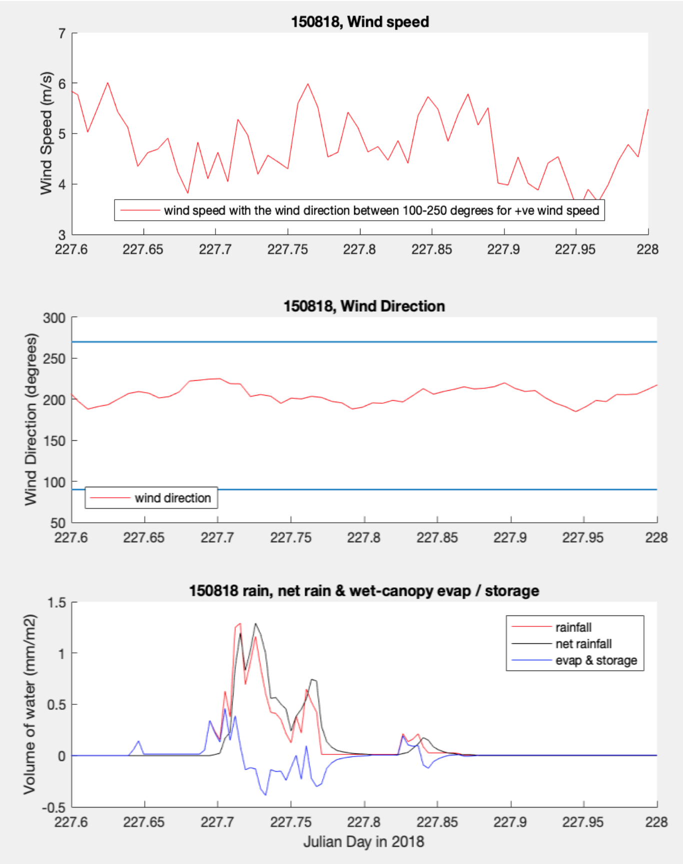


Event 16-17.03.19 – non-leafed
Large event made up of 4 distint mini-events
The first has a large volume with long duration and medium intensity, TF is high and WCE low
TF starts 22mins after RF, when 1mm of RF occurs and stops 18min before RF
WCE during wetting up phase



Other 3 peaks are low volume ((2) medium duration and low intensity, (3) low duration and intensity, and (4) low duration and medium intensity)
TF commences within a few minutes with a low TF%
Wind direction is variable – greater TF than RF occurs for peak 1 when direction changes to closed/open canopy boundary
Wind speed is variable but medium
Frumau indicated a high TF as more horizontal RF towards the open canopy and other 3 events had lower horizontal RF

Figure 3-36:Time series graphs of TF, WCE and RF (16-17.03)



Event 15.08.18 – Leafed

Over 14mm of RF
Previously wet with medium duration wind direction to open canopy with fluctuating but high wind speed
TF high and negative WCE
TF occurred when RF reached 1.2mm
WCE accounted for the start of the event during wetting up phase

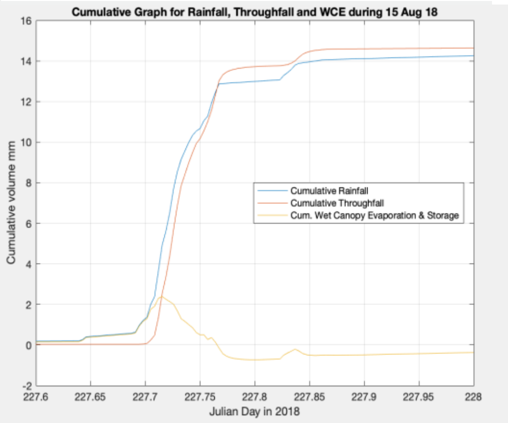
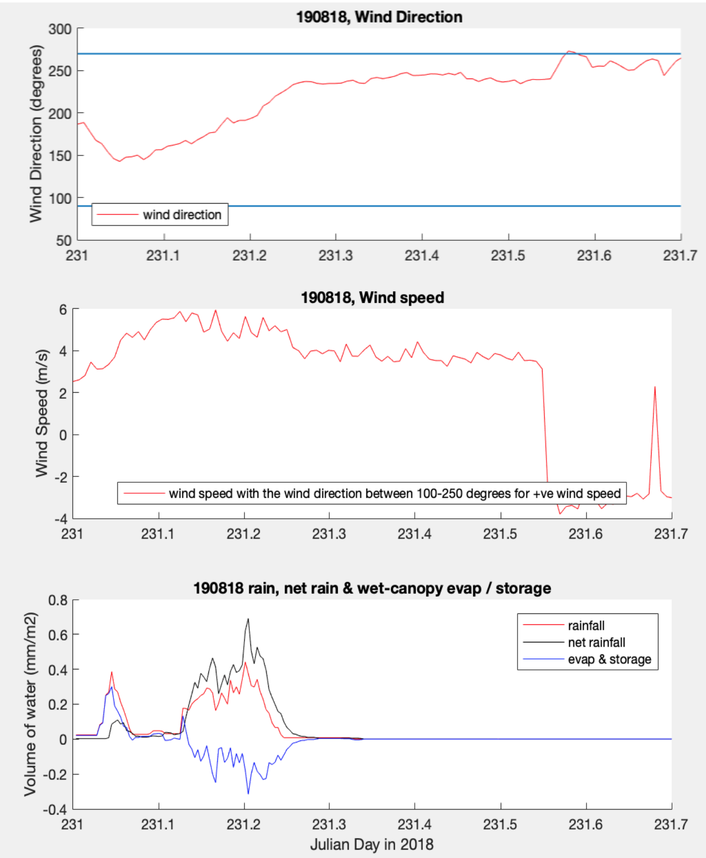


Figure 3-37:Time series graphs of TF, WCE and RF (15.08.18)



Event 19.08.18 – Leafed

Previously dry with medium duration and intensity
TF once 1mm of RF
TF% high and produces neg WCE
Wind direction towards open canopy throughout with wind speed ~3m/s for the first peak and 5m/s for second
Second event shows the canopy dried out between events but TF resumes much quicker

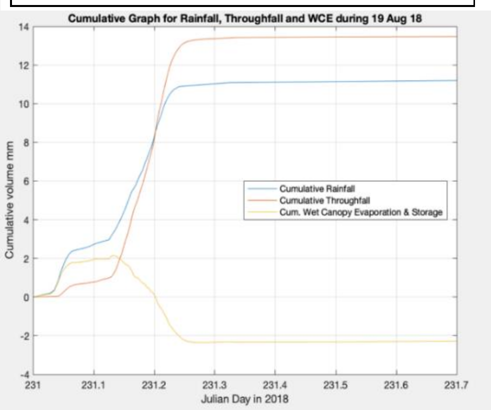


Figure 3-38:Time series graphs of TF, WCE and RF (19.08.18)

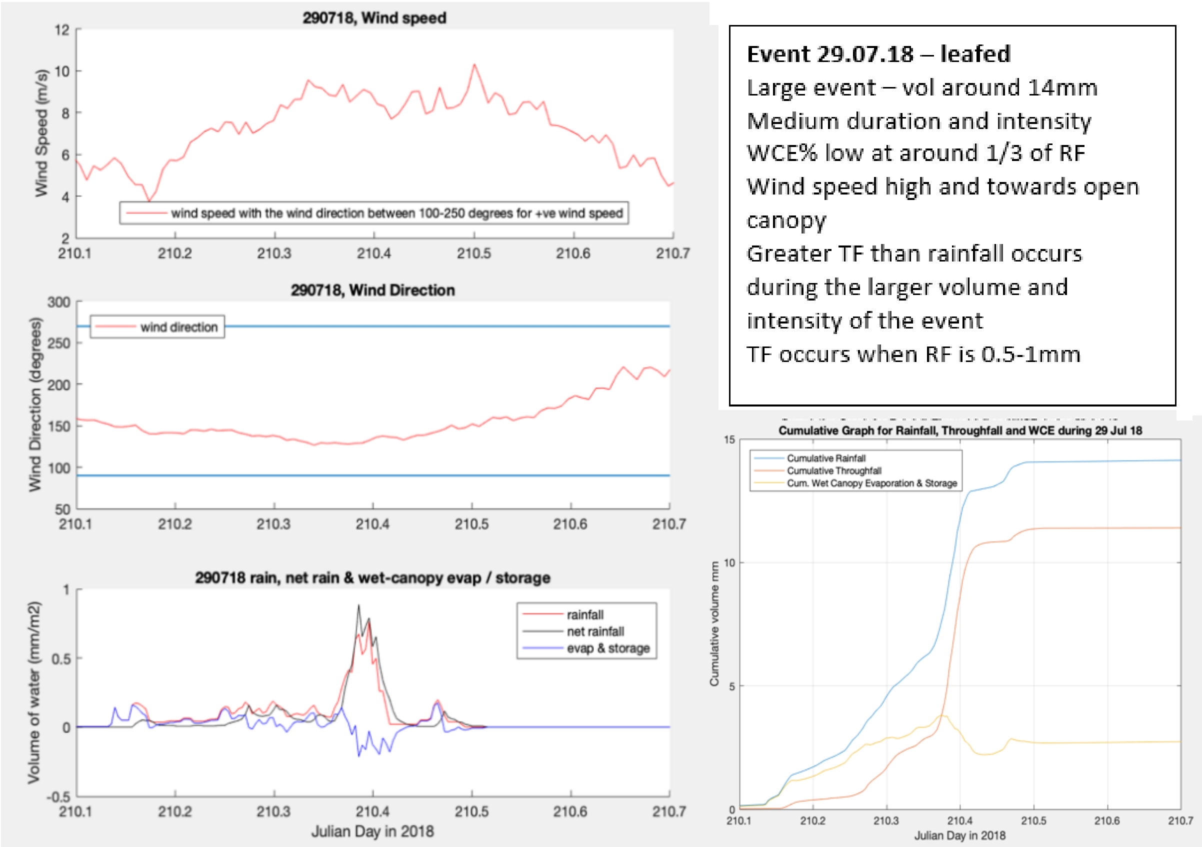
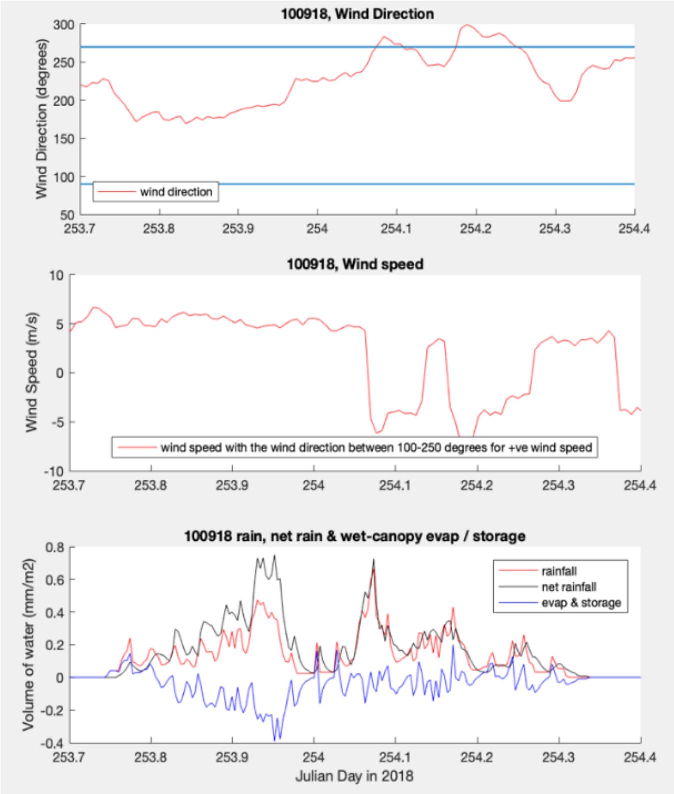


Figure 3-39:Time series graphs of TF, WCE and RF (29.07.18)

Largest events recorded (>20mm) show varying mini events within the whole storm. The amount of negative WCE that occurs varies through events (Figure 3-40). The wind direction and speed are important indicators for this to occur (Figure 3-41-Figure 3-43). Throughfall during these events can occur anywhere from 0.5-4mm (Figure 3-40 and Figure 3-42). This is influenced by meteorological factors such as temperature and wind speed. These events are generally long duration with a medium-high intensity. The throughfall can occur immediately if previously wet or can be delayed by >1hr (Figure 3-41). The throughfall has been shown to persist for a longer time after the rainfall has finished than for smaller events (Figure 3-41). This is particularly the case in events that have high wind speed suggesting the canopy is hit by the wind causing the stored water to fall as drip. The measurement uncertainty (Figure 3-42) in Storm Callum could be a reason for the negative WCE, however this cannot be the case for all as many have larger negative WCE than this event, showing negative WCE does occur.



Event 10-11.09.18 – leafed
Wet before event as can be seen in the small amount of WCE before TF
Long duration and medium intensity
TF starts before RF reaches 0.5mm around 18mins after RF starts
Fairly consistent wind speed ~5m/s
Wind direction in open canopy causing negative WCE and as changes to closed canopy TF decreases

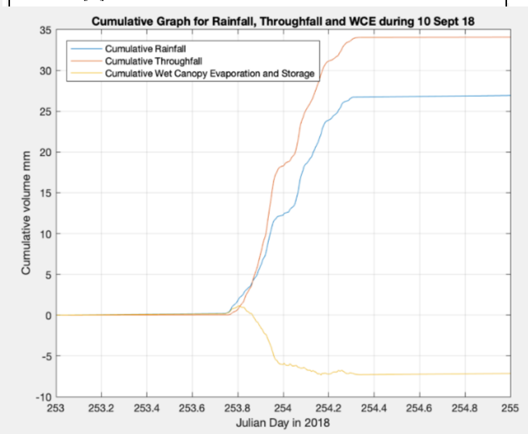
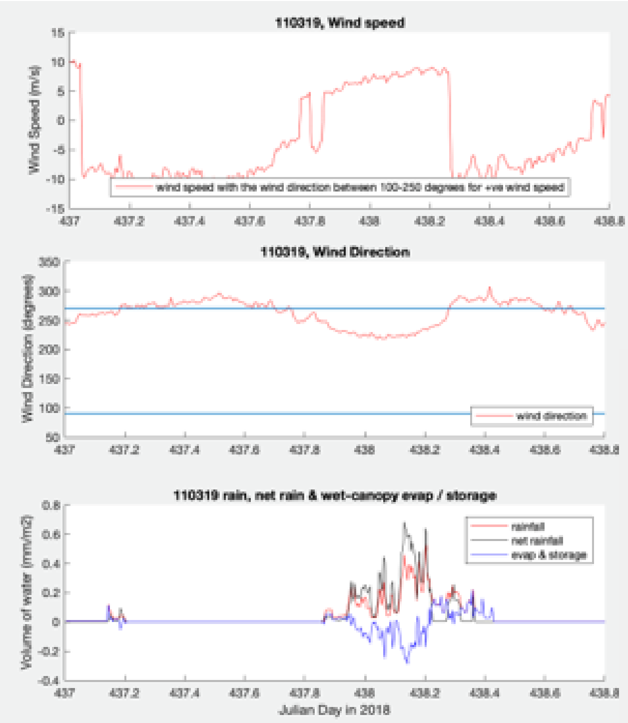
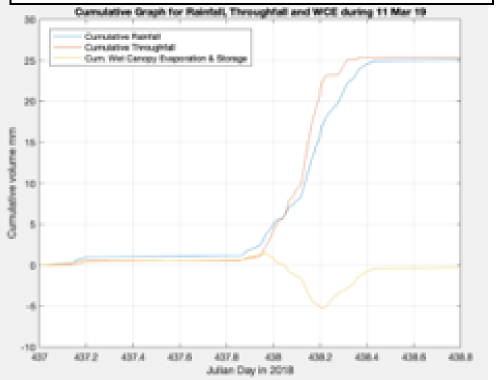


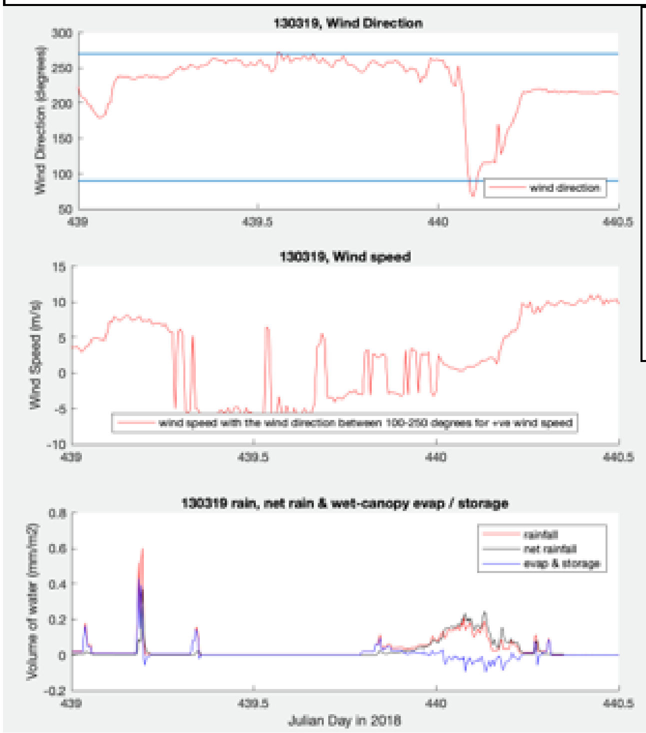
Figure 3-40:Time series graphs of TF, WCE and RF (10.09.18)



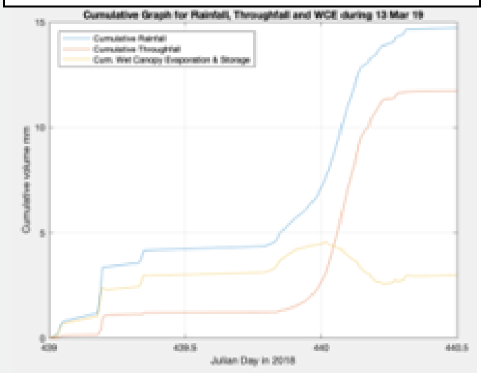
Storm Gareth 11-14.03.19 – non leafed
One of largest events lasting over 4 days with on/off rainfall events
Storm Gareth had a very high wind speed, which decrease before the rainfall
Long duration with medium intensity
TF% was high
First event wetted the canopy & didn't dry out as TF started quickly in 2nd



TF becomes larger after initial wetting of the canopy after this the wind direction plays an important role (TF decreases as direction changes towards closed canopy
Frumau gauge shows high horizontal rainfall towards the open canopy TF commenced when 0.5mm was reached within 6 minutes of rainfall commencing
TF persists for 1hr 20mins after RF due to drip from high winds
Wind speed is consistently high

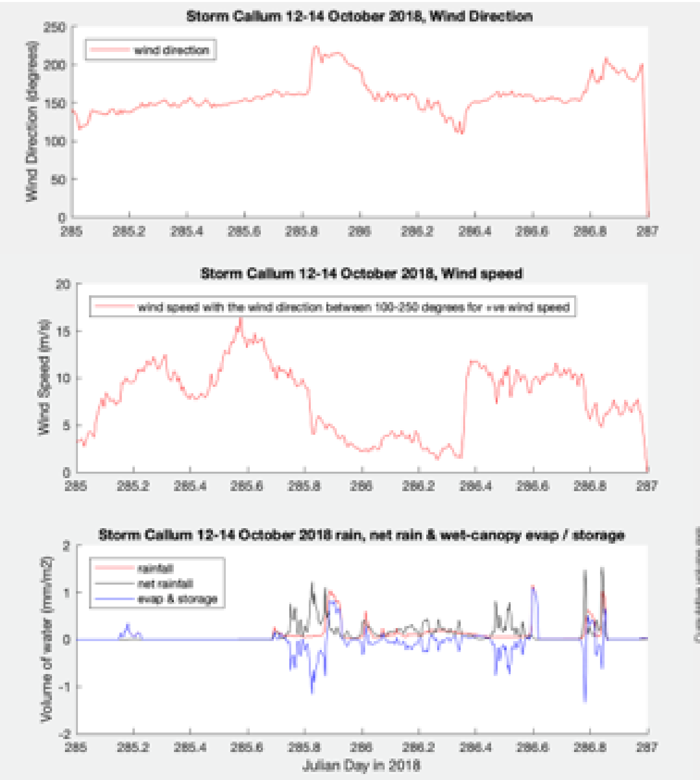


The second part of the storm (13-4 Mar)
Canopy dried to some degree
TF commencing 1hr 6min after RF
Long duration and low intensity with 3 mini events before.
TF high and stops 54min after RF indicating the wind was causing drip
3 mini events are quick RF events where WCE is medium or high

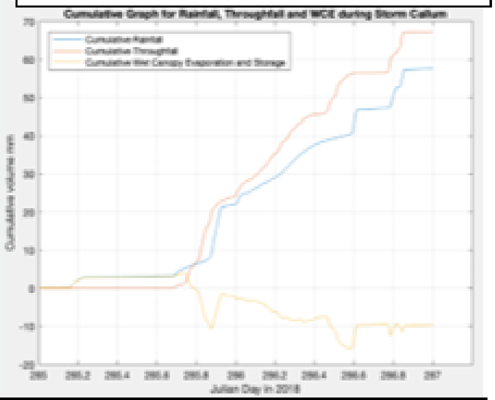


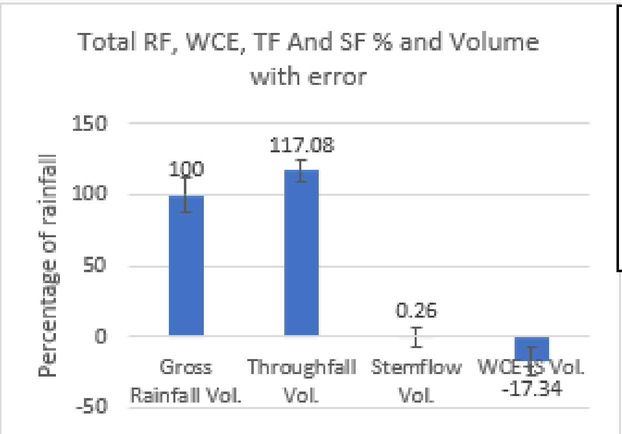
Wind direction moves towards the canopy and increase in wind speed when TF is higher than RF
The Frumau gauge shows the initial peak with low TF has vertical RF and higher towards closed canopy, second peak with medium TF has some horizontal RF to open canopy; the 4th has similar proportions of vertical and horizontal rainfall but with the majority of rainfall towards the open canopy meaning the TF is high as the canopy collects more water.
WCE is positive over the entire event

Figure 3-41:Time series graphs of TF, WCE and RF (11-14.03.19)



Storm Callum 12-14.10.18 transition period
Long duration and medium intensity
TF accounts for the majority of RF occurring and starts when RF reaches 4mm
WCE is high for the first initial peak then becomes negative
Wind direction to open canopy and wind speed varies significantly thoughout the event





Where there is a lower wind speed, the TF to RF percentage is lower than where the wind speed is higher
For this event the TF and RF are within their uncertainty suggesting that TF may not be higher than RF in this instance (however other events disprove this as the reason)

Figure 3-42:Time series graphs of TF, WCE and RF (12-4.10.18)

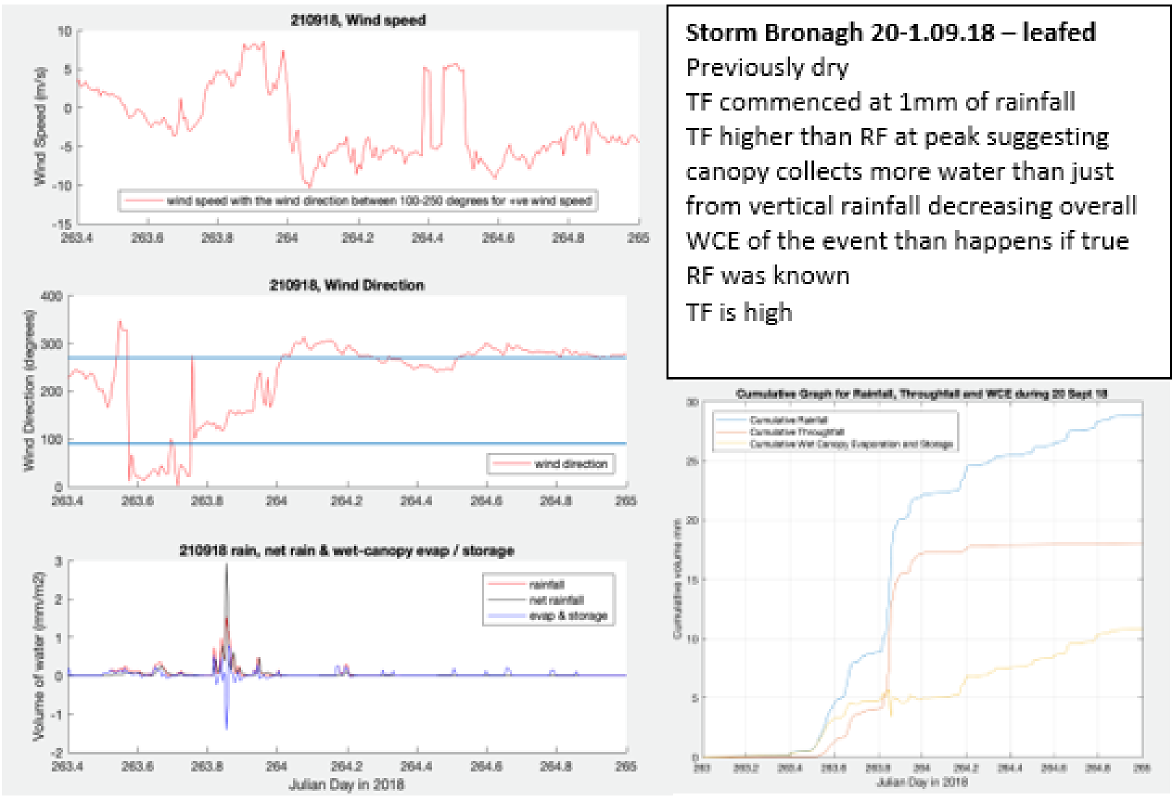


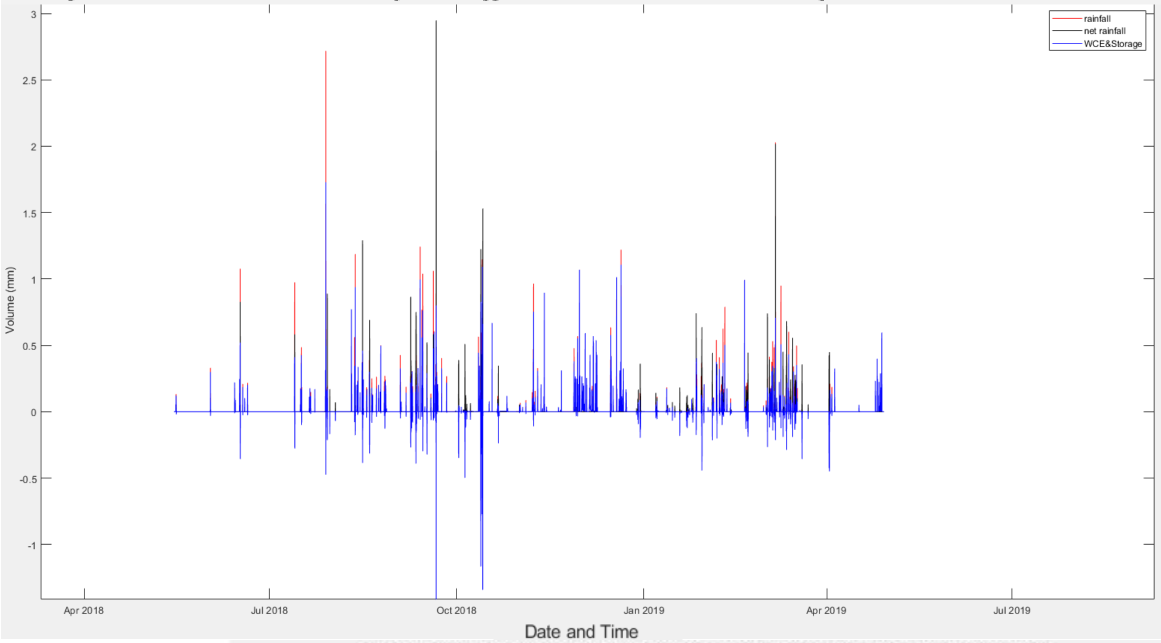
Figure 3-43:Time series graphs of TF, WCE and RF (20-21.09.18)

3.7 Modelling

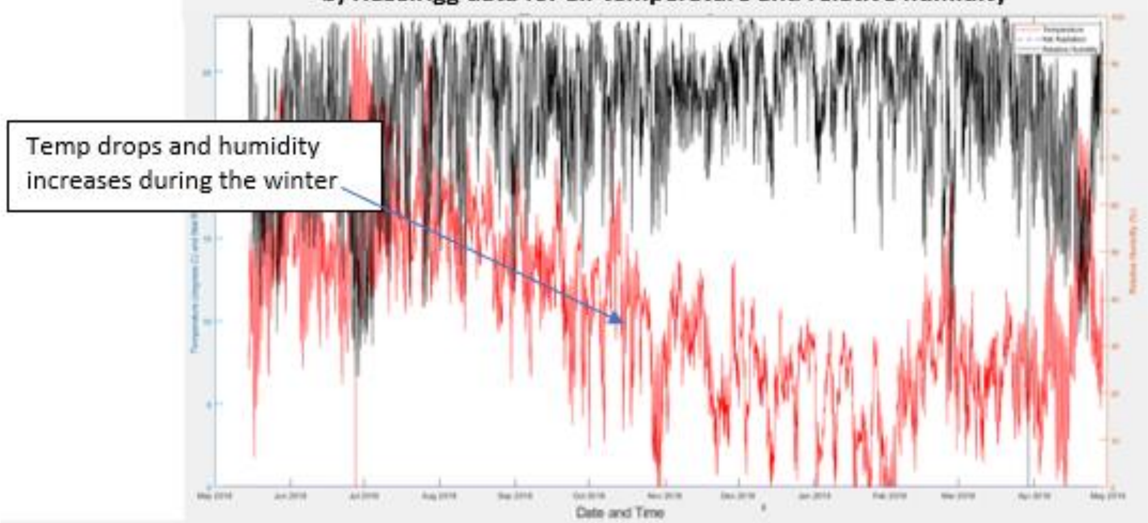
3.7.1 Penman Equation

The Penman equation shows the potential for evaporation i.e. "the loss expected over a surface with no limitation on water", which relates to atmospheric conditions (Beven, 2012). As the Penman equation shows the potential evaporation it fits the measured WCE&Storage poorly as is much larger over the year. Figure 3-44 shows the fit produced against the actual WCE&Storage data is poor as predicts no evaporation at night and predicts the potential evaporation as much lower than measured particularly during largest events and winter. It is unable to predict WCE when throughfall is higher than rainfall causing a negative WCE.

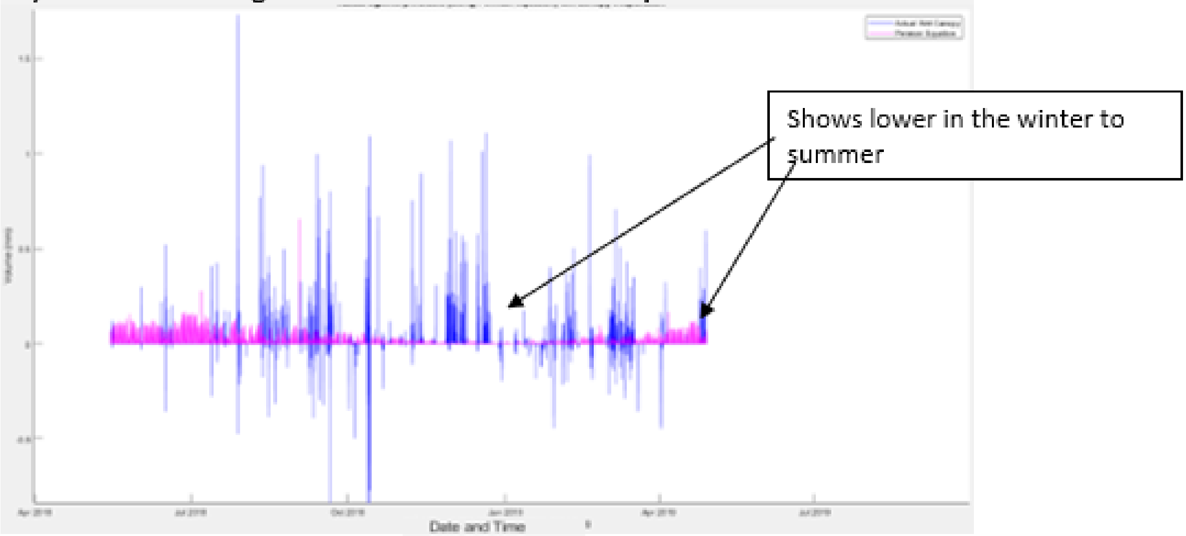
a) The measured rainfall, throughfall and WCE over the year



b) Hazelrigg data for air temperature and relative humidity



c) Measured WCE against modelled from Penman equation



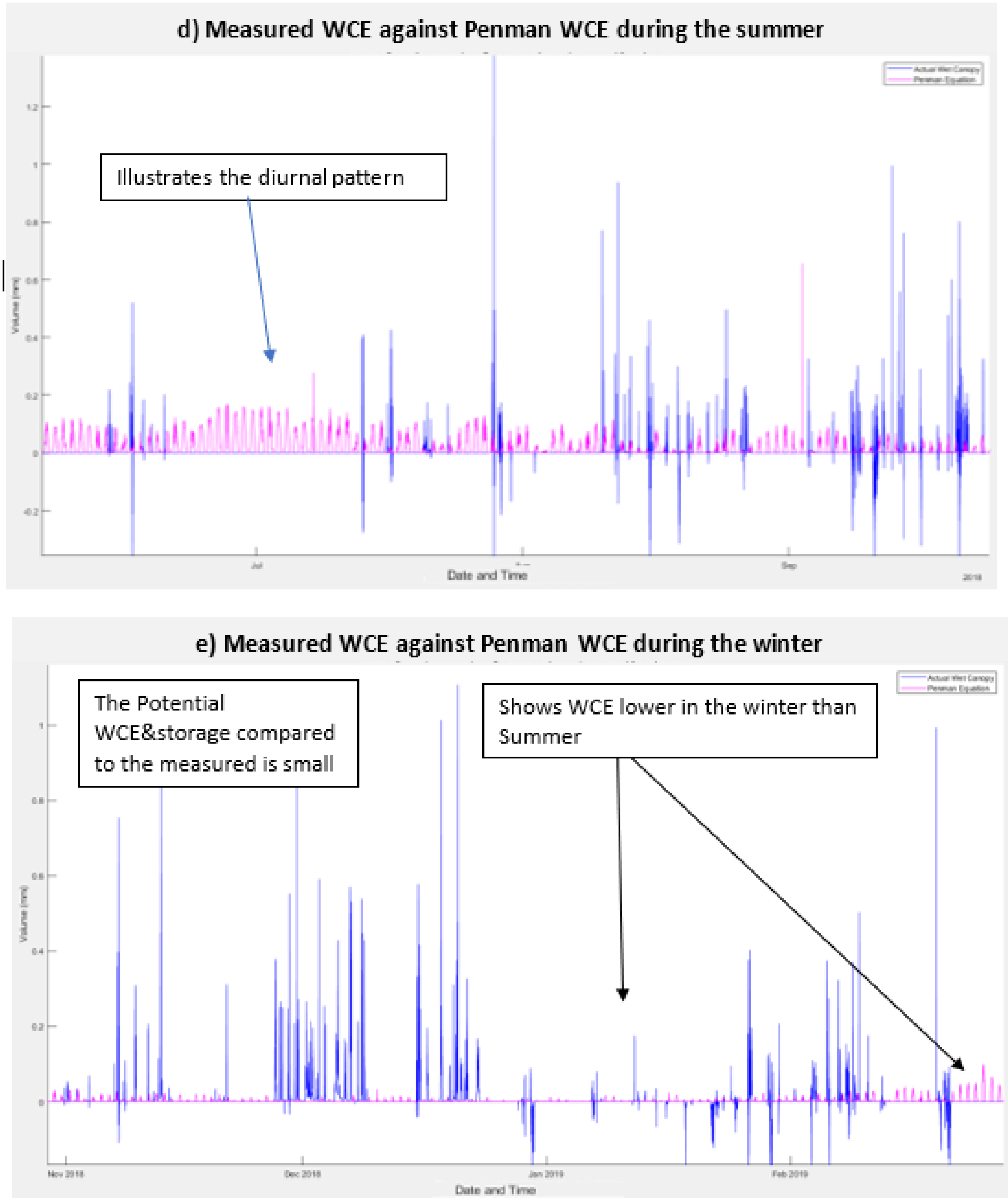
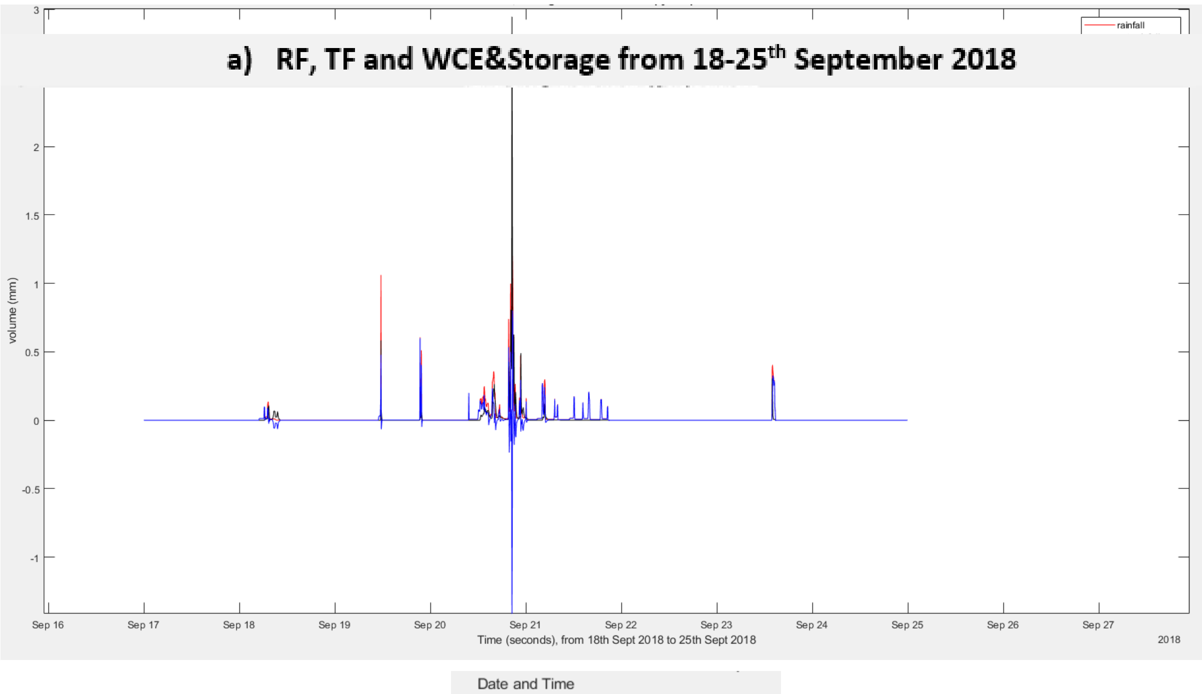


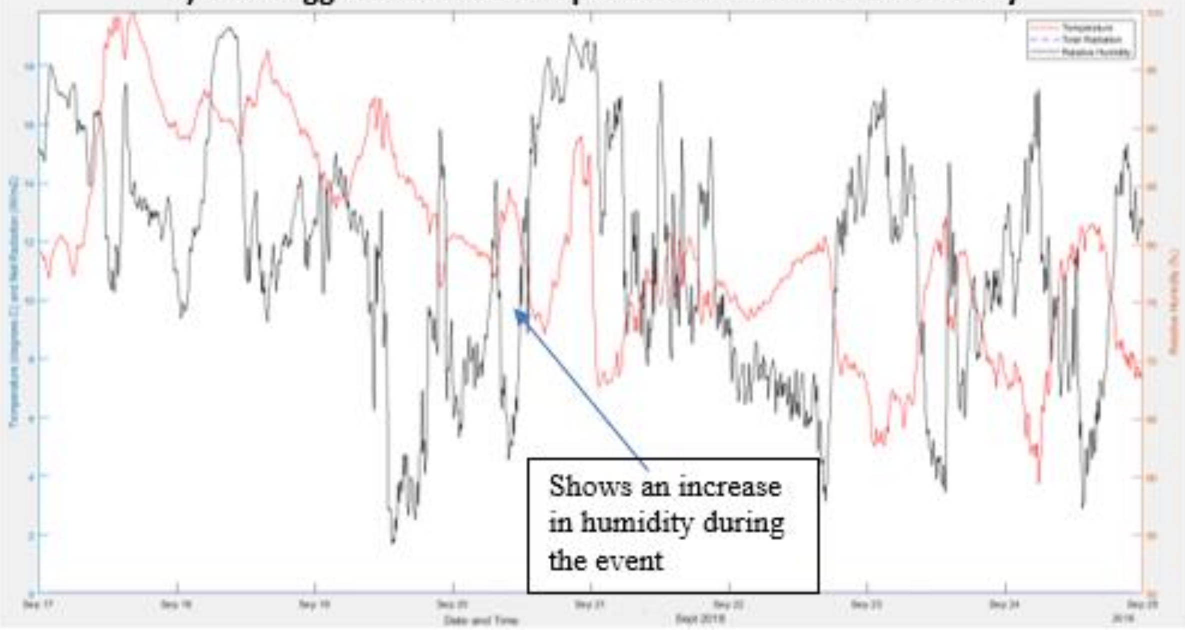
Figure 3-44:(a)rainfall, throughfall and WCE over the year, (b)Hazelrigg data utilised for the Penman calculation, (c)WCE data against Penman's potential evaporation, (d-e)difference between summer and winter

The Penman equation produces an annual and diurnal cycle (Figure 3-44). The model significantly struggles to predict any evaporation during non-leafed but produces a better prediction during the leafed periods. During the leafed period, the evaporation is closer to the magnitude that is seen in the measured data; However, it struggles to predict evaporation for larger events. Penman equation cannot predict the measured negative WCE (Figure 3-44), which is caused by a water balance error, which if corrected would increase the WCE further meaning the model would be worse at predicting the WCE. Therefore, the model produces a very poor fit.

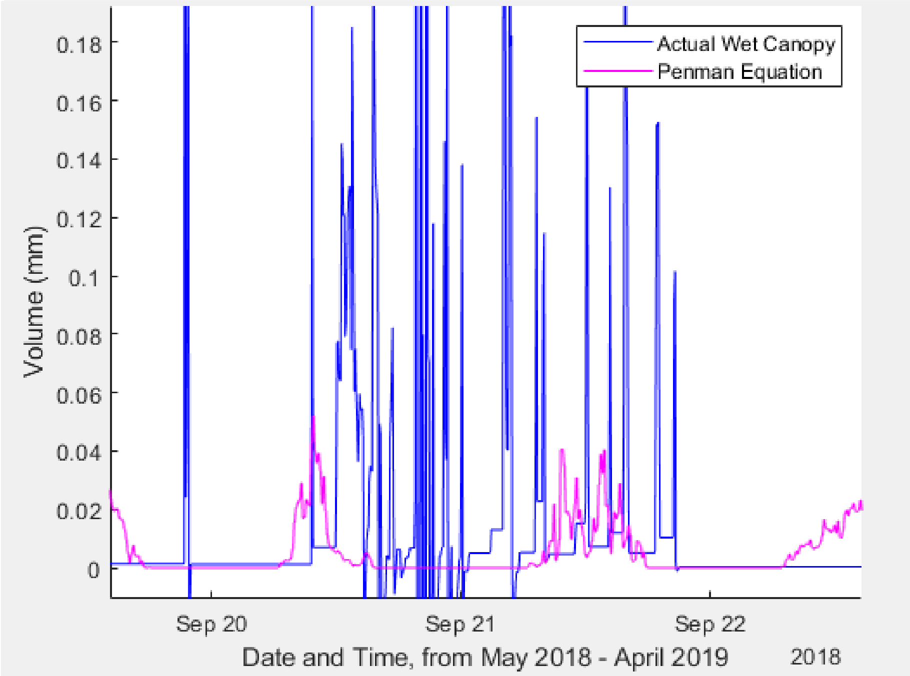
The model is closer to predicting the smaller events (
Figure 3-45). There is an obvious diurnal cycle produced by this model caused by the meteorological factors (net radiation and temperature) (
Figure 3-45). The relative humidity is often higher when rainfall occurs so is a good indicator of this, but rainfall does not always occur when it is higher. The temperature can be seen to increase during the larger event when more evaporation occurs; However, this also coincides with greater rainfall. There is no distinct relationship between 1 meteorological factor showing that they all play a part in canopy evaporation (
Figure 3-45). The model predicted evaporation is a lot smaller per event than the actual evaporation but larger on an annual scale due to the potential evaporation when rainfall does not occur. The model has no attempt at predicting the night evaporation. This lack of night evaporation is due to the importance the model puts in net radiation; however, some evaporation occurs at night due to the wind speed and temperature. The model delays the evaporation to the following day where an event occurred at night.



b) Hazelrigg data for Air temperature and Relative Humidity



c) Measured WCE &Storage plotted against Penman Equation



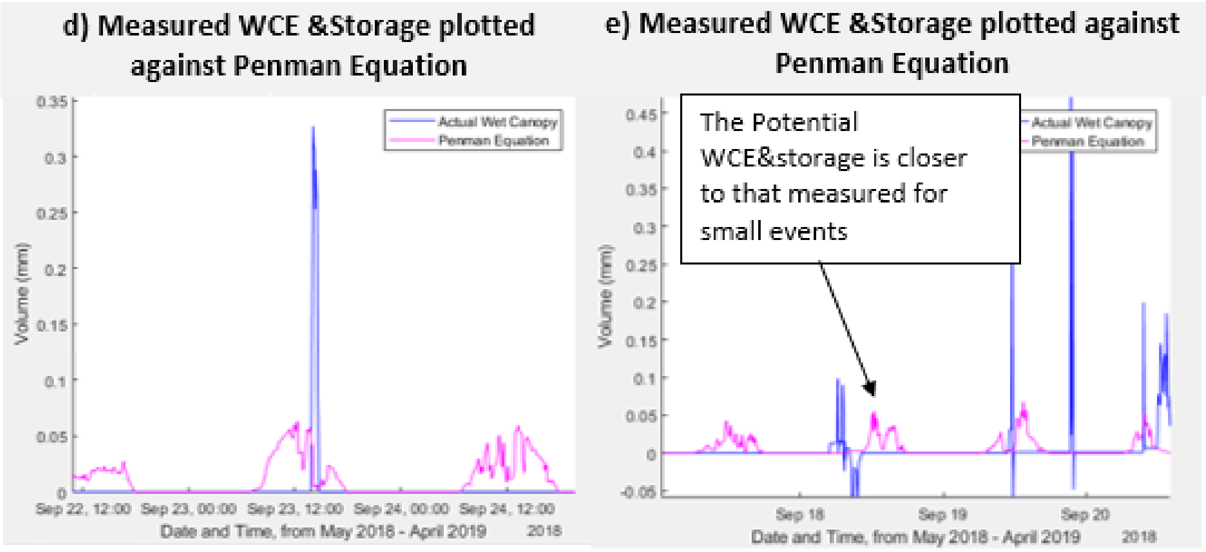


Figure 3-45:Data for 18-25.09.18. (a)rainfall, throughfall and WCE&Storage measured data (b)Hazelrigg relative humidity and temperature and (c-e)WCE data against the potential evaporation from the Penman equation

3.7.2 Physical Model – Rutter Models

3.7.2.1 Canopy Capacity

The canopy capacity (S) is the accumulated rainfall to the point where throughfall begins. Figure 3-46 shows throughfall against rainfall for each event. These straight-line equations are:

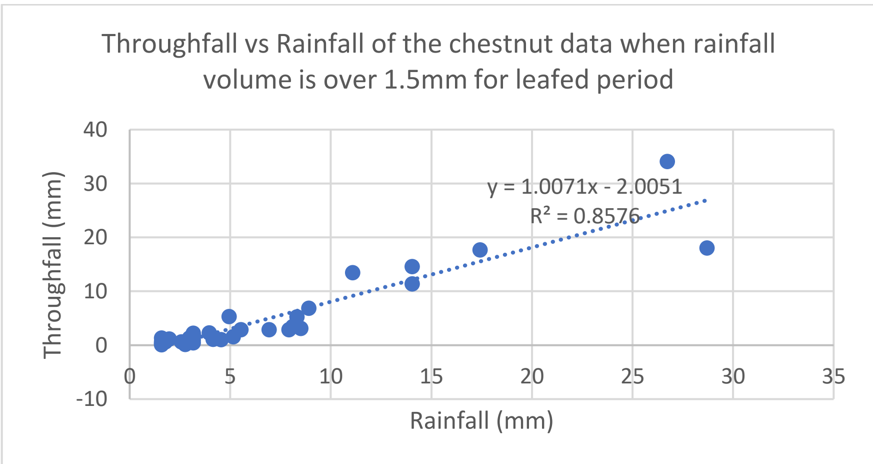
Equation 3-1:Winter/non-leafed period:

$$y = 0.8977x - 0.838$$

Equation 3-2:Summer/leafed period:

$$y = 1.007x - 2.0051$$

This equation shows that S=1.99mm for the leafed, 0.933mm for the non-leafed, and the transition period is linearly integrated as when leaf loss occurred is unknown. The leaves are more likely to be lost during a couple of storms.



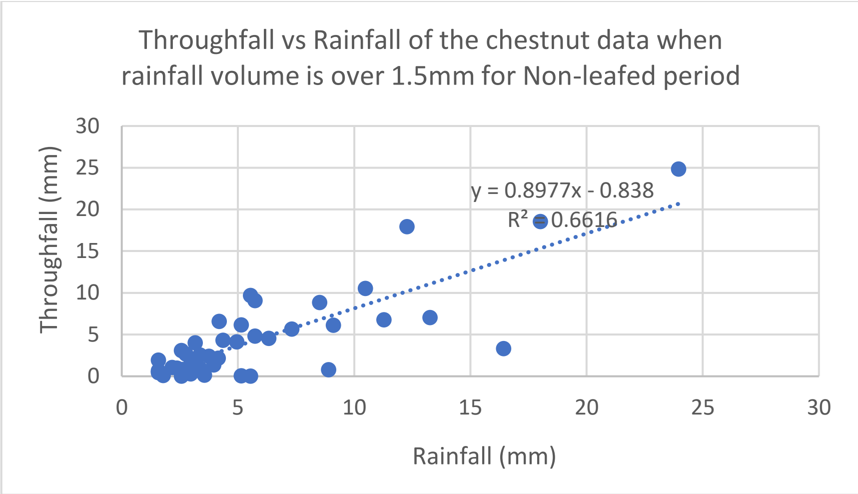


Figure 3-46:Throughfall vs rainfall volumes of each rainfall event over 1.5mm volume (as per Gash and Morton's (1978) method) with at least 2 hours of preceding dry conditions. The point at which the x axis is crossed is the canopy capacity at the point TF starts. Leafed and non-leafed periods are segregated, and transition events ignored.

3.7.2.2 Free Throughfall Coefficient

The free throughfall coefficient (p) is calculated by plotting rainfall vs throughfall for events <1mm (Gash and Morton, 1978). A regression line is plotted (Figure 3-47) and the coefficient of regression is p.

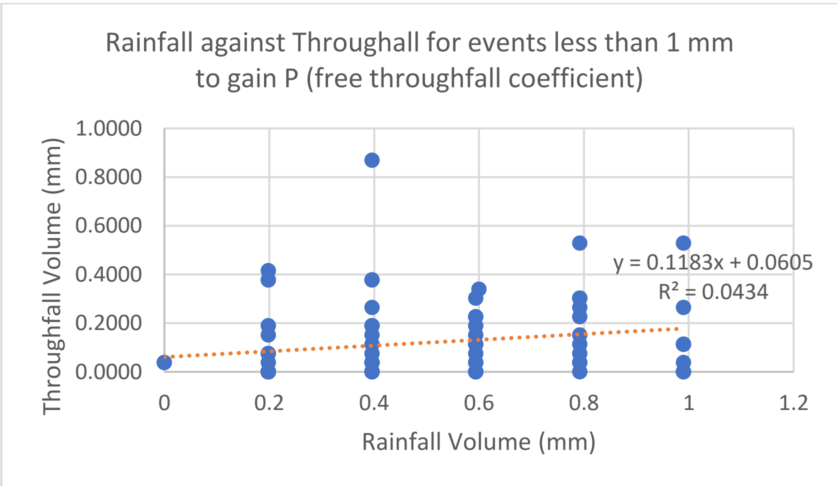


Figure 3-47:Throughfall volume against rainfall for events of ≤1mm to determine the coefficient of regression (i.e. p)

p is 0.1183, is significant but only just therefore would have a very large standard uncertainty.

3.7.2.3 Stemflow

The part of the Rutter model that defined stemflow has been excluded as Chestnut stemflow is small so is within the data collection uncertainty.

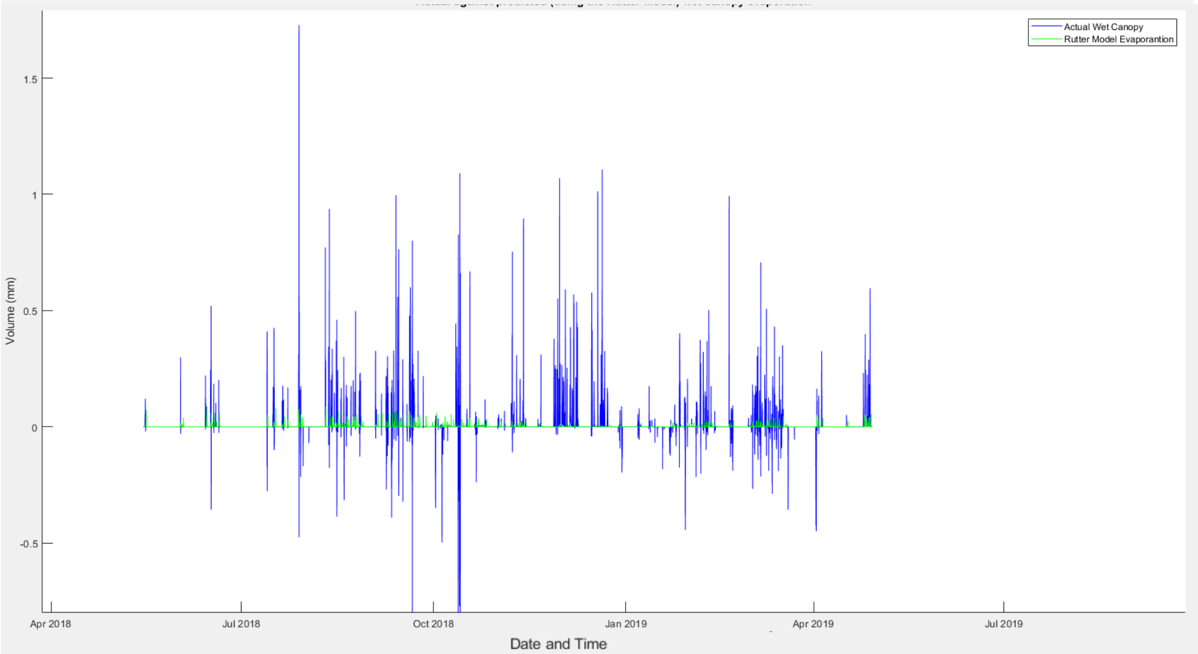
3.7.2.4 Model Results

The graphs (Figure 3-47) show the predicted evaporation using the Rutter model against measured indicating the model does not fit the measured WCE&Storage especially in negative

WCE events. This model is particularly poor at predicting evaporation during the dormant season due to its relationship with the Penman equation; but is closer to predicting potential evaporation during the summer (March-August).

The measured WCE&Storage shows that the water is stored and/or evaporated immediately on start of rainfall and agrees with the 2-hour period often given for drying out (Varley et al., 1993). The measured WCE&Storage does not decipher whether the water is still in the canopy or already evaporated whereas the Rutter model shows the evaporation (not whether the water is stored in the canopy). The Rutter predicts evaporation can occur during and after the event when it occurs in the day. However, it is delayed at night until the next diurnal evaporation period. This can lead to several evaporation periods for the same event (
Figure 3-49).

a) The modelled (Rutter Original) evaporation against measured WCE over the year



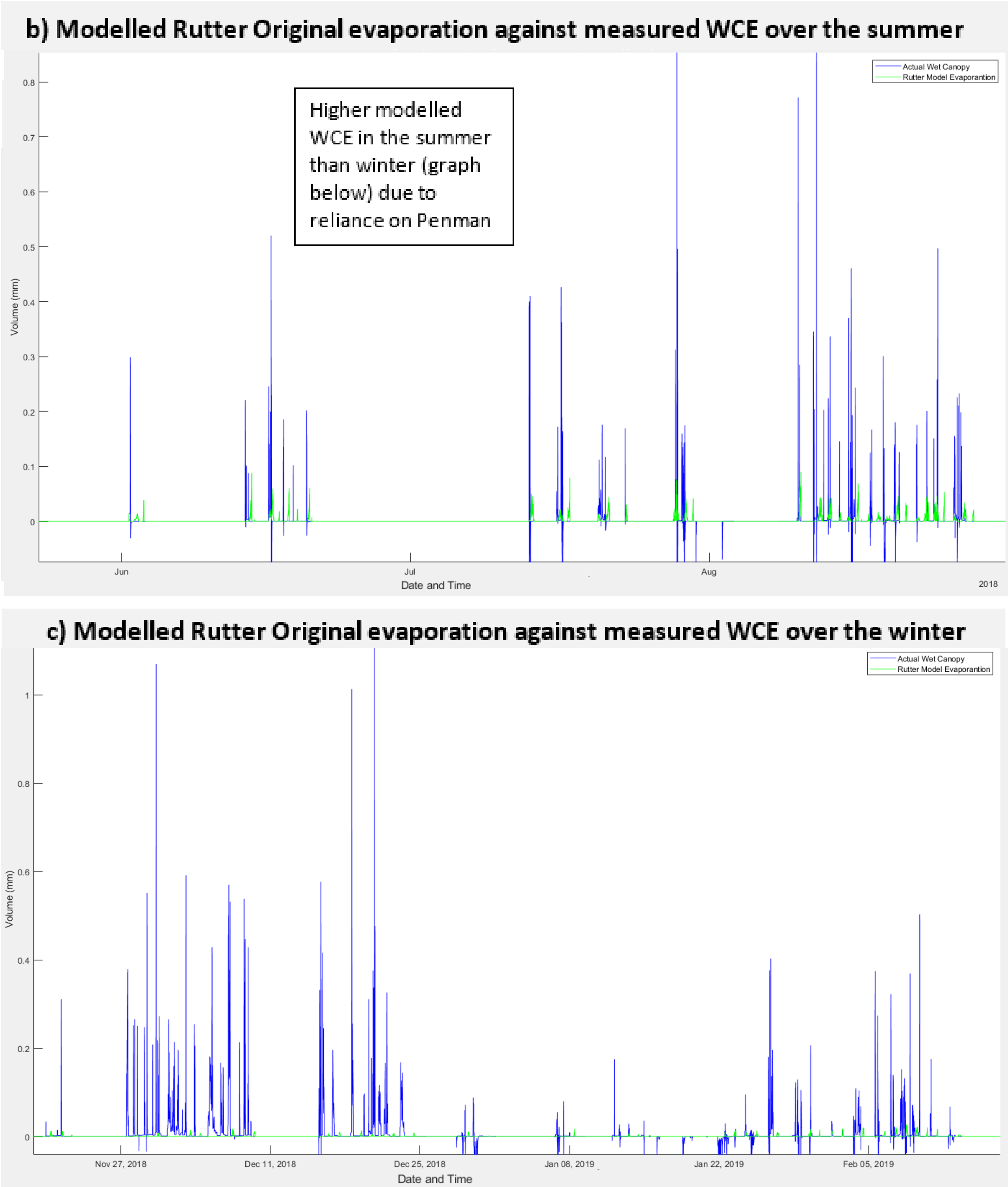
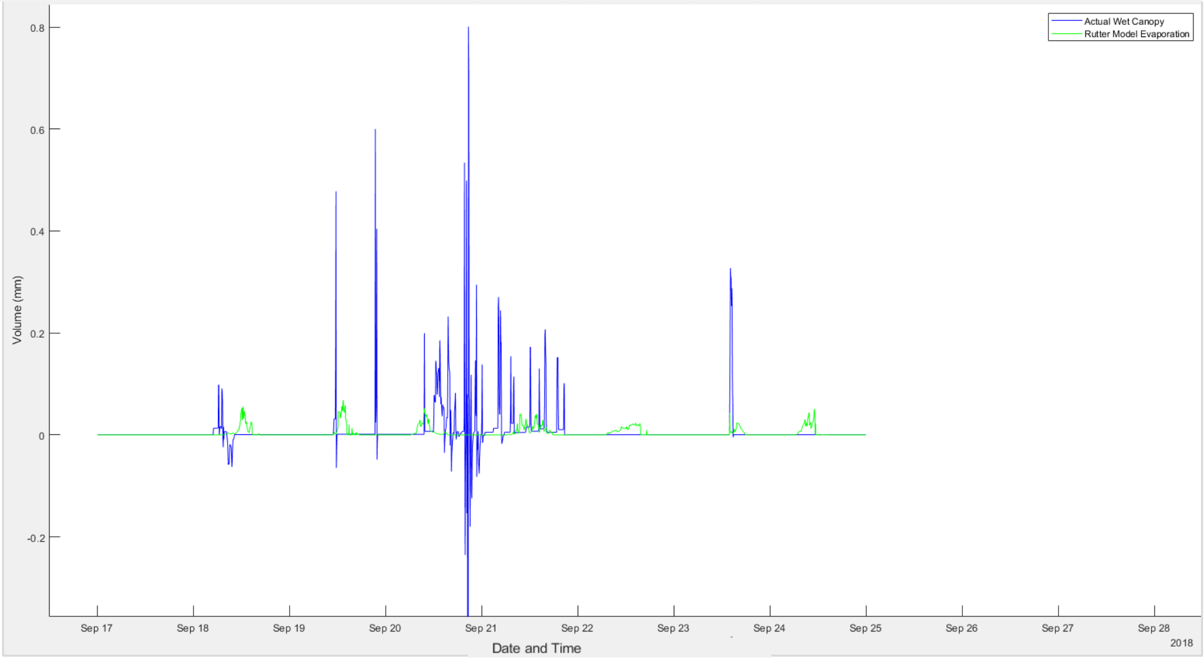
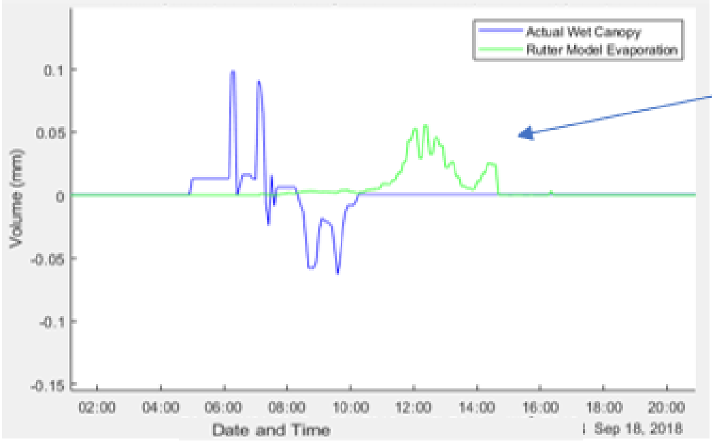


Figure 3-48:(a-c)predicted, using the Rutter Model, against measured WCE&Storage annual, summer and winter

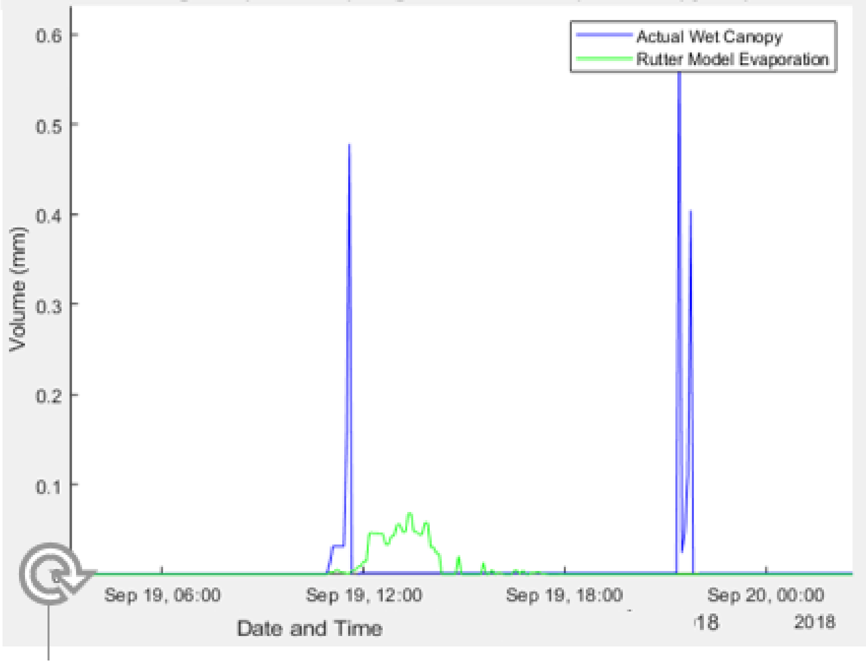
a) WCE from Rutter model against measured WCE&Storage from 18-25th September 2018



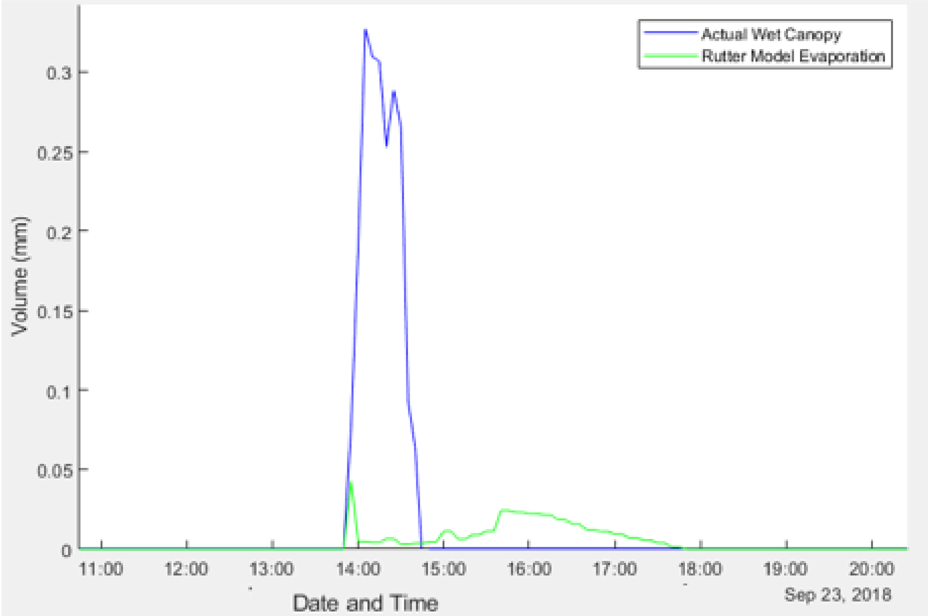
b) WCE from Rutter model against measured WCE&Storage



The Rutter model is delayed compared to measured which shows WCE&storage not just WCE like the model.
Here the evaporation is delayed until the following day when the RF occurs at night



c) WCE from Rutter model against measured WCE&Storage



d) WCE from Rutter model against measured WCE&Storage

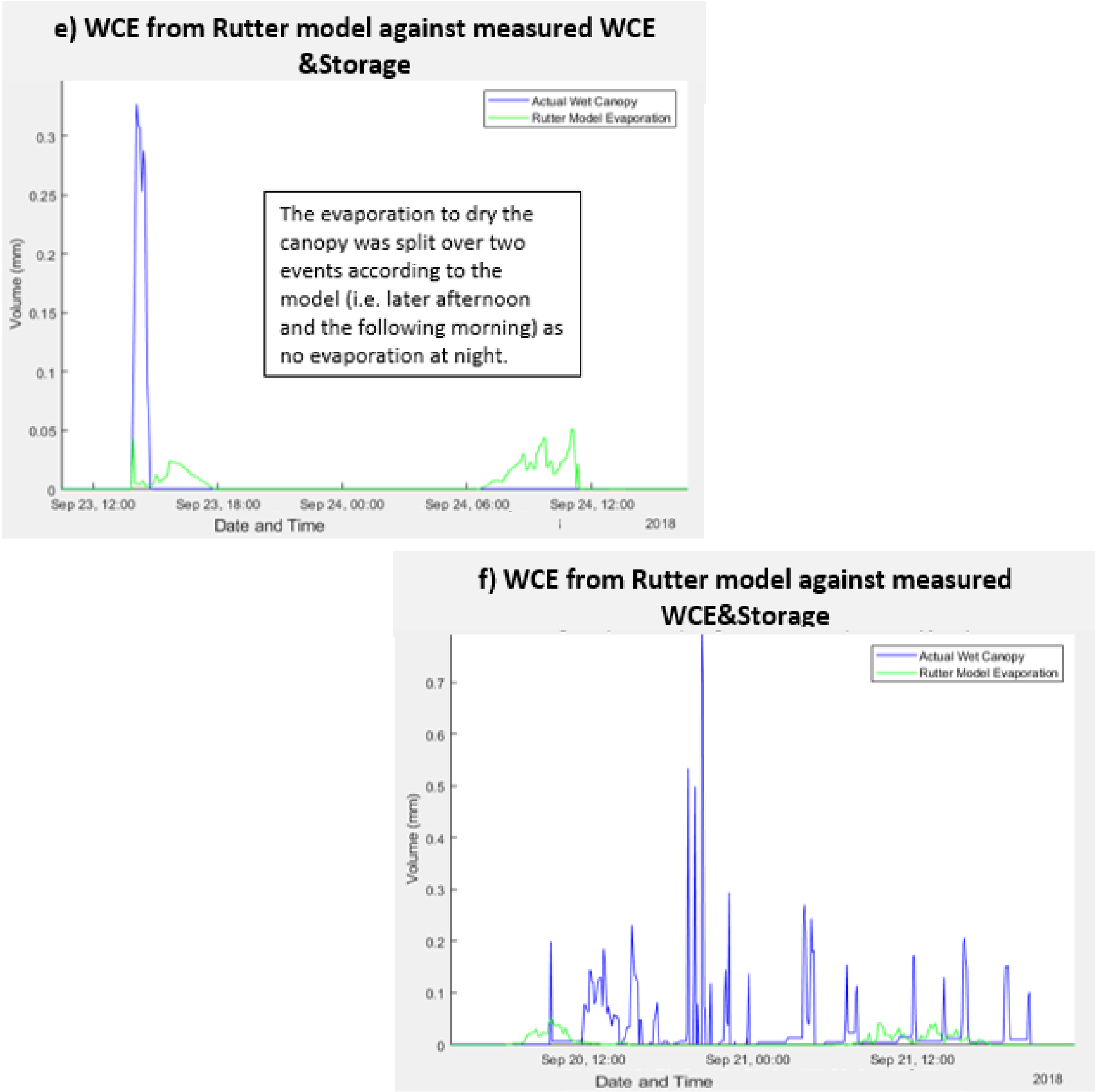


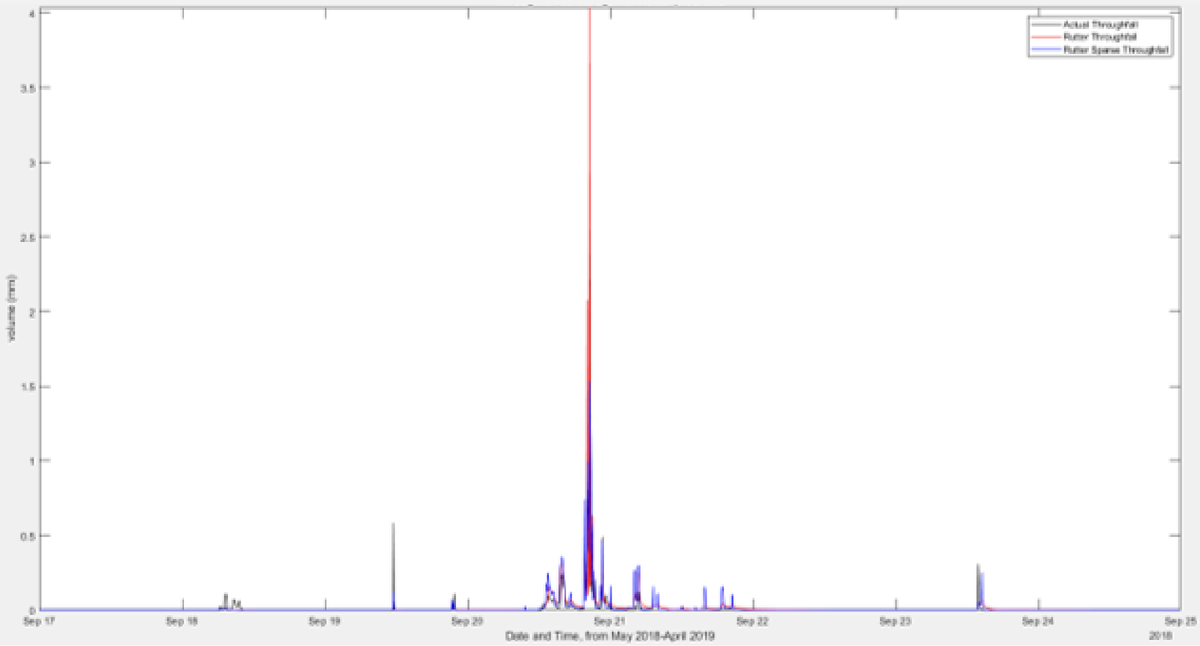
Figure 3-49:Predicted, using the Rutter Model, against actual evaporation (18-25/09/18)

Where negative WCE in the measured WCE&storage is seen, this can be for two reasons: 1 the change in storage at 5-min time-step (

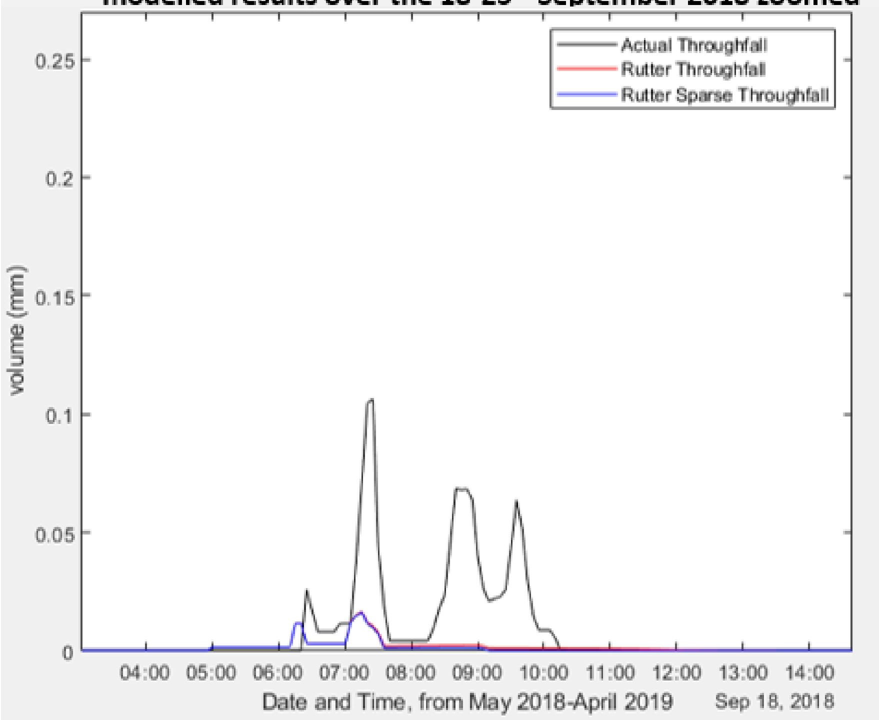
Figure *3-49*) (e.g. winds blowing the canopy and more water falling as drip than rainfall) and 2 the water balance issue from increased collection of rainfall, which if corrected would increase WCE% The model is unable to predict any negative WCE due to how it assumes the canopy drains down. At a longer time period the model is unable to predict the amount of water evaporated as it is massively underestimated, which would be even greater with the water balance issue corrected.

The Rutter model underestimates the throughfall (Figure 3-50) during shorter events, this indicates towards the measured throughfall being higher than that potentially collected per m^2. Rutter also overestimates the throughfall for larger event, which would lead to the underestimation of the WCE for this larger event.

a) Measured throughfall against Rutter (Original and Sparse) modelled results over the 18-25th September 2018



b) Measured throughfall against Rutter (Original and Sparse) modelled results over the 18-25th September 2018 zoomed



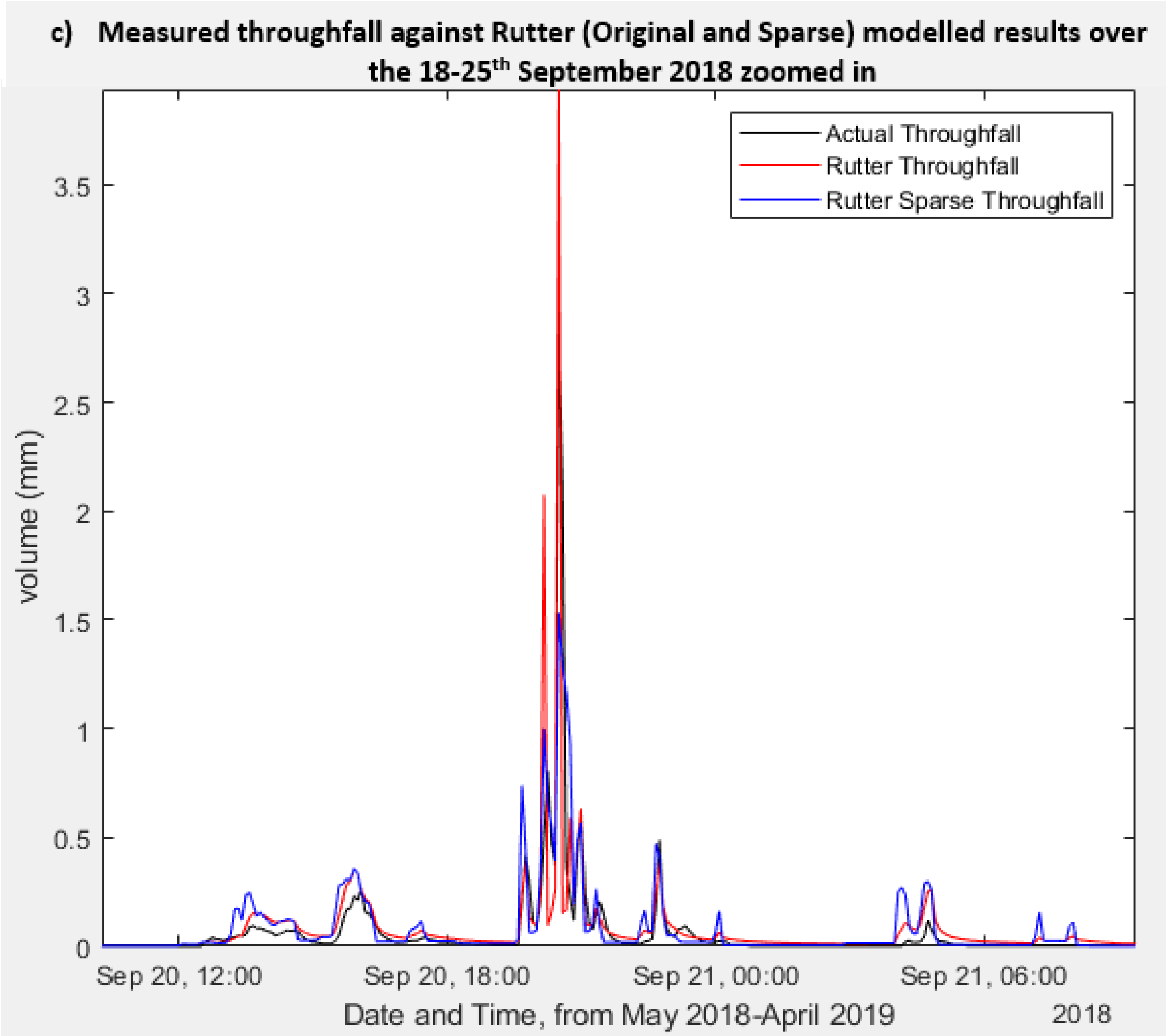


Figure 3-50:Throughfall for Rutter Original and Sparse models against the measured showing that the measured is larger than modelled during the peak but is overestimated in the smaller events.

During winter the original Rutter model holds the water in the canopy longer and above the canopy capacity (S) as the drainage rate is not high enough to drain the canopy quickly (Figure 3-51). When the rainfall gets particularly high the model crashes with C plummeting before returning to being higher. It was also noted that when the canopy store suddenly decreases and increases back during a storm can be linked to where WCE is seen in the measured data to be negative, but this occurs more in larger storms. Therefore, the Rutter Sparse model was used (Valente et al., 1997) as this solved this problem as seen in the graphs in Figure 3-52.

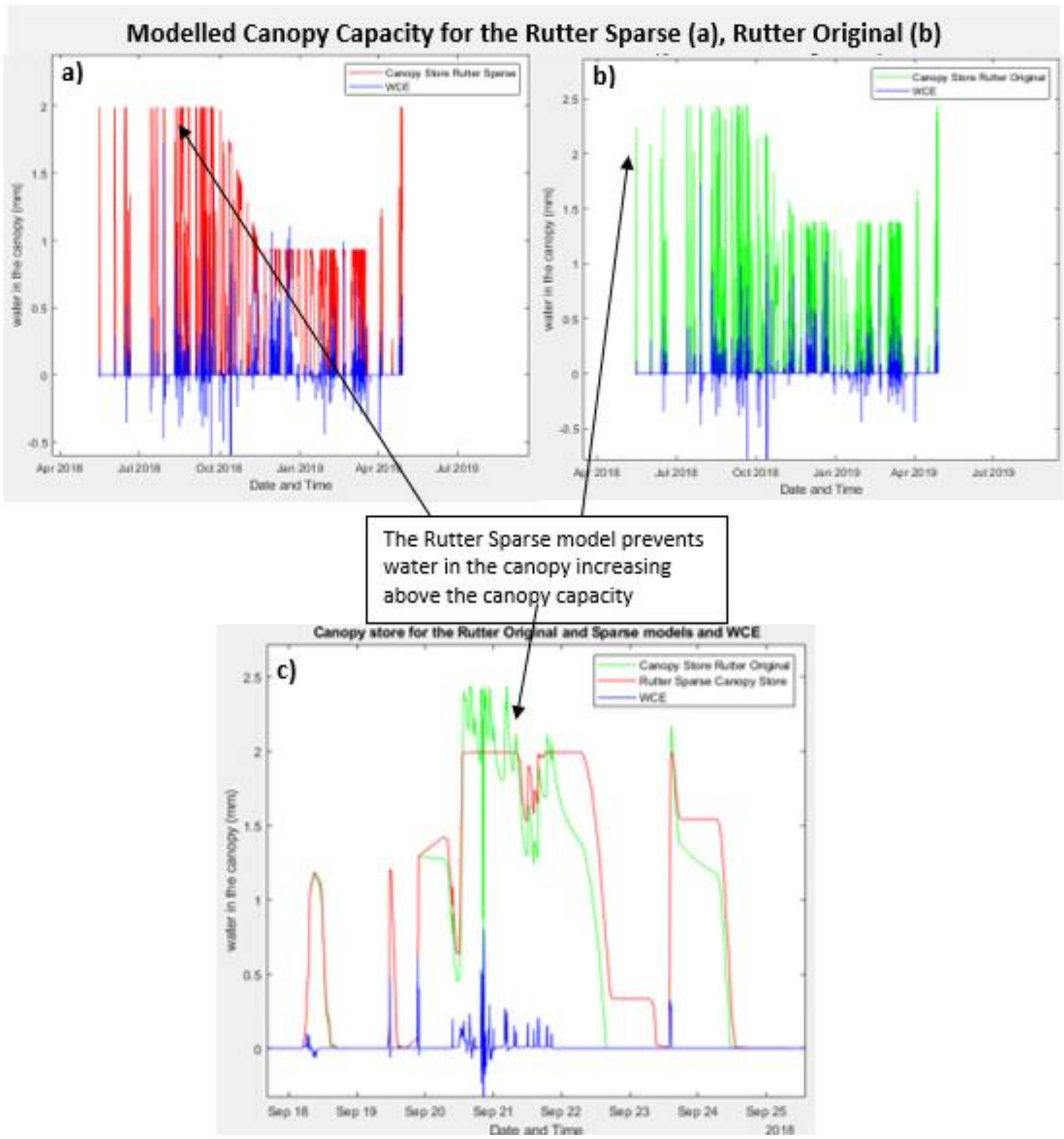
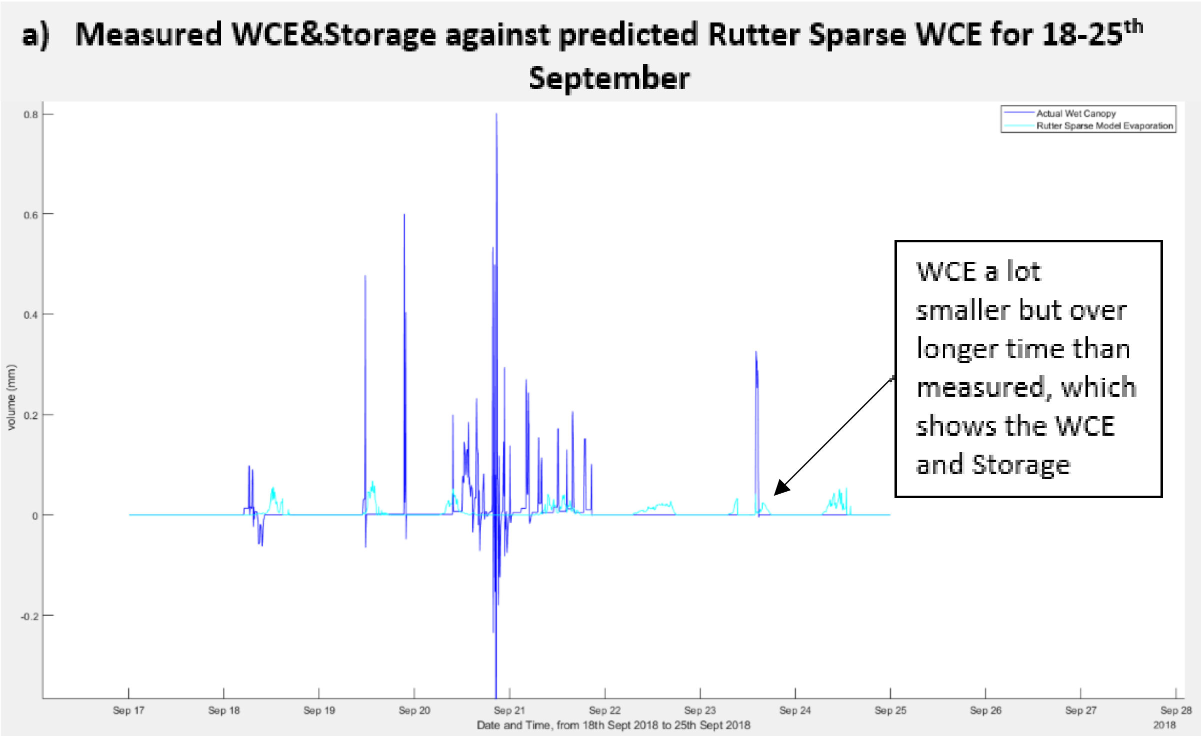
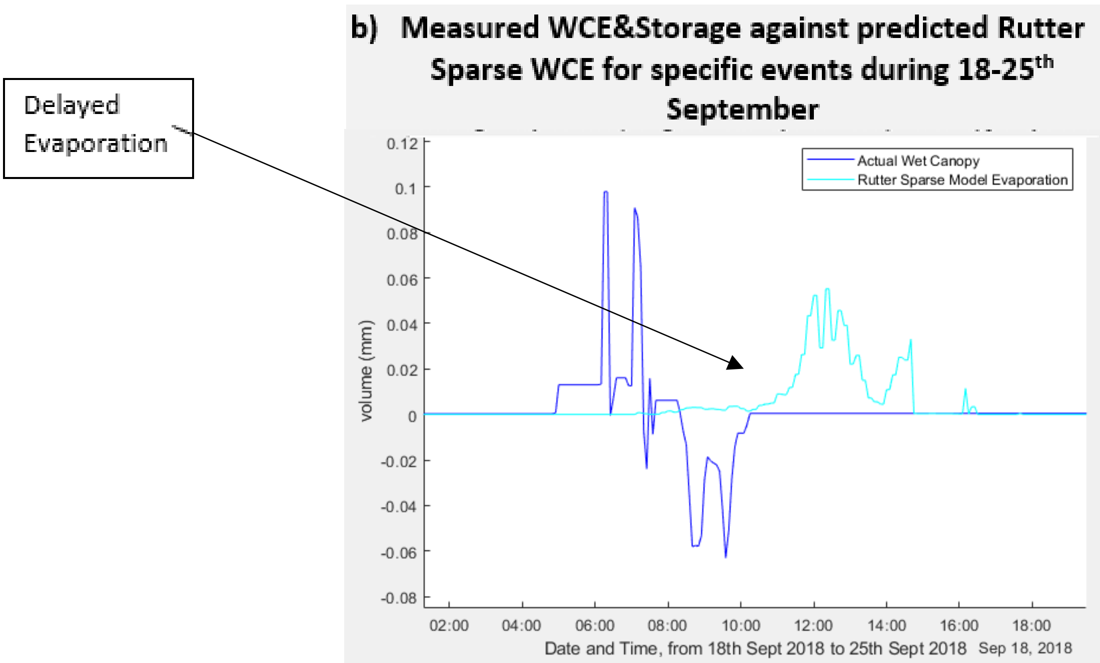
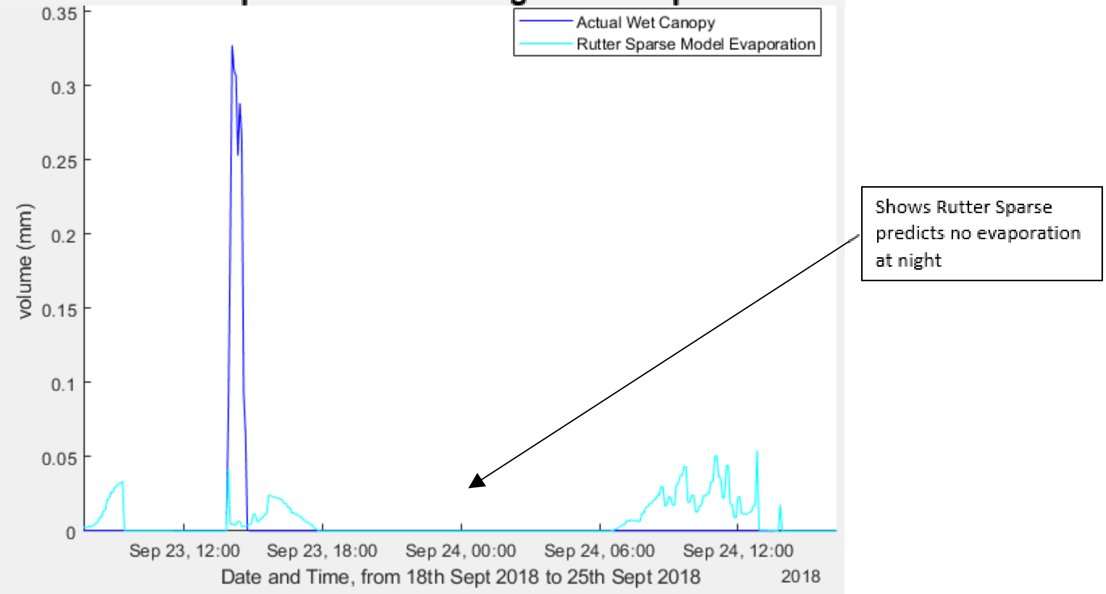


Figure 3-51:Annual canopy store for Rutter Original and Sparse. Shows where C plummets when RF is high and WCE is negative.

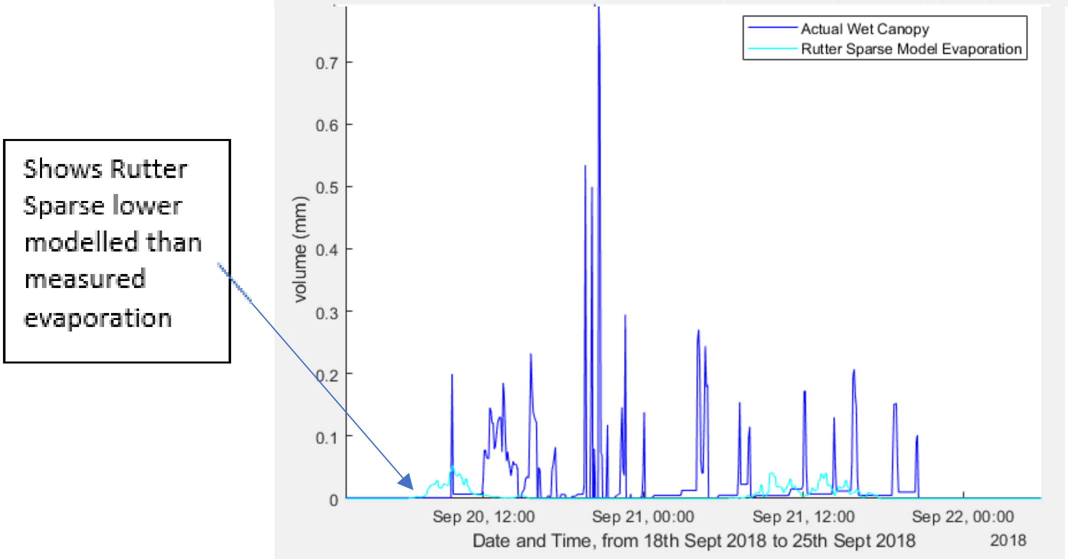

a) Measured WCE&Storage against predicted Rutter Sparse WCE for 18-25th September
Actual Wet Canopy
Rutter Sparse Model Evaporation
WCE a lot smaller but over longer time than measured, which shows the WCE and Storage
volume (mm)
0.8
0.6
0.4
0.2
0
-0.2
Sep 17
Sep 18
Sep 19
Sep 20
Sep 21
Sep 22
Sep 23
Sep 24
Sep 25
Sep 26
Sep 27
Sep 28
2018
Date and Time, from 18th Sept 2018 to 25th Sept 2018


b) Measured WCE&Storage against predicted Rutter Sparse WCE for specific events during 18-25th September
Delayed Evaporation
Actual Wet Canopy
Rutter Sparse Model Evaporation
volume (mm)
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
02:00
04:00
06:00
08:00
10:00
12:00
14:00
16:00
18:00
Date and Time, from 18th Sept 2018 to 25th Sept 2018
Sep 18, 2018

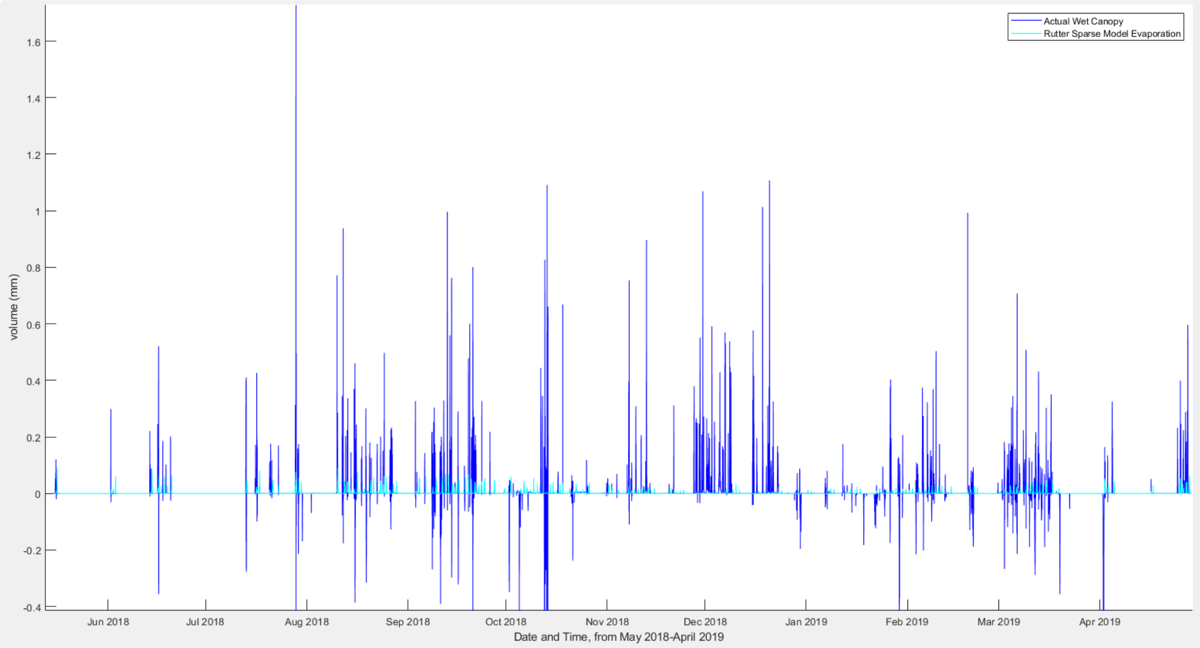
c) Measured WCE&Storage against predicted Rutter Sparse WCE for specific events during 18-25th September



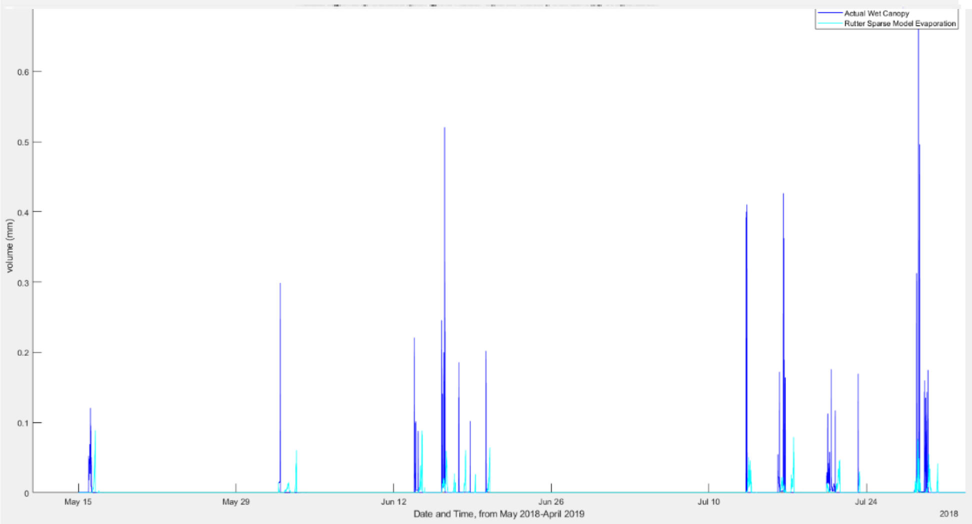
d) Measured WCE&Storage against predicted Rutter Sparse WCE for specific events during 18-25th September

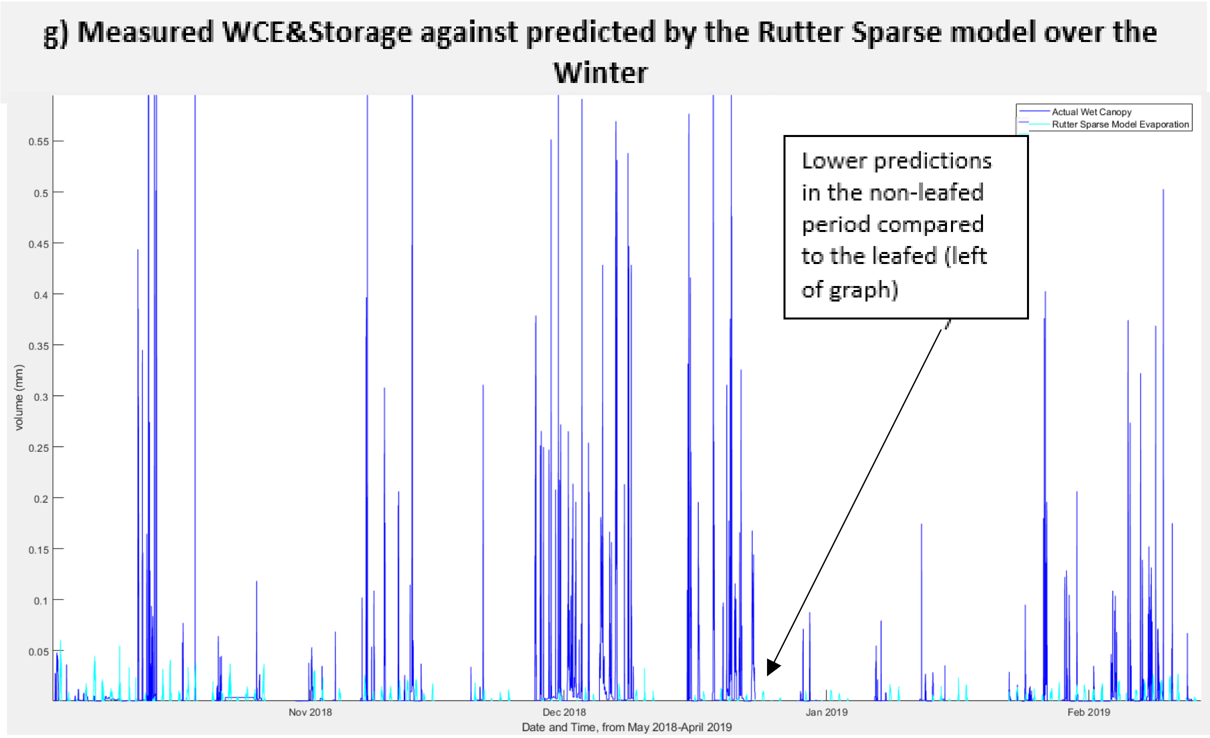


e) Measured WCE&Storage against predicted by the Rutter Sparse model over the year



f) Measured WCE&Storage against predicted by the Rutter Sparse model over the summer





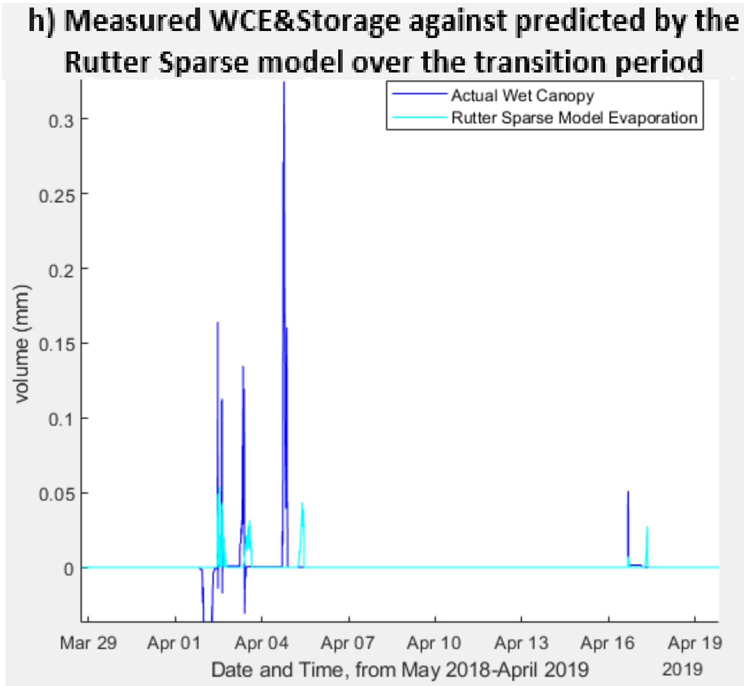


Figure 3-52:Rutter Sparse model graphs

The Rutter Sparse model continues to underestimate the WCE (Figure 3-52 graphs a-h). The Sparse model uses the same principle as the original in predicting the WCE occurs during or after the event depending on the timing (i.e. not at night restarting the next morning) of the rainfall event. However, the processes assumed by the sparse model cannot be solely those at play (i.e. to the wrong magnitudes or others play a larger role in WCE of edge trees) as the WCE is significantly underestimated.

Graph B (Figure 3-52), as well as others, shows that a small amount of negative WCE in the measured WCE&Storage can occur at the end of the event (or even during the event when rainfall decreases). This is due to the method of calculating the WCE&storage in each time step, which does not account for water being left in the canopy at the end of the event and being converted to throughfall via drip particularly when windy. This produces a higher throughfall than rainfall (after the rainfall has decreased/stopped) leading to a negative WCE. This is not the same as the overall negative WCE&Storage measured for some events due to the water balance error.

The Sparse WCE is better at predicting the measured WCE&Storage in the summer than winter.

The Canopy Capacity in the Rutter sparse is capped at different values for leafed and non-leafed and assumes the transition is linearly decreased between values (Figure 4.13). C also takes longer to drain in the Rutter Sparse than Original.

The throughfall of the Rutter Sparse is underestimated for smaller and largest events and overestimates for medium events (Figure 3-50). Over the 18-25.09.18 period TF is overestimated by the Rutter Original (28.4mm) and Rutter Sparse (26.2mm) to the measured (21.0mm)

3.7.2.5 What it shows

Below are graphs of the measured WCE with the predicted evaporation from Penman, Rutter and Rutter Sparse. The graphs (

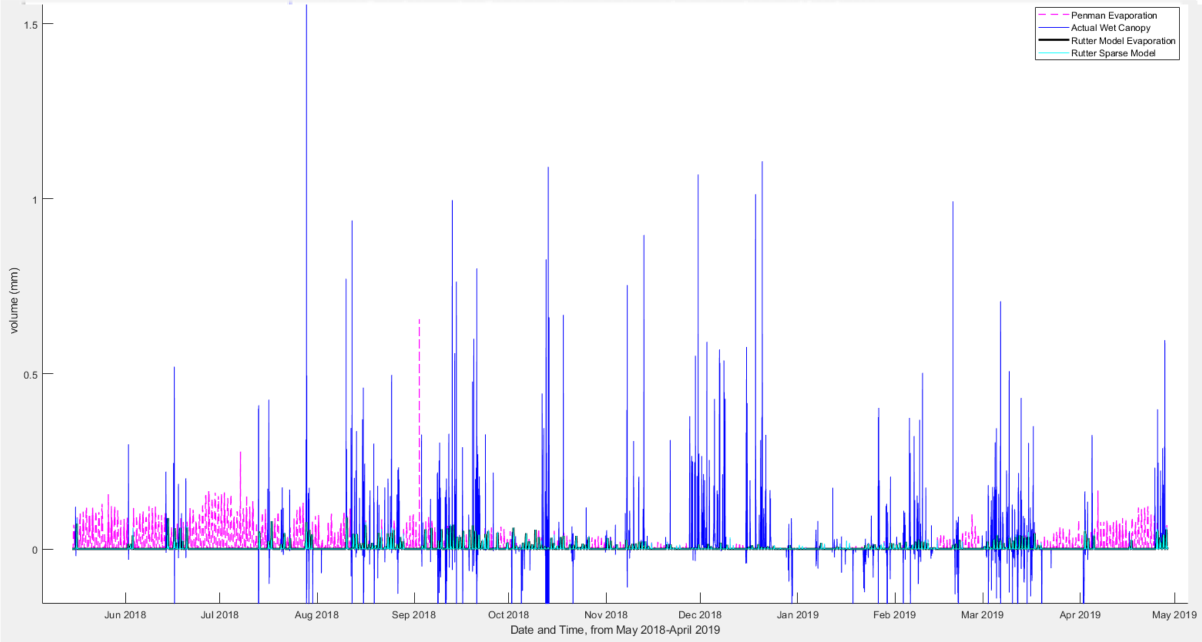
Figure 3-54-Figure 3-55) show that the Rutter models are better (although still poor) at predicting the summer events especially during the warmer weather. The models throughout the year are better at modelling the small events and poorer at modelling the medium or large events. Winter events are very poorly modelled with the modelling ability improving during the transitional period when the weather improves. The models only predict evaporation occurs in the day so it can start evaporating during a daytime event or the following day if the event is at night. The model evaporation can extend to several days in some events. The graphs also show a longer time to evaporate the canopy water than the measured WCE&Stoarge, which shows storage.

The models are unable to model negative WCE events (Figure 3-55) as the models cannot account for the water balance issue. If the water balance was corrected the WCE would be higher meaning the overall WCE predicted by both the Rutter models would be further underestimated.

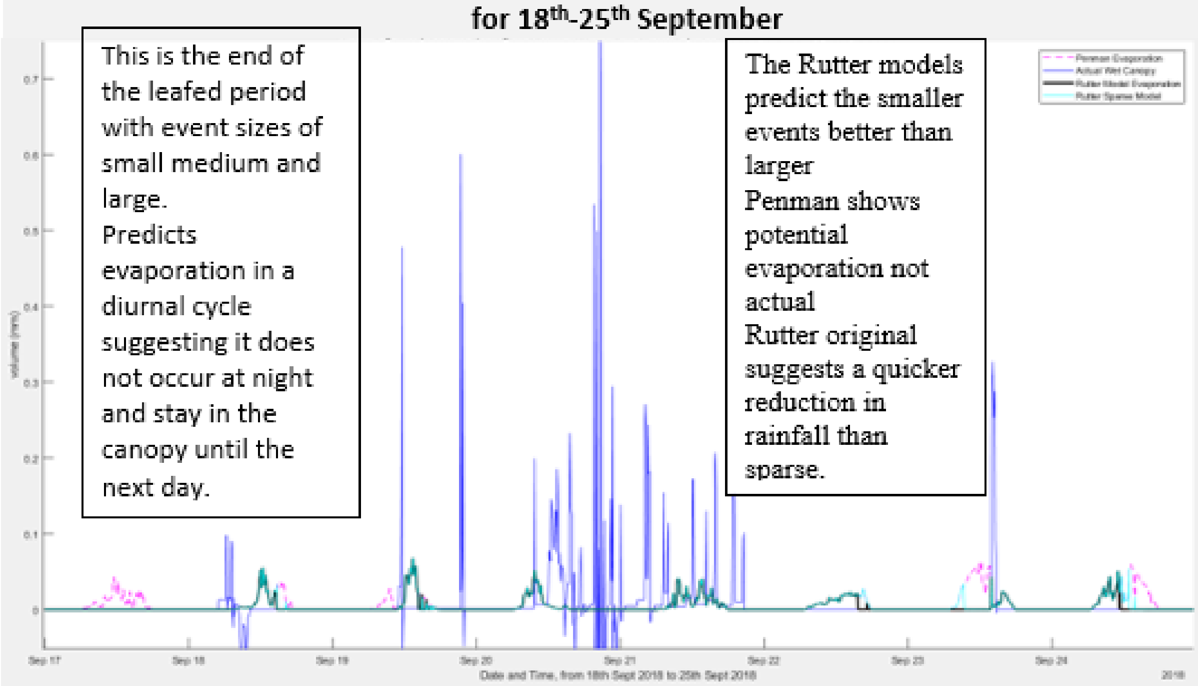
Penman (

Figure 3-54) shows the potential evaporation if the canopy was always wet, whereas the Rutter models show modelled evaporation The Rutter original and sparse are very similar except the canopy capacity is limited prolonging the evaporation in the Rutter Sparse.

a) **The measured WCE&Storage against the Penman, Rutter Original and Rutter Sparse models for the year**



b) **The measured WCE against the Penman, Rutter Original and Rutter Sparse models for 18th-25th September**



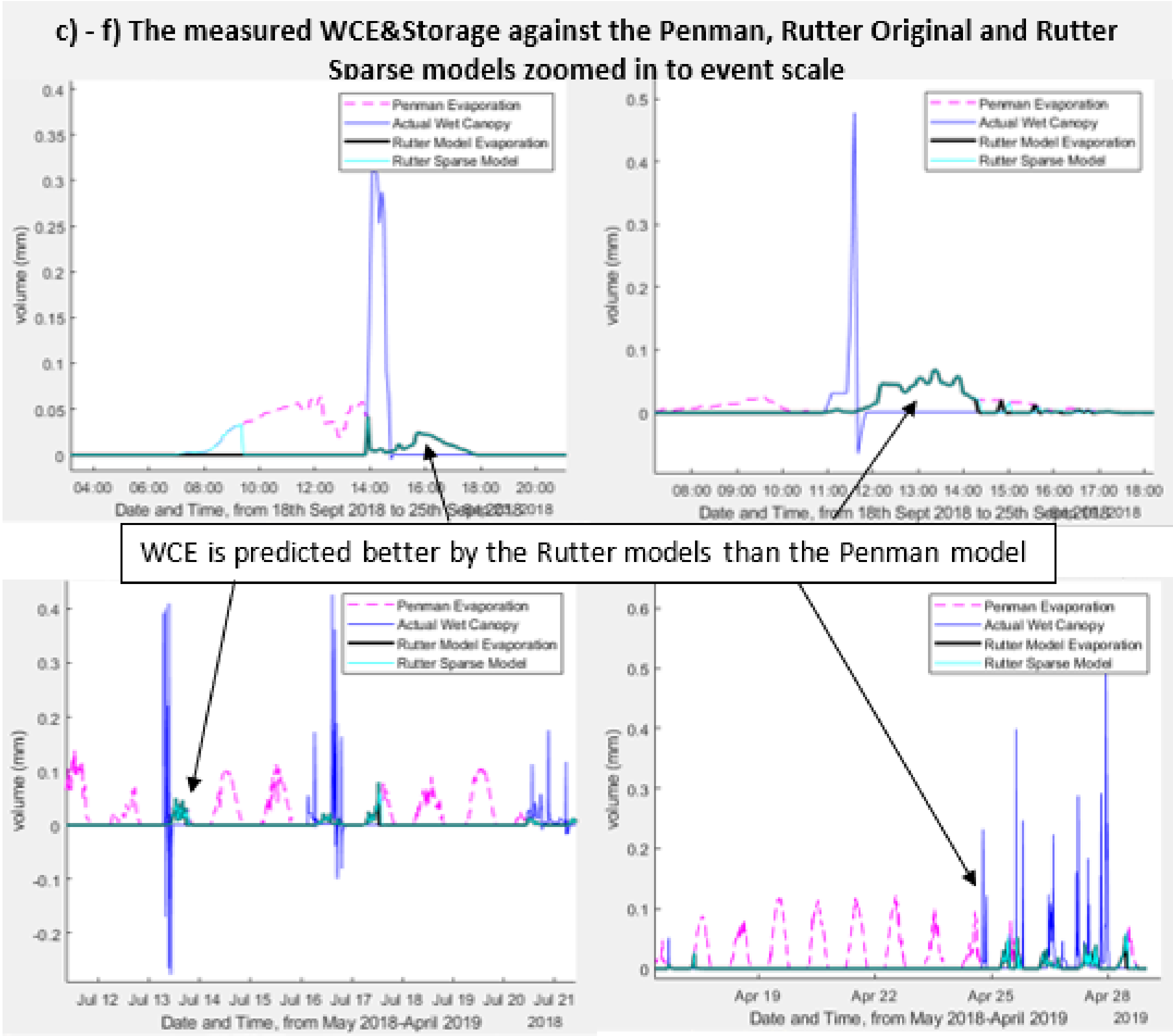
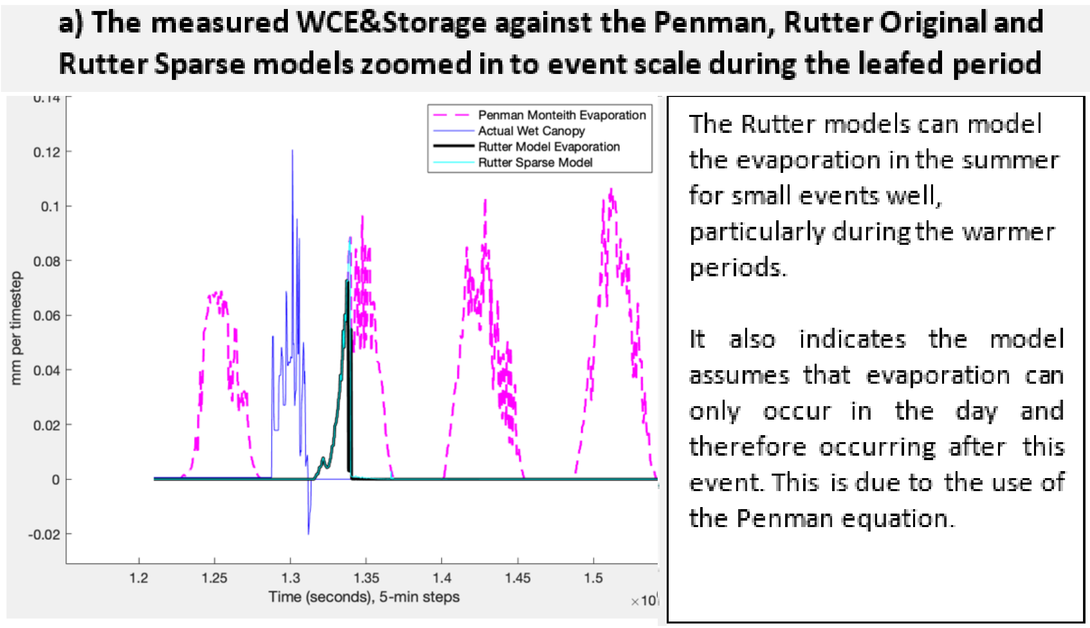
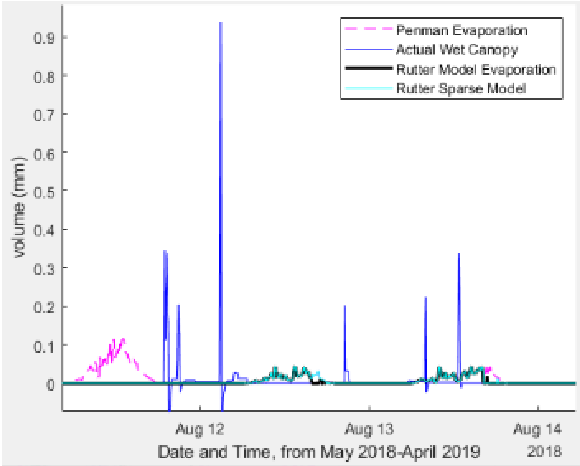
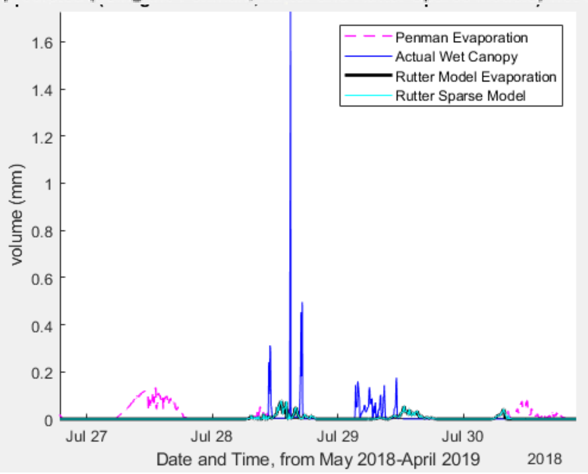


Figure 3-53:measured against predicted evaporation using the Penman, Rutter Original, and Rutter Sparse models



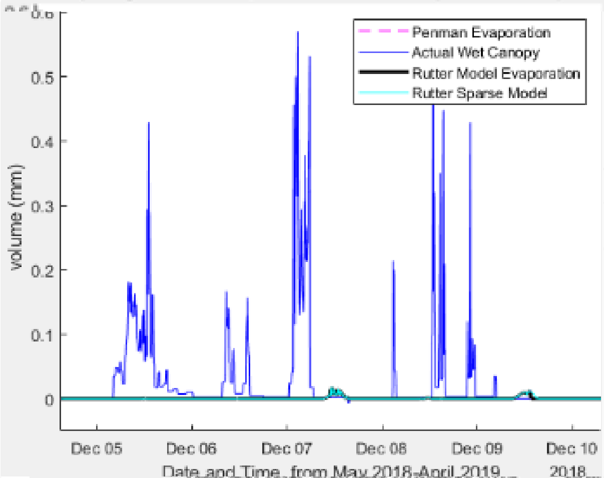
b) and c) The measured WCE&Storage against the Penman, Rutter Original and Rutter Sparse models zoomed in to event scale during the summer period

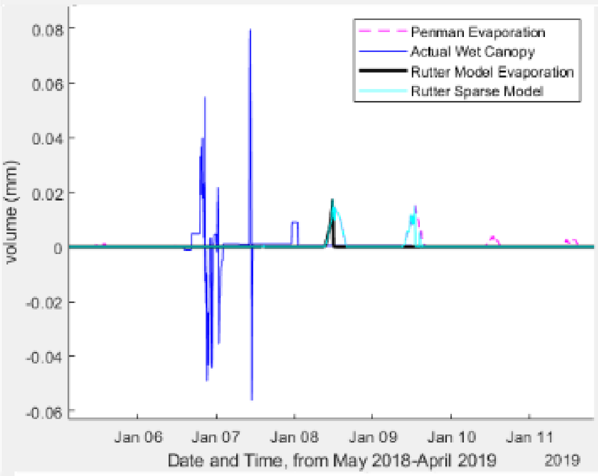




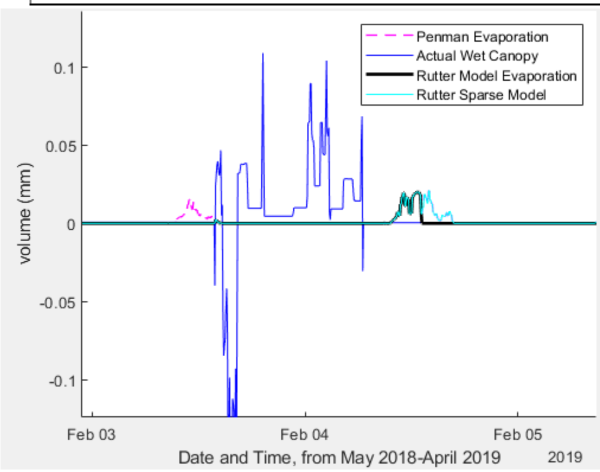
The models struggle to predict volume in the summer for medium or large events. These show that where rainfall occurs during the day the model will allow evaporation during the event.

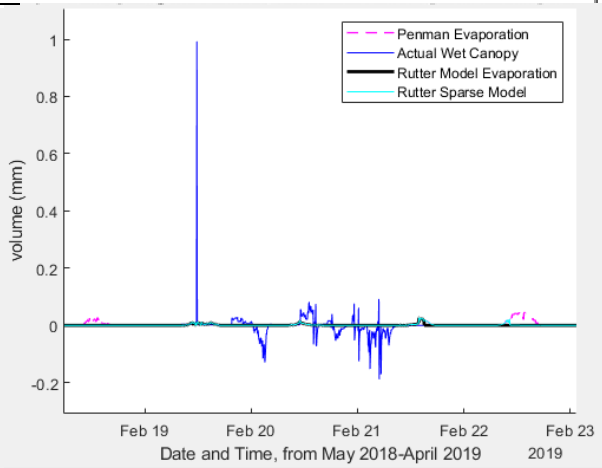
d) - g) The measured WCE&Storage against the Penman, Rutter Original and Rutter Sparse models zoomed in to event scale during the winter period



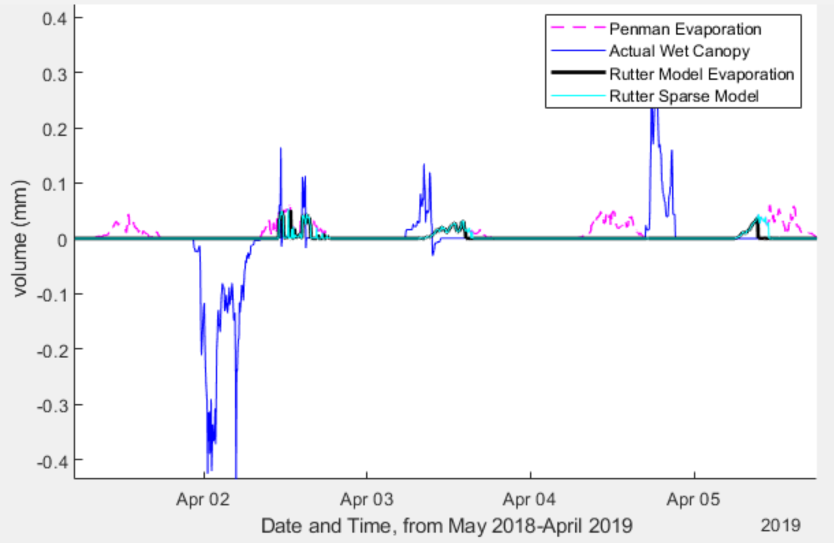


It has been shown that there is a poorer fit in the winter (non-leafed period) with an even larger underestimation. Some events taking several days to dry out.





h) The measured WCE&Storage against the Penman, Rutter Original and Rutter Sparse models zoomed in to event scale during the transition period



The transitional (leafed to non-leafed) period shows an improvement in modelling on the non-leafed period. It also provides better modelling of smaller than medium or large events.

i) The measured WCE&Storage against the Penman, Rutter Original and Rutter Sparse models zoomed in to event scale during the summer period

It shows that even in summer the models indicate a longer time to evaporate the water in the canopy as the measured shows storage as well as evaporation. This is summer 2019 and also shows a similar prediction to summer 2018 i.e. they model the smaller events better than medium or larger events.

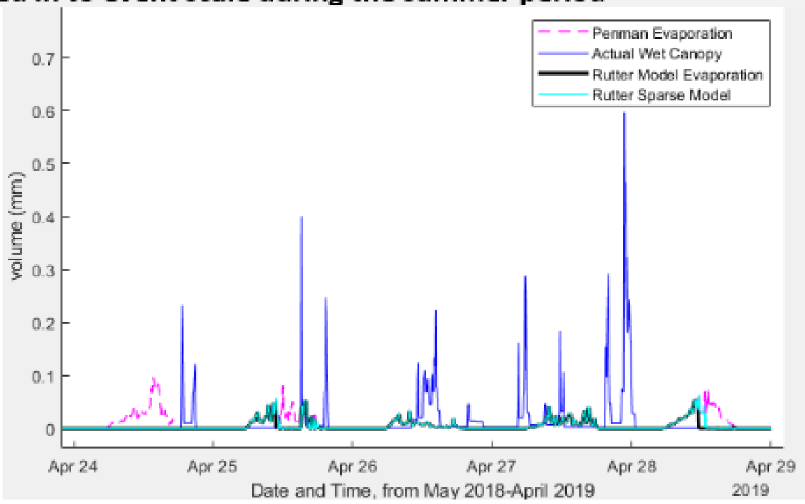
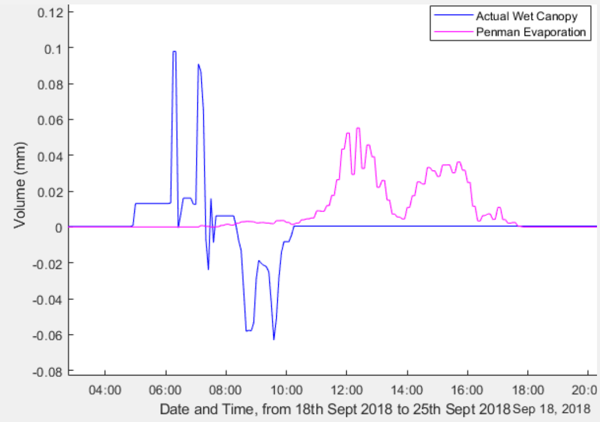
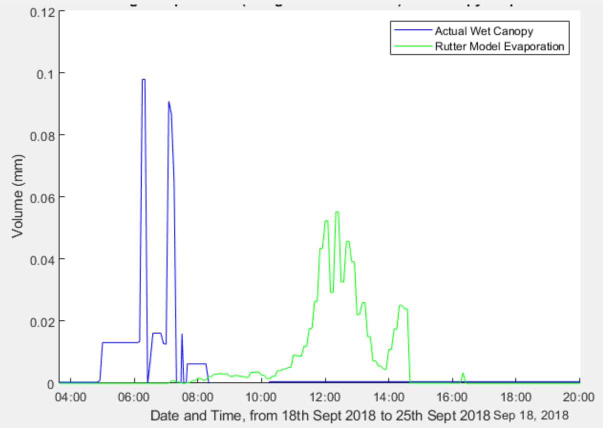
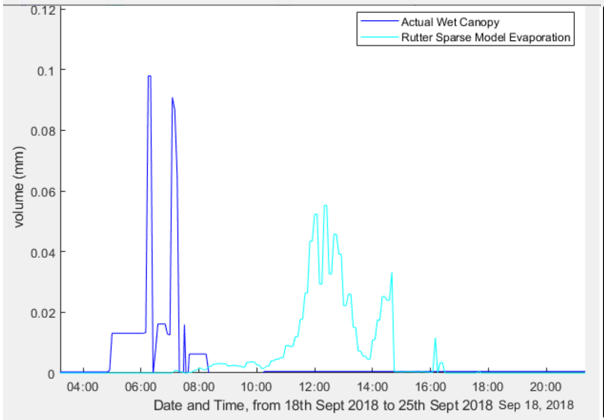


Figure 3-54:How well the models fit the leafed, non-leafed and transitional periods

a) The measured WCE&Storage against the Penman, Rutter Original and Rutter Sparse models zoomed in to event scale for small events

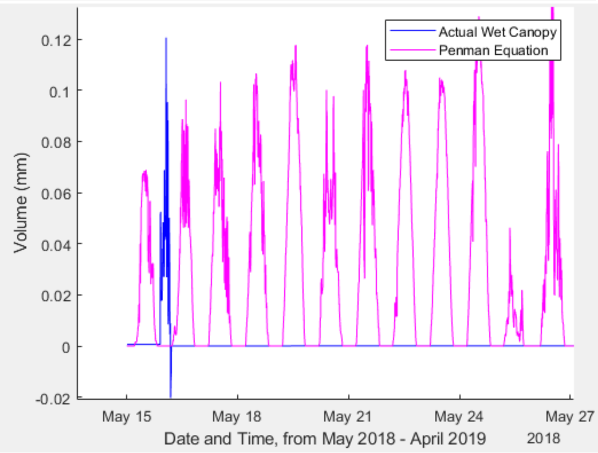


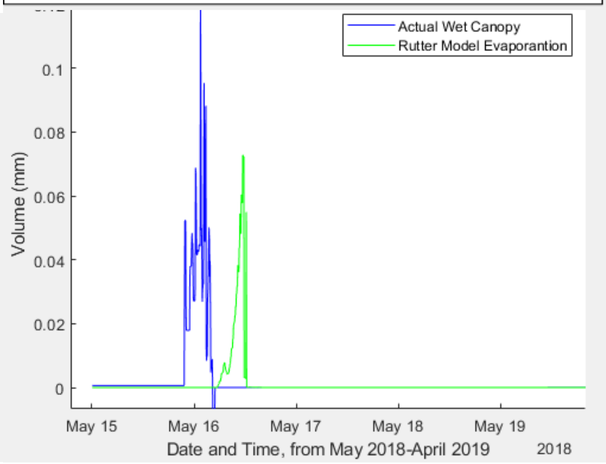


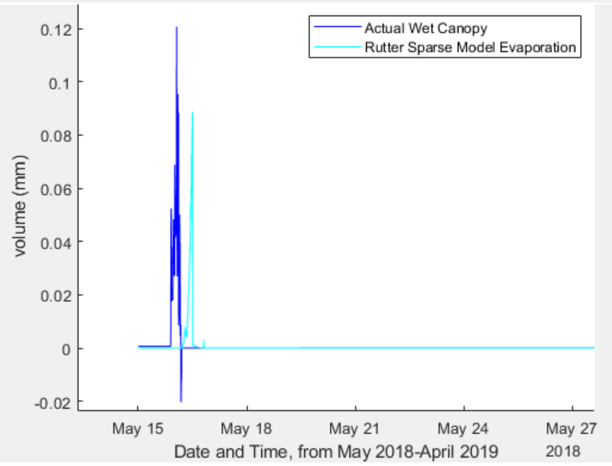


This shows an example of a small event which models match well. It can be seen the models delay the evaporation until the daytime when the event occurs at night or can start evaporation fairly quickly when the event occurs during the day.

It shows the Rutter original (green) predicts faster evaporation than the Rutter Sparse (blue).







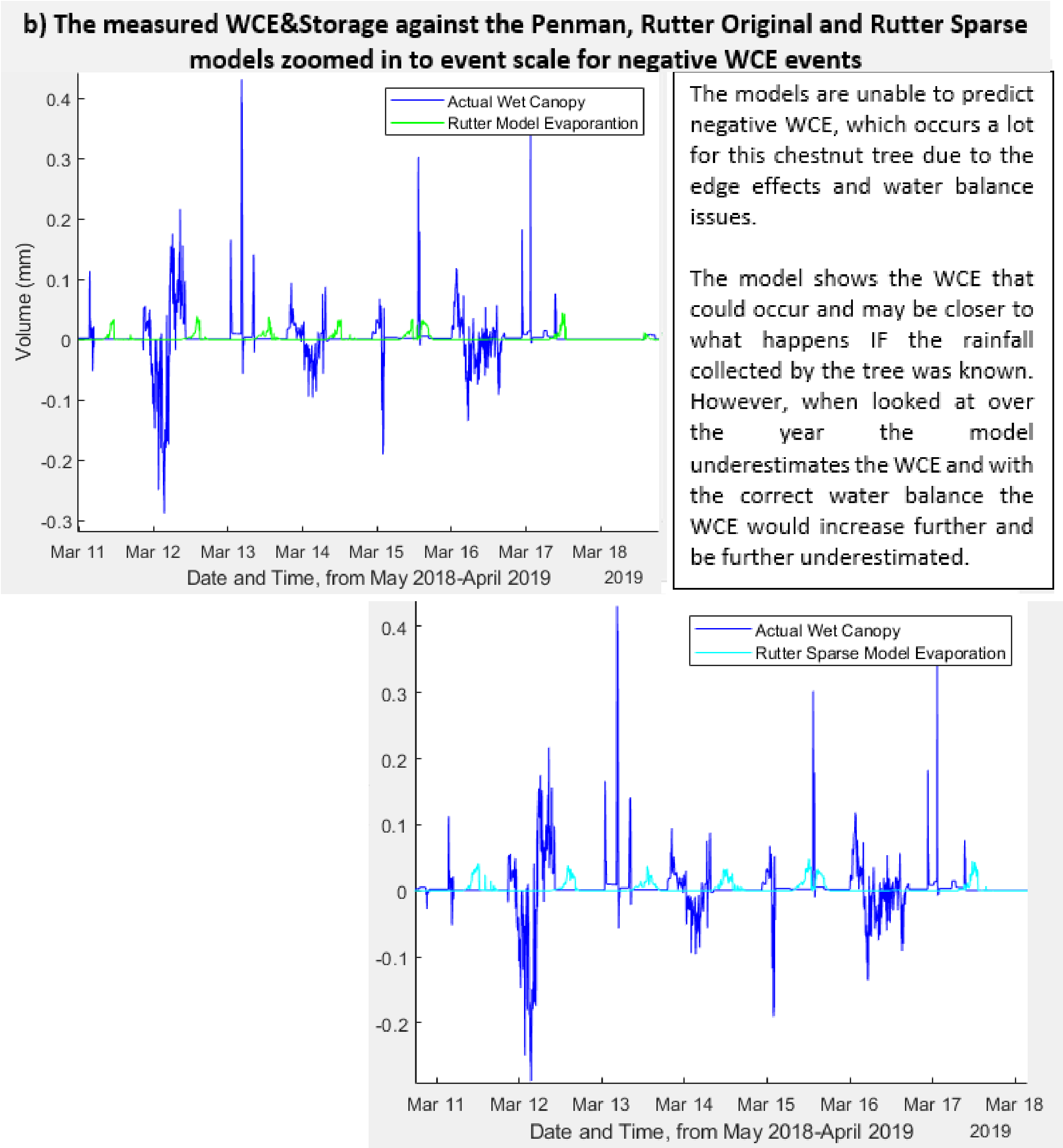


Figure 3-55:Model graphs according to small and negative events

Neither Penman, Rutter nor Rutter Sparse (with their original parameters **Error! Reference source not found.** and) predict the annual volume of evaporation well (Figure 3-56). The measured evaporation (291.18mm/year or 37.68% of rainfall) is on the lower end of that expected (240-360mm/year according to Water and Climate Change, 2020) but would be higher if the true rainfall collected was known. Penman produced a similar volume in the week commencing 18-25th September suggesting the week is near evaporation capacity. Penman over-estimates evaporation for the year, as it predicts potential evaporation so is predicting potential evaporation when the canopy is dry and unable to evaporate water. The Rutter and Rutter sparse underestimates the measured evaporation by >50%, with the Rutter Sparse being 10% closer to modelling the measured evaporation. During the non-leafed and transition periods the modelled evaporation is much lower.

All models show that evaporation relative to rainfall is significant regardless of the model and throughout the year. The models are much more capable at predicting the WCE for the summer. However, the models are poor at predicting the non-leafed WCE (Figure 3-57**Error! Reference source not found.**).

Error! Reference source not found. separates the temperature, wind speed and direction for the non-leafed and leafed periods. It shows that the prevailing wind direction is SSW and hence the open canopy. As expected, the temperature is lower during the non-leafed period than leafed and negative WCE temperature lies within this range as includes both summer and winter events. The wind speed is higher during the non-leafed than the leafed period which could have aided the high WCE due to ventilation of the tree. Figure 3-57 shows the Rutter Sparse is better able to predict the WCE than the Rutter Original or Penman although it is still poor.

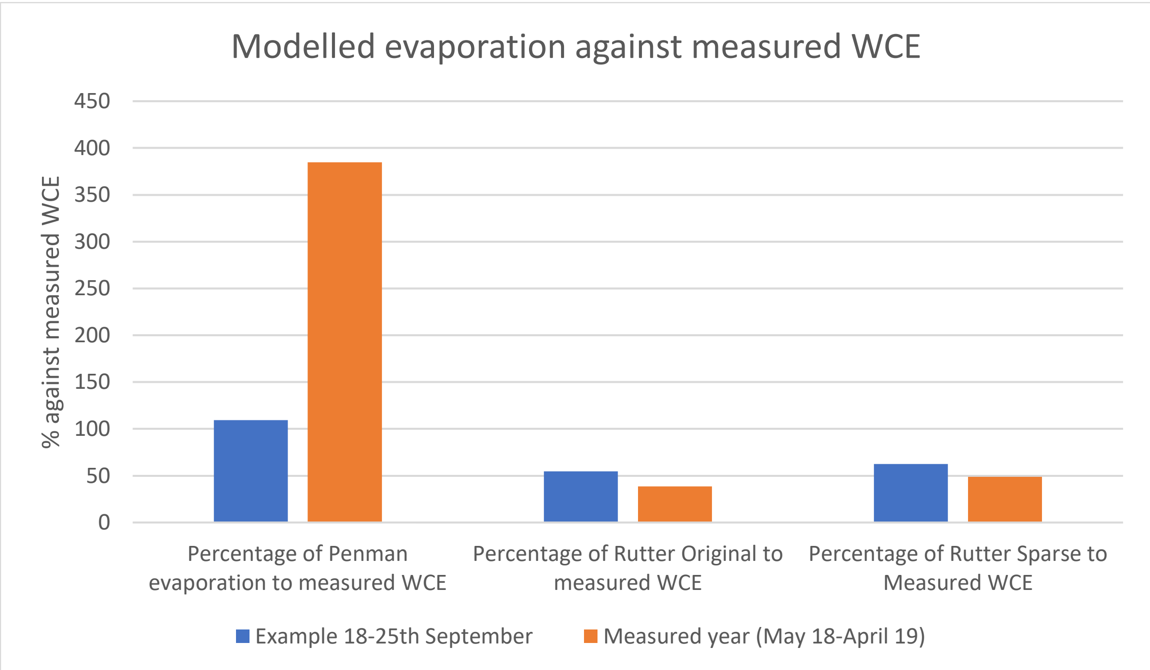


Figure 3-56:Modelled evaporation against measured WCE

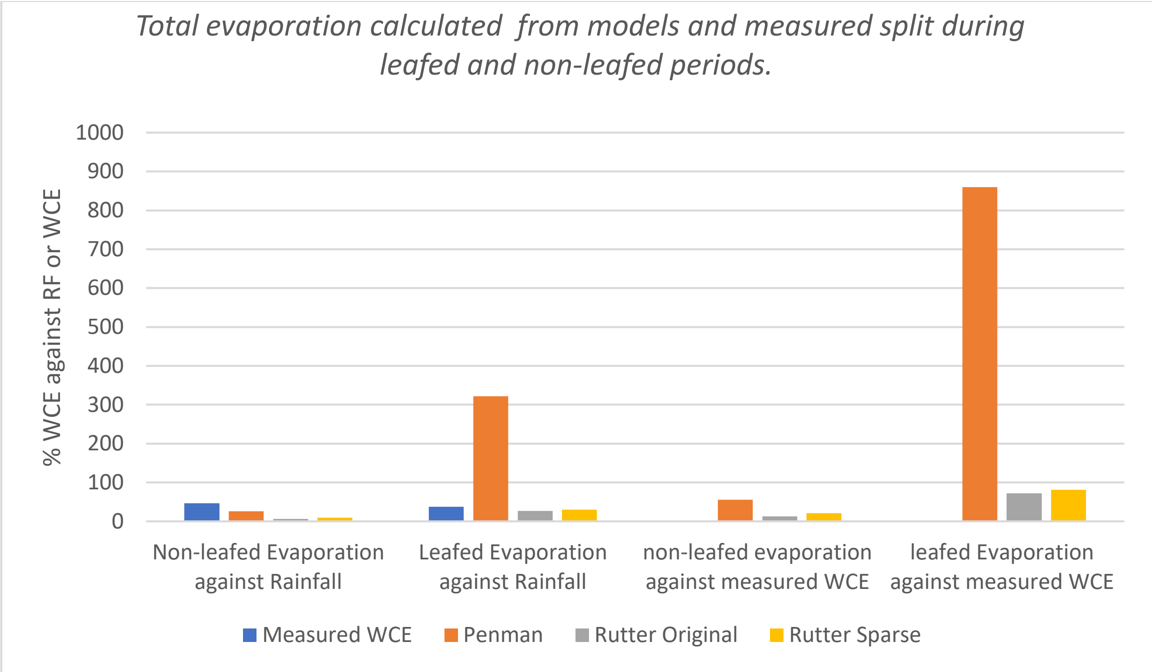


Figure 3-57:Total evaporation calculated from models and measured split during leafed and non-leafed periods.

3.7.2.6 Sensitivity Analysis

When altering the parameters, the best fit to the total volume of measured evaporation in both the Rutter original and Rutter Sparse can be achieved by altering the S (canopy capacity) and p (throughfall coefficient). Altering the canopy capacity increases the store within the trees canopy, however, this was originally calculated using the actual data from events more than 1.5mm. The throughfall coefficient alters the rainfall converted to TF and was also calculated from this data for those events less than 1mm; Therefore, altering these values may mean they are less able to be replicated elsewhere. This indicates other processes could be involved and requiring other processes to be modelled with dependence on other conditions e.g. horizontal rainfall when wind direction is towards the open canopy and wind speed above a set value.

It was found altering b and Ds had little effect once S and p had been made larger, although did improve the fit while S and p were at their original values (see ***Error! Reference source not found.*** *and*). When:

- S is increased the evaporation increases,
- Ds is decreased to increase WCE,
- p is decreased to increase WCE,
- b is increased to increase evaporation until it reaches 14.

The 'best fit' is when the Rutter models parameters are logically altered to allow the model to have the closest fit to the measured data. The best fit was gained by increasing the canopy capacity (S) and decreasing the throughfall (p) for the year to allow the canopy to hold and evaporate more rainfall. Although these original values came from the data the model was underestimating the volume of water in the canopy. Other combinations could also produce this best fit total for evaporation as seen in **Error! Reference source not found.**, for example increasing the drainage coefficient up until 14 and decreasing the drainage rate increases the water in the canopy and hence increasing WCE.

shows that the annual best fit (although using a different S value than for the period 18-25th September) provides the best modelling of the overall WCE using 2 different S values for the leafed and non-leafed period. The best fit S can be seen to vary through the year (ie different for 18-25th September than annual), which has different weather conditions leading to requiring different parameters under leafed/non-leafed conditions.

Both models produce the same total evaporation during the 18-25th September. However, the Sparse model has the ability to produce a better fit over the whole year than Rutter Original model.

The models predict more evaporation but still predicts this will only occur during the day due to the processes the Penman assumes (Figure 3-59).

Table 3-7: Variables that can be altered within the Rutter models and their best fit (in bold)

	Original	Best fit for period 18-25th Sept	Other combinations	Annual Best fit
Rutter Original				
S–Canopy Capacity (mm) Calculated from measured data according to Gash and Morton (1978) method.	2.0048	7	7	**12.8 summer and 10 winter**
p–Throughfall Coefficient Originally calculated from measured data	0.1183	0.001	0.001	**0.001**
Ds – Drainage Rate (mm) Originally calculated by Rutter (1971) and used by Rutter (1975) and Gash and Morton (1978)	0.0038	0.0038	0.001	0.0038
b-drainage coefficient Varied between 3-4.6 in Gash and Morton (1978) therefore took a middle value as the range made little difference in the outcome	3.4	3.4	7	3.4
Rutter Sparse				
S–Canopy Capacity (mm)	2.0048	7	-	**12.8 summer and 10 winter**
p–Throughfall Coefficient	0.1183	0.001	-	**0.001**

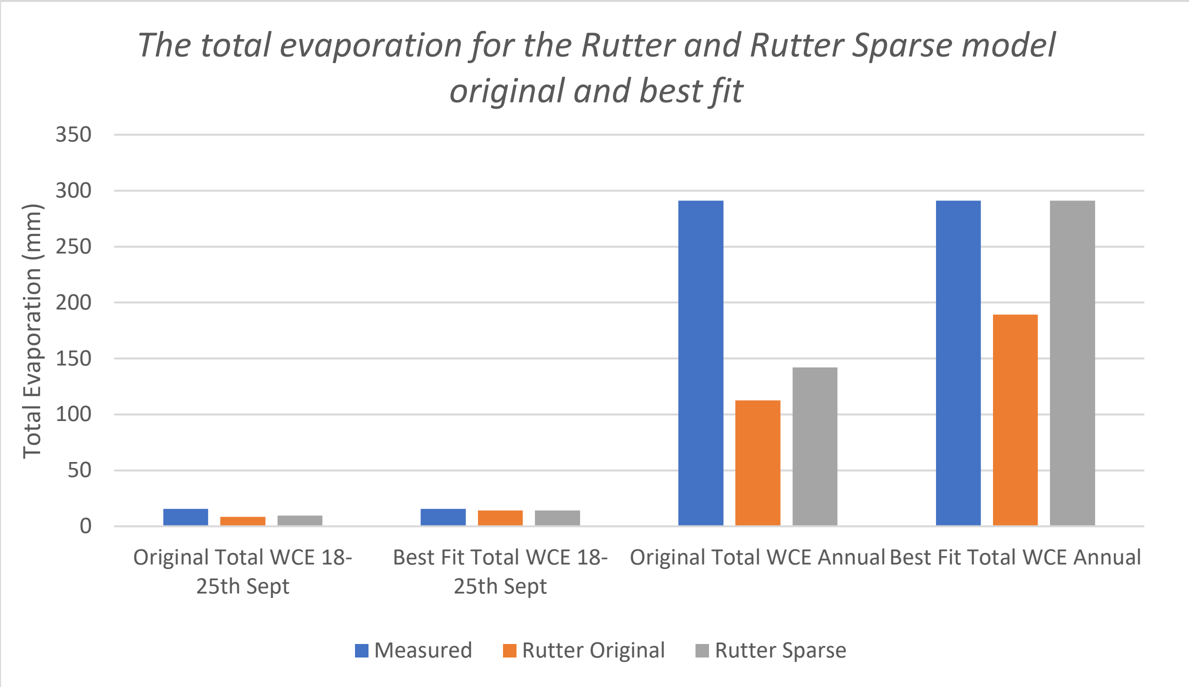


Figure 3-58: Total evaporation for the Rutter Original and Sparse model were altered to the Annual best fit values

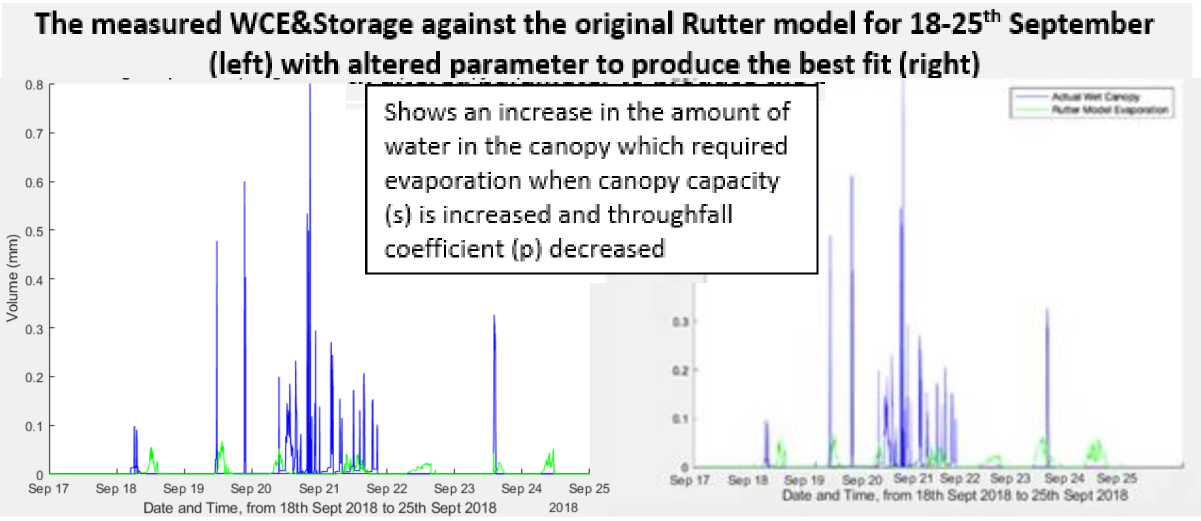


Figure 3-59: Original Rutter model (18-25/09/18) and altered parameters to produce a better fit to the total

A further option is to look initially at the Penman equation where the aerodynamic resistance was altered to the same for all time-steps. Page (2019) research into the aerodynamic resistance, which suggests an Ra value below 6 and particularly below 2 increases the potential evaporation substantially (Figure 3-60). This was also the case for this study where a value of around 5s/m (as expected for a woodland) was used instead of the model's aerodynamic resistance calculated from Hazelrigg weather station wind speed data per time-step. The Hazelrigg data had an average aerodynamic resistance of 5.4s/m. It was as low as 1.12s/m but with some much higher values; the data has a positive skew with a median of 3.6s/m. This provided an evaporation near to the measured with the original Rutter slightly underestimating and Rutter Sparse slightly overestimating. This is more in line with other papers results suggesting the aerodynamic resistance could be different to that the model predicts.

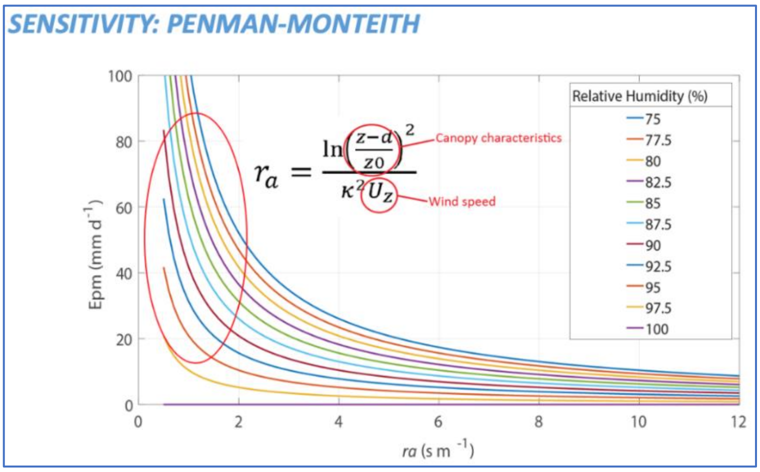


Figure 3-60:Sensitivity of the Penman evaporation to aerodynamic resistance (Ra) relating to humidity (Page, 2019)

As it was found that the true rainfall captured by the tree was larger than that measured,

Figure 3-61 shows an increase in rainfall to account for the horizontal rainfall. This shows that if the true rainfall was known the models would be less able to model the measured WCE.

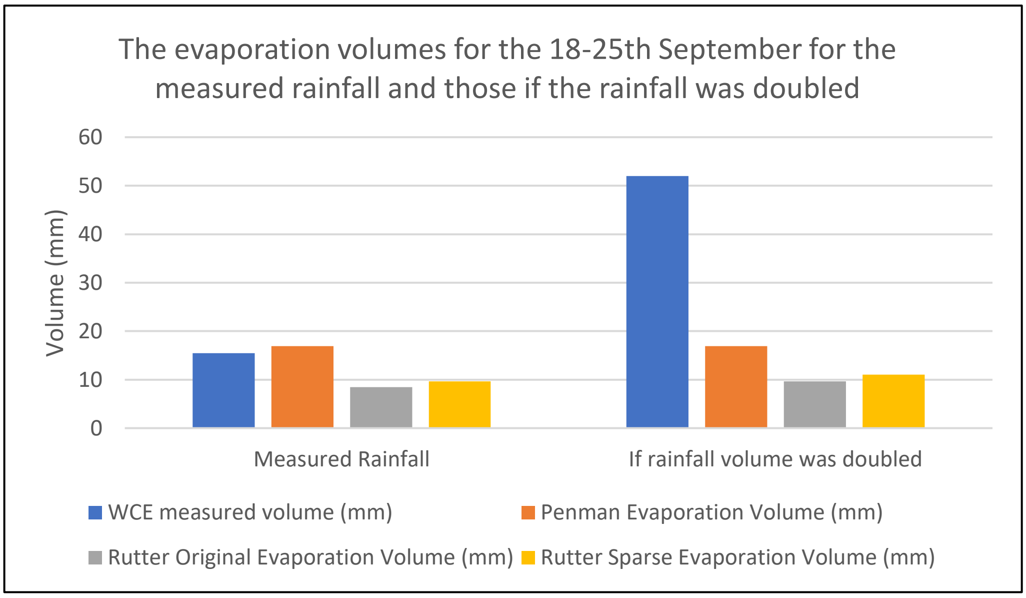


Figure 3-61:Total evaporation volumes of the measured and modelled WCE of the (18-25/09/18)

4 Discussion

4.1 Measured data

4.1.1 How does my data compare to that in literature

Stemflow:

A synthesis and analysis of data undertaken by Magliano et al. (2019) agreed that the stemflow is a small percentage of rainfall. Stemflow has been found to vary from 1 (Hewlett and Nutter, 1982 and Sinun et al., 1982) to 20% (Kirby et al., 1991 and Jones, 1997) with the majority suggesting stemflow is on the smaller end of this. Stemflow exponentially increases from 0-15% as storm event size increases (Magliano et al., 2019). Temperate deciduous forests generally have a stemflow of 3-6% (Price and Carlyle-Moses, 2003) that is the same as that found for all the trees of 3.65% (with rainfall correction), which is lower due to the Chestnut tree’s low percentage. Those with edge effects vary from 1-16% (Klassen et al., 1996 and Neal, 1993), which the stemflow of these trees lie within.

Stemflow is generally higher in the non-leafed than the leafed period () agreeing with Levia and Germer (2015), which has been seen for the Oak and Beech trees. However, the Chestnut tree’s stemflow is higher in the leafed period. As the Chestnuts stemflow was different from the other trees it suggests that the tree structure (not meteorology) is the reason for this. Unlike the other trees which have their branches pointing down into the trunk, the Chestnut does not, with large branches pointing towards the ground and a much larger and denser canopy area with larger leaves, suggesting that when leaves are present the tree is able to capture and funnel more water towards the trees stem ensuring the roots have enough water. In the non-leafed period less water is captured and falls directly as throughfall. Although the volume is a lot smaller the difference is not caused solely by the uncertainty in data collection.

Throughfall:

Throughfall values have been found by Magliano et al. (2019) to increase from 60-80% as rainfall increased in arid environments. This same pattern was seen with this data, with the smallest events having a throughfall of 0 up to the largest with a throughfall of greater than 100% of gross rainfall. The average annual throughfall for all trees is 54.39% (with rainfall correction); ranging from 46.6% for Beech to 70.45% for the Chestnut (). These are within the ranges (34-95%) seen within the literature (Jones, 1997 and Levia and Frost, 2006).

All the trees except the Chestnut were significantly different in TF between non-leafed and leafed period. Throughfall was found to be larger in the non-leafed than leafed period with the transition lying in the middle. This was found to be the same by Geiger (1957 in Jones 1997). However, the difference was much larger in the Oak and the Beech unlike the Chestnut which was similar to Geiger (1957) findings. The difference for the Chestnut was attributed to its structure as the tree’s branches pointed away from the stem towards the ground producing more drip points/throughfall instead of directing the water towards the trunk as stemflow. The small difference between summer and winter suggests the canopy structure which is dense with branches captures a lot of the rainfall. The non-leafed period recorded a greater number of smaller events than the leafed period, which would provide a lower throughfall indicating throughfall may be higher if measured another year when larger rainfall events occurred.

WCE%:

The novel finding of this research is the high WCE rates. WCE was found to have an annual average for all trees of 41.97% (with corrected rainfall), which is very different per species (Chestnut 29.35%, Oak 35.29% and Beech 52.28%). These are high due to the increased ventilation from edge effects, increasing evaporation (Herbst et al., 2006). This indicates that one large area of trees (e.g. woodland) has a lower benefit than the same area of trees that is spread out (e.g. a belt so the edge is largest) as the edge effects increase the water collected by the tree and increase ventilation, increasing the amount of rainfall evaporated compared to the interior of the forest. The WCE for the edge trees measured are higher than other WCE values within the middle of woodlands for the UK, and closer to the hedge WCE measured by Herbst et al. (2006), which was also attributed to edge effects. This suggests, along with the Frumau gauges' clarifications of increased throughfall being related to horizontal rainfall increasing rainfall collection by the tree, that the trees' WCE was regularly affected by edge effects.

Ketteridge (1948) found WCE lies within the range of 6-48% for hardwoods. Measured WCE is higher than that found at Plynlimon (25%) but on the higher end of 29-49% by Anderson and Pyatt (1986 in Johnson 1990) although these were looking at coniferous trees. The WCE rates found for trees measured at the edge of forests vary significantly from 38% (Law, 1956), measured 24km to the East of Lancaster University although for coniferous trees, to 14-16% (Neal, 1993).

Tree canopies on the edge see increased ventilation and hence higher evaporation (Klaassen et al., 1996). Tree canopies on the edge also see increased collection of horizontal rainfall some of the time, which varies from not occurring to being large enough to cause negative WCE (Neal et al., 1993; Herbst et al., 2006). Herbst found that the increased collection area could be corrected by using the true collection area instead of the aerial canopy area. Without correction edge trees produced varied results from negative to high WCE. WCE has been reported to be up to 30-40% of the gross rainfall where there are frequently wetted dense canopies in windy environments (Shaw et al., 2011), agreeing with this data.

The measured values are on the higher end of that found in other studies; this has been attributed to increased ventilation due to their edge location so results were higher (Hankin et al., 2016 and Klassen et al., 1996). The increased evaporation seen at the edge was attributed to the wind velocity and direction which causes the canopy to dry quicker by Klassen et al. (1996).

WCE has been found to be largest in the leafed period. All periods produce significant amounts of WCE. The difference between leafed and non-leafed in the Chestnut tree is small but WCE% is slightly larger in the leafed period whereas the Beech and Oak difference is much larger. The marked difference being small between the leafed and non-leafed periods was also found by Reynolds and Henderson (1967). This may be due to the greater number of small (9.7% leafed and 12.69% non-leafed of total event volume) and medium (44.7% leafed to 48.8% non-leafed) events in the non-leafed period, which would increase the WCE closer to that in the leafed period. This could have a more profound effect on this chestnut tree as the tree is more affected by horizontal rainfall causing negative WCE, than the other trees (except the NE Oak). Horizontal rainfall affects trees particularly on the edge (Penman, 1963). The horizontal rainfall occurred more often in larger events, with fewer larger events (by volume) occurring in the winter. The greater number of larger events occurred in the leafed period which could mean the true rainfall collected has a larger underestimation, and hence smaller WCE than actually occurs.

Hankin et al. (2016) study found that the WCE% during the non-leafed period, in similar environments to the UK, usually ranged between 10-20%, although some outliers exist. The measured WCE (22.05%-39.43%) is within these outliers. The highest value (beech) is under that seen by Herbst et al.'s (2006) hedge which was picking up horizontal rainfall and slightly above the highest tree WCE value (36%) measured by Noirfalise (1959). The other values for oak and chestnut sit within these measured values but are on the higher end. This indicates that the edge increases the WCE slightly due to the extra ventilation received by the canopy.

The leafed period of the non-leafed results collated by Hankin et al. (2016) in **Error! Reference source not found.**, shows that the variation between leafed and non-leafed can be large (Leyton et al., 1967) or similar (Geiger, 1957 in Jones 1997). The annual WCE for the leafed period was 55.75%, which is below that found by Leyton et al. (1967) in the UK for Hornbeam but is above all other tree values. The tree species leafed values ranged from 34.9%-66.84% (). Although the Chestnut seems lower in this data set, the WCE% is in the middle of those recorded (**Error! Reference source not found.**) for leafed periods in a similar environment to the UK. The Oak and Beech WCE are well above any found for the same species trees. This all indicates that the trees are affected by the edge with greater ventilation aiding evaporation.

Although higher evaporation occurs for trees on the edge they were not shown to be beneficial at reducing rainfall reaching the ground during large storm events. Therefore, suggesting that the planting of trees would not have much effect on flood peaks as the WCE over the largest events is a small percentage of rainfall. This is especially the case for the type of flooding that is typical of the UK (i.e. a succession of major events producing wet antecedent conditions leading to the water storage being full and water unable to penetrate the ground leading to surface water flooding). However, the planting of trees can reduce the wet antecedent conditions meaning that the flooding event can be delayed/chance of it occurring reduced with the planting of trees.

Rainfall:

It is debatable how much systematic error and tip delay can be seen within the rainfall data at the 5-minute time-steps. The Frumau gauges indicate more vertical rainfall was collected than for the EML gauge for nearly every event (66% more rainfall in total). Also, the data from the nearby Hazelrigg weather station over the same period was higher than the EML rainfall collected (on 24/34 occasions) with an average volume of 28% lower for the EML gauge. This was not related to event size. There is also a larger systematic error in the throughfall collectors (13.7%).

In conclusion, the higher rainfall rates at the other two nearby rain gauges suggests the EML gauge underestimates rainfall, however this underestimation is not great enough to mean all the negative WCE events would be removed. It also insinuates that the large average WCE recorded could in fact be larger. This uncertainty highlights the requirement to measure the rainfall input to the canopy vertically but also from a horizontal perspective for the open canopy. From looking at the processes occurring, it is also believed that the actual rainfall received by the canopy is underestimated due to the horizontal rainfall received by the canopy, which in turn could produce a larger WCE.

4.1.2 Why is WCE% high?

This high WCE is seen in all trees with the Chestnut and NE Oak significantly reducing the WCE with the negative WCE measurements. The data is within the ranges found by others but on the larger side of this. A high WCE could be caused by:

- ***Event size***. Small events have a higher WCE and there is a large amount of small and medium events producing a larger WCE. In fact, the year was found to be slightly drier than average (excluding December and March) using Hazelrigg weather station data. This along with the greater number of rainy days than average suggested that there were a greater number of smaller events, potentially contributing to the higher WCE.

- The ***loss of throughfall*** in the trough to evaporation or incorrect calculation of the trough area. The calculations of the trough area are in **Error! Reference source not found.** and have been checked to ensure this is calculated correctly.

  The loss of throughfall was a problem in Plynlimon with pine needles sitting in the trough trapping water, however the angle of these are higher here to prevent pooling and debris is removed regularly. Although the amount of water lost between entering the equipment and being collected varies per tree it was found not to relate to the trough angle for these trees.

  The 2.24% uncertainty in throughfall loss is higher than that suggested by Kurtyka (1953, in Pollock, 2018) who found -1.5% explained the uncertainty in rain gauges for evaporation and adhesion. However, the uncertainty would be larger for troughs due to their size increasing adhesion and evaporation. Sevruk and Hamon (1984) found the wetting up and evaporation uncertainty of a rain gauge to be 4-6% which is slightly higher but does not account for the high WCE.

  The two trees with the largest uncertainty (NE Oak and Chestnut) have the largest variation in WCE and those with negative values. Although if the throughfall was underestimated it could cause lower WCE (and larger negative WCE values) therefore not explaining why WCE is so large as the uncertainty would only reduce the WCE by 2%.

- ***Edge effects***. Trees on the edge have increased ventilation than within a forest, therefore allowing a greater WCE and causing higher than average WCE. Law (1956) found at Stocks Reservoir in Lancashire that a high WCE (38%) was found which was attributed to the edge effects from ventilation and collected more horizontal rainfall (Penman, 1963) as the equipment was too close to the forest edge. Increased ventilation was reported by Klaassen et al. (1996).

The EML rain gauge underestimates the volume as it is smaller than Hazelrigg and Frumau gauge readings. The EML gauge is known to underestimate due to the increased wind speed at 1m height (Pollock, 2018). The Frumau collectors suggest that the WCE value is underestimated (69.4% compared to 17.6% for the EML rain gauge during that same period) as even during the positive WCE events horizontal rainfall hits the open canopy suggesting the true rainfall the tree receives is larger than the measured value. A critical issue (although proving that WCE on the edge is large) is that the true value of the WCE is unknown as the amount of rainfall hitting each area of the open canopy is unknown and attributed to increase collection of horizontal rain. If the true amount of rainfall collected by the tree was known the negative WCE would be positive and WCE would be even higher.

Overall it has been found the WCE is high at 41.97%, due to the increased ventilation and would be higher still if the true rainfall collected by the trees was known. With this in mind, it has been shown that trees have a big role to play in NFM and reducing the amount of water reaching the ground particularly in small and medium events and reducing antecedent conditions for large events. This value is higher than originally thought so the data will play an important role in NFM modelling to gain accurate output for where and quantity of trees to plant.

4.1.3 Why does WCE appear to be negative?

The results found that some events when the wind is high, and the wind direction is to the open canopy that negative WCE can be calculated. Negative WCE can occur during any sized event but is more likely to occur as the events increase in size i.e. stormier conditions.

Thomas (2013) found negative WCE and attributed this to drip, inclined rainfall and wind while Neal et al., (1993) attributed it to underestimating the rainfall collection. On the other hand, Herbst et al. (2006), corrected their data for hedges to account for the area the hedge collects the rainfall from rather than just where it stands, ensuring this problem was not encountered. This data agrees with Neal et al., (1993) that rainfall collection is underestimated.

The collection uncertainty is 12%, which is lower than the negative WCE seen. The fact that rain gauge catch decreases with increase in storm size (Chang and Harrison, 2005) due to turbulent air and rain, could add to the issue with negative WCE. Also, with every m/s increase in wind speed the under-catch increases by 2.4% (Larson and Peck, 1974). However, the rain gauge under-catch can be 5-20% (Rodda and Smith, 1986), which would not account for all the negative WCE that is seen.

The spatial variability in the throughfall collection showed that drip points do occur, but these did not cause the larger throughfall than rainfall to be collected. The spatial variability indicated larger values away from the trunk where the canopy is denser and funnels more water as stemflow. The higher throughfall is where the tree is susceptible to collecting horizontal rainfall, indicating more rainfall is collected than over the rest of the tree as confirmed by the Frumau gauges.

The Frumau gauge data suggest that when a WCE value is calculated using the Frumau horizontal and vertical data, that the negative values become positive (although unknown for largest negative values, which were not seen during the Frumau measurement period). Negative values would still occur when measuring the horizontal rainfall in one place rather than at various locations around the open canopy as it is location specific due to wind direction. The Frumau gauges showed the cause was the underestimation of the rainfall. These events mainly occur for the Chestnut and NE Oak. Zijp (2005) thesis illustrates that emergent trees sticking out of the main canopy play a role in capturing wind-driven rain. Herbst et al.'s (2006) hedgerow collected more rainfall during small events with high wind speeds causing the coefficient of free throughfall, when calculated per unit canopy area, to be negative. The hedge caused a rain shadow of similar width to the hedge downwind indicating it was collecting the extra rainfall. The rain shadow was also seen within the Frumau data when horizontal rainfall occurred with the windward corrector collecting more rainfall than the leeward collector.

4.1.4 Why is the WCE measured to be negative in largest Storms and is this actually the case?

It was previously found that as storm size increases the importance of trees in relation to runoff and the buffering effect of drier soils under forests decreases (Bathurst et al., 2011a), which is agreed with these results on WCE.

It was found that ¾ of largest events produced a negative WCE, although this is only a small sample size it is obvious that the true rainfall volume collected by the tree is underestimated.

Jetton (1996) found the WCE in events over 10mm rainfall was underestimated due to severe underestimation of rainfall captured by the tree. The underestimation of rainfall captured by the tree is also believed to be the case here as the negative WCE events and Frumau gauges show the tree collects more rainfall than would directly fall on the canopy, which was found by Herbst et al., (2006) to cause a rain shadow, therefore indicating the trees have an effect on a larger area than just directly below the canopy.

Further studies would be required to determine the true volume of rainfall collected by the trees on the edge compared to that which directly falls on them. This could be undertaken by having numerous Frumau gauges around the edge of trees (with varying open amounts of open canopy) or shelter belt to measure horizontal input for a set canopy area. These will be collated along with the vertical input to determine the overall input of rainfall to the tree. The 2 Frumau Gauges (one at the open and closed canopy sides) used in this experiment would not be enough to accurately measure the horizontal rainfall around all the open canopy (open from the East through to the West).

4.1.5 How does the weather effect WCE?

The most important factors that affect the WCE are the wind speed and direction, which determine whether a negative WCE can be measured due to the increased rainfall collection and ventilation. The type of event has a great influence as smaller events produce higher WCE, shorter events produce more WCE, as do dry antecedent conditions as the canopy store is likely to be empty allowing greatest storage.

4.1.6 What are the wetting up and drying out periods?

An average wetting up is 0.35mm of rainfall, however the time-series graphs show wetting up is highly variable from 0 to several mm. Wetting up is affected by previous conditions, event length and potential for evaporation e.g. temperature, wind speed and net radiation.

Drain down has a similar variability from some, usually smaller, events having throughfall cease prior to rainfall indicating light rain where the water can sit in the canopy and be evaporated to events, particularly larger, where throughfall occurs several hours after rainfall with higher wind speeds suggesting the wind causes the water to fall from the canopy as drip.

4.2 Modelling

Predicting evaporation is complex due to environmental conditions (wind speed, temperature, humidity, wind direction and rainfall intensity) and requires stores to be included to accurately simulate the process and meteorological conditions. The complexities led to the use of the Penman equation, which provides the potential evaporation (i.e. does not account for whether the canopy is wet). The Rutter original and sparse models were used to account for rainfall but underestimate WCE. The original Rutter model assumes a closed canopy unlike the sparse version which fits the data better (although still poorly).

The measured WCE/annum was on the lower end of normal evaporation that would be seen. Although there were greater number of rainy days than average which would provide the wet canopy for evaporation to occur suggesting that WCE should be higher. However, this suggest the known issue with rainfall collection is the cause for the lower WCE values. The measurement period was also 15 days shorter than a year, and the drier summer than average means there was less wet canopy conditions for evaporation to occur leading to the lower value.

As per the hypothesis, the edge effects increase ventilation increasing WCE while the capture of horizontal rainfall by the open canopy producing large throughfall volumes decreasing WCE (and creating negative WCE) means the models cannot predict the WCE. The models are poor at modelling these effects and hence are poor at modelling total evaporation, which is agreed with when the rainfall input is doubled to account for horizontal rainfall. Therefore, either these models require alterations if they are to be used just with vertical rainfall data or a more accurate measurement of horizontal rainfall collection is required.

The measured timeseries shows when evaporation and storage occurs unlike the models which shows evaporation providing a better idea of the processes that occur. However, the models are clearly missing some processes due to the poor total estimations. Therefore, further modelling needs to be undertaken to determine if another model or alterations to the Rutter Sparse model (which had the better fit of the Rutter models) can provide a replicable fit. It has been shown that increasing the canopy store or reducing the aerodynamic resistance enables a better fit.

4.2.1 Are the total values and timings similar between measured and modelled?

The short answer is no, none of the models model the total measured evaporation data well (seen in Figure 3-56). The Penman overestimates WCE (384.61%) with it underestimating in the non-leafed period and massively overestimating in the leafed period. This indicates the Penman equation puts a larger emphasis on the temperature/net radiation, but wind plays an important role in evaporation during the non-leafed period. The leafed period with its large over estimation suggests that the year was drier than normal (also agreeing with the measured and historical rainfall data) providing less opportunity for wet canopy conditions and hence measured evaporation to occur. Also, the fact several negative WCE events occurred artificially lowering the measured WCE.

The Rutter Original and Sparse underestimate the evaporation (38.6% and 48.79% of the measured evaporation respectively) by over 50%. The Rutter sparse models the evaporation better than the original as it removes the drainage rate and coefficient. The WCE would also be larger if the water imbalance was corrected therefore further underestimating WCE suggesting alterations are needed to fit the data. These models require a greater importance on the ventilation of the canopy (i.e. aerodynamic resistance). The models predict leafed (due to the reliance on net radiation) and smaller events better and are unable to predict when negative WCE occurs due to the water balance issue.

The models suggest that evaporation occurs during the day however it has been found (Iritz and Lindroth, 1994) that WCE can occur at night due to wind suggesting all processes are not modelled correctly.

The Rutter Sparse model simpler approach would fit the data better. It provides a similar pattern to the original model although takes longer to drain the canopy as it predicts larger evaporation/storage volumes.

4.2.2 Why do the Rutter models underestimate?

The Rutter model has been found to underestimate evaporation by 50% (Calder et al., 1986 in Bonell and Bruijnzeel, 2005), which is similar to the underestimation found here due to the edge effects of the tree not being taken into consideration, in particular the increased canopy ventilation. This can be modelled through changing the aerodynamic resistance.

The throughfall is predicted by both Rutter models (*Figure 4.12*) to be higher for the small and medium events and lower for the large events. The fact that the throughfall for larger events, where a greater number of negative WCE events occurred, is overestimated suggests throughfall is higher than expected as the tree is collecting more rainfall and hence WCE would be higher.

4.2.3 How does the model deal with negative WCE?

Negative WCE occurs due to a water balance issue of the true amount of rainfall being taken up by the canopy being unknown. If known it would produce a higher WCE, leading to a further underestimation of the total amount of evaporation predicted by the models.

Herbst (2008) found negative WCE occurred particularly during small events with high wind speed whereas here it was found in all event sizes with high wind speeds. As expected, none of the models are able to measure the negative WCE. The Rutter Original model assumes a closed canopy (Muzylo et al., 2009) (i.e. assumes there are no gaps in the canopy) so can only account for rainfall hitting the top of the canopy. Therefore, the model is unable to account for horizontal rainfall which hits the side of the canopy. The Rutter Sparse assumes gaps in the canopy but also only assumes rainfall is collected from the canopy top. These models do not account for the larger collection area of the canopy sides during horizontal rainfall, which then funnels into a smaller area under the tree concentrating the rainfall. Horizontal winds need to be taken account of in any model as planting small woodlands and trees in hedgerows are likely to capture more rainfall.

Herbst (2008) also found due to some negative WCE values that the coefficient of throughfall calculated from his data was negative. This could indicate that the p value for the chestnut tree is not representative for this tree due to these large throughfall values. This indicates that the p value would need recalculating with a corrected rainfall that takes account of the rainfall extra rainfall collected from the sides of the tree

4.2.4 High rates of evaporation and modelling?

The models struggle to predict the high rates of evaporation as these are high compared to literature. Other studies do not look at trees that are under edge effects therefore comparing one to the other is not possible as the edge effects play an important role. For this reason, the models struggle to predict the evaporation and therefore require further adaptation to take account of edge effects including wind speed and direction towards the open canopy increasing ventilation and increased rainfall capture.

Beven (2012) suggests that trees in wet and windy environments (such as Lancashire) can have interception rates of over 20%, which would agree with the measured data, rather than the Rutter model which suggests winter produces much less evaporation than occurs.

Valente et al. (1997) (**Error! Reference source not found.**) found that throughfall is modelled well in Portugal, showing models can predict throughfall/evaporation well in some environments. Gash and Morton agreed with this for the Thetford Forest in the UK, likewise for Whelan and Anderson (1995). However, the throughfall for the Chestnut in Lancashire is not modelled well due to the edge effects as the true rainfall was unknown.

Table 4-1: Rutter Model data found by Valente et al. (1997)

Valente et al 1997 Pine	Observed	Rutter Original	Rutter Sparse
Interception loss	153.8	198.5 29.1%	150 -2.5%
TF	778.3	736.1 -5.4%	783.9 +0.7%
Eucalyptus			
Interception loss	100.8	140.7 39.6%	97.4 -3.4%
TF	922.8	889.8 -3.6%	930.6 0.83 %

In the less severe cases of edge effects, but where more rainfall is collected but producing a positive WCE, the Rutter model still underestimated these. The WCE of these events would be even larger with the correct input of rainfall and therefore the models would be underestimating it further.

4.2.5 How does the modelling of Leafed vs non-leafed compare?

The Penman has an extremely poor fit during the dormant state, where it was found that the actual evaporation is larger than the potential evaporation. The model parameters mean that during winter when there is lower temperatures and net radiation, which are important in predicting evaporation, evaporation is poorly predicted. The models underestimate the importance of wind speed, with the models predicting no evaporation occurring at night. This indicates the error is within the parameters. This is also the case for the Rutter models as they rely on the Penman equation. Beven (1979) agrees the Penman equation exhibits high daytime sensitivity during summer periods but underestimates the importance of winter evaporation. The Rutter model would potentially predict the evaporation in warmer environments better.

The sensitivity analysis suggests that different canopy capacity values for the leafed and non-leafed periods would benefit the modelling.

These models emphasise how we have in the past underestimated the power of evaporation from trees during the non-leafed periods and how this needs to be taken account of now. This shows the importance trees can play in reducing water reaching the ground all year round, and hence the role they can potentially play in flood peak reduction.

4.2.6 How well do models replicate WCE through an event?

The measurement of throughfall through events is not seen often globally and not at all within the UK for deciduous trees providing a unique dataset.

In short, the answer is models do not replicate WCE well. The models predict smaller events better than medium and larger events, which are poorly predicted (Section 3.7.2.4*)*. This is due to the major underestimation in total evaporation volume due to the larger rainfall collection area of edge trees.

The models have a poor fit over the time-series suggesting a different theory for the processes that occur unlike the measured data which indicated evaporation and storage. The Penman equation shows a diurnal pattern (acknowledged by Beven, 2012) due to it taking account of meteorological conditions (net radiation and temperature) that can play a larger role during daylight hours. However, Penman fails to predict the potential evaporation during the night, which will occur due to the ventilation of the canopy due to Penman underestimating the importance of wind speed, calculated from aerodynamic resistance, at removing water. Although the model is influenced by meteorological conditions, these have a smaller effect than the aerodynamic resistance, which introduces vegetation type to the equation (Beven, 1979). The underestimation of wind speed could be different than predicted due to the edge effects of the tree and the location within the UK, which is known for being wet and windy. Wind speed would play a larger role during winter months when they are higher, and rainfall is greater producing more horizontal rainfall. The model assumes night-time evaporation does not occur, with WCE continuing the following day, but Iritz and Lindroth (1994) found that it does and is mainly controlled by vapour pressure deficit and ventilation/wind speed.

Through an event the models clearly struggle to simulate negative WCE, which has been shown to be influenced by wind speed and direction. However, the high wind speed and direction combination does not always lead to negative WCE indicating the storm itself plays a role e.g. intensity, duration and volume. The models would be unable to predict negative WCE as they do not assume throughfall could ever be larger than rainfall as WCE is calculated using the throughfall coefficient. This indicated a more complex process occurs, which would require model alterations to be accounted for.

The Rutter model determines WCE from the canopy capacity and water in the canopy. When water in the canopy is more than the capacity, the evaporation in the canopy equals the Penman equation; therefore, the model shows a similar pattern and varies from Penman when $C<S$. The Rutter model (Gash and Morton, 1978) shows that more water is held in the canopy (C) in winter, however, this also goes above the canopy capacity (S). This has been improved in the Rutter Sparse (Valente et al., 1997) to ensure drainage happens immediately when the storage capacity of the canopy is reached.

It was discussed by Ghimire et al. (2012) that the method used for calculating the Canopy Capacity is not as good/reliable for providing the canopy capacity, although used by many others including Rutter et al. (1971) and Valente et al. (1997). These values of S are above Ghimire et al. (2012), and in line with that calculated by Herbst et al. (2008). Ghimire et al. (2012) found S can increase significantly from 0.89mm in other environments. However, S that has been calculated here is within their values found by others.

The canopy store for the Rutter Original and sparse in Figure 3-51 indicates that the original does not cap the canopy capacity which leads to the model crashing when rainfall is particularly high as the canopy cannot drain it, unlike the sparse version. Therefore, the sparse model is better at modelling the processes that occurs as the canopy cannot hold water above the canopy capacity.

The models are likely to be able to model those trees in the middle of woodlands with greater consistency as the negative WCE seen here was caused by the trees being on the edge. The model struggled due to the edge effects the trees were under e.g. collecting greater rainfall than the canopy area due to the open canopy sides, during certain weather conditions. The models modelled the WCE well during the day although struggled during the night and the winter periods as aerodynamic resistance played a larger role in WCE for these periods.

4.2.7 What can we learn from the modelling compared to the measured WCE?

The measured data shows the evaporation and storage of the water in the tree canopy; however, the model shows that evaporation itself does not occur immediately. It cannot be assumed that the measured WCE&storage is when evaporation occurs as it is showing when it is stored. The Rutter models have been found to model the processes well in many environments/locations globally, so can be used to help describe the processes relating to when the evaporation occurs. However, modelling of the processes has been quantified for the middle of woodlands opposed to the edges, which is where it struggles to predict evaporation due to the lower importance it shows the aerodynamic resistance compared to other meteorological factors.

The model assumes evaporation only occurs during the day as it requires a higher net radiation and temperature therefore predicting a larger evaporation in the leafed period (especially the hotter/sunnier times of the year). If the aerodynamic resistance was more important in the model, the night-time and winter evaporation would be more accurately measured.

4.2.8 How does the processes act/function with climate?

The time-series graphs show that meteorological conditions, such as wind, play a large role in throughfall.

The models show that the temperature and net radiation slows down evaporation when they decrease, which are modelled within Penman equation.

The wind direction is especially important for trees on the edge as it has a large influence on the edge effects especially if toward an open canopy allowing greater collection of rainfall. Wind speed plays a large influence on the rainfall trees receive due to horizontal rainfall occurring in higher wind speeds, which for edge trees can be received on the open canopy. These are not modelled.

4.2.9 Are Model alterations required?

It has been shown that increasing parameter S (canopy capacity) and decreasing p would allow for a better fit. However, the value of S was higher than Ghimire et al. (2012) and in line with Herbst et al. (2008), although these both modelled within woodlands so may not be the case for edge trees. The value was increased well above these which may then invalidate the possibility of modelling another data set. Ghimire et al. (2012) agreed this method of calculation of the canopy capacity was not good or reliable. Although the alterations to this parameter of this extreme has not been seen elsewhere, these have not been modelling the edge effects of the trees; therefore the need for a larger store is understood due to the larger canopy of edge trees compared to the aerial area of trees within a woodland. Also, p could be incorrect as it is determined by the data whose rainfall total is incorrect.

Another option would be fixing the aerodynamic resistance as per Page (2019) study to below 6s/m where below 2 has the greatest impact on increasing evaporation. The Ra using Hazelrigg data had values from as low as 1 and increasing much higher at times but an average of 5.4s/m. Fixing the Ra to 5s/m, which is a realistic value for woodlands, led to a better model than the varying Ra. The uncertainty in the actual Ra could provide the reason the model did not fit the data initially.

Calder et al. (1986) in Bonell and Bruijnzeel (2005) found that the Rutter model also underestimates the evaporation by 50%. To make this fit the data better they increased the canopy store and the aerodynamic conductance. These alterations ensured a better fit to their data set, but alterations have been varied between data sets (Schellenkens et al., 1999 In Bonell and Bruijnzeel, 2005) as it did not allow a good fit to other datasets. It has been suggested by Bonell et al. (2005) that the Penman equation is in some way inappropriate regardless of its sound basis.

Alteration of the Rutter Sparse model, which had the best although poor fit, would be required to improve its fit. Potentially WCE could be modelled better:

a) by increasing the store to 12.5 in the summer and 10 in the winter and decreasing the coefficient of TF to 0.001 to keep more water in the canopy,
b) changing aerodynamic resistance to around 5s/m
c) taking account of extra drip in windy conditions when it lies on the canopy, this is seen in the time-series graphs
d) or a new process that can predict negative WCE due to the edge effects using wind speed and direction for the trees capture of horizontal rainfall/accurate measurement of the horizontal rainfall being collected by the canopy.

However, Beven (1979) states that altering parameters to make a better fit means it is more difficult to obtain another good fit as the model may not necessarily model the processes that occur. Therefore, altering the model may provide a worse fit to other data and hence would need to also be modelled with other data after any alterations made to ensure a good fit elsewhere. This would particularly be the case here where one tree is being modelled so may not be a typical tree.

Alternatively, a different model may be a possibility. For example, the Xiao model (Muzylo et al., 2009) as it also deals with rainfall angle and lead inclination, which could produce a better model fit and reduce the overestimation. This issue is likely caused by the edge effects on the tree, but these must be taken account of as the trees planted as part of NFM will be single and in small groups

5 Conclusions and Recommendation

5.1 Key Findings

5.1.1 WCE Measurements

Trees concentrate water towards their roots allowing water to penetrate deeper into soil layers, losing water through transpiration and evaporation and slowing overland flow helping to reduce flooding at least for smaller and medium events.

Edge trees see increased ventilation leading to high WCE% of gross rainfall (41.97%), and hence could reduce hydrograph peaks when used as NFM, if in large enough quantities for small and medium sized events. When separated by species it is particularly high for Beech (52.28%) and Oak (35.29%) and slightly smaller but still high for Chestnut (29.35%). The higher WCE rates than trees in other studies within the middle of woodlands was due to increased ventilation of the canopy.

The trees on the edge of woodlands were found to intercept more rainfall than their aerial surface area due to horizontal rainfall causing water balance issues. Negative WCE was found to occur in some events; this was more prevalent in the larger events however can occur in any. It was found that a large wind speed with the direction towards the open canopy usually contributed to this as horizontal rainfall occurred causing the tree to collect more rainfall than would fall on the tree. Where this is the case the true WCE would actually be larger as throughfall to actual gross rainfall would be smaller.

The WCE for the Chestnut tree was found to be significantly higher when the horizontal and vertical rainfall collected by the Frumau Gauge was used to calculate the WCE over the measurement period (8th March-25th April 2019). This increased the WCE% from 17.6% when using the gross rainfall measurement to 69.4% when using the Frumau gauges rainfall collection as the rainfall collected increased relative to the throughfall increasing WCE. The negative WCE (although only small negative values were seen during the Frumau measurement period so unknown for the larger negative values) became positive and WCE increased, by varying degrees, in all events. Negative WCE was caused by not taking account of the horizontal rainfall collected by the tree. The actual values collected by the tree could be improved further by placing several Frumau collectors around the open canopy of the Chestnut tree to determine its true collection around the whole of the open canopy.

Agreeing with the hypothesis, it was equally found that WCE is important not only in the leafed period (55.75%) but, although smaller, also in the non-leafed period (31.07%). This was similar for Oak and Beech; However, the chestnut was similar between both the leafed and non-leafed period, which was attributed to the tree structure. As per the hypothesis, the difference in these periods is significant but the WCE during the non-leafed period is large enough to play an important role in removing water. It was found that WCE is affected by many variables including wind speed, wind direction, storm size, and leafed/non-leafed period. Horton (1919) found that throughfall and stemflow varied according to storm size. This data agrees with his findings and the hypothesis that with the increase in storm size throughfall increases and WCE% decreases. The WCE% data for the largest events (-7.69%) would initially suggest that trees cannot aid in flood reduction for the largest events but can reduce the antecedent conditions. Further investigation showed that the tree concentrated the water by collecting more than their canopy area, funnelling it under the tree (as throughfall). This also means that water collected by the trees is not hitting the ground nearby reducing the rainfall nearby. Once corrected for the actual rainfall, the WCE would also increase for these largest events but as WCE decreases as storm size increases it suggest that the trees will reduce the hydrograph for the small and medium events but with a much smaller effect for larger events. The extent of WCE occurring in the tree is unknown, requiring further analysis into the true amount of rainfall captured by the edge trees in these largest events as well as any rain shadow effects that occur.

The time-series graphs show that the wetting up length and volume varies significantly between events depending on storm characteristics (including size, duration and intensity), temperature, wind speed and whether conditions were previously wet or dry. Throughfall in smaller events generally stops prior to rainfall, indicating that the end of the events involve drizzle whereas larger evens' throughfall can stop 1-2 hours after rainfall especially in windy conditions where water stored in the canopy is blown off as drip.

Flooding events occur with a large storm but not all as they are exaggerated by the ground conditions being saturated from previous events removing a potential water store. Trees have the potential to reduce this store from filling up through WCE during smaller previous events providing a larger initial store during a large event. Therefore, could play a role in reducing the hydrograph prior to storms occurring.

Planting trees as NFM will provide a larger benefit than previously thought by reducing the amount of water reaching the ground for most events. The data supports the argument that planting more trees (even in small belts or individually) is valuable due to their edge effects. It will also allow more accurate modelling of the number and location of trees required to provide a benefit to reducing the hydrograph peak. This data provides the Lune Rivers Trust and Woodland Trust, as well as many other charities and organisations, with evidence of the benefit of planting trees. It shows the benefit that could be provided if even small areas and single trees are planted along boundaries or for shelter and the incentive to keep planting any area possible with trees. However, will require a large amount area to be planted to have a big impact on flooding.

5.1.2 Modelling

Key findings from the modelling review found that no model fit the data well with the Rutter Sparse (48.8% of the actual evaporation) having a better fit than the Original (38.6%) or Penman (384.61%), without alterations.

The Penman equation poorly matches the evaporation timeseries especially during the dormant phase. This is because it shows the potential evaporation as it does not account of whether the canopy is wet to allow for WCE. The models provide an insight into the processes that occur, with a diurnal cycle due to its reliance on net radiation and temperature as well as other weather conditions. This reliance leads to the equations struggling to predict winter evaporation. The Penman equation predicts that evaporation only occurs during the day so for night-time events it assumes the water is stored in the canopy until the following morning.

However, this does not take account of wind induced evaporation and infers the reliance on net radiation is extremely important. This continues to be the story for the Rutter models as they are both largely influenced by the Penman equation. However, these models both underestimated the evaporation by over 50% providing a poor fit to the data.

The Rutter models struggle to model the non-leafed more than the leafed period with the best fit seen during the warmer and drier conditions. The Rutter models are poor at modelling the edge effects (ventilation and hence larger WCE and horizontal rainfall and therefore greater capture of water causing negative WCE) when using vertical rainfall data. These models would also further underestimate the evaporation if the horizontal rainfall collected by the tree was known as WCE would increase. It is important to take account of the edge effects as the majority of trees are being planted in belts and single trees not large areas of forest.

When altered, the models fit the data better with either a larger store (by increasing the canopy capacity, which was different between leafed and non-leafed periods, and lowering the throughfall coefficient) or changing the aerodynamic resistance within the Penman equation, agreeing with Page (2019). This agreed with my hypothesis, that the edge effects cause a major problem with modelling due to ventilation increasing the WCE and horizontal rainfall producing a negative WCE. These models fail to predict the importance the tree plays in reducing water reaching the ground especially in the dormant period. Therefore, in conclusion alteration to the Rutter Sparse model requires the changing of the aerodynamic resistance to a fixed value of around 5 s/m (which is an accepted value for trees) from the varying Hazelrigg data to provide the best fit. Alternatively, using the Gash model could fit better as Muzylo et al. (2009) found that hardwoods are more likely to be modelled by this model or the Xiao model to take account of wind speed and inclination.

Although the study indicates edge trees remove larger amounts of rainfall before it reaches the ground than previous measured in the middle of woodlands, the amount of water that needs to be removed will require large areas to be planted.

5.2 Review of Methods

The interception measurement has uncertainty of 12.2% and 7.74% for rainfall and throughfall, respectively, due to wind speed, splash, evaporation, and adhesion. There is uncertainty from debris in the equipment, although this is emptied regularly to minimise this, and some have been found to occasionally blow over in the largest winds.

Ideally the stemflow collection could be improved by utilising a tipping bucket to record stemflow in high frequency, however the budget would not allow this. The equation for calculating shows the evaporation and water stored in the canopy, therefore it is not just showing evaporation. It also assumes drip is from new rainfall not the water stored in the canopy. This is because the equation only takes account of what happens in the specific time-step, not what has occurred before.

Other improvements would be to have the wind speed and direction, temperature and humidity measured at canopy height on campus rather than at Hazelrigg Weather Station.

A major limitation in relation to the potential of reducing the flood risk is the number of large events that were recorded (only 4). This reduces the potential to accurately decipher the effect of the trees' evaporation during the largest of storms. Further research is needed into the rainfall actually captured.

This rainfall collection is limited now that it is understood that trees on the edge collect more rainfall than that which hits the canopy vertically. To know the true amount of rainfall hitting the canopy would provide accurate results of true WCE.

Other limitations include the equipment being blown over on several occasions needing more robust fastening in place, and the equipment required daily emptying during the leaf loss period to ensure the gauge was not blocked. If more funding for equipment was available, it would have been beneficial to have stemflow collectors on all trees and for the Chestnut stemflow to be on a tipping bucket gauge to provide more insight into the processes occurring.

The models are limited to the data that is utilised especially the uncertainty from its collection method. Also, these models do not take account of soil water and transpiration of the trees. These models have been shown to both fit and not fit evaporation data in various environments. However, these models have been well utilised globally and limitations are well known. The models may have a good representation of the data collection area however these are not accurately scaled up (Muzylo et al., 2009) involving several errors. They have been used in the UK with limited frequency and not at all for deciduous trees with high frequency looking through the storm. These models need to be tested more thoroughly within the UK. This would likely occur more if the coding/software packages for the models were freely available, which will also reduce the potential for error in creating the code.

The large number of parameters required makes it difficult to run these models as collecting the data takes time and money, are also not easily obtained and are site specific (Muzylo et al., 2009).

Models allow the alteration of the parameter values to fit measured rates. However, this makes it extremely difficult to predict the changes in parameter values over time to obtain another good fit (Beven, 1979). Beven (1979) states that seasonal and diurnal variations in the evaporation mean those models (e.g. Gash) that use average parameter values will cause a further uncertainty.

An uncertainty in the modelling of this data is caused by the equation assuming evaporation is calculated from the difference between rainfall and throughfall. This works over the entire storm but not at 5-min increments (e.g. during the event) when evaporation is delayed, or rate changed depending on weather conditions.

Some meteorological parameters are easier to measure unlike the net radiation which involves other energy fluxes which are more difficult to quantify (Beven, 1979). The estimation in Ra and Rc will produce significant error (Beven, 1979). The rate of evaporation is highest under wet canopy conditions but the Penman equation neglects to account for whether the canopy is wet or dry therefore providing the amount that could possibly evaporated under wet conditions. Whereas the use of Rutter where it predicts evaporation from intercepted rainfall, may take place at a potential rate of Rc=0 therefore reducing the uncertainty. Although the model is influenced by meteorological conditions, these have a smaller effect than the aerodynamic resistance, which introduces vegetation type to the equation between sites (Beven, 1979).

5.3 Broader Significance and Contribution to New Knowledge

This study has provided the first study of WCE data through storms for deciduous trees in England. Few studies into deciduous trees in the UK having been undertaken with the majority looking at coniferous forests (e.g. Law (1956)). This unique data shows the processes that occur through storms for deciduous trees highlighting the importance of WCE even during the dormant stage, which has been previously underestimated due to the loss of leaves.

A high WCE (agreeing with Law, 1956) was found for all trees indicating that this is true for mature deciduous trees that are within belts of trees or planted singly. The edge effects cause higher WCE due to increased ventilation. Also, if the collection of the true amount of rainfall was known, which was increased by horizontal rainfall, the negative WCE over a storm would not occur and WCE% would be even higher. This reduction in rainfall reaching the ground (excluding other benefits trees provide) means it should not be overlooked as an NFM option.

The fact that very little data has been collected in the UK on deciduous trees, means this data set is vital. It is significant for the Lune Rivers Trust and Woodland Trust, who have more evidence to persuading landowners, politicians, and others, of the importance of planting trees to help reduce flood peaks. It has been clearly found that even planting trees in hedgerows/boundaries and in shelter belts/woodland-pasture to limit the influence of the farms operations, which is where NFM would be implemented, would provide a significant benefit if carried out over large areas.

This data will be important in accurate parameterisation of NFM models, as lower rates of WCE were previously used and have been collected locally to take account of meteorological conditions that are different on the west coast compared to other locations nationally. This will allow for accurate modelling of the number and location of tree planting to reduce flood peaks (e.g. in the Cumbria Model (Chappell et al., 2017) as well as provide evidence for the EA Evidence Base.

To utilise a model, these alterations need to occur: changing the aerodynamic resistance to 5s/m in the Penman equation allows the Rutter Sparse to more accurately predict the measured evaporation. This agrees with findings by Page (2019) that below 6s/m the evaporation increases and significantly increases below 2s/m. Another option is to increase the canopy capacity and reduce the throughfall coefficient, hence increasing the store.

5.4 Carbon Analysis

Critically trees alter the soil's capability to store carbon as well as in above-soil biomass. This critical co-benefit of trees provides added benefits to utilising trees as NFM as well as reducing the use of concrete flood defences, which produce high amounts of CO_2. Converting grassland/croplands to woodland can have a large benefit on reducing water reaching the ground and hence reducing the flood peak and store a significant amount of carbon.

The increase in tree planting will mitigate any of the CO_2 emissions produced from undertaking this research (from equipment manufacture with no emissions from transport to and from site). Based on the 2011 LULFUCF emissions and removals of greenhouse gases supporting dataset (Malcolm et al., 2013), annual greenhouse gas emissions in Scotland were calculated by Fielding and Matthews (2014) as follows:

- Croplands produce $3.09tCO_2eha^{-1}$
- Grasslands produce $-0.40tCO_2eha^{-1}$
- Woodlands produce $-4.81tCO_2eha^{-1}$

Therefore, converting farmland (grassland and arable croplands) to woodlands can have a large difference on CO_2 emissions. The Lune rivers trust is persuading farmers in the Lune basin (66,300 ha area) to convert farmland to woodland. Within the UK 69% (DEFRA, 2014) of the total area is agricultural land (17,100,000 ha). This is in line with the Government's aim of convincing farmers to convert 12% of agricultural land to woodland, required to meet the government's target by 2060 (BBC, 2017 and The Guardian, 2018). This is to improve England's low forested level of 10% compared to Europe's 35% (BBC, 2017) but would still fall behind Scotland's target of 25% increase (Bell and Greaves, 2010).

Grassland baseline that could be converted to woodland:

- Lune area has 45,204ha of farmland (Lancashire County Council, 2013)
- 42,829ha is grassland
- Grassland produces $-0.4tCO_2eha^{-1}$
- Grassland in the Lune currently produces $tCO_2e=42{,}829*(-0.4)=-17{,}131.6tCO_2e$

Arable baseline that could be converted to Woodland:

- Lune area has 885ha of arable
- Arable land produces $3.09tCO_2eha^{-1}$
- Arable land in the Lune currently produces $tCO_2e=885*3.09=2734.65tCO_2e$

Therefore, the total tCO_2e produced by farmland today is $-14{,}396.35tCO_2e$.

If the 12% increase in land coverage for woodlands suggest by the government is implemented, to increase the 10% coverage. The baseline carbon within this area totals:
$-14{,}396.95 * 0.12 = -1{,}727.63tCO_2e$

This means the following land area needs conversion:

- Arable land potentially converted to woodland=885*0.12=106.2ha
- Grassland area potentially converted to woodland=42,829*0.12=5139.48ha
- Total converted area=5245.68ha

This gives -37901.04tCO_2e when converted to woodland instead of grassland: (5245.68*(-4.81))+(-14396.95-1727.63)=37901.04
Tree planting has co-benefits for retention of the nutrient of aquatic carbon. Water quality data from the local Demonstration Test Catchment project has shown that the loss of aquatic carbon and other nutrient losses mitigate NFM measures, which produces an avoided cost of £9000 per farm in this region. Giving a potential financial saving of £7.2 million for Cumbria; it is reasonable to assume this is similar for Lancashire if NFM is implemented widely (CaBA, 2018).

5.5 Recommendations for Future Research Priorities

The work that would specifically further this project and the understanding of it includes:

- Determining the true rainfall that edge trees collect.
- Running the Gash model as Muzylo et al. (2009) found that it is used more often to model Hardwoods and/or the Xiao model, which accounts for rainfall angle and lead inclination.
- Utilising this evaporation data and a suitable model to parameterise catchment scale models and within the whole water balance. This will determine the best locations and number of trees to plant, without slowing the flow for fast catchments (which would cause peaks to coincide and potentially cause larger floods) but also take account of the meteorological conditions and terrain.
- A sensitivity analysis could be undertaken by adding ±20% and ±10% of uncertainty to each of the parameters while keeping others constant as per Cui and Jia (2014).

This study has highlighted that the following could be undertaken to improve the study area:

- The initial Frumau data collection suggests that a larger study should be undertaken for the trees on the edge to determine how much rainfall is truly collected. This should include more gauges around the open canopy, and more trees within the study.
- Undertake the same measurements and modelling on other trees (species and size) to determine if the results are the similar for these, whether edge effects occur, and which species has the highest WCE. This would also involve different locations around Lancashire and Cumbria.
- Using an alternative experimental design with a control tree to compare to the centre of a woodland block or with 5 transects running 300m into a forest block each with 10 trees. This would allow the effect of edge effects to also be determined and to what distance into the woodland this affect occurs.
- What effect tree planting has on rainfall on the leeward side of the trees, but also further away in respect of the water re-entering the atmosphere and causing rainfall elsewhere i.e. is the rainfall increased elsewhere at a sub continental scale? TeLinde et al. (2001) suggests that when WCE occurs small-scale circulation of the water applies leading to the conclusion that it cannot be assumed that just because WCE removes water that it directly reduces the flood peak but may cause a delay as the water is recycled and rains again. This would require further study looking at stable isotope contents of rainfall and throughfall along elevation gradients i.e. windward to leeward sides.

- To study a whole section of tree belt to gain insight into how trees affect each other, and single/a mix of species affects evaporation indicating the most beneficial tree species or mix of species and more about edge effects.
- The frequency of which physical model is used varies around the world and in different environments. Model's use in the UK is limited and not at all for deciduous trees with measurements through storms. This could be increased by producing software packages that will allow for other academics to run their data in these models without needing to create the programmes, which will also reduce the potential for uncertainty.
- The wider catchment effect of trees by looking at streamflow changes before, during and after trees are planted showing changes as they mature. A method to gain data could be to compare bounded overland flow plots to gain the 'streamflow per unit basin area' that travels on the surface of slopes between woodlands, recently planted areas and adjacent moor/pastureland (Chappell et al., 2004) to measure changes in overland flow.
- Another method to determine the benefit trees can provide is to measure the soil moisture content or topsoil permeability between woodland and pasture to indicate if deciduous trees are drying soils and reducing the likelihood of rapid saturation overland flow and changing form of rainfall runoff nonlinearity of floods (Chappell at Ternan, 1997).

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