ASSESSING THE IMPACT OF NEW WOODLAND CREATION ON CATCHMNET HYDROLOGY AND FLOOD RISK

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ABSTRACT

Woodland creation is a known broad measure used as part of nature-based solutions for different catchments. Previous research studies have established the multiple benefits of woodland creation related to more comprehensive catchment research. However, those benefits have been researched on a broader catchment scale rather than on the small scales that include cultivation practices. This created a lack of evidence for studies related to the hydrology of cultivation techniques. This case study added unique values to researching different cultivated areas (plough, excavation mounding and hand-screefing cultivation) in Menstrie catchment, Scotland.

For this study, the cultivation techniques were monitored for two years regarding runoff and sediment delivery at the field scale. Seven different plots (one unplanted plot, one hand-screefing plot, three plough plots and two excavation mounding plots -P6, P7) were monitored on microscale level (< 0.5 km^2). Furthermore, monitoring included surface water level monitoring from two streams (Inch 1 and Inch 2) of the main water course in the Menstrie catchment. For better understanding of hydrological behaviour data has been analysed from dry (API30 ≤ 20 mm) and wet (API30 > 20 mm) weather perspective. However, according to monitored data, the study distinguished differences between runoff and sediment delivery from different cultivation plots and their effectiveness. On sub-catchment level main findings highlighted forest cover importance. This clearly showed that Inch 1 sub-catchment had lower values of runoff water than Inch 2 sub-catchment for any weather conditions. Inch 2 sub-catchment had 25 % more grassland cover than Inch 1 sub-catchment. On another hand, monitored cultivations plot and unplanted plot discovered hydrology on microscale for dry and wet weather conditions. Analysed data showed that runoff water will first in unplanted plot area, followed by peaty based plough plot, hand-screefing plot, brown soil-based plough plots and excavation mounding plots during dry weather conditions. On the other hand, the fastest response for wet weather conditions will occur in unplanted plot area, plough plots, lowland excavation mounding plot, followed by hand-screefing plot and upland excavation mounding plot. Then, the highest amount of runoff for dry weather conditions occurred in the case of unplanted plot, peaty soil-based plough plot and lowland excavation mounding plot, since wet weather conditions had unplanted plot, hand-screefing plot and lowland excavation mounding plot. However, those finding was associated with cultivation design, slope of catchment area, slope of channel, soil type etc. However, the highest amount of sediment delivery refers to plough plots since hand screefing plot and excavation mounding plots monitoring plots have experienced significantly less sediment delivery. Those data have been analysed in connection with precipitation, runoff peak and runoff volume.

Overall, this research defined hydrology and sedimentology of different cultivated areas depending on main properties of monitored plots. Those findings can be improved by further research in the same area.

Dedications

To all PhD mums, it is hard to finish a PhD with a baby, but it is possible.

To my son Nikola who is the greatest inspiration in my life.

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DECLARATION STATEMENT

Research Thesis Submission

Name*:*	Martina Egedusevic		
School:	School of Energy, Geoscience, Infrastructure and Society		
Version:	Final	Degree Sought:	PhD in Civil Engineering

Declaration

In accordance with the appropriate regulations I hereby submit my thesis and I declare that

1. The thesis embodies the results of my own work and has been composed by myself
2. Where appropriate, I have made acknowledgement of the work of others
3. The thesis is the correct version for submission and is the same version as any electronic versions submitted*.
4. My thesis for the award referred to, deposited in the Heriot-Watt University Library, should be made available for loan or photocopying and be available via the Institutional Repository, subject to such conditions as the Librarian may require
5. I understand that as a student of the University I am required to abide by the Regulations of the University and to conform to its discipline.
6. I confirm that the thesis has been verified against plagiarism via an approved plagiarism detection application e.g. Turnitin.

Submission

Submitted By *(name in capitals):*	Martina Egedusevic
Signature of Individual Submitting:	Мартина Егедушевић
Date Submitted:	**09/03/2023**

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LIST OF PUBLICATION

Parts of this thesis have been published at conferences.

<u>Conference Presentations:</u>

[1] **Egedusevic M**., Allen D., Beevers L., Vaughan A., Cullen S., Nisbet T.R., Haynes H., 2017a. Runoff characteristics of cultivation practices for woodland creation: field evidence from the Menstrie catchment. The Seventh International Conference on Flood Management, September 2017, University of Leeds, England, United Kingdom

[2] **Egedusevic M**., Arthur S., Beevers L., 2018. New forest creation- research with impact EGIS Symposium 2018: research with impact, Postgraduate Centre, Heriot-Watt University, Institute for infrastructure and environment, April 2018, Edinburgh, United Kingdom

[3] **Egedusevic M**., Beevers L., Arthur S., 2019a. Runoff characteristics of different cultivations in Menstrie catchment, Scotland: From field observations to model development. EGU General Assembly 2019 conference, April 2019, Vienna, Austria.

[4] **Egedusevic M**., Beevers L., Arthur S., 2019b. Natural Flood Management in Menstrie catchment, Scotland: Does it work? EGIS Symposium 2019: Research with impact, Postgraduate Centre, Heriot-Watt University, Institute for infrastructure and environment, May 2019, Edinburgh, United Kingdom

<u>Posters:</u>

[5] **Egedusevic M**., Haynes H., Allen D., Beevers L., Cullen S., Vaughan A., Nisbet T.R., Pettit A (2016). **“**Natural flood management: assessing the impact of woodland creation on flood risk”. Poster presented at annual poster competition hosted by Chartered Institution of Water and Environmental Management, The Teacher Building, October 2016, Glasgow, United Kingdom

[6] **Egedusevic M**., Beevers L., (2017). “Natural flood management: assessing the impact of woodland creation on flood risk”. Poster presented at Infrastructure & Environment Scotland 4th Postgraduate Conference, University of Edinburgh, May 2017, Edinburgh, United Kingdom

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GLOSSARY

API	Antecedent precipitation index
Qbp	Base flow peak height per catchment area
Qbv	Base volume per catchment area
Qv	Runoff volume per catchment area
Qp	Runoff peak of water per catchment area
Qpt	Total peak height
Qvt	Total runoff of water per catchment area
CEH	Centre of Ecology and Hydrology
CMC upstream RG	Clackmannanshire council upstream rain gauge
CMC downstream RG	Clackmannanshire council downstream rain gauge
DTM	Digital Terrain Model
EBA	Ecosystem-based Adaptation
Ed	Event duration
EGS	End of the growing season
FRM Act 2009	Flood Risk Management (Scotland) Act 2009
GIS	Geographical Information System
GR	Growing season
HWU	Heriot-Watt University
HWU RG	Heriot-Watt University rain gauge
I	The intensity of rainfall per event:
IRSTEA	National research institute of science and technology for environment and agriculture, France
JHI	James Hutton Institute
KGE	Kling–Gupta efficiency
LRM	Linear regression model
MOD	Modelled
NGR	Non-growing season
NSE	Nash and Sutcliffe's efficiency
NFM	Natural Flood Management
OBS	Observed
PBIAS	Percentage bias
P	Precipitation amount per event
P1	Plot 1 (unplanted monitoring plot)
P2	Plot 2 (hand-screefing cultivation monitoring plot)
P3	Plot 3 (plough cultivation monitoring plot)
P4	Plot 4 (plough cultivation monitoring plot)
P5	Plot 5 (plough cultivation monitoring plot)
P6	Plot 6 (excavation mounding monitoring plot)
P7	Plot 7 (excavation mounding monitoring plot)
RG	Rain gauge
RQ	Research questions
Rt	Response time
RMSE	Root Mean Square Error
SC	mentSedimentcollection
SEPA	Scottish environmental protection agency
SGS	Start of growing seasson
USA	United States of America

Tp	• Time to peak
UK	• United Kingdom

Chapter 1 Introduction

1.1 Research context

In recent years, global warming and the effects of climate change have become a topic of significant conservation efforts and a critical factor in discussions about increasing occurrences of floods and droughts [7]. As experts have underscored climate changes the precipitation patterns [8], [9]. For example, it increases the number of storms, glacial retreats, floods, rising sea levels, forest fires and droughts, often with severe consequences for the affected population and the environment. Therefore, there is an urgent need to develop adaptation and mitigation strategies capable of addressing environmental hazards caused by the current and future changes in climatic conditions [10].

In flood hydrology complex engineering refers to measures implemented to reduce the adverse impacts of flooding via the construction of artificially engineered structures. Those methods include channel straightening, dredging, dams, barriers, and other structures. Furthermore, United Kingdom (UK) lowland floodplains have been disconnected from the river channels due to complex engineering methods applications. Even though complex engineering approaches traditionally seek to stabilise channel morphology and improve hydraulic efficiency, these approaches have their limits. Those solutions can increase flooding downstream and often overlook river sediment transport [11]. Also, robust flood defence structures are expensive [12]. Overall, rivers naturally have highly variable flow regimes, with various pools, meanders, inner cliffs and slip-off slopes [13]. However, a more stable state is generated from complex engineering techniques with a subsequent decline in levels of biodiversity. According to this, managing flood risk in a natural way prevents some of these negative impacts shown through complex engineering. Further section examined novel approaches in the flood risk reduction field.

1.2 Ecosystem-based Adaptation and Natural Flood Management

A decade ago, the Ecosystem-based Adaptation (EBA) concept was introduced as a novel approach to natural resources management under increasingly variable and perturbed climatic conditions [14]–[16]. In particular, EBA reconciled risk reduction by increasing the contemplated system's resilience instead of predicting a specific outcome [17], [18]. An example of EBA is the Natural Flood Management (NFM) approach, represented as the option of reducing flood risk with a range of benefits.

The policy changes in the concept of natural flood control were scientifically reviewed by Haeuber in the United States of America (USA) in 1998 [19]. This review introduced previous flood issues in the USA and possibilities for policy changes in the direction of Natural flood management. Aligning with this, Western Europe and UK scientists recognised this concept in the early 2000s as a new approach to flood risk reduction by using natural processes, including land-use change.

1.3 Natural Flood Management in Scotland

The government introduced the NFM concept in Scotland by establishing the Flood Risk Management (Scotland) Act 2009 [20]. In compliance with this Act, the use of NFM has been developed by the Scottish environmental protection agency (SEPA) as a novel approach in Scotland. The techniques explored in this research consider a catchment-based, holistic approach that focuses on the effects of woodland creation and associated management practices on runoff generation and flood flows [21].

NFM is an ecosystem approach to flood risk management that uses different techniques to alleviate downstream flood naturally flows through hydrological and morphological processes. It uses cost-effective, sustainable methods to create a more integrated, catchment-based approach - managing land and water simultaneously. In Scotland, a key feature of NFM is land use change and improved land management, especially tree planting, aligning with the UK’s drive towards expanding woodland creation for multiple benefits [22]. One notable planting scheme in Scotland was the new woodland creation site at the Menstrie catchment. This catchment has a high flood risk from a flashy runoff response. Therefore, the Menstrie catchment (Clackmannanshire) provided an ideal opportunity to analyse this NFM measure in a steep, upland catchment. Cultivation techniques used during the afforestation process provided various research opportunities. Therefore, the research in this thesis was focused on the Menstrie catchment and the local Jerah Farm Woodland Creation scheme, which enabled investigations of the effects of tree planting and associated management operations on flood risk alleviation downstream. Furthermore, the selection of variables for analyses has been presented in Chapter 3.

1.4 Problem statement

Woodland studies have been researched under wider catchment areas, often including large areas (from 10 km^2 to 100 km^2) [23]. Those types of research created a wider knowledge of catchment behaviour, not including smaller plots or cultivation practices. There is a certain gap in hydrological understanding of the impacts of young woodland creation on flood generation and risk management. In particular, knowledge is lacking about the effects of different cultivation techniques on flood runoff and sediment movement [24], [25]. New research is needed in the exploration of the hydrological variables involved would improve knowledge of the effectiveness of woodland creation as an NFM measure to inform future forest policy and practice.

1.5 The research aims and main objective

The aim of the presented research is to map, analyse, quantify, and understand how new woodland planting schemes affect dynamics in water storage movement/sediment supply and the interrelationships of these processes at the catchment level. However, the present research will also improve understanding of the contribution of NFM to reducing flood risk for impacted communities through better databases, catchment modelling and working practices. To meet this aim, this thesis focused on designing and undertaking field-based monitoring and analyses (sediment movement and runoff) and established relationships between monitored data over two years. In accordance with the aim, specific objectives have been developed as follows:

(1) To identify a suitable Scotland site for assessment as a case study of new woodland creation

(2) To identify the type of cultivations for monitoring runoff and sediment movement

(3) Carry out data collection for each of chosen cultivations and sub-catchment areas.

(4) Compare changes between chosen plots (runoff and sediment supply). Also, compare changes in a runoff for chosen sub-catchments.

(5) Develop a validated hydrological model that can be used for updated flood risk assessment for the case study site and scenario testing/appraisal of cultivation techniques, best management practices, and woodland establishment.

1.6 Research questions

The following research questions (RQ) are addressed in this thesis:

RQ1: How do different cultivation techniques affect surface runoff volume and timing? Which factors control delivery?

This question will be answered by Objectives (1), (2), (3), and (4) and understanding how cultivation techniques affect the critical processes involved at both small and large catchment scales.

RQ2: How does sediment delivery from each cultivation technique change over time due to woodland development?

This question will be answered by achieving Objectives (1), (2), (3), and (4) (see Section3.1) and understanding the critical sediment transport processes. The relationship is established through Objectives (1), (2), (3), and (4) and examines the interaction between rainfall characteristics and sediment delivery/movement. The pattern of sediment delivery during 13 months of study was quantified and linked to cumulative rainfall across specific sediment collection dates.

RQ3: What is the preferred cultivation technique for minimising flood generation, and can this be reliably predicted using hydrological modelling tools?

This question will be answered by achieving Objectives (4) and (5) (see Section 3.1 and 4.1) and quantifying the interactions between cultivation method, sediment delivery and peak flow generation.

1.7 Thesis structure

Chapter 2 – Literature review

Chapter 2 critically examines the current research literature and its relevance to the main topics underpinning this project: climate change, flood risk and NFM. In addition, it provides an overview of the main NFM options and describes the hydrological modelling approach.

Chapter 3 –Experimental methodology

Chapter 3 outlines the methods that were applied to address RQ1 and RQ2. It first introduces the case study catchment, the experimental design, implementation and analyses of empirical data, performance and analyses.

Chapter 4 -Modelling methodology

Chapter 4 outlines the methods that were applied to address RQ3. It discusses the hydrological lumped model, model setup, calibration and validation.

Chapter 5 –Experimental results

Chapter 5 presents the results pertaining to RQ1 and RQ2.

Chapter 6 - Modelling results

Chapter 6 provides results pertaining to RQ3.

Chapter 7 -Discussion

Chapter 7 provides a discussion of all research questions. Finally, it addressed findings on the level of cultivations and sub-catchments findings.

Chapter 8 - Conclusions

The final chapter presents overall conclusions and recommendations for further research. It draws together the main points from the discussion of each analysis chapter and contextualises the results.

Chapter 2 Literature review

2.1 Chapter scope

This chapter aims to establish a framework for the research, define relevant terms, and critically examine work in the field of study. The literature review addresses the following: the link between flooding issues in the United (UK); the implementation of NFM options, including hydrological processes; the evidence-based impact of woodland creation on flood generation, including advantages and disadvantages of using different types of cultivation technique; evaluation on flood control/ reduction by using woodland creation measures; and the evaluation of models that have been used to assess the impacts of NFM.

2.2 Flooding issues in Europe

An increasing number of natural disasters have been reported across Europe by the European Commission, of which flood is one of the costliest [26]. The damage of floods can persist for a long time after the flooding is gone. The European region often experienced floods causing extensive damage and disruption [27]. However, the magnitude of such events' physical and human costs can be reduced if we area adequately prepared [28]. For example, some have been more affected than others. Some of the areas such as north-western Romania, south-eastern France, central and southern Germany, northern Italy, and eastern England experienced recent economic losses due to flooding [29]. Furthermore, a large flood in 2014 affected 1.6 million people in the Western Balkans (Serbia) [30]. This flooding occurred for several reasons, including engineered flood protection failure and non-controlled urbanization.

Given the current magnitude of flooding and increasing flood frequency across the globe caused by global climate change, more research about flood risk reduction is needed. This fact often comes from a lack of possible solutions that consist of complex engineering measures. Regarding this problem, the concept of nature-based solutions was introduced in many European countries as a more sustainable approach to flood risk management [31]. Therefore, its effort should be embedded in the broader risk management context to be monitored and reduce losses from flooding in the longer term.

2.3 Flooding Issues in the United Kingdom

Climate analyses produced explicitly for the UK proposed that floods and drought will affect the UK in higher occurrence. The public and academic auditoriums recognize river flooding increases. More than 5 million people are at risk of surface flooding in the UK [24]. There have been several severe floods in recent decades, including the Carlisle flood in January 2005, flow, and floods in Scotland in 2015 [32]–[34]. The recent increase in flood events across the UK was analyzed by Collet et al. [35], which were defined as “future hot spots” at risk of increased flooding by the 2080s. Other researchers pointed out the same conclusion with respect to small watercourses, especially in Scotland since 1988, with increased values of maximum discharge for many rivers, especially in west Scotland [36]. This suggested that future flood risk depends on essential receptors such as economic development and environmental changes.

Recent UK flooding in winters from 2015 to 2018 implies the importance of natural control floodplain storage, which land management practices should combine to reduce flood risk [34], [37]. Furthermore, the FRM Act 2009 sets a framework for responsible authorities to exercise their functions collaboratively toward the overall reduction of flood risk in Scotland [20].

2.4 Natural Flood Management

FRM Act outlined the Scottish Government's need to minimize flooding effects and use a more sustainable approach to achieve that. Under this Act, SEPA must work closely with local authorities to develop the most suitable measures for reducing flood risk. In compliance with this Act, the introduction and use of Working with a natural process which processes which can be named NFM as well. This is a relatively novel approach to flood risk management, which uses cost-effective, sustainable techniques to create a more integrated, catchment-based approach to managing both land and water [21]. This includes land use change and management to improve hydrological and morphological processes, a prominent example of which is woodland creation. The Scottish Forestry Strategy aims to increase woodland cover from 17.1% to 25% of Scotland's land area by the second half of this century [38]. To realize this ambition requires ~15,000 ha of new woodland to be created per annum, which will help to mitigate climate change, stimulate economic development, and provide other benefits, including sustainable flood management. According to The Scottish Forestry Strategy, upland afforestation can reduce flood runoff by increasing evapotranspiration and soil infiltration [34]. It can also induce lower runoff peaks and extend lag times between rainfall and flow peaks caused by higher roughness [21]. However, there are still a lot of concerns related to the effectiveness of NFM, the location of the applied measure and the measure that will be applied [39].

Relatively recent guidelines published by Environmental Agency promoted the use of NFM to reduce flooding in the subject area [40]. Those guidelines have been developed in correlation with the previously published evidence base that promoted the idea of working with natural processes (WWNP) [23]. Also, the WWNP document provided a synthesis of case studies that have been applied on river floodplains, woodlands, runoff reduction and coasts that has applied solutions for flood risk reduction.

2.5 The approach used in the implementation of NFM options

There are many roles of NFM to consider when answering the question of the impact of NFM on flood risk reduction. For example, implementing NFM measures has different approaches influenced by spatial/catchment scale and size of flood events.

Table 2.1: River and catchment-based NFM measures [21]

Measure group	Measure type	Main action
Woodland creation	Catchment woodland	Runoff reduction
	Floodplain woodlands	Runoff reduction/ floodplain storage
	Riparian woodlands	Runoff reduction/ floodplain storage
Land management	Land and soil management practice	Runoff reduction
	Agricultural and upland drainage modifications	Runoff reduction
	Non-floodplain wetlands	Runoff reduction
	Overland sediment traps	Runoff reduction/sediment management
River and floodplain restoration	Riverbank restoration	Sediment management
	River morphology and floodplain restoration	Floodplain storage/ sediment management

	Instream structure (e.g., large woody debris)	Floodplain storage
	Washlands and offline storage ponds	Floodplain storage

NFM offers much scope for sustainable flood risk mitigation, slowing and storing flood waters, and providing other multiple benefits. Existing measures implemented in the UK context are shown in Table 2.1. Implementation is guided by locational and scale factors. According to this, there is a specific lack of research in quantifying NFM measures.

Woodland creation involves three types of NFM measures: catchment woodland, floodplain woodland, and riparian woodland.

2.5.1 Woodland creation as an effective NFM measure

Woodland creation is a fundamental NFM measure and significantly contributes to climate change mitigation [41]. It can positively impact the hydrological processes of a watercourse through canopy interception and slowing runoff, as well as supplying a range of benefits to the ecosystem, including reducing net carbon emissions, providing shelter to plant life and fauna, and helping in the stabilization of riverbanks [42], [43]. Also, woodland improves soil structure, increases organic material, and has transpiration effects on soil moisture [44]. In addition, woodland creation reduces flood risk through specific fundamental hydrological processes, including increased water use by evapotranspiration [23], enhanced soil infiltration and soil water storage, and greater hydraulic roughness slowing flood runoff [45].

UK Biodiversity Action Plan (1992-2012) set out objectives related to riparian woodlands creation and restoration of the floodplains [46]. These two types of woodland creation were initially encouraged due to the conservation benefits such an arrangement would offer. However, studies by Broadmeadow and Nisbet from 2004 highlighted the important contribution they could make as flood control measures. This arrangement would focus on planting directly in the overland flow path to increase flow resistance, slow the water flow, and lowered water depths within the low-risk forest area. However, this technique is challenging to adopt in areas of high land value (i.e., agriculture) or where river corridors are very narrow and constrained [47]. Therefore, NFM attention is afforded to more comprehensive catchment planting on hillslopes in the floodplain area.

According to McCulloch, woodland creation has been linked continuously with reducing downstream flooding by reducing surface runoff [48].

However, the UK has far less woodland than other European countries. Forest covers just 13% of the surface compared to the EU average of 43%. The Scottish Forestry Strategy [38] aims to expand woodland cover to 25% of the land area by 2050 to provide various benefits, including lowering flood risk in affected catchments. According to SEPA's NFM Handbook [21], there are three relevant types of woodland creation: floodplain woodlands, riparian woodlands, and catchment woodlands. Furthermore, the role of each woodland type is considered below.

Catchment woodlands

Catchment woodland is woodland that includes a catchment area, including all possible types of trees, cultivation techniques, specific forms of sediment management and two other types of woodland (riparian and floodplain woodlands). Potential areas for planting of catchment woodlands are mapped using a wide range of data held by different institutions (such as SEPA, EA, Forestry Research, Forest companies etc.) that provide information about runoff reduction, sediment management, flood storage, most appropriate tree species etc.

The impact of catchment woodland on hydrological processes has been researched for centuries. This was shown in a review by Bosch and Hewlett, which generated an assessment of paired catchment across golpe dated from the beginning of the 20th century [49]. Furthermore, this study included 98 catchments and treated them as paired based on forest and clear-felling. Those catchments have been chosen from the perspective of the same topography and climate. However, an enormous discovery has been provided on the basis that forest cover decreases water yield, and opposite effects have been related to clear-felling. Twenty-three years later, Brown managed to add 72 catchments to the Bosch study for analyses of water yields in paired catchments [50]. Brown's study showed that a catchment needs more than five years to show changes in the new equilibrium. This period applies in the case of afforestation since deforestation takes a shorter period for a new equilibrium. Even though paired catchment studies provided sufficient evidence of the influence of forest hydrology, the variation between catchment topography, annual rainfall, soil type and other conditions would not be identical on the catchment level. According to that, a single catchment case study has become more popular in recent years, and the EA evidence dictionary has summarised them on the UK level [23]. This report highlighted three important catchment woodlands case studies where the Coalburn catchment study has been included as a case study with long monitoring history. However, this catchment provided evidence that in the first 5-year peak flow increases and time to peak decreases by a third. By continuing monitoring of this catchment, it has been discovered that cultivation practices have influenced those peak flow increases in the first five years. However, all research proved that the hydrological process could have a lot of complexity behind it, and that is necessary to have a long-term case study where meaningful insight into forest cover changes can be gained through time.

Traditionally, catchment woodlands have been recognized as an effective measure for slowing aa flow [51]. The Pickering case study showed that the effects of slowing the flow apply to peak flow and effects on its decreases. Decreases of flow peak are higher for smaller events (14%) since less frequent floodings have just a 6% decrease in peak flow. However, there is recent research done by Xiao that looked into the woodland's role in the UK [52]. This study catchments across Ireland, the Scottish border and Wales and compared data before and after the cutting of trees has been done. The main finding applies to the fact that forests can reduce base flow since its impact on the reduction of peak flow decreases in case of larger events.

The influence of catchment woodland on flood risk reduction depends on many other properties. There is constant debate regarding catchment size influences flood generation. So, according to evidence provided by EA effectiveness of smaller catchments (<10 km2) [37]. Also, reflecting on larger catchments is more difficult due to more catchment properties included, but even medium (10-100 km2) and large catchments (>1000 km2) still have the capacity for flood risk reduction. However, just a few case studies have been taken into account for medium and large-size catchments. This highlighted the need for evidence for medium size catchments similar to the Menstrie case study [3].

Some of the global case studies included New Zealand [53], North-West Europe and southern Europe [54], England [55], USA [56] and that have studied the long-term effects (over 6, 15 and 20 years) of woodland establishment on flood flows. New Zealand case study showed that the effects of planting are not apparent until year seven since England And European case studies showed effects after five years. Those two case studies have referred to the peak flow values. On the other hand, the USA researched outflow from two catchments and found out that outflow is lower in the catchment that has a higher percentage of forest in place. However, long-term monitoring has highlighted a lack of knowledge, such as:

- The geospatial component of monitoring is a fundamental consideration for woodland effectiveness. However, there are a lot of properties that should be taken into account for analyses, such as climate, topography, location, vegetation type etc.
- The effect of forestry operations on runoff water since cultivation has been looked at from a catchment perspective and was not researched on a small scale level.

According to available literature for coachmen woodland case studies, there is a certain need for more empirical results that will fill a definite gap in forest hydrology understanding and modelling. Those results can be used further for the modelling and paired catchments.

Floodplain woodland

Floodplain woodlands comprise woodland that lies in the fluvial floodplain and interacts with regular flood occurrences. Unfortunately, potential areas of planting floodplain woodlands are often subject to urbanization or deforestation as they bring the concept of "living by the river" [57]. This concept can bring very diverse effects on one environment. Also, due to this fact, the effects of the floodplain woodlands are more challenging to measure due to many floodplain woodlands being disconnected from the river channel (such as by embankments, flood defence infrastructure etc.).

Empirical studies investigating the impact of the floodplain on flood peaks are very rare in the literature [58]. However, a recently published report by EA showed that the main characteristic of floodplain woodland is slowing down the flow and holding water in fluvial floodplain [23]. This created great potential for floodplain woodlands for downstream flood risk reduction. This. This potential is mainly connected to Manning's coefficient, widely known as hydraulic roughness [59]. Research from the Tisza River in Hungary indicated that the hydraulic impact of the floodplain is controlled by vegetation density, height, and structure [60]. On the other hand, various studies have modelled the effects of the flood plain using 1D and 2D models [61], [62]. Thomas and Nisbet [63] study that researched the establishment of flood plain at River Cary in the length of 2.2 km showed a delay of flood water of 140 minutes and 71% increase in flood storage. Another study by Connell, modelled floodplains in Central Wales [64] showed that floodplain woodland decreased peak flow.

However, modelling evidence of floodplain woodlands suggests [23] the following:

- extension of flood hydrograph that causes attenuation of the flood water and slows the flow in the downstream area
- higher rate of water use by trees and practical flood storage
- possible backwater effect, which can extend upstream up to 400 m and has the benefit of delaying flood water downstream

Alternatively, better floodplain woodland under-testing can be done through the involvement of more receptors. This can be related to seasonal vegetation changes, detailed replication of different species in the floodplain area, etc. However, this can be hard to measure and quantify in the model and certainly creates a gap for future research case studies.

Riparian woodlands

Riparian woodlands are located in riparian zones immediately alongside watercourses, streams, lakes etc. According to this, riparian woodland usually comprises a narrow area and often can be extended to both sides (<5m) of a stream or watercourse. According to EA's main report role of riparian woodland is to slow down the flow, sediment management and reduction of riverbank erosion [23]. However, there is very little evidence in empirical case studies for riparian woodland effects that has usually been researched on the whole area of the catchment. According to catchment studies by Broadmeadow highlighted, the benefits of riparian woodland are connected to sediment management, erosion control and water quality control [47]. Furthermore, few empirical studies have monitored the effects of riparian woodland establishment on flood flows, although modelling demonstrates the scope for flood peak reduction, including for significant flood events [65].

The best source of data was the effects of riparian woodland provided through modelling. According to Orellana [66], the MIKE SHE models predicted that planting in the riparian zone (9% of catchment) led to a 2% reduction in the most significant flood event (100 years return period). In contrast, the application of a spatially distributed model of the Lymington River catchment by Dixon [67] found that restoring the riparian zone (40% of the catchment) reduced flood peaks by 19% observed through de-synchronization of the timings of sub-catchment flood waves.

These previous modelling studies highlight the importance of riparian woodland placement, suggested that reducing flood water by physical obstruction [63]. However, an essential measure for streamflow reduction is widely known as Large Woody Derbies

Dams. There are many types of LWD, including natural dams, semi-natural dams, and engineered and semi-engineer [68]. According to the literature, LWD can have diverse effects if not fixed in the riverbed by following downstream and causing damage. Their stability is still under research [69]. However, this approach can add to the complexity of modelling riparian woodlands, and that might lead to the conclusion that more conceptual models should be involved to understand the processes involved (soil type, vegetation type, catchment slope, species choice etc.)

2.5.2 <u>Land management practices as NFM measure</u>

Significant changes in land use in the UK have happened in the past seventy years and have been driven by different UK policies [70]. Land practices will be used for changes in the landscape, and Scotland's Third Land Use Strategy (2021-2026) highlighted the importance of land use changes at the rivers and water bodies level [71]. Furthermore, this strategy sets out the long-term measures for sustainable use of the land in Scotland. However, UK Forest Standard Practice Guide that was recently published refers to designing and managing forest and woodland areas to reduce flood risk [72]. Likewise, this guide considered land management practices for forest cultivation by expanding benefits of its. According to that, adverse effects can be reduced by using suitable cultivation types to reduce the immense runoff. This includes less invasive cultivation types such as mounding and implementation of downslope furrows. All of this complemented the natural flood management manual (C802F) recently published by CIRIA, which provided many examples related to land management practices in the UK that have been used for forest and agricultural lands [73].

According to the literature, the design of the land management practices in the agricultural and forest field might have a crucial influence on not creating adverse effects by using them [74]. Adverse effects can refer to soil erosion [75], loss of land [74], increases in runoff [76] etc. On the other hand, land management can reduce surface runoff through improved soil infiltration, increased water storage and reduced erosion [80]. Example case studies of land management from the UK perspective are limited. Examples of those case studies are Loddington Case Study (Leicestershire) and Pontbren Case Study. Loddington Case Study discover that minimum couture cultivation can influence downstream flood risk [76]. On the other hand, Pontbren case study discovered an important lesson for community engagement in the hydrological process where framers implemented measures on their land [77].

Examples from USA include a field study from Missouri that shows the significant effect of cover crop management practices on soil hydraulic properties by increasing saturated hydraulic conductivity over time [78]. On the other hand, a study from Artés introduced forest evolution in Spain over 50 years in a 6632 km^2 size catchment and found the importance of using effective and sustainable forest management practices [79].

Furthermore, a four-year monitoring UK-based study in the Bowmont catchment, Scottish Borders, suggested using specific wooden structures and showed a decrease in erosion and sediment disposal in the widening channel that causes delays in runoff water [80]. Soil and crop management measures, runoff control features, agricultural and upland drainage modifications, non-floodplain wetlands and overland sediment traps are all examples of potentially effective land management techniques [81]. Lastly, land management practices can be used as an effective measure for forest land management. However, the forest design must be carefully considered using a forest guide and lessons learned from previous case studies.

2.6 NFM and runoff water changes in woodland areas

The Scottish Forestry Strategy outlines the Scottish Government's goal for woodland expansion [38]. The dual interest shared by NFM mandated by the EU and the Scottish Forestry Strategy creates favourable political conditions for woodland creation within Scotland to meet both guidelines of the Floods Directive and fulfil a country-specific goal [82]. Afforestation, therefore, represents a prominent measure within the NFM strategies. Managing runoff water in woodland areas as part of NFM measures has become popular in the UK. This is often seen as a sustainable solution in the management of flood risk downstream. However, NFM is commonly defined as:

> "Techniques that aim to work with natural hydrological and morphological processes, features, and characteristics to manage the sources and pathways of floodwaters. These techniques include the restoration, enhancement and alteration of natural features and characteristics, but exclude traditional flood defence engineering that works against or disrupts these natural processes" [21]

NFM has two overarching goals: reducing maximum flood peak by attenuating flow downstream [83]. These two concepts prevent flooding downstream. Projects installed upstream of the flood risk and appropriately located are likely the most effective [23]. According to Iacob, researched 25 forest and woodland schemes. There is a significant relationship between afforestation and flood peak attenuation referring to different return periods where greater potential is found for smaller events [84]. However, NFM strategies rely on one or a combination of underlying mechanisms to lower flood peaks and attenuate flows. The following mechanisms are important:

- Soil infiltration: increase infiltration to reduce overland flow [85],
- Water storage: using the capacity of ponds, ditches, reservoirs, channels, or soil to retain flood waters and accentuate the time for the main channel to reach peak flow [42], [86],
- Slowing the flow: increasing resistance to flow to limit overwhelming the main channel [31], [54]

However, afforestation also brings the following benefits: infiltration of runoff water upstream that causes reducing flood risk downstream. Furthermore, the presence of the trees in the catchment increases evaporation, interception, and infiltration. However, the tree attenuates the time taken for rain falling in the catchment's upland reaches to the river, lowering the peak flow and extending the lag time in the storm hydrograph [21].

Looking from the perspective of hydrological processes influenced by trees, it is possible to define four important processes: evaporation, transpiration, interception, and evapotranspiration [87]. Figure 2.1 represents the key processes. However, the central role of afforestation is in increasing infiltration. Furthermore, infiltration can be related to many other processes, such as the time of the year [88], tree species [80], soil type and morphology [88], etc. Still, those processes can be beneficial for downstream flood risk reduction.

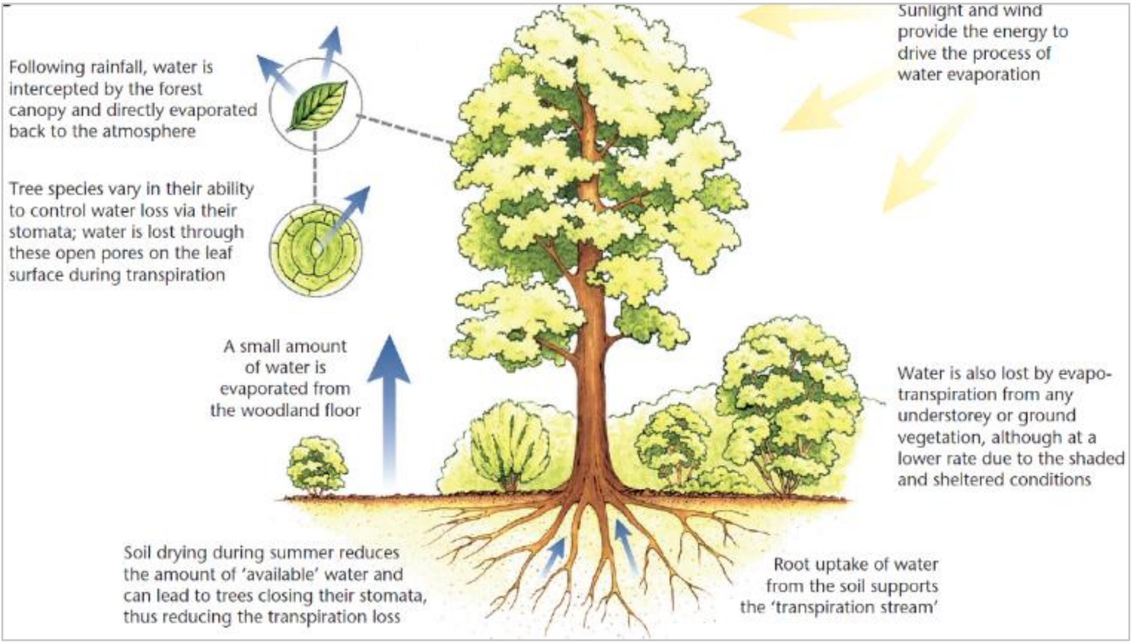


Figure 2.1: Water use by trees [87]

Lastly, the systematic review by CEH of 80 case studies provided evidence that increasing tree cover will decrease flood peaks [89]. Furthermore, this review showed that only modelled data would provide sufficient evidence of decreeing flood peaks by increasing woodland cover will decrease flood peaks. Lastly, considering other woodland properties, such as forest management practices, definitely needs more research.

2.6.1 Evidence-based on the impact of afforestation

Woodland expansion is a nationally and internationally recognized measure with a limited assessment of its benefits (see Section 0). In addition to that, this section will explore evidence that has been provided in the literature related to afforestation from the UK and global perspective. Globally, the potential benefit of mitigating floods by afforestation at the catchment level was recognized 40 years ago [90], [91]. After four decades of research, many controlling variables have been identified on the catchment and sub-catchment levels. However, this fact makes the quantification of woodland benefits more challenging.

The study by Farley [92] analyzed 26 catchment datasets with 504 observations over 20 years located in Africa, New Zealand, India and Europe, which included annual runoff and low flow. They found that grassland conversion to forestry (any species) resulted in a yearly runoff reduction of 44 % (+-3%). In addition, they found that the reduction in runoff was related to mean annual precipitation (MAP), where the largest absolute impact was founded in high-rainfall areas (Figure 2.2).

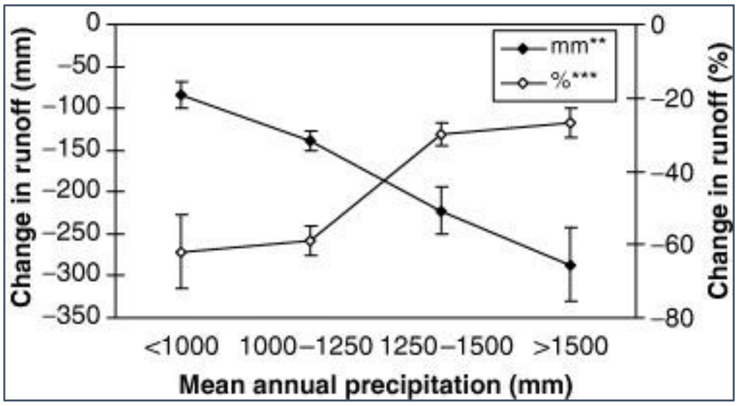


Figure 2.2: Mean change in runoff following afforestation as a function of mean annual precipitation for sites that were initially grasslands [92]

A similar study was undertaken by using data from 98 catchments in Africa, the USA, Japan, Canada, Australia and New Zealand [49]. It was found universally that afforestation decreases the annual water yield in downstream catchments while deforestation increases it. The average size of the catchment used in this study was 80 ha. Forest expansion is, therefore, commonly accredited with the decreased runoff seen in the Iberian Peninsula. Further, Furthermore, a recent study by Buendia [25] investigated a Mediterranean upland catchment called the Ribera Salada, located on the Iberian Peninsula and revealed that an increase in forest cover could reduce streamflow, including peak flows. The catchment underwent a significant land-use change in forest cover between 1957 and 2009. As in previous studies, afforestation was associated with runoff reduction (annual decrease in streamflow was around 20%). Within a similar time frame, Gallart and Llorens found a decrease in discharge from the River Ebro of up to 40%, again attributing this to natural afforestation [93]. Those two case studies refer to the Iberian Peninsula. A more recent global study by Bathurst considered four catchments from different corners of the world, including UK-based catchments [94]. However, it has been discovered that more forested catchment has lower peak discharge magnitude for a given return period. Also, there is a higher influence on peak discharge in the case of lower flows. The study by Ranzi [95] investigated the effects of afforestation in the Mella River catchment in the Italian Alps. Climate change and other anthropogenic influences have significantly impacted recent history. For example, the 311 km² catchments were afforested within the upland reaches. At the same time, due to the lack of demand for wood as a resource, cultivated areas became smaller as forests naturally grew without being felled. Ranzi found that the surface runoff changes significantly over the study period due to natural forest growth. However, Ranzi recorded reduced flood peaks and volumes. However, all previously explained studies have highlighted the importance of extending the numbers of the catchment to confirm further phenomena that have been discovered. More recent research related summarised the findings of 75 studies in Chile [96]. However, it was possible to identify twenty gaps related to a lack of basic information about forest cover (this also included basic hydrological processes). Identifying a clear trend within NFM literature is complicated by such unpredictability.

Researched examples of small-scale afforested catchment studies include the Pontbren catchment in Welsh uplands of 12.5 km2. This catchment has been well instrumented, and forest cover was 7%, so it was used for testing scenarios of the forest cover expansion [97]. On the modelling scale, peak flow was found to be lower by increasing afforestation in the catchment. On a similar scale to the Menstrie catchment (12 km2), case studies include two Balquhidder experimental catchments: the Krikton (6.8 km2) and Monachyle (7.7 km2) [76]. Two models (TOPMODEL and IHACRES) were applied to investigate the different responses to land use change (0-100 %). Both models predicted that afforestation decreased the quantity of runoff. A further case study in Plynlimon also involved a comparison of two catchments [98]: the two-thirds afforested Severn (8 km^2) and moorland upper Wye (10 km^2). Water usage was 21% higher, and flow peaks were lower in the Severn catchment compared to the Wye catchment.

Significant effects on flood flow at small-scale catchments can be identified from academic literature when moving from intensively farmed catchments to moorland. Simulations indicate the potential benefits of afforestation can be significant at that scale in terms of reducing flood peaks and sediment yields. At larger scales, impacts on flood flows could not be consistently identified from monitoring data. Calder and Newson's work resulted in a generally accepted rule of thumb that 10% of an upland catchment that was covered by the mature forest would reduce water yield between 1.5-2% [99].

Notably, the above studies did not consider the impact of cultivation practices and felling operations on stream flow, which can exert significant power over the potential flood management benefits. These aspects are considered below.

2.6.2 Impact of afforestation on land management processes in hydrology

The studies described in previous sections stem mainly from specific measures implemented in relatively small, disconnected pockets of a catchment. Due to short record studies dominating the literature, predicting long-term environmental changes and isolating afforestation's impact is challenging, mainly because ecosystem services do not correspond in space and time [100], [101].

Most studies reported in the literature were short-term investigations or in the process of monitoring [3]. Therefore, predicting long-term environmental changes or isolating the impact of afforestation is challenging, mainly because ecosystem services do not correspond in space and time.

Thus, without outcomes from long-term studies, the under or overestimation of the potential impacts of afforestation on flood risks is likely. Roberts [102] predicted that over 50% of UK current planted woodlands might increase runoff, to the detriment of flood risk management. Therefore, the impact of afforestation cannot be assimilated without investigating pre- and post-planting procedures [98].

Initially, the effects of afforestation are dominated by pre-planting processes, namely cultivation and drainage. Stott and Mount [103] reviewed UK plantation forestry and its impacts on sediment yields and downstream channel dynamics. They separated the phases of forestry and their associated effects. The initial ground disturbance phase increased runoff: the catchment recovered as the forest matured and the canopy closed. However, overland flow increased significantly during felling [104]. The forest cycle in the British uplands often began with ploughing as the process was often cheap, fully mechanized, and quick to implement. However, the creation of deep furrows has been found to increase surface runoff and channel flow, potentially increasing downstream flooding [96].

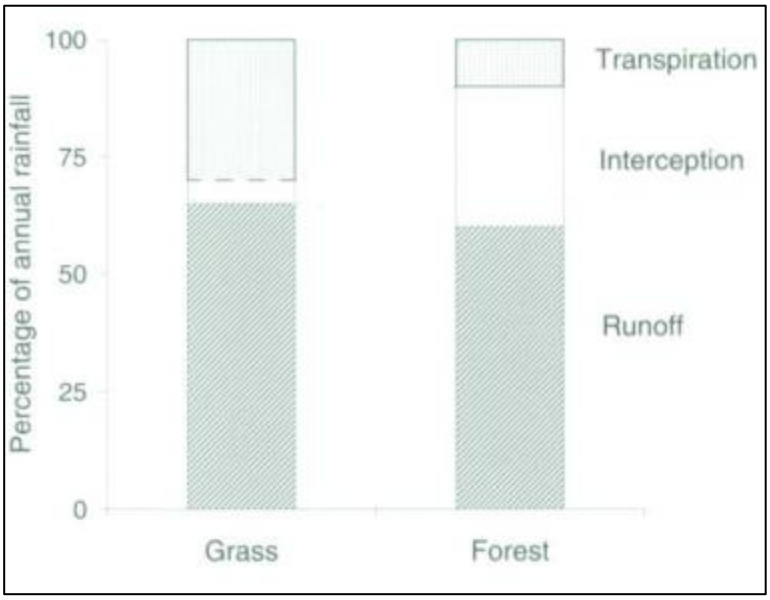


Figure 2.3: Summary of hydrological changes at Coalburn, from the grassland to the forest. This generalised schematic shows the change in water balance in that interception became a more significant proportion of the annual rainfall, resulting in a smaller percentage converting to runoff [105]

Over a 20-year observation period, Robinson [105] found that the peak flow from the catchment increased up to 15-20% immediately after a site was grassland ploughed for forest planting. This change in peak flow decreased by only 5% across the 20-year observation period. Although site-specific, this long-term study reveals the potential impact of ploughing to reverse the benefits of afforestation for a significant period of the forest's life cycle. Similarly, in Scotland, the Coalburn catchment was ploughed in the 1970s in preparation for afforestation, removing the moorland. This cultivation process is thought to have increased the annual water output of that catchment by 70 mm and temporarily reduced evaporation losses (Figure 2.3). As a result, the water was no longer pooling on the moorland; rather, it channelized within the furrows of the plough lines. The long-term record of this site shows that the water yield remained slightly higher (5-10%) than the baseline moorland period for 20 years after complete afforestation [105]. The water yield declined only 1-5% once the forest was 25 years. This equates to half the life cycle of the wood resulting in higher water yields from the catchment due to the combination of removing the moorland vegetation and the slow closure of the canopy, attributed to limiting climatic conditions [105].

Hudson's [106] study of Llanbrynmair catchments, Wales, found water yield increased after extensive cultivation, similar to Coalburn [105]. That was, however, followed by a much quicker environmental recovery, resulting in the water yield-reducing before the forest was ten years mature. The difference could be associated. This difference could associate with the changes in guidelines on how cultivation practices methods were implemented in the field after 1988. This mainly refers to abandoning the use of the deep plough. They again emphasize the importance of site-specific hypotheses, which were similar between Coalburn and Llanbrynmair catchments according to soil type (predominantly peaty soil), planted areas (approximately 90% for both) and some small areas that had to be replanted over the years. Contrasting with the results reported by Hudson and Johnson, Bird found that in the first two years of monitoring, the water yield level decreased by 90% [106], [107]. In this case, they did not find that the initial land management processes had long-lasting negative impacts on flow peaks. Other academic studies have highlighted the destructive nature of the end of a forest's life cycle upon catchment hydraulics. These conclusions, again, were connected to specific catchments with specific climate variables.

Nisbet and Thomas [43] found that clearing the forest had the most extensive negative consequences on downstream flow. They found that the process of clear-felling likely increased runoff for up to 15 following years. Runoff only subsided once the catchment was replanted and the canopy closed. The impact of felling for timber harvest is likely to have the most significant impact due to the more considerable infrastructure demands beyond the cutting down trees, i.e., roads and the use of large trucks. This activity increases runoff because the soil can become compacted and further degrade. The weight of truckloads disturbs natural hydrological cycles. Researchers in the early 1980s and 90s investigated the impacts of small upland afforestation and found that moorland ditching, road construction, clear-felling and tree growth caused significant sediment load changes into catchment [103], [108]. Siriwardena [109] studied the effects of clearing 16,500 km² of natural forest in Queensland, Australia. They measured a 78% increase in runoff due to this deforestation, although some have attributed this to a general increase in rainfall. They modelled the forest and clearance for this trend and found that even after accounting for the effect of the increased rain, deforestation increased runoff by 40%.

Hewlett and Helvey [110] reported a detailed experiment in which two catchments in the humid Appalachian Mountains underwent a land-use change. In one of the catchments, 0.44 km² in size, the mature hardwood forest was clear-felled after 18 years of field data collection, including 77 storms. After felling, the stormflow volume in the 30 flood events monitored in the three-year treatment period increased by 11% and the mean peak flow by 7%. Ziemer [111] found similar results and showed how clear-cutting 67% (471 m^3/ha) of the total timber volume in the South Fork catchment, California, with a drier climate, produced a 4% increase in the peak flows after logging. Burch [112]studied two small catchments of south-eastern Australia with an even drier climate and found the effects of complete clearing of the eucalypt forest increased total runoff volumes for most of the 12 storm events selected for investigation. The storm response was similar in the two catchments when initial soil moisture conditions were close to saturation.

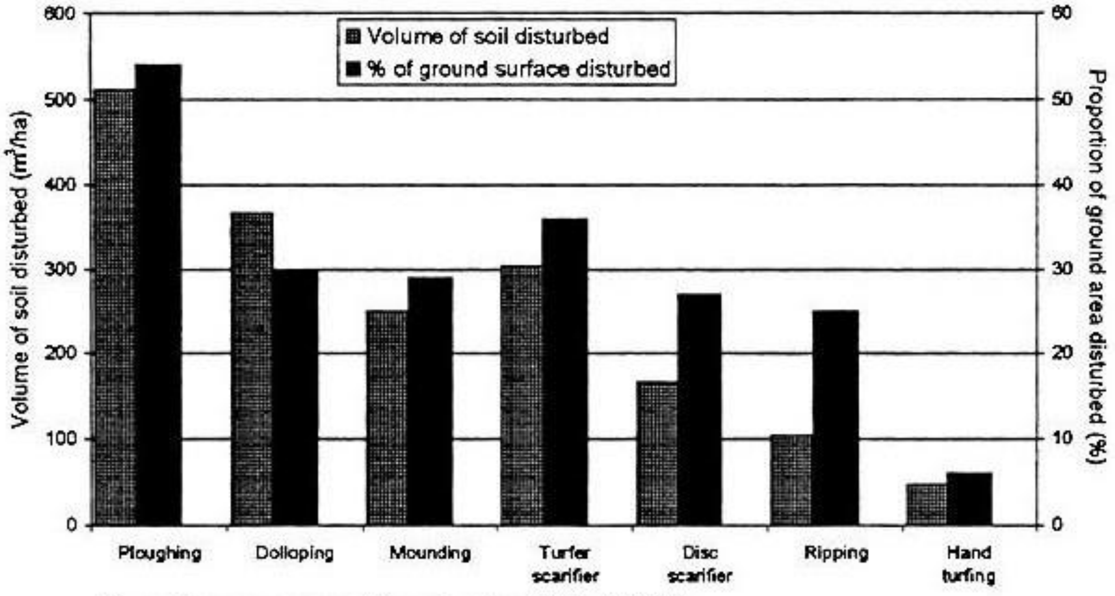
The removal of the tree does not eliminate all water use by trees. Studies have shown that replacing an old growth stand with a young one can result in a marked increase in water use [113]. The remaining water use depends on whether the tree is on the forest floor—the better the undergrowth, the lower the impact of felling on the catchment hydrology. Johnson's [98] study of a catchment at Balquhidder, Scotland, showed that if a thick pile of the brash remains after felling, it can intercept as much as 15% of annual rainfall. Calder and Newson [114] found that gradual planting over several years, cultivating the plantation at shorter intervals and smaller plantation areas, may be preferable to planting the catchment at once and clear-felling together. Cornish [115] found that clearing a forest that makes up less than 20% of a catchment will unrecognize the change in water yield. When forest thinning occurs, for example, in Calder [116], removing every third row of trees resulted in a decrease of 2% in inception rates. This rate of loss is minor. Predominantly, this is thought to be due to the ability of the remaining trees to grow and rapidly close the gap in the existing canopy.

Academic literature has generally found that falling less than 20% of a catchment will have a negligible impact on water yield. In the UK, government funding for long-term experimental studies is limited. Therefore, very few schemes have been applied at a suitable scale or measured for long enough pre- and post-planting to provide conclusive evidence of their effectiveness in reducing flood risk. Even with a more considerable evidence base, unpredictability remains, and new monitoring and modelling techniques will be needed to inform the decision-making process.

2.7 Sedimentation and NFM process

Menstrie case study examined sediment delivery from different cultivation plots. By following the development of woodland creation, it is necessary to understand the complex process of a hydrological relationship between forest development and sediment movement. Examination of this relationship was researched in the past, and several studies record the negative impacts of afforestation in the early stage. This includes effects on water supplies caused by high suspended sediment concentrations [82].

During the early stages of tree growth, immediately after cultivation, there can be an increase in sediment runoff and sediment load within river catchments (Robinson et al., 1998). The study by Worrell [117] found that the amount of sediment generated varied between cultivation techniques. From a soil perspective, the most disturbing cultivation practice was ploughing, followed by excavator mounding and hand screefing, which disturbed the least (see Figure 2.4). In addition, creating deep plough furrows has increased surface runoff and channel flow, potentially contributing to more significant downstream flooding.



Figures shown are averages of examples given in Worrell (1996)

Figure 2.4:Disturbance of the upper ground layer by different cultivation techniques [117]

Furthermore, ploughing accelerated the rate of runoff and demonstrated a shorter time to peak alongside an overall rise in peak flows. This is illustrated in a study by Birkinshaw within the Coalburn catchment, Kielder Forest, Northern England, one of the longest-term studies (40 years) of non-stationary hydrology during forest plantation and growth [65]. For instance, results indicated that ploughing increased annual streamflow by 50 – 100 mm compared to the original upland grassland vegetation [79]. This exemplifies the non-stationary hydrology of a catchment during the forest plantation cycle, resulting from a rise in intercepted evaporation and reduction in discharge with increasing tree development.

Since soil disturbance plays a crucial role in sediment delivery during the early stage of forestry development, changes in cultivation practice and design [118] can influence sediment losses. A significant change introduced by the Forestry Commission was retaining a buffer strip at the end of the ploughed area (Chapter 3- Figure 3.7) to collect and retain sediment. Strategically placed buffer strips can effectively mitigate the movement of sediment and nutrients and slow runoff [119].

Alternative methods of cultivation, such as hand screefing and excavation mounding, because much less soil disturbance but cost more, so economics can often be a limiting factor [21]. However, these techniques are required on more sensitive and complex sites to control the risk of sediment runoff, such as on the steep ground.

2.8 Hydrological modelling and selection of models

Hydrological processes over catchments can be explored from the NFM perspective (such as the reduction of flooding). Hydrological models allow understanding different hydrological processes related to land-use changes due to longer prediction. For example, they can predict possible scenarios due to the number of complexities involving a highly nonlinear process within a hydrologic system. The inputs and outputs of a hydrological model draw on measurable variables structured through a set of linked equations. The collection of equations that transform the inputs into outputs is known as the system transformation.

According to Chow [120] transformation of a hydrological model selection depends on several factors that can be summarised in five key points:

- The space-time distribution of evaporation and precipitation,
- The topography of the catchment concerning the magnitude and direction of slopes,
- The vegetation cover, land use and agricultural practice,
- The hydro-geological properties,
- The conductivity, porosity, and storage capacity of the underlying soil.

Those points indicate that hydrological modelling can have a variety of objectives, depending on problems that need to be investigated further. Singh and Woolhiser [121], among others, summarised the different aims of hydrological modelling as follows:

- Extrapolation of measurements connected to space and time,
- Improvement of understanding of the model to assess the impact of change, such as land-use change,
- Development of a completely new model or modification of the old one.

There are two main types of models [122]:

- Basic lumped models treat the catchment as a single entity with constant physical characteristics and input values. This model also applies to the study of small catchment and sub-catchment areas (< 1 km2).
- Semi-distributed models are a variation of the lumped model approach. In the case of semi-distributed models, the catchment is split into slightly smaller sub-basins, each with distinctive physical characteristics and input values [121]. A semi-distributed model can, therefore, represent the essential features of the catchment while at the same time requiring fewer data and lower computational costs than fully distributed models.
- Distributed models are the most complex model in hydrological modelling. Distributed modelling splits the catchment into many small sub-basins [66]. This can be done using a grinding method, flow planes, hydrological response units, or triangulated networks. At the same time, all distributed models use average boundary conditions and catchment characteristics. This approach provides more information on how the hydrological system operates within the catchment and is more applicable to the larger catchment scale.

Hydrological models can be deterministic or statistical. The issue of uncertainty is addressed in Chapter 4 and Chapter 7 in relation to the specific model used in this research study. The following figure (see Figure 2.4) shows the difference between the three modelling methods in the context of the Menstrie catchment area.

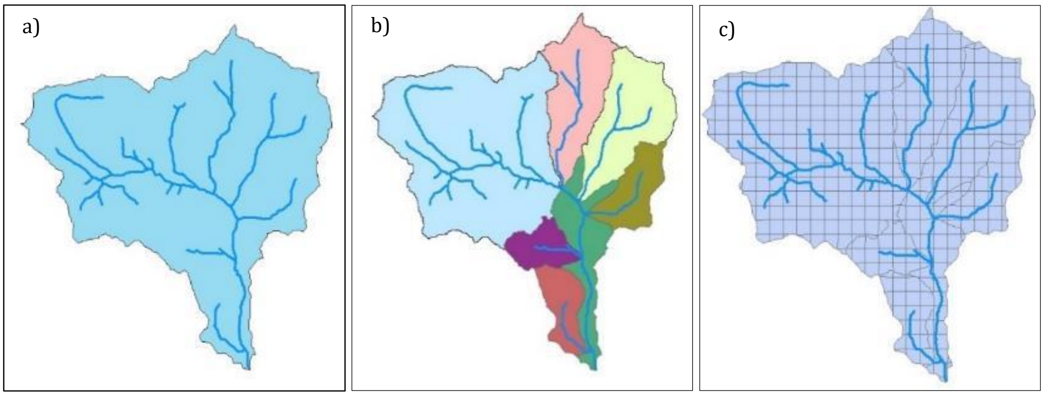


Figure 2.5: a) Lumped model b) Semi-distributed model c) Distributed model developed in Menstrie catchment

Commonly used models such as the SHETRAN model [123] and the GR4H model [124] are freely available. The SHETRAN is a physically based spatially distributed hydrological model that can simulate water flow, sediment transport and solute transport in the catchment [125] at the daily or hourly time step. The SHETRAN model requires a detailed digital elevation model (DEM) where inputs are from 50 m to 5km. Furthermore, this model requires a land cover map, time series of rainfall, evapotranspiration and a delineated watershed. Also, the approach of this model is that grid cells can be used in different sizes depending on the DEM availability in the catchment. Then, the grid cell will influence uncertainty and possible overland flow simulation [126].

GR4H is a lumped hydrological model used by numerous scientists worldwide [3], [127]. The GR4H model is a variation of the GR4J hydrological model [128]. Both models come under a chain of airGR models created and developed by IRSTEA, France, in the early 1980s. The GR4J model is a daily rainfall-runoff model and comprises four input variables: precipitation, temperature, potential evapotranspiration and flow. The GR4H model is an hourly adaption of the GR4J model and focuses on four parameters: production store capacity; water exchange coefficient; one-day maximal routing store; and the unit hydrograph, denoted by '$x1$', '$x2$', '$x3$' and '$x4$', respectively [124].

By contrasting both models, this research study considers and implements a GR4H lumped hydrological model to analyze the hydrological performance of the selected Menstrie catchment monitoring areas. The lumped model was chosen due to the small size of the Menstrie catchment and component study areas, as well as due to the short period of observations (two years of monitoring). However, there are many different types and variations of lumped hydrological models. The lumped hydrological model selected for this study is the GR4H model (using hourly time step), a change from the more widely known GR4J (using daily time step) model because of the hourly availability of data in this study.

2.8.1 Modelling on microscale monitored areas (< 2 km2)

Modelling on microscale monitored areas has been considered in this section due to research monitoring in Menstrie catchment that has been done on a microscale for cultivation practices and sub-catchment areas.

According to a recent report published by the EA, there are few studies based on field data in new woodland creation areas [23]. So far, seven UK-based studies have been presented in the report related to woodland creation, reflecting the increasing difficulty of measuring flows, controlling land use change and ensuring watertight conditions as catchment size increases. However, modelling studies predict that catchment woodland can reduce flood flows at this scale. Furthermore, there is a certain lack of evidence of any cultivation types (plough, excavation mounding and hand-screefing) modelling. On the other hand, modelling of woodland about medium size catchments (10-100 km2) showed medium scientific confidence and suggested that not many independent studies have been established as evidence of flow water reduction for this size of catchments [23]. Nevertheless, as was identified in the Menstrie catchment study was the only one in Scotland related to microscale monitoring and modelling of different cultivation (< 1 km2) and sub-catchment areas (< 2 km2) [3].

Nevertheless, few research papers assessed relevant microscale modelling in the GR4H model. For example, Viville [129] used an early version of GR4H [143] in the Strengbach catchment in eastern France for comparison with TOPMODEL in flood generation. This catchment was afforested mainly with Norway spruce (65% of the area), whose total area of the catchment is 0.8 km2. In this study, the GR4H model was used to simulate the performance of the high-flow event in the catchment area and compared it with TOPMODEL's performance. Both models showed satisfactory performance for the modelled event determined by comparison to measured data.

Furthermore, the GR4H model has been successfully constructed to represent catchments in Europe and New Zealand [130], where similar catchment characteristics and weather conditions occurred to the Menstrie catchment in the Ochills. There are a few more studies [131]–[133]that have implemented the GR4H model and used an array of data for small catchment areas. However, the GR4H model is not used to analyze and compare the effects of different cultivations on runoff water in the hillslope catchment. Moreover, specific research questions were assessed through analyses in Chapters 5 and 6. Those analyses and GR4H model output aimed to explore the broader application of this research and answer all posed research questions.

2.9 Summary of research gaps

The following gaps were identified in the research literature:

Catchment woodland:

- There is a lack of field evidence related to the woodland's role in flood risk reduction for small catchments and sub-catchment areas provided by empirical data [23].

Cultivation techniques:

- There is limited field evidence of the effects of different cultivation techniques on flood generation.
- Plough cultivation, excavation mounding, and hand-screefing cultivation techniques were never monitored in Scotland's sub-catchment areas. This suggested insufficient evidence in hydrological signatures.
- There is limited evidence of sedimentation from different cultivation [117].

Modelling data:

- There is a lack of studies that use data from the field for modelling of hydrological effects of different cultivations (and sub-catchment areas on their extent). Cultivation is researched on a scale of the catchment, not smaller scales or plots [23], [105].
- There is a lack of studies that use the GR4H model for modelling small catchment areas (< 2 km2). However, only a few case study has been founded on this level [129]–[131].

In terms of modelling the impact of different cultivation at the catchment scale, work for this thesis was identified as the only research in Scotland. Studies are lacking.

Chapter 3 Experimental methodology

3.1 Introduction

A lack of understanding of how NFM processes related to hydrology and geomorphology interact was identified in Chapter 2. Afforestation was acknowledged as an NFM approach, and lack of knowledge is evident in the absence of hydrologically based field evidence connected to different cultivation techniques. Furthermore, academic research surrounding afforestation has been dominated by un-validated models predicting hydrological gains from runoff reduction, flow attenuation, and flood storage [108]. This study in the Menstrie catchment documented the hydrological implications of cultivation practice. In turn, it acts as a quantitative study depicting the impact of early-stage forest development from cultivation, drainage, and maintenance, canopy closure, thinning, felling, and restocking. By achieving the research aim and objectives, the present research will improve understanding of the contribution of NFM to reducing flood risk for impacted communities through better databases, catchment modelling and working practices.

Very few studies [44], [92] have been monitored at a suitable scale or measured for long enough pre- and post-planting to provide conclusive evidence of their effectiveness in reducing flood risk. However, even with a more considerable evidence base, unpredictability remains, and new monitoring and modelling techniques will be needed to inform the decision-making process. To achieve a fuller picture of the potential consequences of an afforestation project, one must consider the broader implications of afforestation when used in the context of NFM.

Finally, this chapter sets out the methodology and analyses undertaken for RQ1 and RQ2. Regarding addressing field-based overland flow and sediment experiments assessing the effects of different cultivation techniques, RQ1 (How does sediment delivery from each cultivation technique change over time?) has been pursued. Detailed experiment design and locations are outlined below. The experimental design and installations are complete and followed by an outline of study variables. Data analyses were carried out to address RQ1. Furthermore, regarding field-based experiments assessing the effects of different cultivation techniques on sediment delivery, RQ2 (How does sediment delivery from each cultivation technique change over time?) has been pursued. The sediment experiments are outlined similarly to overland flow experiments. The experiment location was described and explained in relationship with RQ2.

3.2 Case study catchment

This research study was located within the catchment of the Menstrie, which has an area of c. 12 km^2 and is situated in Clackmannanshire in Southeast Scotland (see Figure 3.1). The uppermost reaches of the catchment lie 5.3 km from the outlet of the Menstrie river, where it joins the River Devon with the River Forth some 2.5 km to the south. The catchment lies on the western face of the Ochil Hills and is surrounded by Loss-Hill, Dumyat, Myreton Hill and Consular Hill. Relatively steep slopes (~ 45 degrees) immediately below the catchment drain into the Menstrie catchment. The soil geology of Ochil Hill is predominately rocks of Devonian age since the oldest rock are early Devonian Ochil volcanic formations [134]. The catchment comprises the Menstrie and a series of smaller tributaries, including Inch 1, Inch 2, and Inch 3. The Menstrie catchment drains to the Menstrie village, with a population of 2800 people [135].

Three bridges cross the Menstrie river: the Ochil Road bridge, the A91 road bridge, a vehicle access track, and a footbridge in the village [12]. All have a sufficient capacity for high flows and, thus, a relatively low risk of blockage [135]. With the village at the foot of a broad glen, the area has experienced various flood events over many years, most significantly in August 2004, September 2009 and August 2012 [136]. According to SEPA, the Menstrie catchment is potentially vulnerable to flooding due to the site's flashy rainfall-runoff characteristics and steep slopes. It has been established that the area is at risk from surface and river flooding. This represents a more significant risk due to the nature of the many burns and watercourses [12], [135]. A flood map (generated by SEPA [136]) represents the area deemed to be vulnerable to flooding from the river and surface flooding in Menstrie village and surrounding villages.

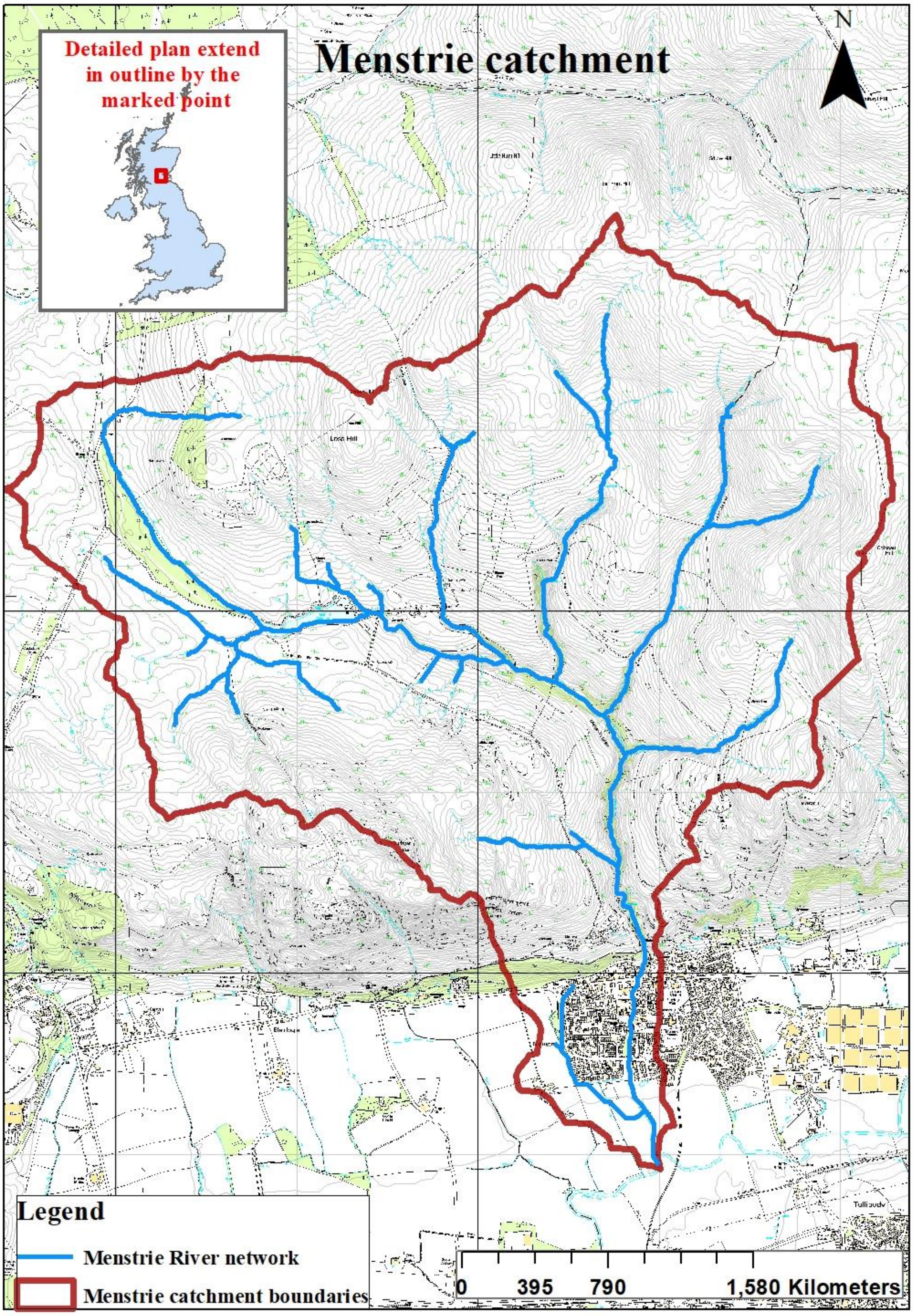


Figure 3.1: Location of Menstrie catchment with the river network

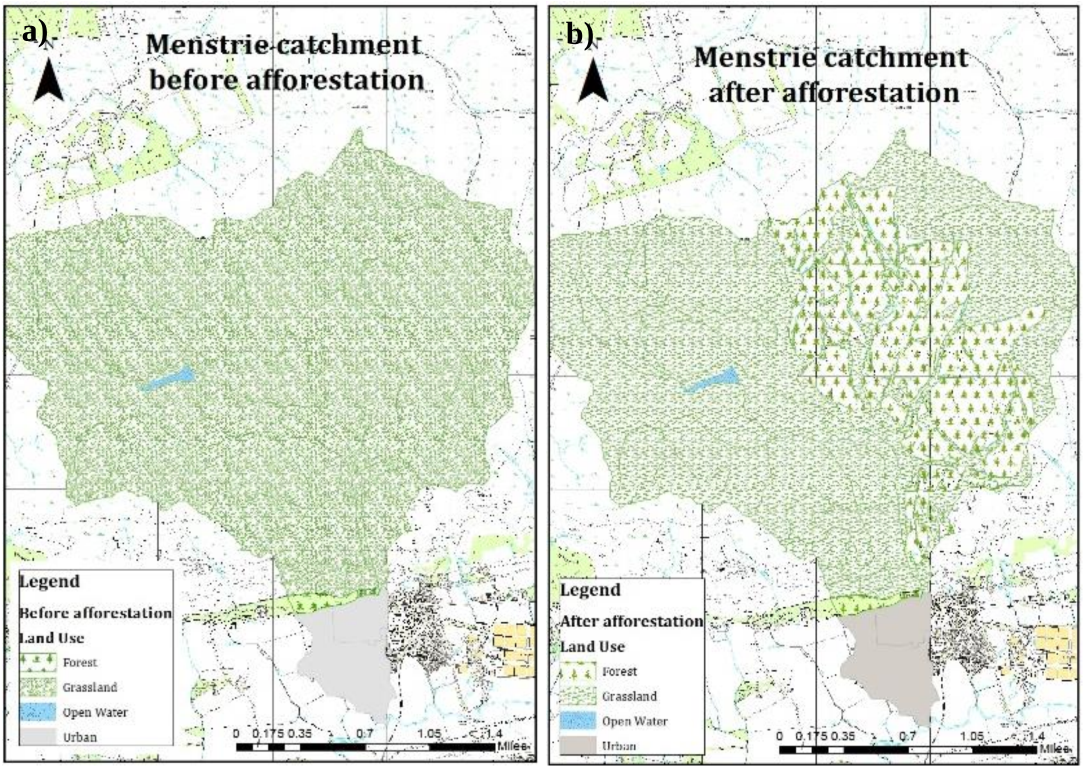


Figure 3.2: a) Menstrie catchment before afforestation b) Menstrie catchment after afforestation

The Menstrie catchment was the location for the Jerah project [137], involving a sizeable commercial woodland creation scheme undertaken by TillHill Forestry in 2015 (consisting of up to 1.3 million trees) covering around 998 ha of land or 27 % of the Menstrie catchment. Figure 3.3 illustrates the Jerah project timeline and woodland creation development (see project boundaries in Figure 3.4). Regarding woodland cover, the Menstrie catchment previously comprised very few sparse woodland areas, mainly restricted to remnant riparian trees along the banks of the Menstrie river (see Figures 3.2a and 3.2b).

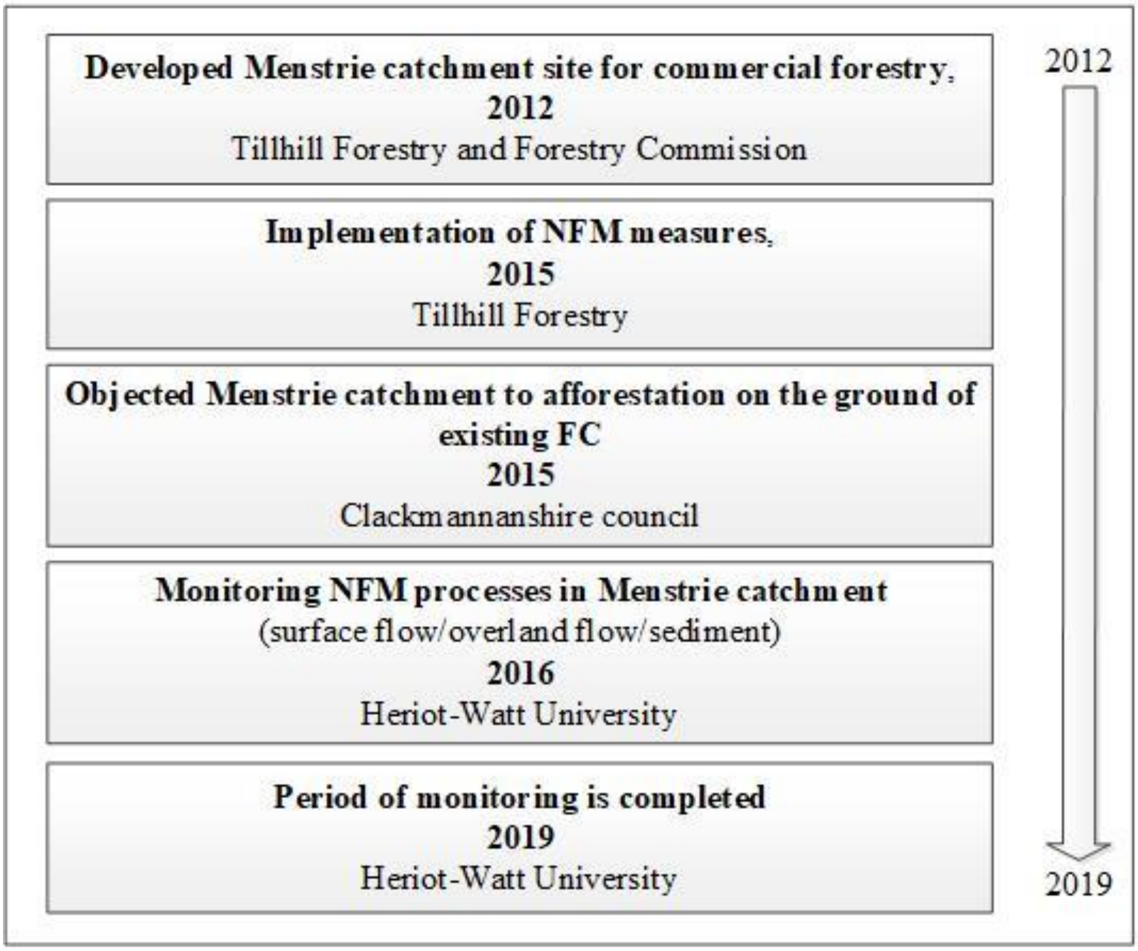


Figure 3.3: Timeline for the Jerah project in the Menstrie catchment

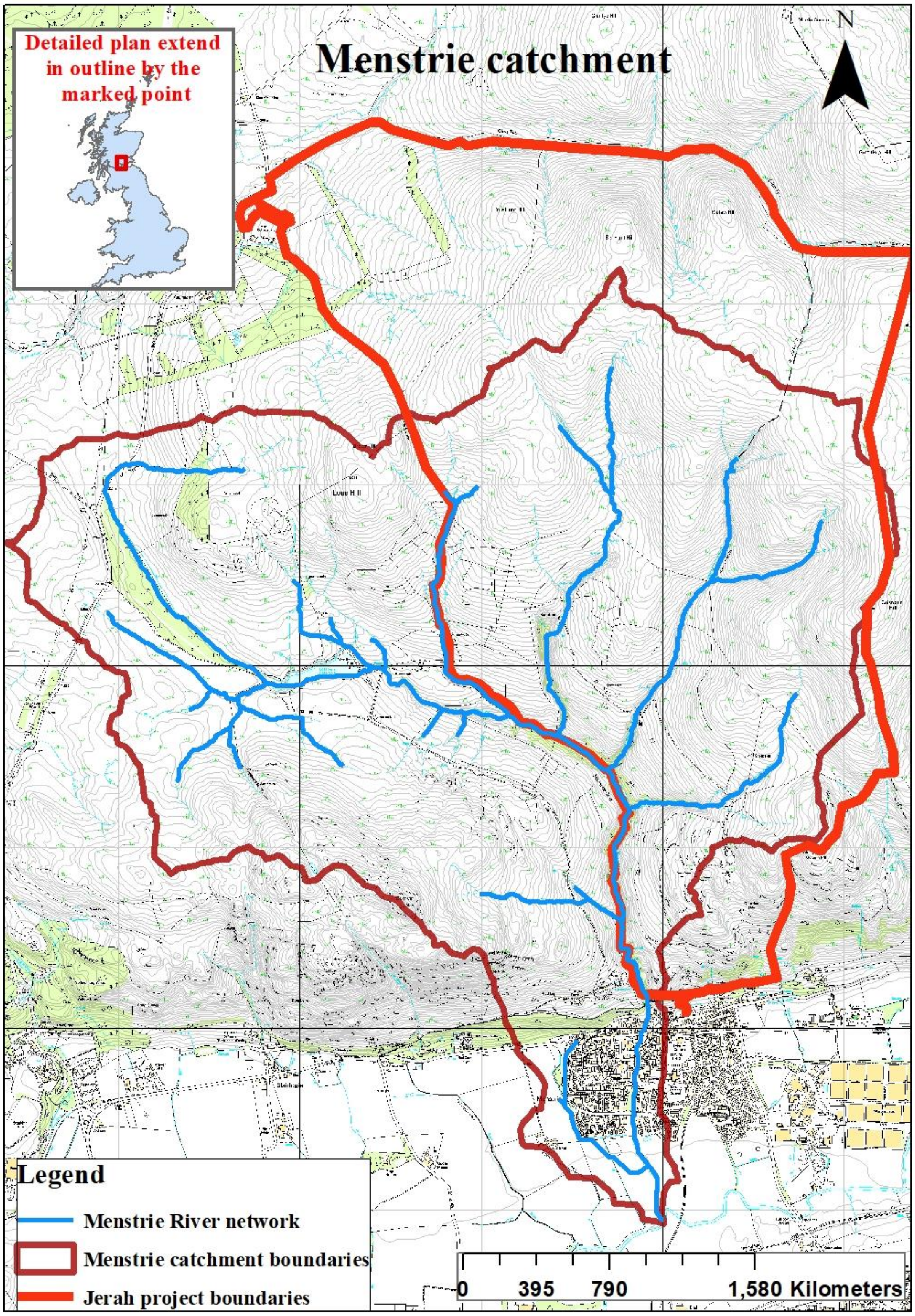


Figure 3.4: Jerah project boundary in the Menstrie catchment

The Menstrie catchment was selected for this study due to several factors (in accordance with Objective 1 – Section 1.5):

- Due to Scottish Forestry Trust grant funding [138], the catchment was well-equipped to monitor surface runoff after the afforestation phase. In addition, grant No P15-256 was allocated under this research project to HWU titled "Woodland planting and Natural Flood Management."
- Support from Tillhill Forestry (who undertook the woodland creation in Menstrie catchment), Forest Research (who helped in the assessment of fieldwork locations) and Clackmannanshire Council (who helped in administrating permission for site access and all possible stakeholders' involvement)
- Dominant land use was recently changed from grassland to forestry in 2015, which corresponds to the topic of this research
- Interest and support from local groups and flood bodies, including Menstrie Community Resilience Group and the Scottish Flood Forum

Within the Menstrie catchment, the main sites used for experiments were located within the Inch 1 (water level and sediment experiments) and Inch 2 sub-catchment areas (water level experiments).

3.2.1 Land cover changes in Menstrie catachmnet

Sub-catchment level

The significant land cover changes during 2015 in sub-catchments Inch 1, Inch 2 and Inch 3 were the conversion of grassland areas to forests. Different extents of this conversion process are described in Table 5.4.Table 3.1. The most extensive change occurred in the Inch 1 sub-catchment, where total afforestation accounted for 67% of the total area (see **Error! Reference source not found.**Table 3.1). Dominant cultivation that was applied over those three sub-catchments was the plough cultivation technique. Therefore, this sub-catchment has been selected as the principal study location for monitoring the effects of different cultivation techniques on runoff flow formation and occurrence. Inch 3 sub-catchment was monitored for nine months at the beginning of this research study. Still, due to the frequent breaking of instrumentation and non-reliable data, it was omitted from this study. Specific forest and vegetation development categories behaviour changes (F1, F2, F3, F4 and F5) are explained through hydrological events variables for two years of data on Inch 1, Inch 2 sub-catchment, cultivated areas and unplanted plots. (see Table 3.10).

Table 3.1: Land changes in different sub-catchments

	Forest areas	**Cultivation percentage per sub-catchment**		
Sub-catchment	Percentage of land changes from grassland to forest (%)	Plough cultivation (%)	Excavation mounding (%)	Hand screefing (%)
Inch 1	67	49	5	32
Inch 2	41	31	0	58
Inch 3	57	47	0	10

Cultivation practices

One of this research's critical points is understanding the effects of different cultivation techniques on runoff flow formation and the relationship between runoff flow and sediment delivery for different precipitation events. Seven study plots were selected, where three cultivation techniques (plough, hand screefing and excavation mounding) were employed on six plots. At the same time, the seventh one was an unplanted plot and served as a control, as described in Section 3.4. The research findings will contribute considerably to understanding runoff flow and sediment movement over cultivated areas (RQ1). Those events correspond to runoff flow events that happened in cultivated areas. The condition for each cultivation technique category are presented/described in Table 2 (Chapter 3).Table 3.11. The small catchment area of each Plot has been established through the average slope area, position and channel gradient. Tree densities were determined across the three different cultivation techniques, giving the highest levels in the ploughed areas.

Table 3.2: Tree planting density for cultivation practices and unplanted plots

Cultivation	**Unplanted plot**	**Hand screefing**	**Ploughed ground**	**Excavated mounded ground**

Tree planting density per 100 m2	0	29	38	28

3.3 Existing data sets

Existing data sets included temperature, river discharge, and precipitation (Table 3.3). The accuracy of those data is defined in Table 3.3. Moreover, their location is identified in Figure 3.6, Figure 3.9 and Figure 3.18. Spatial data sets, such as the Land cover Map, were developed with data from the Centre of Ecology and Hydrology (CEH), The James Hutton Institute (JHI) and the TillHill Forestry database. The National Soil Map for Scotland 2013 [139] was used for this study. Also, the existing shape files of current afforestation in the Menstrie catchment were provided by Tillhill Forestry, while LIDAR data were provided by the Scottish Government Remote Sensing Portal (2017) [140]. LIDAR data were a combination of a 1 m and 5 m resolution Digital Terrain Model (DTM) due to the fact that only this has been available. The DTM was used to define the catchment area of the Menstrie and the surface runoff experimental sites. Existing data sets were collected for modelling and experimental analyses. Rainfall, temperature and water level data were used in the hydrological modelling.

Table 3.3: Existing instrumentation in Menstrie catchment

Variable	Source	Time step	Unit	Accuracy	Location
Rainfall	Clackmannanshire council	15 minutes	mm	±2%	The upstream rain gauge in the Menstrie catchment
Rainfall	Clackmannanshire council	15 minutes	mm	±2%	The downstream rain gauge in the Menstrie catchment
Rainfall	Privately owned for personal research by Peter Emmis [134]	1 minute	mm	±6%	Menstrie village
Temperature	Privately owned for personal research by Peter Emmis [134]	1 minute	0C	±6%	Menstrie village

Water level	Clackmannanshire council	15 minutes	m	±0.25%	Menstrie village

3.4 Experimental locations in Menstrie catchment

3.4.1 Surface water level monitoring locations

The surface water level experiments were established on first-order streams of Menstrie river called Inch 1 and Inch 2 (see blue star in Figure 3.5). The location of instruments was established according to the accessibility (culvert installed in those locations has been used for instrumentation). This used cross-sections under the road that both tributaries flowed through. The estimated monitored areas are presented in Figure 3.6. The instrumentation was called Stingray 2.0 Portable Level-Velocity Logger and had an operational depth from 25.4 mm to 4.5 m with an accuracy of ±0.25%. These provide 15-minute data appropriate to capture the response of the sub-catchment and provide appropriate resolution for flood model calibration.

Both tributaries were monitored due to similarity in soil structure (see Figure 3.7), consisting of predominantly brown soils and contrasting levels of woodland creation (67 % forest cover of Inch 1 and 27 % forest cover of Inch 2).

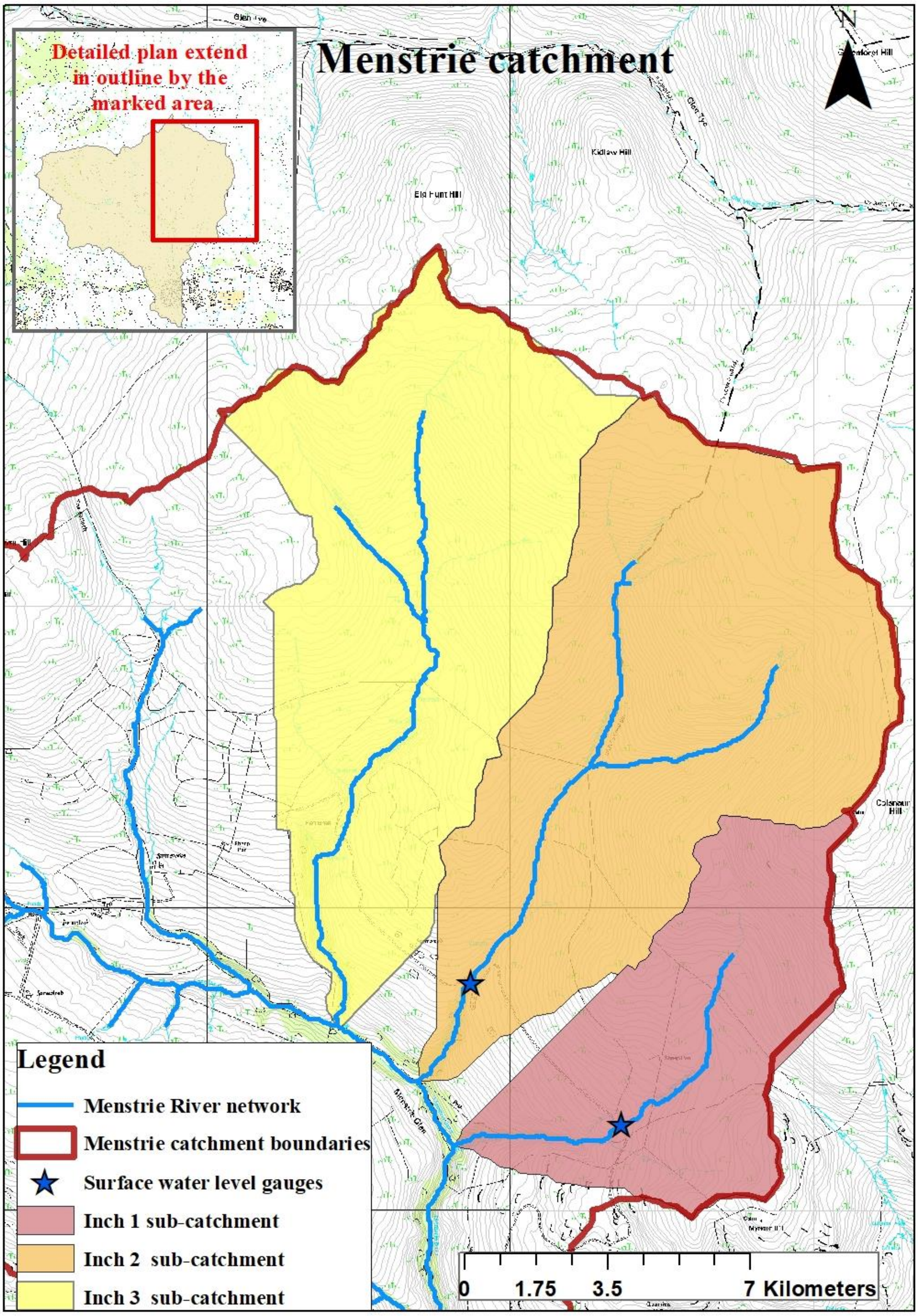


Figure 3.5: Inch 1, Inch 2 and Inch 3 sub-catchment areas in the Menstrie catchment

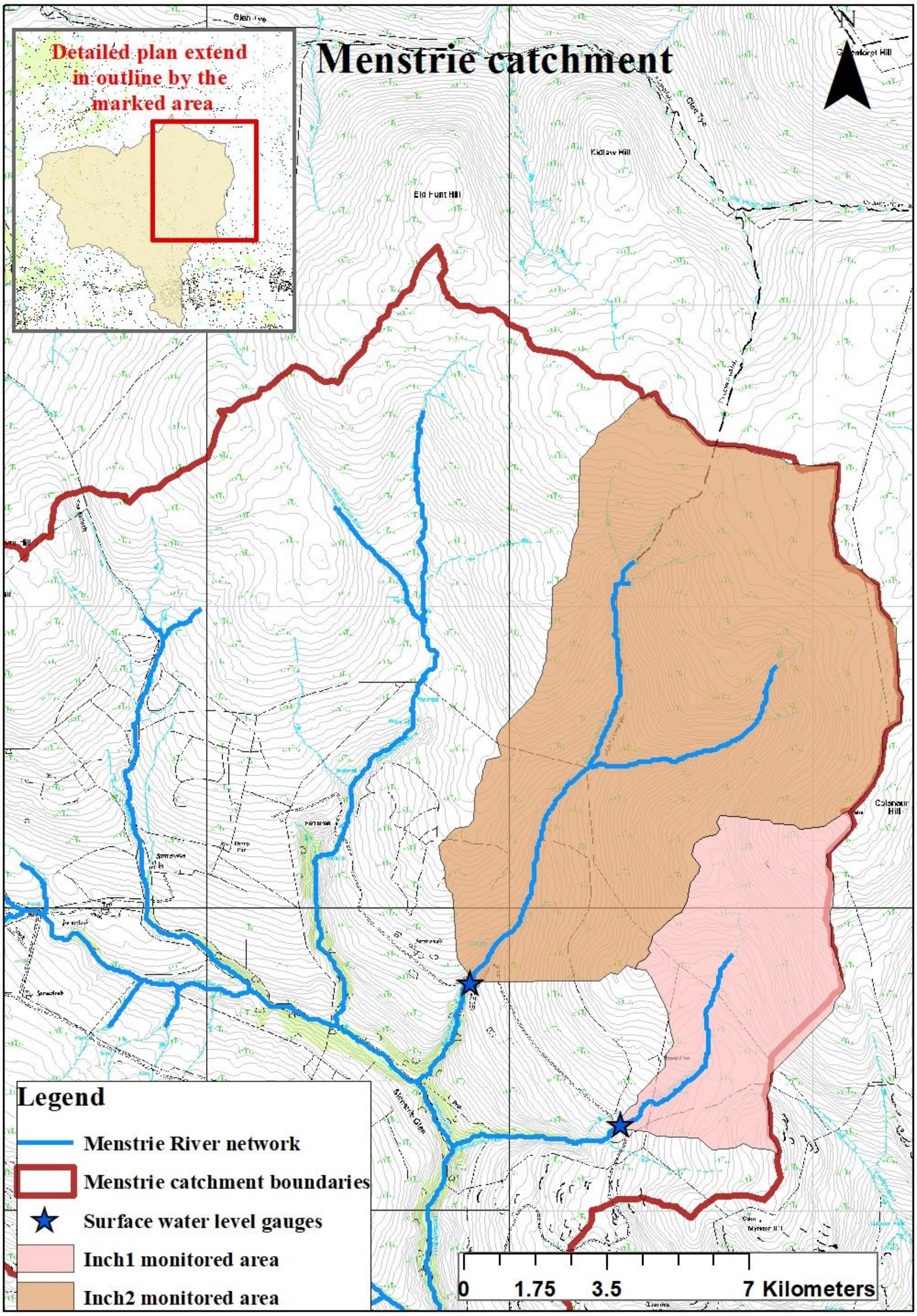


Figure 3.6: Inch 1 and Inch 2 monitoring areas in the Menstrie catchment

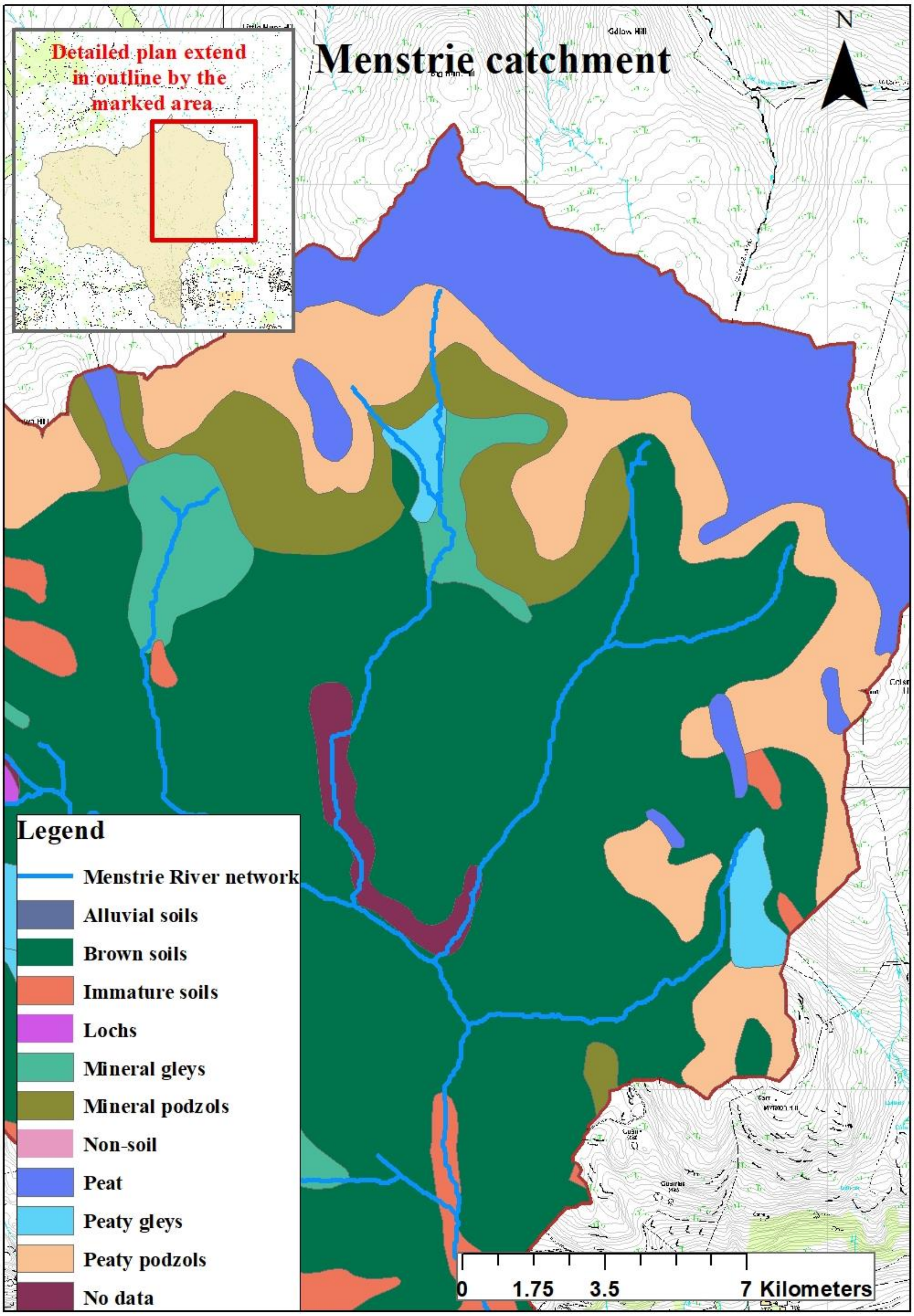


Figure 3.7: Soil map closely focused on Inch 1 and Inch 2

Those tributaries have been monitored from July 2016 to December 2018, allowing hydrological modelling through the GR4H model (Objective 3 -Section 1.5). The contribution area of Inch 1 that was monitored is 0.52 km^2 (57% of the total sub-catchment area), and the entire catchment area of Inch 1 is 0.90 km^2. The contribution area of Inch 2 that was monitored is 1.74 km^2 (93% of the total sub-catchment area), and the entire catchment area of Inch 2 is 1.88 km^2. Forest cover for sub-catchments monitored areas was 59% and 35% for Inch 1 and Inch 2, respectively. The data logger data provided information on water level (m) and velocity (m/s).

3.4.2 Runoff water level monitoring location (for different cultivation techniques)

The experimental locations for different cultivated areas were chosen around the Inch 1 sub-catchment area due to excellent accessibility (see Figure 3.9).

Cultivation history background

Five cultivation methods were employed to prepare the hillside for afforestation; shallow ploughing, excavator mounding, rotary mounding with inverted, hinged, or trenched mounds, hand mounding and hand screefing (see Figure 3.8 and Table 3.4). The definition of each cultivation has been provided in the following section. The Sitka Spruce was the main dominant species in the Jerah project (65% of Jerah project areas) and formed in all monitored areas for this project.

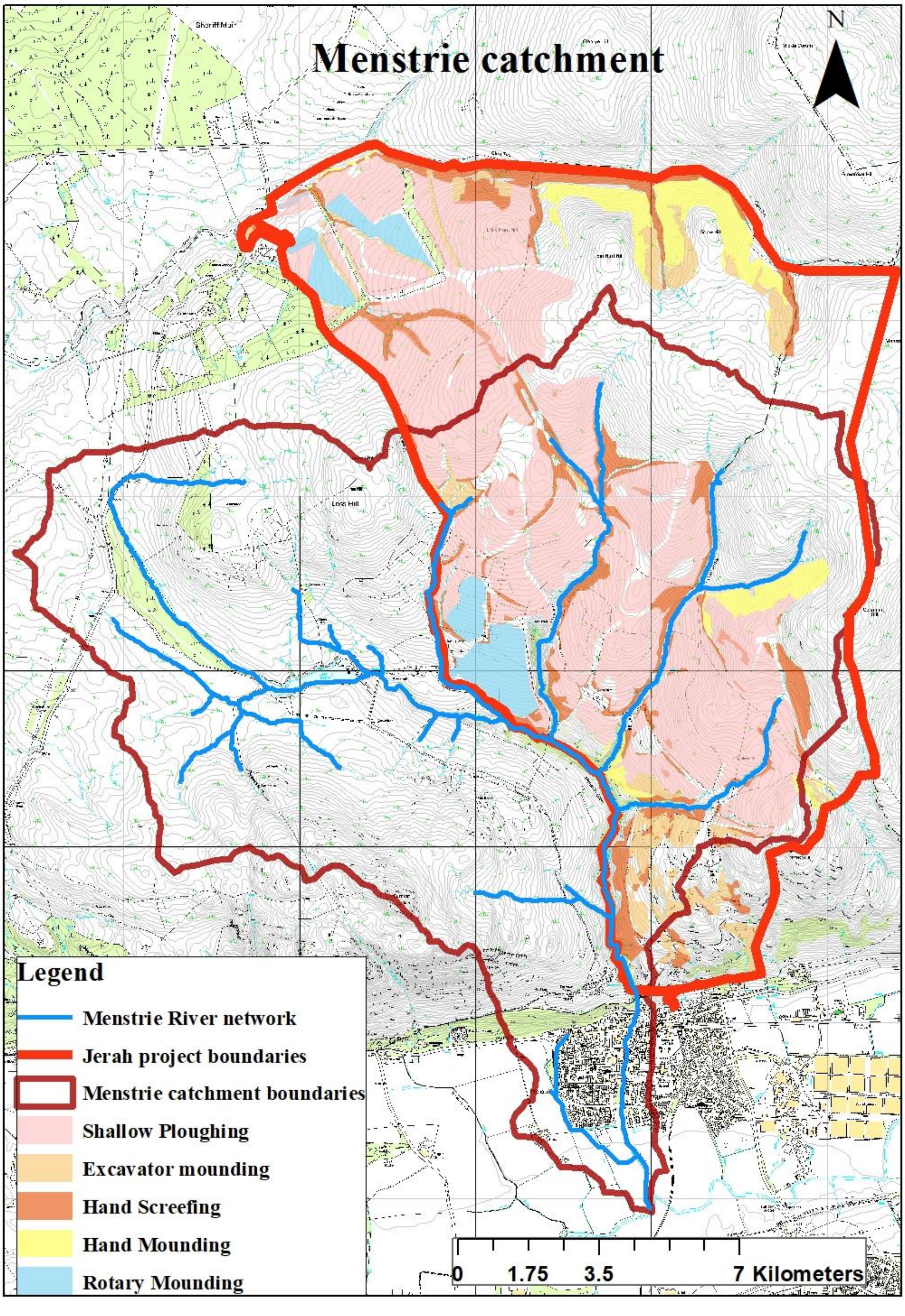


Figure 3.8: Cultivated areas over the Jerah project

Table 3.4: Cultivation methods applied over Menstrie catchment

Cultivation Method	Number of Trees Planted	Additional Information
Shallow Ploughing	643,900	Used regular cross-drains to reduce runoff
Excavator Mounding	69,900	Inverted, hinged or trench mounds
Rotary Mounding	232,100	Dry soils. Using regular cross-drains
Hand Mounding	222,600	Steep and wet slopes
Hand Screefing	116,000	Steep and wet slopes

The most significant cultivated area over the Jerah project was shallow ploughing (see Figure 3.8), accounting for 50% of the trees planted. Ploughing is when the soil is loosened or turned in preparation for planting to variable depths. It is known to cause significant disruptions to soil structure [141]. This process can be detected decades later [142]. The standard forest plough, with a furrow depth of 45cm, is intrusive by agricultural norms. The Forestry Commission's terminology labels a shallow forest plough as up to 30 cm, a deep plough between 45 and 60 cm, and intense ploughing as anything up to one metre. Although cheap, fully mechanized and quick to implement, this method creates furrows intrusive to the environment, even with shallow ploughing.

Alternative manual cultivation methods, such as hand mounding, cost between £200-£300/ha; economics can often be a limiting factor [20]. Furthermore, mounding methods are more expensive than ploughing methods. Costs will increase when ground conditions are poor, and slopes are steep [21]. Menstrie, for example, required alternatives to ploughing due to slope gradients and the risk of soil erosion. Despite this, the cost of ploughing is significantly lower because manual methods are more expensive. Excavator mounding accounted for 69,900 trees, involving the creation of 10-50 cm high mounds of soil, at regular intervals, by a tractor, into which trees are planted.

On the other hand, simple hand screefing with a spade or hoe accounts for 116,000 trees. The hand screefing method includes planting a tree by clearing the vegetation and humus layer, creating a planting site and minor lasting damage to the soil surface. This method doesn't include mound creation. Further cultivation methods used in the Menstrie catchment are hand mounding and rotary mounding. Hand mounding consists of hand application on steep and wet slopes since rotary mounding includes application on dry soils. Those two methods consisted of manual work for planting trees and were not subject to this study due to the limited project budget.

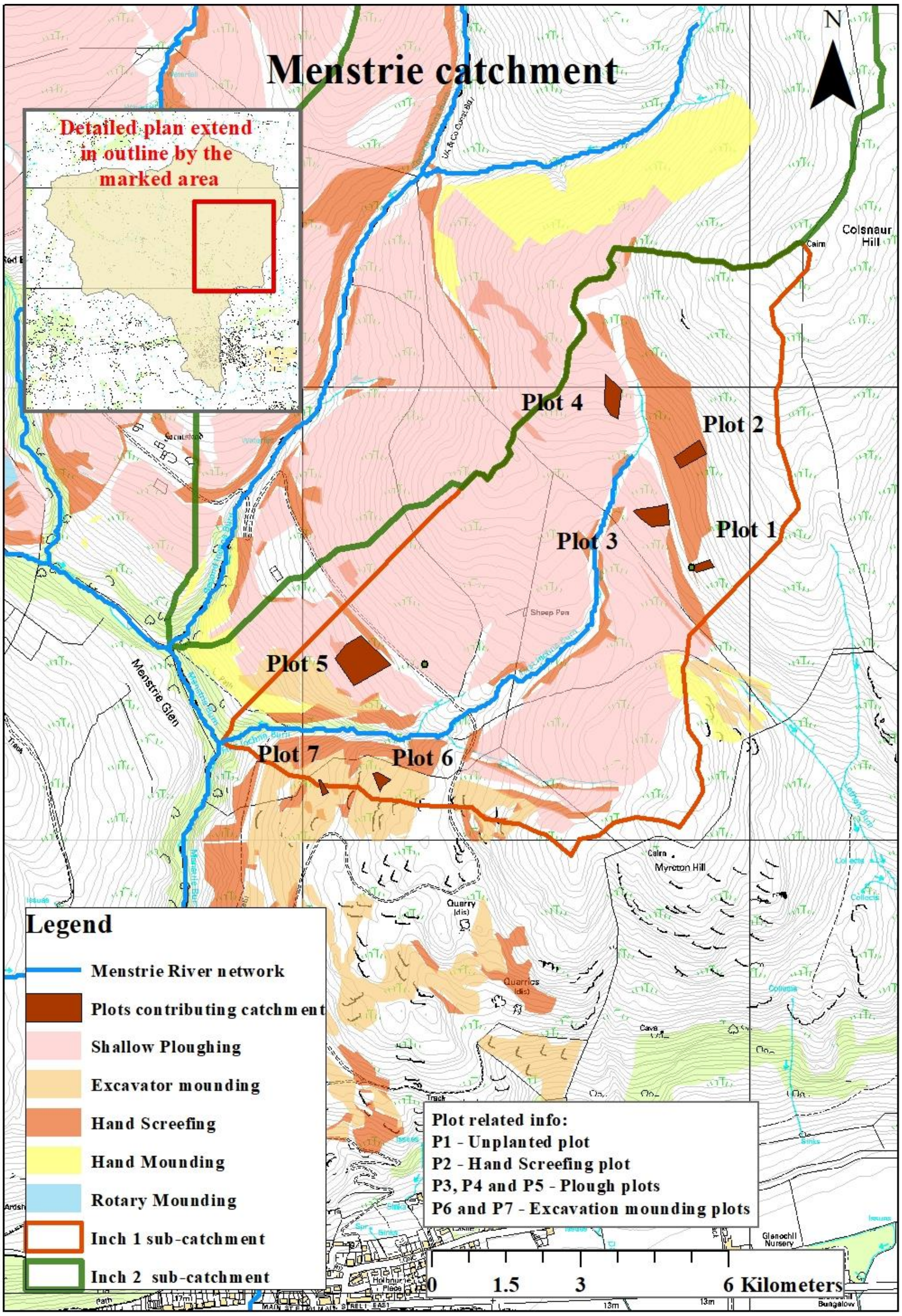


Figure 3.9: Monitoring locations of different cultivated areas over the Menstrie catchment

The scale of any of these impacts is expected to be a function of two main factors; the amount of soil disturbed, and the proportion of the ground surface area directly affected. The site at Menstrie catchment provides an opportunity to appraise a wide range of ground preparation techniques, the effectiveness of best management practices and the impact that early-stage forest development, namely cultivation, can have on the efficiency of flood management throughout the life cycle of the forest.

Monitoring locations

Seven study field plots connected to cultivation techniques and unplanted plots in the Menstrie catchment were monitored from November 2016 to December 2018. In the case of the ploughing cultivation, the cross-drain was used as a monitoring point at each site. Hand screefing and excavation mounding do not create a furrow channel, so a separate channel had to be excavated to collect and monitor runoff. The installed instruments' location is presented in Figure 3.9 and Table 3.5. provides details of the different cultivation treatments with the main physical features important for hydrological modelling. The instrument used is a senix ultrasonic level sensor specifically designed for low-powered remote level and distance monitoring that use ultrasonic sound waves to measure distances to objects and fluids.

Experimental locations for runoff experiments (Figure 3.9) were chosen based on the following (Objective 2 – Section 1.5):

- Those locations were relatively easily accessible and safe for approaching (by car or on foot)
- The visit to the experimental location was possible even during bad weather conditions (that occurred in the Winter of 2018)
- The similarity between the slope of the channel and the catchment area.
- The extent of the contributing area draining each cultivation treatment

Table 3.5: Cultivations and unplanted monitoring plot's main characteristics

	Plot 1	**Plot 2**	**Plot 3**	**Plot 44**	**Plot 5**	**Plot 6**	**Plot 7**
Cultivation	Unplanted plot	Hand screefing	Ploughed ground	Ploughed ground	Ploughed ground	Excavated mounding	Excavated mounding
Catchment area (m2)	695	2493	2500	2756	7480	1486	1560
Underlying geology	51% Brown soil 49% Immature Soil	100% Brown soil	26% Brown Soil 73% Peaty gleys	70% Brown soil 30% Peat	100% Brown soil	100% Brown soil	100% Brown soil
The slope of the channel (degrees)	35	45	15	17	17	21	13
The slope of the catchment area (degrees)	61	62	59	58	52	45	20
Aspects	NE	NW	NE	NW	NW	SW	NW
Elevation	380	410	320	420	240	245	220

Experimental setup and implementation

The surface runoff water level meters (seven Senix sonde sensors associated with LogBox electronic data logger) were used for monitoring seven plots (See Table 3.35 and Figure 3.49). Collected data addressed RQ1 by examining precipitation events resulting in surface runoff flow in different cultivation setups.

A flume was installed with a circular opening and radius of between 30-52 cm (see**Error! Reference source not found.** and **Error! Reference source not found.**). The variation in radius was due to the following:

- The need to match site conditions and minimize soil disturbance
- Different terrain conditions
- Monitoring channel dimensions (wider channel in case of plough cultivation)

The circular flumes were placed carefully into the ground at the surface level, allowing water runoff to flow into the flume. Where necessary, a "V notch" was placed in the upper part of the flume. This allowed water to enter the measuring channel. Furthermore, this pointed water to leave at a right angle to the measuring instrument. An ultrasonic sensor (Senix Sonda) was located on a plastic (Plot 3, Plot 4 and Plot 5) or metal (Plot 1, Plot 2, Plot 7 and Plot 9) support above each flume measuring water level. The necessity of a "V notch" was determined according to interrupted soil when the instrument was put in place, ensuring that biological content, sediment particles and any other obstacles stayed away from the flume monitoring area. The sensors were calibrated in the laboratory under available flume conditions. The calibration was performed using a laboratory flume and changing the water volume and slope. Also, sensors have been brought into the laboratory due to often sensor breakages. In that case, calibration was done in the laboratory before there been set up in the field again.

Runoff depth in the flume (m) was converted to discharge (m3/s) estimates by using the Manning equation (see Equation 3.5).

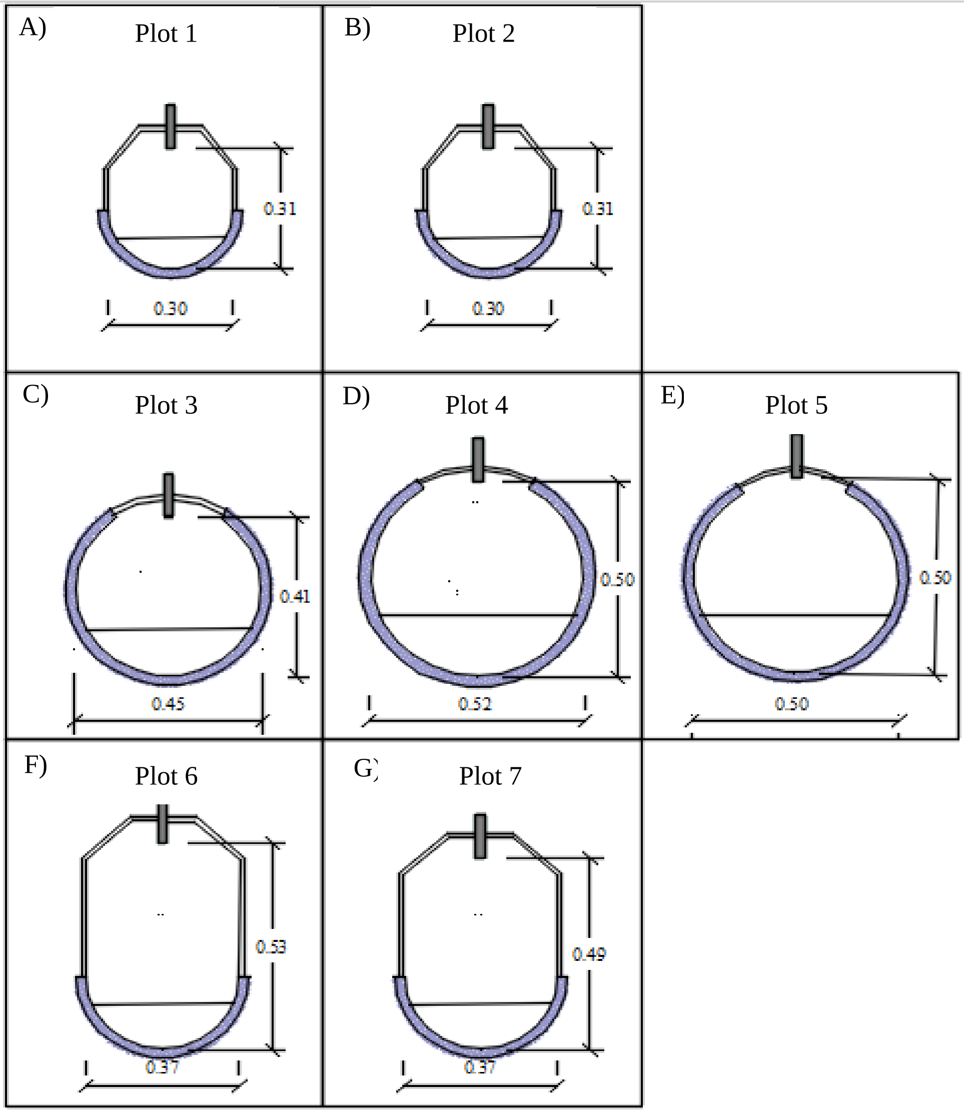


Figure 3.10: Surface runoff experimental set up for A) Plot 1 (unplanted plot) B) Plot 2 (hand-screefing) C) Plot 3 (plough cultivation) D) Plot 4 (plough cultivation) E) Plot 5 (plough cultivation) F) Plot 6 (excavation mounding cultivation) G) Plot 7 (excavation mounding cultivation)

*all measurements are in metres

Figure 3.11: Photograph demonstrating experimental set up of Plot 5 with “V notch”; photography has been taken by the author looking downslope

According to a finding by Mason-McLean [143] from Heriot-Watt University related to diurnal fluctuations influencing data quality in her research, each measuring instrument has been covered by a protective "hat". Furthermore, this issue has been reported previously in the work of Tekle [144], referring to the possible error of ± 7cm by ultrasonic sensor. However, all collected data in this study was checked straight after it had been collected (monthly data collection was applied). Also, trail cameras have been installed to support event separation and constant data quality monitoring. So far, data quality was reduced during two longer dry periods (see Section 3.3.4) during monitoring time. However, this period covered minimal rainfall (see Section 3.3.4), so runoff events did not occur during that time.

<u>Observation with camera</u>

Cameras (five Trail ABASK wildlife cameras With Waterproof Case Digital 2.4" LCD Screen HD 50 ft Night Vision Distance) installed at the exact point of the field associated with the measuring instrument (seven Senix sonde sensors associated with LogBox electronic data logger). The P1, P3, P4, P5 and P6 monitoring plots have installed cameras. Those observations had a crucial role in event separations. Event separation was done through analyses of collected photographs from cameras. Photographs marked the beginning and end of each event that occurred around different plots.

3.4.3 Important properties of monitored areas

Figure 3.7 map represents the soil type's map. Soil types per monitored sub-catchment cultivation techniques and grass-based areas were outlined in Table 3.6, and the most dominant soil type covered in the sub-catchment area is brown soil (see Figure 3.12 and Table 3.6). Brown soil covered 0.24 km^2 of Inch 1 and 0.85 km^2 of Inch 2 monitored area. This soil has a higher infiltration rate than other soils overlaid. On the other hand, grass areas over Inch 2 cover 1.15 km2, while grass areas over Inch 1 cover 0.22 km2. An essential distinction between grassland areas is that grassland is predominantly in peat/peat podzols areas for Inch 2 since Inch 1 has grassland predominantly in brown soil. Because Inch 2 had higher Qp/Qv, unplanted areas might influence this. However, this can be related to the fact that the P1 monitoring plot has experienced higher runoff than any cultivation (see Section 0).

The total area of the monitored sub-catchments covered with each cultivation area and the unplanted area was outlined in Table 3.6. The total unplanted areas cover 65.6 % of Inch 2 and 40.6% of Inch 1 area. The plough is the dominant cultivation, covering 44.9 % of the Inch 1 area and 29.1 % of the Inch 2 area. According to this, it is likely that plough cultivation has a dominant influence on hydrological changes over both monitored sub-catchments.

According to the JHI, calcification brown soil is well-drained soil with good natural properties for forest development. On the one hand, peat or peaty podzols will not be considered as good as brown soil with its properties. On the other hand, brown soil percentages are higher in the Inch 1 monitored area than in Ich 2 monitored areas. This is likely to have an influence on higher Qp/Qv in Inch 2 sub-catchment areas.

Another important distinction between those sub-catchments is the total number of trees, where the Inch 2 sub-catchment has a dominant number of trees. This is likely to influence higher Rt in the Inch 2 sub-catchment.

Table 3.6: Percentages (%) of soil coverage of individual soil types for each cultivation technique per monitored sub-catchment area

Sub-catchment Area	Cultivation and grass areas	Brown soil (%)	Peat (%)	Peat Podzols (%)	Mineral Podzols (%)	Mineral gleys (%)	Peaty glays (%)	Immature Soil (%)	Total % of cultivated area	Number of trees
Inch1Inch 1	Plough	22.1	2.1	14	-	-	7.5	-	44.9	88.95888958
	Hand-screefing	9.1	0.6	0.4	-	-	0.6	3	14	21.18621186
	Unplanted areas (grass)	15.7	2.5	20.7	-	-	0.8	0.9	40.6	0
Inch 2	Plough	23.2	0.5	2.9	2.4	0.1	-	-	29.1	198.904198904
	Hand-screefing	4	0.2	0.3	0.8	-	-	-	5.3	25.86325863
	Unplanted areas (grass)	22.1	29.3	14	0.1	0.1	-	-	65.6	0

Furthermore, soil type distribution over monitored cultivated areas and unplanted plots are predominantly brown soil (see Table 3.5(Table 3.5), except for P3, and P1 monitored areas. Those two monitoring areas have dominant values of Qp/Qv most of the time. Then another important distinction is related to the fact that the catchment area's slope is very high for those two plots (61 degrees for P1 and 59 degrees for P3). This fact might have influenced increased runoff water flow. However, P4 and P5 areas have a lower slope than catchment areas and deliver less runoff water.

Furthermore, in the case of excavation mounding plots, the slope of the catchment area likely does not influence runoff water values. Therefore, it is more likely that their cultivation design, including many mounds, has affected those areas. Unfortunately, this study could not clearly distinguish what those mounds contributed. For example, P7 likely influences all surrounding mounds when precipitation occurs. Also, underlining soil may influence lower Qp/Qv for P6.

Let's look through the lens of elevation position. It is likely that in case of plough cultivation plot that has been positioned on a higher elevation will deliver the smallest amount of runoff water (P4 plot). This also can be applied in the case of an excavation mounding plot, reefing to the P6 Plot located at a higher elevation.

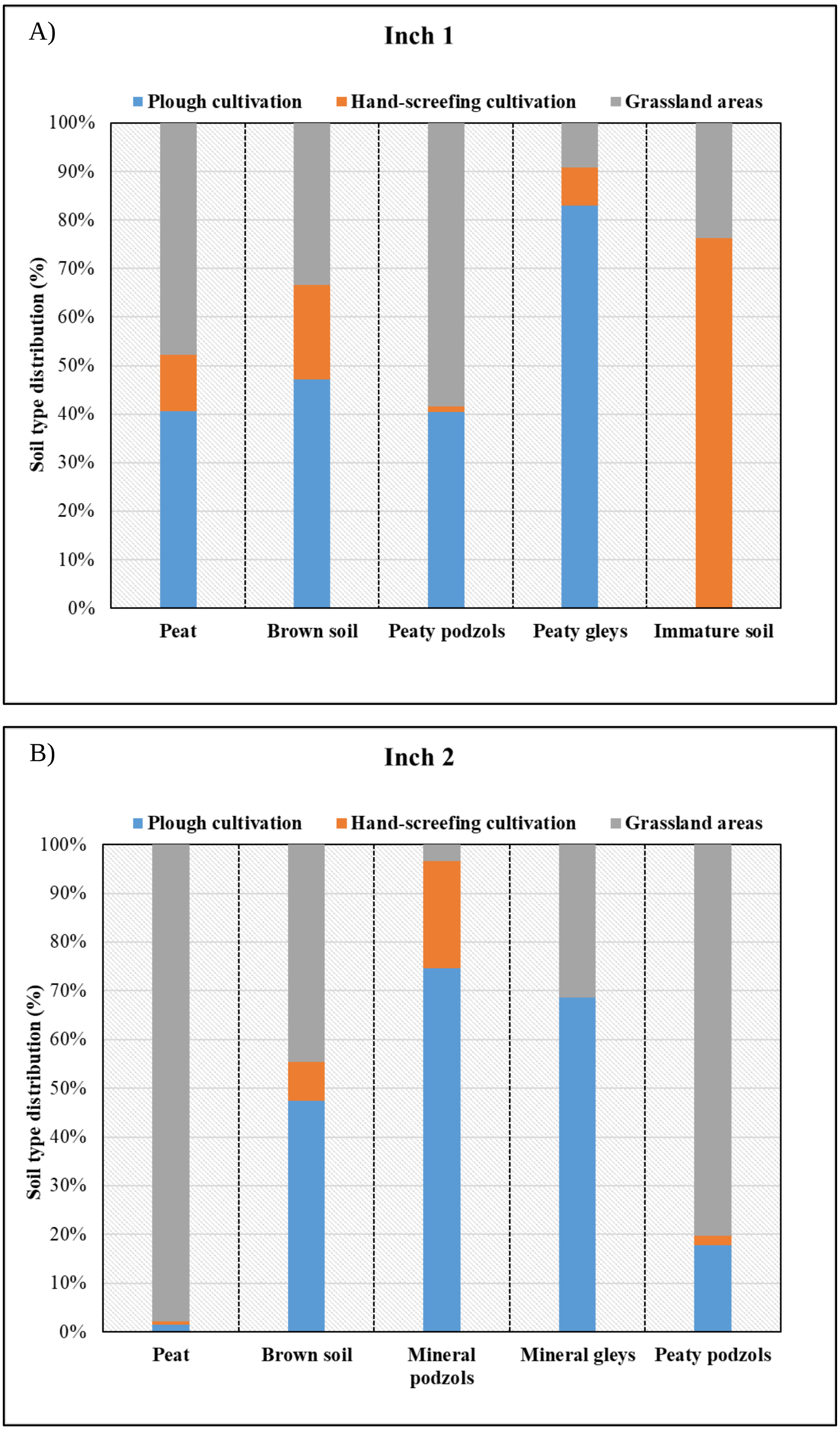


Figure 3.12: Soil type distribution per cultivation for A) Inch1 monitored sub-catchment and B) Inch 2 monitored sub-catchment

3.4.4 Delineation of sub-catchments and cultivated areas plot

GIS tools were used for processing the catchment area for each monitored plot. Furthermore, intensive surveys of each cultivated Plot were taken in 2017 and 2018 to determine the catchment area of each Plot.

Delineation of the sub-catchments

A combination of 1m and 5 m DTM of the Menstrie catchment and the GIS file of the stream network was necessary for catchment delineation. An outlet point was added to represent the experimental site to enable the separation of this catchment from surrounding ones.

Declination of cultivated plot catchment area

Cultivated plots have been delineated through DTM and DGPS surveys. The determination of boundaries for each plot catchment area has been done separately. This process included detailed observation of the monitored area physically. Furthermore, boundaries have been defined by DGPS. This included the following:

Plough cultivated area:

In the case of plough cultivation, it was necessary to form boundaries through a cross-drain and furrow network developed during the woodland creation process. In the case of P3 and P5 plough monitored plots upper boundary was defined as the road crossing the area (Figure 3.13 and Figure 3.14). Moreover, in the case of P4 upper boundary has been defined by an upper drain that has been implemented on top of the monitored area (Figure 3.13).

Hand screefing cultivated area and unplanted Plot

Hand-screefing cultivation of a higher boundary was defined by the implantation of the channel on the top of the monitored area (Figure 3.13). Channel position was determined by the higher end of the hill and the massive rock that appears in the case of the hand-screefing area. Also, the same methodology was applied in the case of an unplanted plot.

Excavation mounding cultivated area

The excavation mounding area did not have an upper channel. The P6 monitoring plot was located in the valley with clear bounders, and P6 has been found on the higher top, again with clear boundaries of the area (Figure 3.14). Moreover, clear boundaries were presented by the terranean constraints.

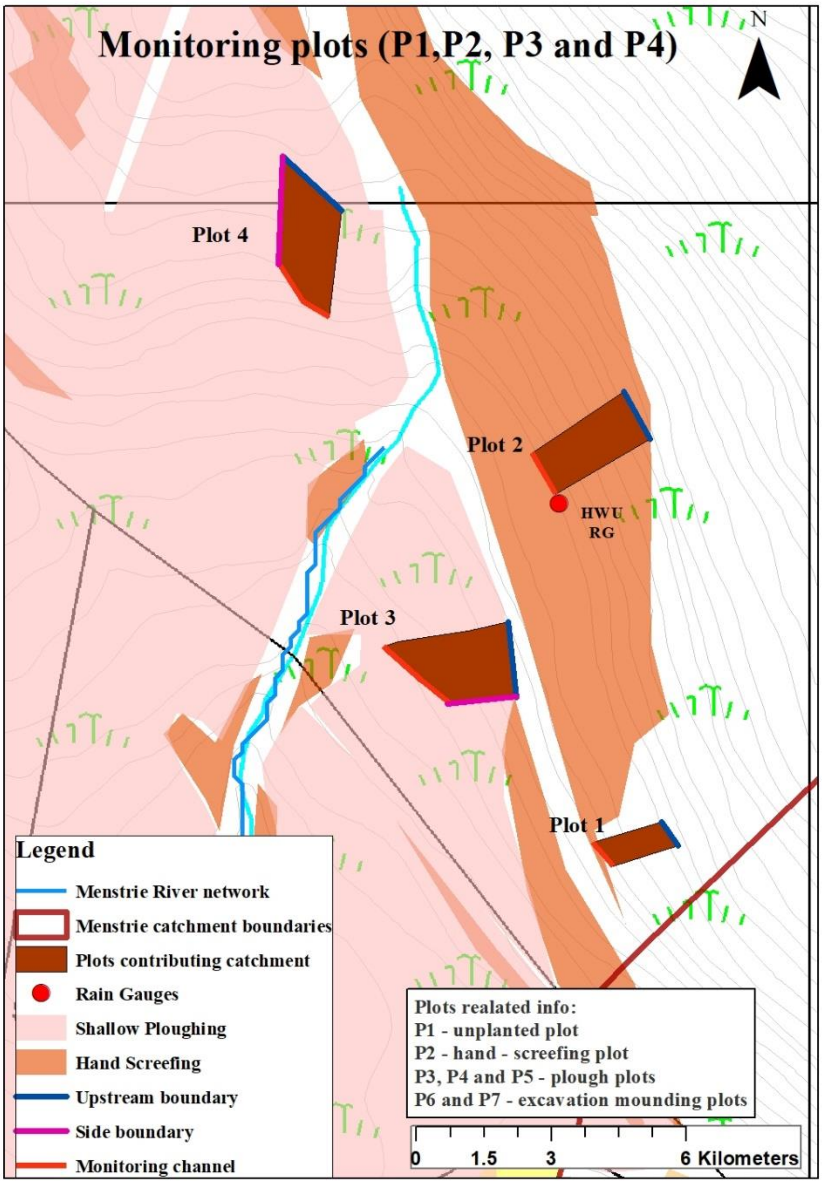


Figure 3.13: Boundaries of the catchment areas related to P1 (unplanned plot), P2 (hand screefing plot) and P3, P4 (plough cultivations plot).

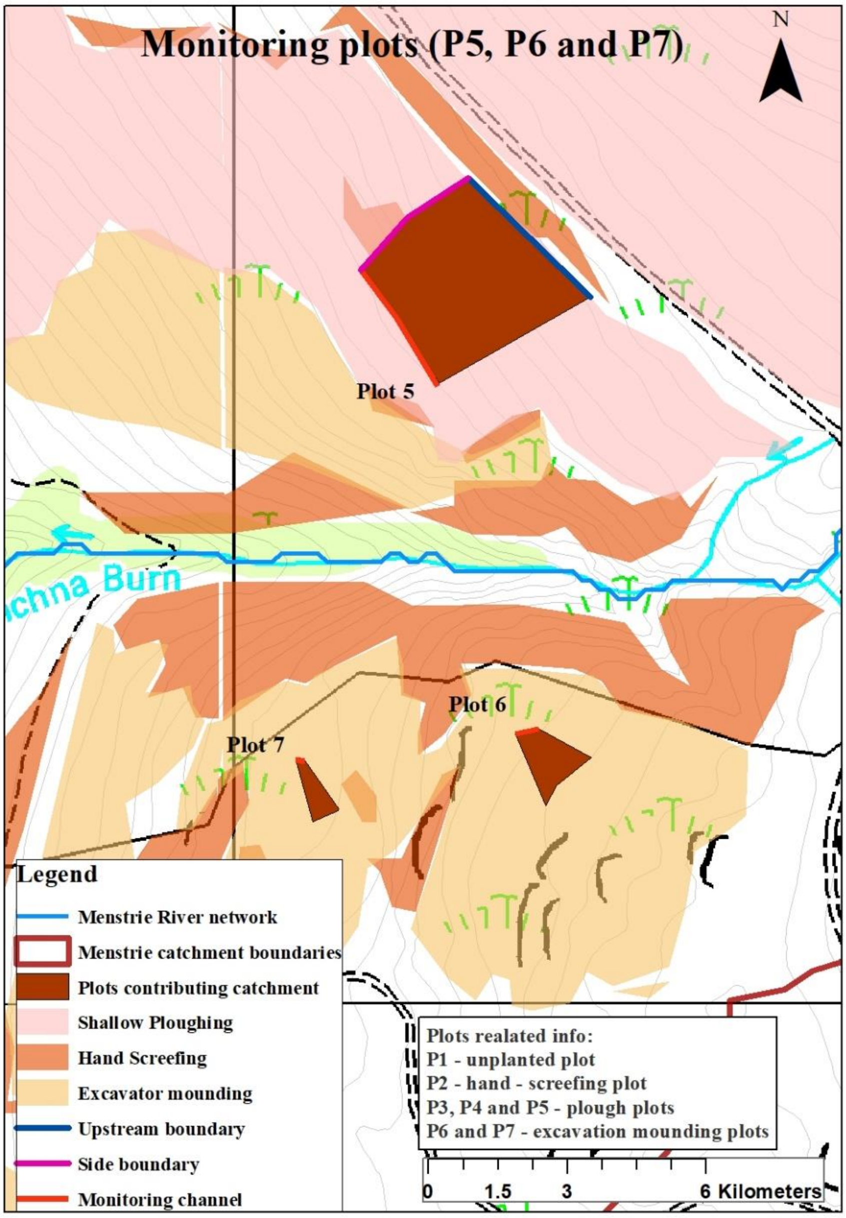
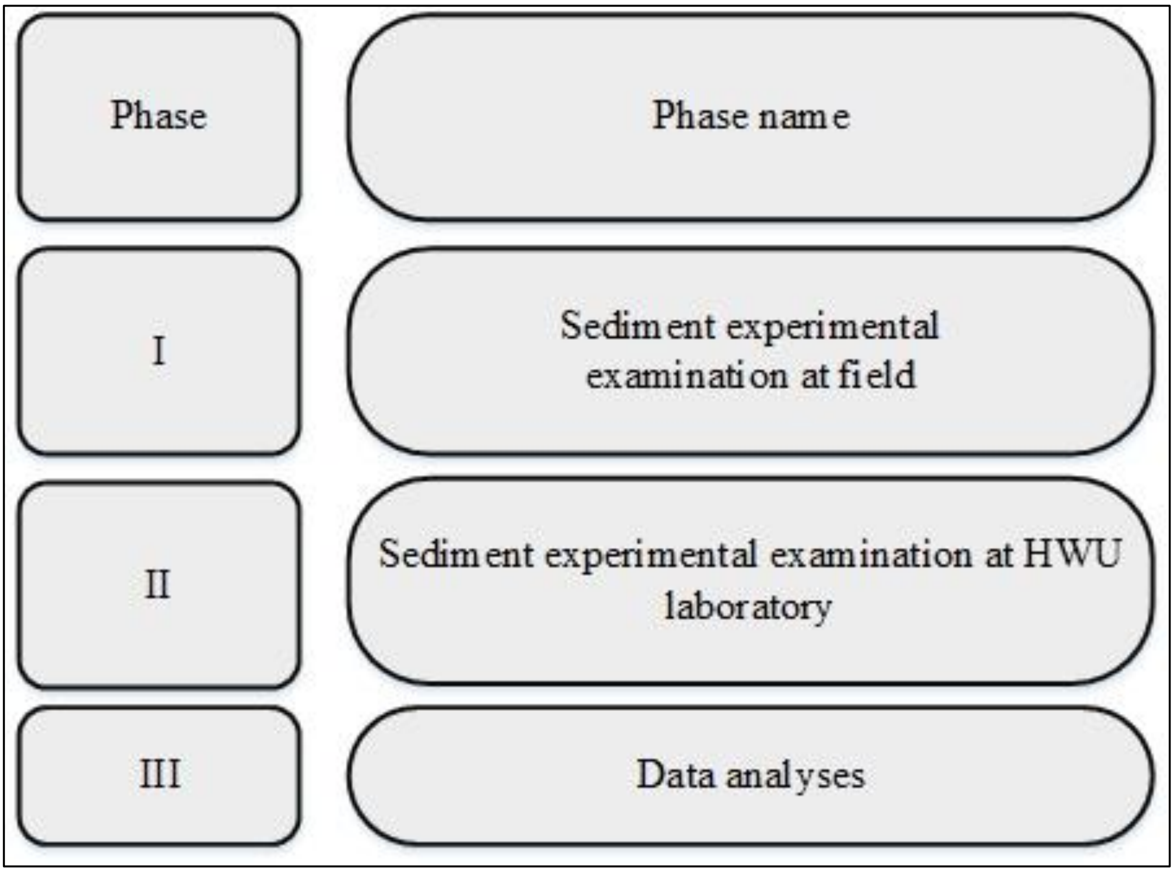


Figure 3.14: Boundaries of the catchment areas related to P5 (plough cultivation plot) and P6, P7 (excavation mounding cultivations plots).

3.4.5 **Sediment experimental monitoring location (for different cultivation techniques and unplanted plots)**

The sediment monitoring experimental methodology is presented in Figure 3.15 and was examined through three phases (Objective 3 - Section 1.5). During phase I, the sediment traps were placed over each cultivation technique from November 2016 to January 2018. The sediment collection was done by using plastic containers. Those containers collected sediment downslope at specific locations. The plastic containers were secured in the ground and levelled up with the topsoil layer [163] (Figure 3.16).



Phase	Phase name
I	Sediment experimental examination at field
II	Sediment experimental examination at HWU laboratory
III	Data analyses

Figure 3.15: Schematic of sediment methodology

Figure 3.16: Sediment sampling containers; photographs have been taken by the author

Each box was labelled with a unique number to ease sample collection and identification. Therefore, the sediment monitoring was chosen carefully at each location and evaluated by TillHill Forestry and Clackmannanshire council. Monitoring of the sediment allowed an examination of possible changes over each channel for different cultivations. Sediment containers were installed as follows:

- Unplanted control: the container was placed downstream of the main drain (cross-drain) that had been put in place as part of the setup (examination of setup is presented in Figure 3.17a)
- Plough cultivation: containers were placed in a main drain (cross-drain) and plough lines. The cross drain had been designed to collect and control runoff from contributing plough lines. In addition, according to forest design, a silt trap was placed at the end of the cross drain to help retain fine sediment. The silt trap was not monitored during this study. The design of each site is displayed in Figure 3.17c, d and e. According to the terrain limitation (that applies to accessibility) for Plot 4 (Figure 3.17d), it was impossible to set up a downstream box to collect sediment. Plot 5 (Figure 3.17e) and Plot 3 (Figure 3.17c) locations did not have this limit, so sediment containers were placed before and after measuring instruments. Furthermore, the Plot 4 site did not install a silt trap during the afforestation process since Plot 3 and Plot 5 areas had this silt trap at the end of the measuring channel.
- Excavation mounding: containers were installed downslope of the entrance and exit of the main drain (cross-drain) in the case of Plot 6 (Figure 3.17f). Furthermore, in the case of Plot 7, containers were installed just downslope of the entrance of the main drain (cross-drain) (Figure 3.17g). A monitoring channel represented by a cross-drain was placed for those sites, and containers were not directly connected to it due to limitations. Containers were placed at the beginning of the main drain (cross-drain) and the end of the channel.
- Hand screefing: The container was placed downslope (Figure 3.17b) in the main drain (cross-drain) established for this research.

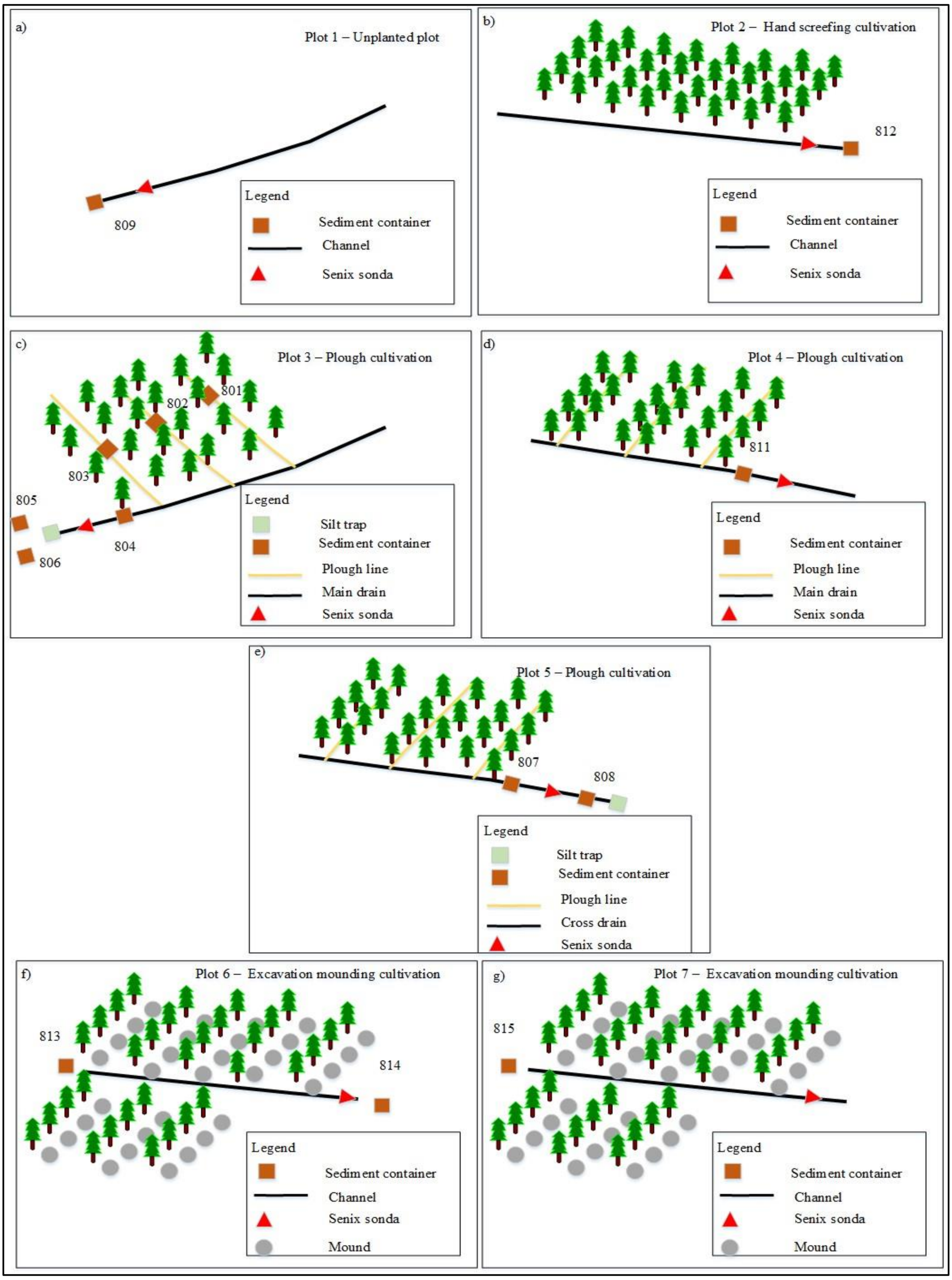


Figure 3.17: Schematic layout of monitored areas design and sediment instrumentation for: P1: unplanted plot (a), P2: hand screefing plot (b), P3: plough cultivation plot(c), P4: plough cultivation plot (d), P5: plough cultivation plot (e) P6: excavator mounding plot(f) and P7: excavator mounding plot (g)

*Direction of the drain is expressed by red arrow

Sediment collection took place once per month between November 2016 and January 2018. The collection period was longer if the site was not accessible due to demanding weather conditions (like in December 2017) and when the site was affected by drought (like in the period of March 2017). The procedure of collection involved removing the sediment trap and draining off excess water, along with any large pieces of leaves and other biological content. Special care was taken to allow the sediment to settle at the bottom of the sampling container.

The details of the containers and container positions applied at the site with a unique container number are presented in Table 3.7 and Figure 3.17.

Table 3.7: The labels of containers for sediment collection

Cultivation / Unplanted plot	**Plot**	**Container position**	**Box number**
Unplanted plot	P1	Downstream container	809
Hand screefing	P2	Downstream container	812
Ploughed ground	P3	Plough line container	801
		Plough line container	802
		Plough line container	803
		Main drain container	804
		Main drain container	805
		Main drain container	806
Ploughed ground	P4	Main drain container	811
Ploughed ground	P5	Main drain upstream container	807
		Main drain downstream container	808
Excavated ground	P7	Upstream container	813
		Downstream container	814
Excavated ground	P8	Upstream container	815

Immediately after sampling, the sediment samples were returned to the Heriot-Watt University laboratory for further analysis. Each bagged sample was weighed wet (g). The samples were then placed into correspondingly numbered trays and dried in an oven for 24 hours at 100 °C. The dry weight (g) was recorded for each sample. The sediment weight (g) is plotted using a bar chart for each cultivation technique. This shows how much sediment was transported between sampling events and for each cultivation technique used.

Furthermore, in phase III, the sediment weight at each Plot over the contributing area (g/m²/day) is plotted to provide a more accurate representation of the;

- how much sediment was delivered from each cultivation technique
- which particle sizes are predominantly represented in each sample
- how this corresponds with rainfall and flow events for each cultivation technique

3.4.6 Experimental location for precipitation monitoring

Precipitation was monitored as part of the experiment. Experimental equipment was installed in the upstream portion of the Inch 1 sub-catchment, where most of the experimental equipment for overland flow measurement was located. In addition, a precipitation gauge recorded precipitation and temperature data on a 5-minute time step.

Menstrie catchment has four precipitation gauges (Figure 3.18):

- Two of them have been monitored by Clackmannanshire Council and placed upstream and downstream in the Menstrie catchment
- One of them was placed and monitored by HWU at the upper reach of the Inch 1 sub-catchment
- One of them in Menstrie village was placed and monitored by Peter Emmis [145] as part of a private research project

Precipitation data from the HWU rain gauge in Inch 1 sub-catchment (<1 km2) were used for the hydrological modelling (see Chapter 6) and experimental data analyses (see Chapter 5).

3.4.7 Temperature and evapotranspiration data

The air temperature was monitored as part of this experiment at a site next to the HWU rainfall gauge.

Potential evapotranspiration data was estimated through the Oudin formula [146] given in:

$$PE = \begin{cases} \frac{0.408Re(T+5)}{100} & if\ (T+5) > 0 \\ 0 & otherwise \end{cases} \qquad \text{Equation 3.1}$$

Re is the extraterrestrial solar radiation (MJ m−2 day−1) given by the Julian day and the latitude, and T is the mean air temperature at a 2-m height (°C). Extraterrestrial solar radiation is determined by the set of equations given below:

$$Re = \frac{24(60)}{\pi} G_{sc} d_r [\omega_\mathrm{s} \sin\rho \sin\delta + \cos\rho \cos\delta \sin\omega_\mathrm{s}] \qquad \text{Equation 3.2}$$

$$d_r = 1 + 0.033cos(\frac{2\pi J}{365}) \qquad \text{Equation 3.3}$$

$$\delta = 0.409sin(\frac{2\pi J}{365} - 1.39) \qquad \text{Equation 3.4}$$

$$\omega_s = cos^{-1}(-tan\varphi tan\delta) \qquad \text{Equation 3.5}$$

Where Gsc is solar constant = 0.082 MJ m−2 day−1, dr is s the relative inverse distance Earth-Sun, ω_s It is the sunset hour angle (radians), ρ is the latitude (radians), δ is the solar declination (radians), and J is the number of days in the year between 1 January and 31 December.

The daylight hours N (hours) is also calculated using the equation below:

$$N = \frac{24}{\pi} \omega_s \qquad \text{Equation 3.6}$$

Daily evapotranspiration was estimated over 24 hours using the following hourly weightings 0, 0, 0, 0, 0, 0, 0.035, 0.062, 0.079, 0.097, 0.11, 0.117, 0.117, 0.11, 0.097, 0.079, 0.062, 0.035, 0, 0, 0, 0, 0 [147].

3.5 Data analyses methods

The water runoff experiments were employed to determine the overland flow generated by the different cultivation treatments. They were designed to identify points of surface runoff attenuation according to a particular location on a hillslope.

The further methodology will refer to the experimental setup and implementation, variables selection used for analyses, precipitation analyses and antecedent precipitation index analyses.

3.5.1 Variable selection

Several variables were identified from the literature and presented in Table 3.8. Those variables have been used for analyses of cultivated areas, unplanted plots, and sub-catchment areas (Objective 4 – Section 1.5).

Table 3.8: Variable selection connected to different cultivation techniques/unplanted plot

Approach	All possible variables
Hydrological variables (Cultivated areas and unplanted plots)	Number of trees in each area Soil type Event duration -Ed Time to peak - Tp Response time - Rt Total runoff of water per catchment area -Qvt Total peak height – Qpt Base flow peak height per catchment area -Qbp Base volume per catchment area - Qbv Runoff Volume of water per catchment area -Qv Runoff peak per catchment area -Qp Precipitation amount per event -P The intensity of rainfall per event -I

According to RQ1, it would be established where different physical preferences influence overland flow and sediment delivery. Therefore, measuring runoff water level and sediment delivery was essential; precipitation data assisted in identifying events.

Monitoring surface flow assisted in deciding relevant and representative events for assessing the effects of the cultivation treatments.

Separation of hydrograph for determination of events

The base flow (Qvb) was defined as the flow immediately before the inflexion point in the hydrograph, and runoff flow volume (Qv) was defined as the specific volume (mm) of the hydrograph after Qvb was deducted. This methodology has been applied to events in unplanted plots, cultivated and sub-catchment areas. Each event has been analyzed separately. In the case of cultivating areas and unplanted plots, Qvb is a variable related to the influence of the previous event and groundwater components since, in the case of sub-catchment areas, this is mainly associated with groundwater.

3.5.2 Precipitation analyses

Using a double mass curve analysis, the local Menstrie village rain gauge was used to infill missing data for the HWU rain gauge. The double mass curve allowed for checking the consistency of data between the precipitation gauges (Table 3.9).

Table 3.9: Precipitation statistics for HWU gauge and Clackmannanshire council gauges from December 2016 to December 2018

Rain gauge	Total rainfall (mm)	Max monthly (mm)	Monthly mean (mm)
Clackmannanshire council upstream rain gauge (CC upstream RG)	2206	173.5	88
Clackmannanshire council downstream rain gauge (CC downstream RG)	1328	158	53
HWU rain gauge (HWURG)	1624	157	64
Menstrie village rain gauge (MVRG)	1998.2	124.8	57

Thiessen polygon method (Thiessen, 1911) was applied to calculate catchment participation. Geographical Information System (GIS) was used for the prediction and preparation of the bisectional area of Thiessen by the following equation:

$P = \frac{\Sigma \mathrm{PiAi}}{\Sigma \mathrm{A}c}$, Equation 3.7

Where: P is the weighted area of the rain gauge, Ai is the area of each polygon (m2), and Ac is the total catchment area (m^2) applied to the Menstrie catchment. According to Thissen polygon methods [148], Figure 3.18 shows that the HWU precipitation gauge covered the area where all experimental instrumentation was based (see Figure 3.18). According to this, the HWU precipitation gauge was used for further analyses. This rain gauge provided data at a 5-minute interval.

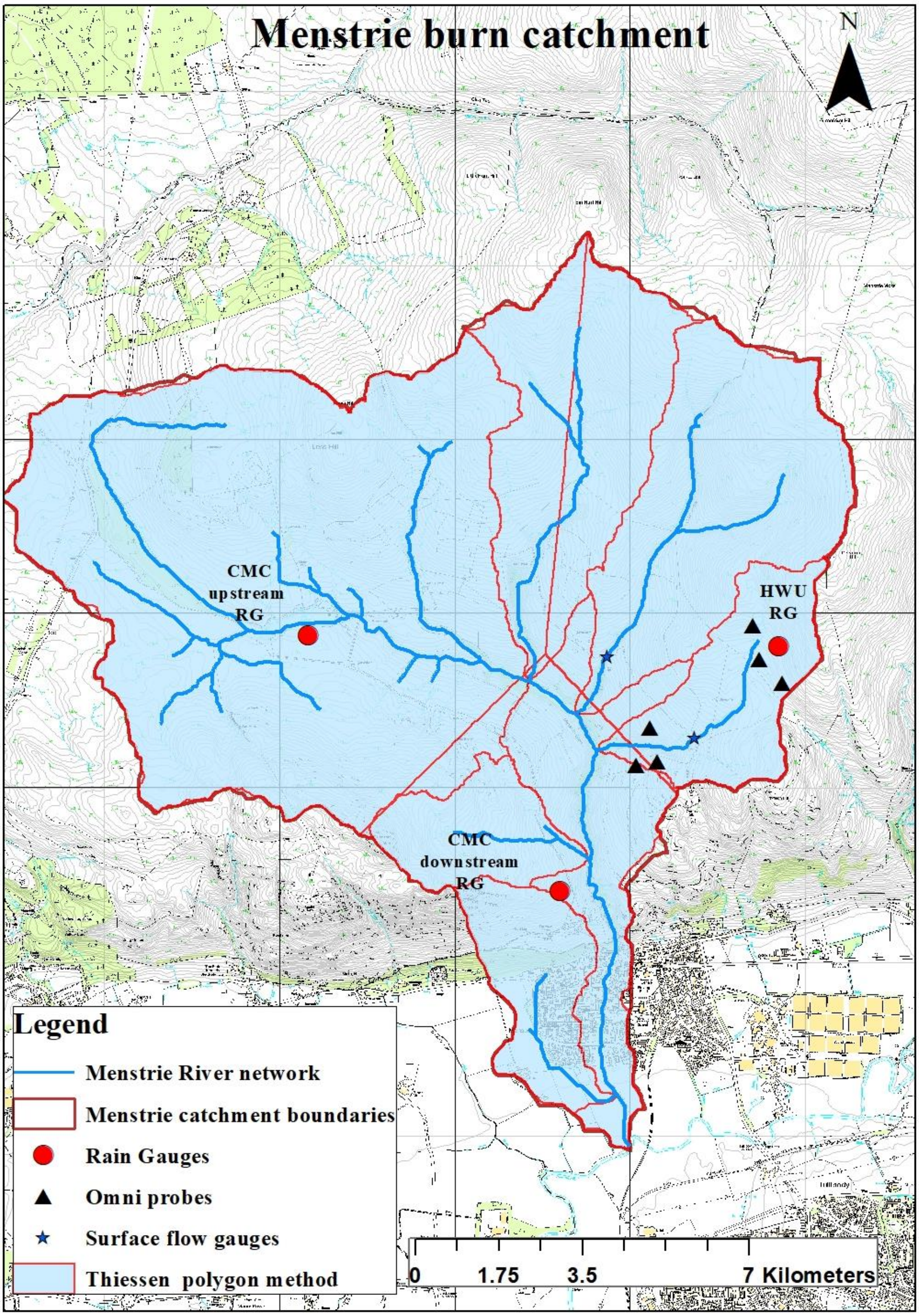


Figure 3.18: Spatial distribution of rain gauges in Menstrie catchment area with the Thiessen polygon method applied

Precipitation event identification and classification for analyses

Individual rainfall events were identified using the HWU rain gauge to examine the response of surface runoff and overland flow.

Determining the minimum inter-event time (MIT) between events was necessary. Calculation of MIT includes several methods [149], [150] that highlight the dependence of catchment size on MIT. The objective was to establish a procedure to decide upon the optimal MIT. Due to the small catchment size of the study plots, MIT was defined as 6 hours [149].

For each event that MIT was defined, volumes were calculated based on the following:

- event duration (hours)
- the total depth of precipitation (mm)
- the intensity of every single event (mm/hour)

Precipitation group's data analyses

Precipitation events have been analyzed through the precipitation groups. Those groups covered events that occurred in the case of dry weather conditions and wet weather conditions. The groups have been defined as DP1, DP2, DP3 and DP4 (see Figure 3.19A) for dry weather conditions and WP1, WP2, WP3 and WP4 (see Figure 3.19B) for wet weather conditions. It refers to the following:

- DP1 and WP1 to precipitation amount from 3 mm to 6 mm
- DP2 and WP2 to precipitation amount from 6.1 mm to 10 mm
- DP3 and WP3 to precipitation amount from 10.1 mm to 15 mm
- DP4 and WP4 to precipitation > 15.1 mm

Precipitation groups allowed analyses related to the number of monitored areas in correlation with selected variables.

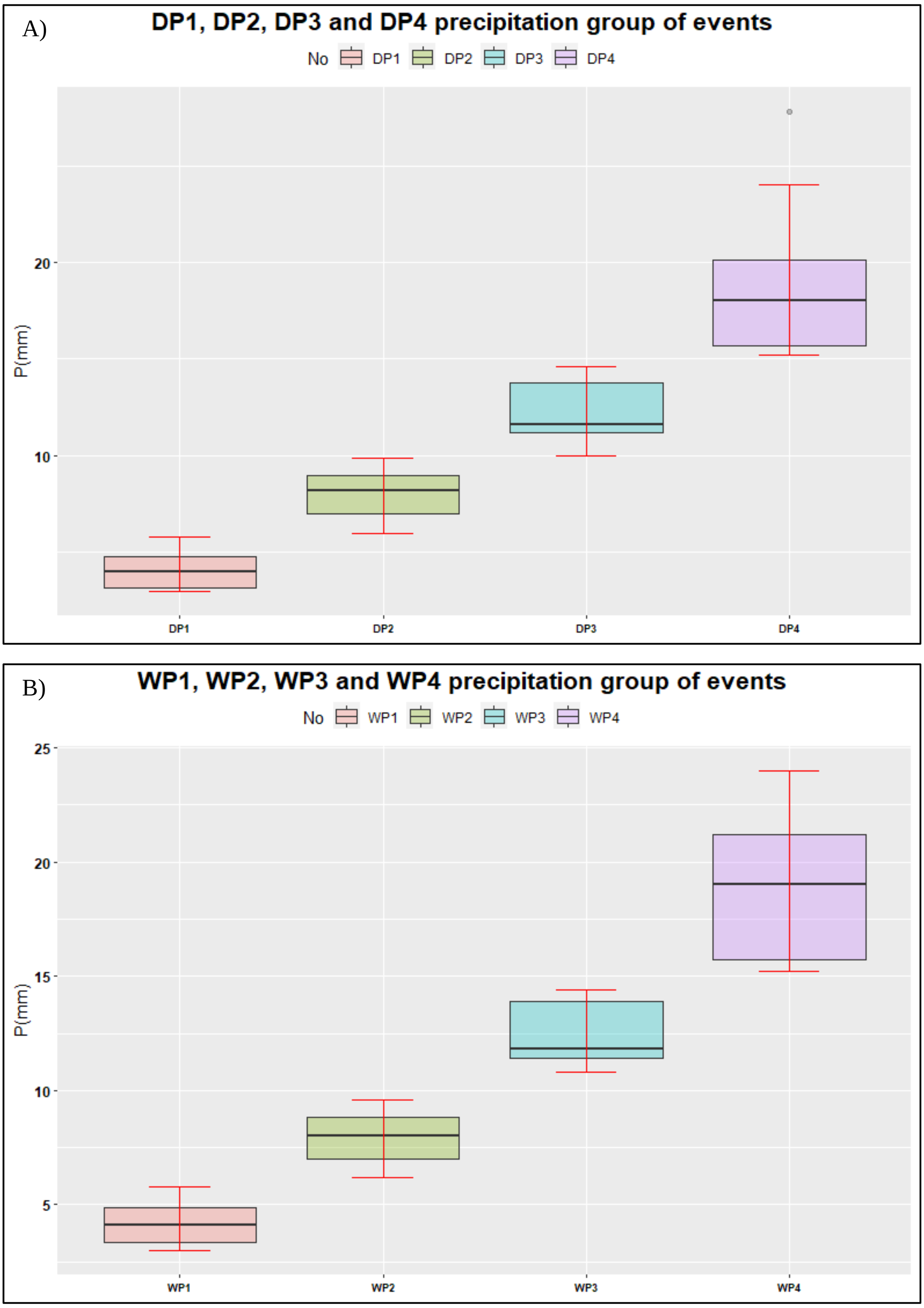


Figure 3.19: Precipitation group of events for A) dry weather conditions B) wet weather conditions

3.5.3 Linear regression model (LRM)

All analyses involved linear regression using R software. The 'Certain' package was used to analyze patterns and trends within the hydrological data.

The variables which were used for LRM included runoff flow peak (Qp) and runoff flow water volume (Qv) in correlation with precipitation (P). LRM signature predicts all monitored plots differently with statistical significance of cross-correlated variables, R2 values, NSE and RSR.

The performance ratings for stream flow proposed by Moriasi et al. [151]were 'very good' ($0.00 \leq RSR \leq 0.50$), 'good' ($0.50 < RSR \leq 0.60$), or 'satisfactory' ($0.60 < RSR \leq 0.70$). NSE is a normalized statistic that reflects the relative magnitude of the residual variance compared with the variance in the observed data (very good ($0.75<NSE\leq 1$), good' ($0.65 < NSE \leq 0.75$), satisfactory ($0.5 < NSE \leq 0.65$) and unsatisfactory ($NSE \leq 0.5$).

3.5.4 Antecedent precipitation index calculation

Antecedent conditions were examined using the antecedent precipitation index (API). This index provides a proxy for soil moisture (which was not measured in the Menstrie catchment) and provides specific information related to dryness or wetness. This information refers to the time before a rainfall event occurred in the catchment. For this study, Saxton and Lenz's formula [152] was used (Equation 3.8):

$$API_i = P_k K^t \text{ ,} \qquad \text{Equation 3.8}$$

Where K is the reduction factor that should be less than 1, t is the time in days, P is precipitation on the day (mm), and i is the selected day. Based on occurrences of more than one rainfall event 30 days prior to the selected day, daily API is calculated according to equation 3.9:

$$API_i = (API_{i-1} + P_{i-1})K \text{ ,} \quad \text{Equation 3.9}$$

A reduction factor of 0.9 was selected based on the literature [153]. Determination of this factor depends on soil properties and potential evapotranspiration.

Dry and wet weather conditions

Further analysis (see Chapter 5) with API30 values was related to separating dry and wet weather conditions [154]. Menstrie catchment experienced two longer dry periods (see a red triangle in Figure 3.16) during in 2017 (31 March 2017 to 12 May 2017, where total P were 4.4 mm) and in 2018 (from 20 June to 14 July 2018, where total P were 0 mm). According to Turner [155], a meteorological wave that occurred from May to June 2018 in the UK was reported on a meteorological period. On the other hand, the dry period that occurred during May 2017 was recorded as one of the top ten warm months since 1981 [156].

According to those observations (see Figure 3.20), it was determined that dry weather conditions refer to where API30 ≤ 20 mm and wet weather refers to where API30 >20 mm (see Figure 3.20). This identification covers the post-dry period that can still be identified as recovery from the dry period [157]. However, after the drought in 2017, the catchment reached wet weather conditions after eight days (API30 > 20), since after a dry period in 2018 catchment reached wet weather conditions after 14 days (API30 > 20). However, this covered both significant dry periods, post-dry periods in the catchment and all other short-term dry periods. Furthermore, those API30 reference points were used in Chapter 5 for separating events under dry and wet weather periods and are very specifically related to the Menstrie catchment.

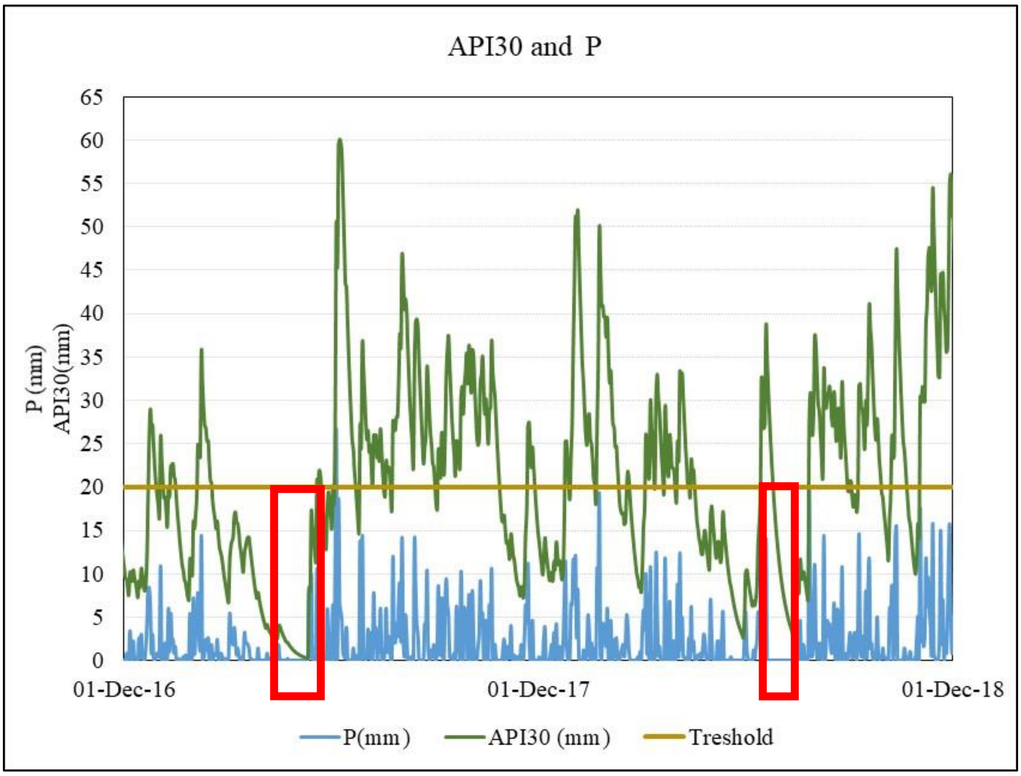


Figure 3.20: API30 and P values for Menstrie catchment from December 2016 to December 2018. The red triangle areas highlighted longer dry periods in the Menstrie catchment.

3.5.5 Calculation of discharge

The definition of a runoff water event was based on the response of each experimental Plot (Plot 1, Plot 2, Plot 3, Plot 4, Plot 5, Plot 6 and Plot 7) and checked using the time-lapse field camera. The categorization of events was influenced by other factors such as seasonal changes (snow, temperature), the effect of the cultivation techniques, and the different catchment areas. The water level data were transformed into discharge values using the Manning equation (Equation 3.10):

$$Q = \frac{1}{\mathrm{n}} A R^{2/3} \sqrt{S} \quad , \qquad \text{Equation 3.10}$$

Where Q is runoff (m3/s); n –Manning coefficient, A – is an area of cross-section (m2), R is the hydraulic radius (m), and S is the slope of the flume.

A cross-section area was identified during the instruments' installation for the cultivated areas and unplanted plots (Figure 3.10). However, the area of the cross-section for the Inch1 and Inch 2 sub-catchment has been known since those two water level monitoring stations were installed in a culvert with a known diameter. Furthermore, the slope of the measuring channel has been measured in cultivated areas and unplanted plots. This is presented in Table 3.5.

The Manning coefficient was selected through an assessment of available limited literature. A study by Kamali [158] found that vegetated furrows have different Manning coefficients upstream and downstream (values vary from 0.0488 to 0.0504 for high and low flows). Furthermore, this study treated furrows with a maximum soil depth of 0.60 m, like the Menstrie catchment; however, since the first study estimated the Manning coefficient in more detail, the value of 0.0504 was chosen to evaluate cultivated areas and unplanted plots.

3.5.6 Definition of growing and non-growing period

Growing (GR) and non-grown seasons (NGR) were identified according to available temperature time series (Figure 3.21). The start of the growing season (SGS) was defined when the daily mean temperature was 5.6 ^{0}C, five days in a row [156]. This temperature is related to location. SGS for Menstrie catchment has been on 8 March 2017 and 5 April 2018. The end of the growing season (EGS) was defined as when the daily mean temperature was lower than 5.6OC, five days in a row [129]. EGS for Menstrie catchment has been on 8 March 2017 and 5 April 2018, 29 October 2017 and 25 October 2018. Defined growing and non-growing seasons have been used as a reference point to understand forest and vegetation development in the Menstrie catchment (see Section 3.5.7).

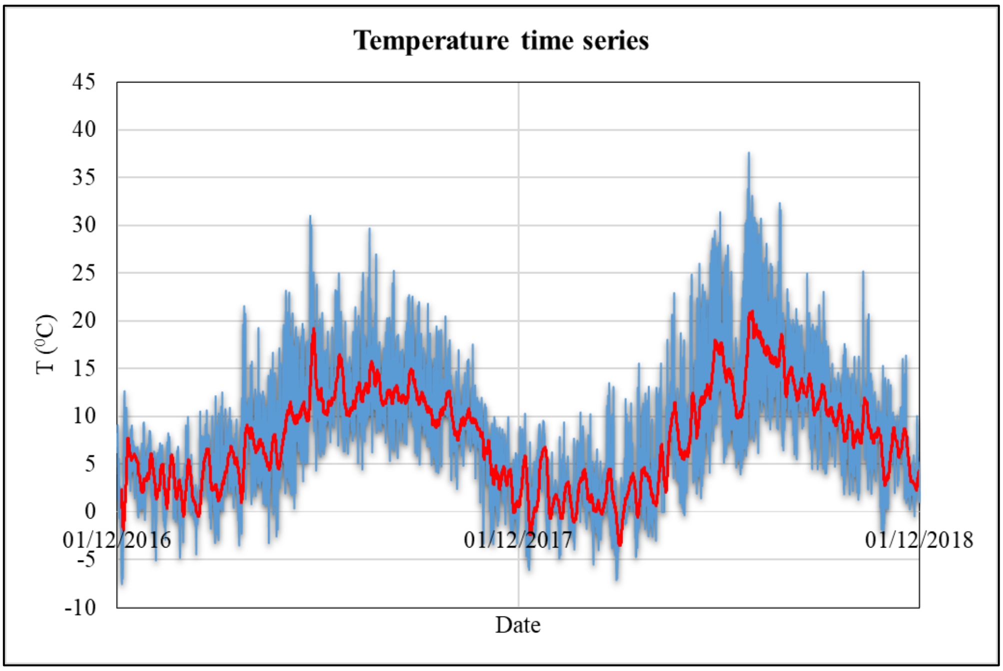


Figure 3.21: Temperature time series from December 2016 to December 2018; the red line represents the average cure of presented data.

3.5.7 Cultivation practices observation trough vegetation development

The cultivated practices observations categories analyze influencing factors when examining distinctions between runoff events for dry and wet weather conditions. They contribute to understanding how runoff flow moves into cultivated and sub-catchment areas (RQ1). The requirements for each category are explained in Table 3.10 and illustrated in**Error! Reference source not found.**. Monthly photographs are summarised in two ways:

- Forest development category: five categories (F1, F2, F3, F4 and F5) that summarised forest growth and revegetation in the field (see Table 3.10 and Figures 3.22 and 3.23)
- Vegetation season category: five categories (NG1, GR1, NG2, G2, NG3) that surmised the growing period during monitoring time (see Table 3.10 and Section 3.5.6)

The Forest Development categories were summarised through forest observation growth, and plough lines/buffer strips vegetation growth (see Figure 3.22).

Table 3.10: Forest and vegetation development categories (F1, F2, F3, F4 and F5) and vegetation season categories (NG1, GR1, NG2, GR2 and NG3) connected to growing and non-growing periods. Figure 3.22 shows vegetation changes across the main drain P3 plough cultivation plot.

Vegetation development category based on grass development in plough lines			**Forest development category**		**Growing and non-growing period**
Establishment stage **50 cm trees height** **Bare soil over plough lines**	NG1	Non-growing	Early Young phase	F1	1st of December 2016 to 7th of March 2017
Medium 1 stage **55 cm trees height** **Poorly visible changes over plough lines (grass)**	G1	Growing	Medium Young phase	F2	8th of March 2017 to 29th of October 2017
Medium 2 stage **62 cm trees height** **Visible changes over plough lines (grass)**	NG2	Non-growing		F3	30th of October 2017 to 5th of April 2018
Medium Late stage **71 cm trees height** **Plough lines have more visible changes in vegetation establishment (grass)**	G2	Growing	Medium Late Phase	F4	5th of April 2018 to 25th of October 2018

Late-stage 80 cm trees height vegetation was firmly established over plough lines (grass)	NG3	Non-growing		F5	25th of October 2018 to 1st of December 2018

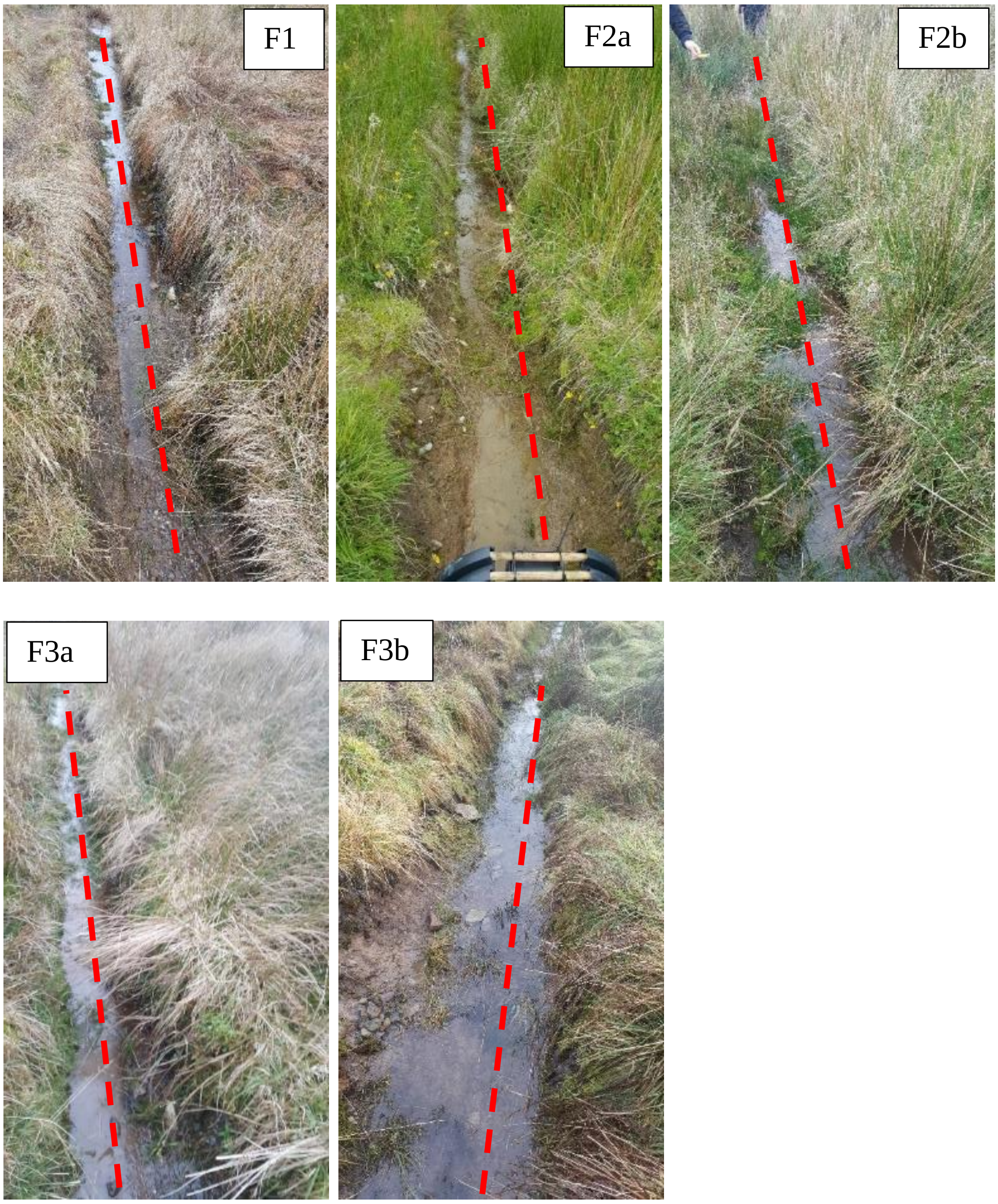


Figure 3.22: Vegetation changes in monitoring channel of P3 plough cultivated area connected to forest development. Categories are described in Table 3.10 above. Periods

presented include the 7th of March 2017 (F1a), middle picture 20th of July 2017 (F2a), 19h of October 2017 (F2b), 7th December 2017 (F3a), and 25th of January 2018 (F3b).

Figure 3.23: Vegetation changes in ploughed cultivation plot. Refer to Table 3.10 for a description of each category: F1) 25th of December 2016 –plough line in P5 plot area, F2) 31st August 2017 – plough line in P5 plot area, F3) 7th of December 2017-plough line in P4 plot area, F4) 1st of June 2018 – plough line P5 plot area, F5) 19th March 2019 – plough line in P4 plot area

Most of the observed precipitation events occurred during F2 (wet weather conditions) and F3 (dry weather conditions) periods when the rate of revegetation appeared to be quickest (**Error! Reference source not found.**). F1 (wet weather conditions) and F5 (for dry weather conditions) categories had little data due to the short length of the observation period. This category has remained as part of this study. The number of observed events per category is presented in Table 3.11 with total catchment precipitation amount, median API30 and median T.

Table 3.11: Forest development and vegetation season categories with corresponding precipitation totals and counts of events. Categories highlighted in red were analysed more thoroughly to elucidate the conditions that caused runoff flow events.

Forest development category	F1	F2	F3	F4	F5	F1	F2	F3	F4	F5
Vegetation season category	NG1	G1	NG2	G2	NG3	NG1	G1	NG2	G2	NG3
Plot/Inch	Number of events									
Plot 1 (2017-2018)	-	-	3	3	-	-	-	3	4	-
Plot 2	4	6	7	8	1	-	21	10	17	9
Plot 3	8	7	6	6	-	-	23	9	8	5
Plot 4	8	3	5	5	-	-	7	12	18	2
Plot 5	12	3	7	5	-	2	16	13	7	5
Plot 6	8	7	9	2	-	-	21	14	2	-
Plot 7	6	4	8	-	-	-	15	12	-	-
Inch 1	5	2	8	2	-	1	22	14	8	7
Inch 2	4	2	8	1	-	-	23	11	8	6
Catchment precipitation totals (mm)	80	59	82	101	10	78	458	259	286	152
Median API30 (mm)	11	8	12	11	13	25	28	27	28	41
Median T (oC)	4	9	2	13	4	2	11	2	11	6

3.5.8 Sediment data analyses

Sediment collection was done every month or every two months, depending on site accessibility during the collection period (from December 2016 to January 208). The number of containers per cultivation and unplanted Plot is presented in Table 3.7.

The accumulated data provided an integrated picture that allowed the research's five objectives to be achieved. The following data were considered during sediment analyses:

- Cumulative precipitation data from HWU rain gauge
- Runoff data from cultivated areas/unplanted plots per catchment area
- Dry sediment weight

Laboratory tests included particle size analysis [159]. This indicates the range of particle sizes present and relative amounts (typically by mass). Every sediment sample shows a range of grain sizes, and sediment grains are usually sized according to diameter. The particle size distribution determines the size of distribution of the sediment. Soil types are grouped according to size. The critical size classifications are gravel, sand, silt and clay.

Sieve analysis was used to assess the particle size distribution. A representative soil sample was passed through 8-10 sieves (arranged in decreasing mesh size from 10 mm to 63µm), and the weight retained on each sieve was recorded. Based on the sediment contained by each sieve, a per cent finer curve (grading curve) was produced by plotting the log of particle diameter on the x-axis and the percentage of particles retained on an arithmetic scale on the y-axis [160].

The purpose of creating these curves and defining these metrics was to:

- Understand differences in the ranges between cultivation techniques and
- Understand the downstream and upstream differences in sediment containers between different cultivations

For all the periods in which sediment was collected, cumulative rainfall (mm) was calculated and divided by the number of rain days to determine sediment weight and runoff produced within each period. Rainfall was plotted against sediment weight and runoff between different cultivation techniques to derive a relationship between these variables.

All significant rainfall events were identified for the whole time series, defined as >3 mm depth of rainfall with no break within six hours.

3.6 Chapter Summary

This chapter addressed the methodology for RQ1 and RQ2. The following section summarises the methods of this chapter.

3.6.1 Summary of methodology for RQ1

The hydrological monitoring implemented on-site address. RQ1 to understand the effects of the different cultivation treatments on on-site runoff. The following analyses were used:

- Examine significant precipitation and runoff events based on available data for cultivated areas, unplanted plots and sub-catchment areas
- An assessment of antecedent conditions using API30 values and event calcification under dry and wet weather conditions
- Classification of precipitation and runoff events under growing and non-growing season
- Examination of events under precipitation groups

3.6.2 Summary of methodology for RQ2

This method addressed RQ2 to understand the effect of the different cultivation treatments on sediment runoff. The following analyses were used:

- Assess sediment runoff during selected rainfall and runoff events for each cultivation treatment.
- Examine the relationship between rainfall, sediment weight, and rainfall / API30 values/ Runoff water.
- Examined particle size distribution from each monitored area and determined differences

Chapter 4 GR4H modelling methodology

4.1 Introduction

This research study used a hydrological modelling tool to understand the collected data better. The modelling process has used the data collected at the field scale using an experimental monitoring approach at the cultivation and sub-catchment scales in the Menstrie catchment. The experimental methodology applied in Chapter 3 is specifically related to the practice field and observations made over field plots toward runoff water creation and sediment delivery.

According to that, this chapter is more focused on the modelling part. RQ3 can address it (What is the preferred cultivation technique for minimizing flood generation and can this be reliably predicted using hydrological modelling tools (using GR4H modelling as a tool?). Hydrological models are powerful tools for understating hydrological processes and a better understanding of runoff water occurrence across catchment areas. For that purpose, it is possible to predict different process that has not been or cannot be measured in the field. Hydrological models can be used for several purposes that vary over different requirements. First, a simple classification can be recognized: lumped and distributed hydrological models. The lumped model presumed catchment as a simple unit with general variables in estimating output parameters. Distributed models predict specific grid square numbers, each with a unique parameter value. This study required the lumped model due to the simplification approach and very small catchment area that would not be fitted in distributed models.

Generally, the development of the hydrological model has usually followed by involving further steps, and Figure 4.1 gives a schematic representation of rainfall-runoff modelling processes with the phase of model development:

- Collection of data for two years and data analyses
- Development of the conceptual model, which describes essential hydrological characteristics of the catchment
- Transforming the conceptual model to the mathematical model, which in general was then with different mathematical equations
- Calibration of the model (where the first year of collected data was used for calibration)
- that fits in the collected data set by adjustment of different coefficients

- Validation of the model against the collected data set (where the second year of collected data was used for validation)

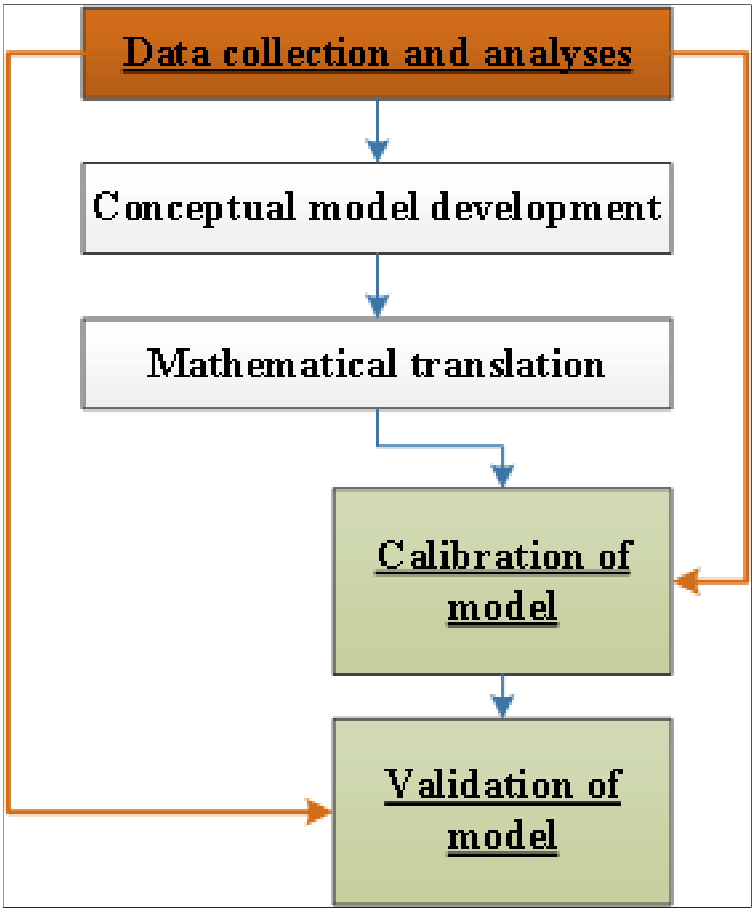


Figure 4.1: Modelling development phases for rainfall-runoff model

According to the requirement and perspective of collected data, the conceptual model suggests using a hydrological lumped GR4H model. This model applied the hourly time step to various climates/catchments in past years [147]. According to an output of this model that represents four-parameter x1, x2, x3 and x4, it is possible to observe hydrological changes for different cultivation with two years of data availability.
Discussion in Chapter 7 will explore the use of lumped hydrological model GR4H to apply different cultivations and sub-catchment level applications.

4.2 Sub-catchment and cultivation scale of modelling

The GR4H model was applied at the cultivation and sub-catchment levels. Its purpose was to the specific impacts of each cultivation on four parameters that were output from each model. Nevertheless, simulation results were assessed in the Inch 1 sub-catchment, Inch 2 sub-catchment, hand-screefing monitored plot (P2), plough cultivation monitored plots (P3, P4, P5), and excavation mounding monitored plots (P6, P7). However, each model is assessed on its scale. The data recorded at each experimental site are compared to simulated flows at the exact location in the model setup.

The time scale of the GR4H model requirements and the area referred to as hourly resolution. This resolution was used for calibration as well.

4.3 GR4H model description

The GR4H model is the lumped hydrological model established by the National research institute of science and technology for environment and agriculture, France (IRSTEA) and applied over different catchments. The GR4H model is a sub-version of the GR4J model with a daily time step. Implementing the GR4 model at daily and hourly time steps is freely available in the "airGR" R package [161]. This implementation is used in the thesis with code adaptations to run a multiple-scale model due to the catchment area of each study plot (represented by different cultivations) and sub-catchment areas (described by Inch 1 and Inch 2), relatively small changes in vegetation growth this model has been chosen as a reasonable solution for implementation. This model uses potential evapotranspiration, rainfall, and flow and temperature data to generate four outcomes: production store (x1), water exchange coefficient (x2), the one-hour maximal capacity of the routing reservoir (x3) and unit hydrograph time base (x4). The detailed explanation is provided parameters are explained in the table and illustrated in Figure 4.1 and Table 4.1.

Table 4.1: Description of GR4H model parameter and explanation of their role

Parameter notation and unit	Explanation of role
x1 (mm)	Production storage is related to the capacity of soil moisture. Also, this can be associated with catchment the catchment's capacity to store water in the soil.
x2 (mm/hr)	The one-hour maximal capacity of the routing reservoir is related to potential changes in the groundwater reservoir. Higher values indicate higher amounts of exchanged water.
x3 (mm)	The maximum capacity of the routing reservoir controls the slow flow component. Higher values are associated with the long slow flow appearance in the catchment area,
x4 (hr)	The unit hydrograph time base is the correlated response time of the catchment.

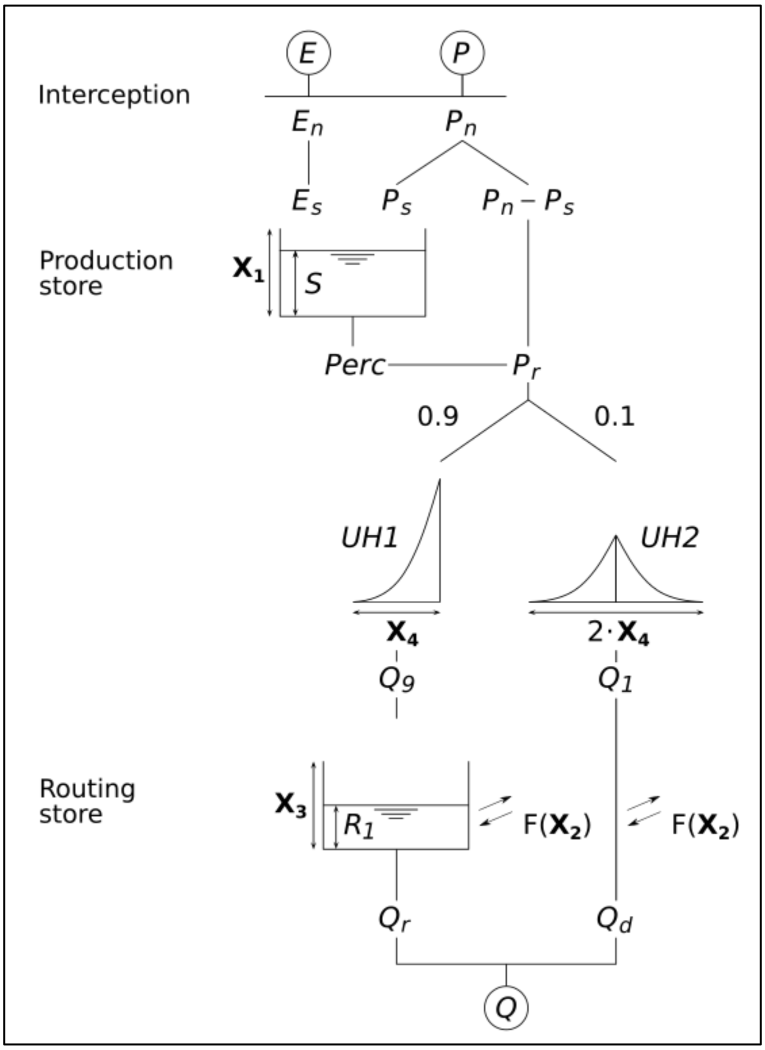


Figure 4.2: Structure of GR4H model: PE: potential evapotranspiration (mm); P: rainfall totals (mm); S: level of the production reservoir (mm); UH: Unit Hydrograph; F(X2): non -atmospheric exchange function; R: level of the routing reservoir (mm); Q: total streamflow (mm); x1: maximal capacity of the production reservoir (mm); x2: water exchange coefficient (mm); x3: capacity routing reservoir (mm); x4: unit hydrograph time base (hour). Detailed description of the GR4H model can be founded in the literature [128].

4.3.1 GR4H model setup

A basic setup of the GR4H model was done using steps: catchment area definition, time step data development and running the model through software. Further explanation refers to the time series processing, delineation of catchment areas warmup period, calibration, validation and optimization of the model. Data required for the GR4H model setup includes time series data in hourly time steps (see Table 4.2).

Table 4.2: Input data for the GR4H model

Input data	**Source**
Precipitation (mm/hr)	See section 3.5.2
Potential evapotranspiration (mm/hr)	See section 3.4.7
Temperature (0C)	See section 3.4.7
Flow data (mm/hr) per catchment area (mm2)	See section 3.5.5

Despite their differences, the GR4H model was selected over SHETRAN for several reasons. The first is related to a user-friendly environment in the form of the RStudio interface and multiple help that was possible to obtain from different users at Heriot-Watt University. In the end, this research study did not have the funding possibility for detailed DEM scanning that was necessary for the SHETRAN model, which led this study to simplify the approach for modelling.

4.3.2 Time series data processing

Precipitation and temperature data were collected from November 2016 to December 2018 (HWU rain gauge). Those were compared with two other rain gauges in the catchment area. The variable annual average was similar to the station in a very close location to the HWU rain gauge, and all stations were located at catchment boundaries. Runoff data was collected through 7 study plots (Figure 3.9), and surface flows data we collected from 2 different gauges from two sub-catchments (Figure 3.6).

4.3.3 Slope measurements

Channel slope and catchment slope characteristics were studied from two perspectives:

- Through DTM use in GIS, that was confirming the average slope of the catchment area using methodology defined by Vianello [162]

- Field surveys on different cultivation plots, including a study of channel slope and average catchment area slope [163].

The values of channel slope (Table 3.5) were used to determine flow through the Manning equation and discussion of results from GR4H modelling.

4.3.4 Warmup period

The initial model setup used four months of warmup for the Inch 1 and Inch 2 sub-catchment since cultivated areas had a month and a half-warmup period. Warmup periods have been choses according to available data, and relevant literature warmup periods have been chosen for hydrologically lumped [164]. This process has been applied to reduce the influence of initial conditions (the catchment can be dry or wet conditions). However, a shorter warmup period in the cultivated area was applied due to the lack of available data. The model was run on an hourly time step.

4.3.5 Model Calibration and validation period

According to the literature, calibration lengths range from 1 year to the maximum length of the hydrological record [164], [165], and the calibration and validation period length has been one year.

4.3.6 Optimization of the model

The quality of the simulation was evaluated by the objective function (OF) related to the observed and simulated flow time series. In the case of GR4H, model three different OF were used: Kling–Gupta (KGE) [166], Nash and Sutcliffe efficiency (NSE) [167] and Root Mean Square Error (RMSE) [168] and Root Mean Square Error (RMSE) [169]. The mathematical definition is presented in Table 4.3. For each parameter set from the GR4H model, the overall model performance is evaluated for each OF, and a detailed analysis of the criterion components is conducted.

While NSE criteria have been defined as very popular by many studies, there were many discussions about this criterion, several authors, and a proposed modification of this function. On the other hand, KGE has been used in cases of low flow. Then, RMSE is an evaluation calculation used to measure the accuracy of the estimated results of the model. In addition, percentage bias (PBIAS) has been used to assess model performance in terms of model bias [151]. Evaluation of each function has been presented in Chapter 6, and KGE has been used as OF for this study combined with PBIAS. Furthermore, evaluation in Chapter 6 showed that model performed better by KGE OF.

Table 4.3: Mathematical definition of KGE, NSE, RMSE and PBIAS that were used to evaluate the performance of the GR4H model

Metric	Definition	Optimal value	Range
KGE	$KGE = 1 - \sqrt{(\alpha-1)^2 + (\beta-1)^2 + (r-1)^2 *}$ (where $\beta = 1 - \frac{1}{2}\sum_{k=1}^{n} \left\lvert \frac{Q_{sim}(Ik) - Q_{obs}(Jk)}{n} \right.$ and $r = \frac{\sum_{i=1}^{n}\left(R_{obs}(i) - \overline{R}_{obs}\right)\left(R_{sim}(i) - \overline{R}_{sim}\right)}{\sqrt{\left(\sum_{i=1}^{n}\left(R_{obs}(i) - \overline{R}_{obs}\right)^2\right)\left(\sum_{i=1}^{n}\left(R_{sim}(i) - \overline{R}_{sim}\right)^2\right)}}$)	1	(-Inf,1)
NSE	$NSE = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O_i})^2}$	1	(-Inf,1)
RMSE	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}}$	0	(-Inf,1)
PBIAS	$PBIAS = \frac{\sum_{i=1}^{n}(Si - Oi)}{\sum_{i=1}^{n}(Oi)} *$	0	(-1,1)

*Where n is the total number of observations, Si is the ith simulated element, Oi is the ith observed element, α a is the ratio between simulated and observed mean, β is the ratio between simulated and observed standard deviation, and r is coefficient of correlation. A mathematical equation is shown in the following equations.

4.4 Model uncertainty errors

Each hydrological model is followed up by uncertainties related to different types of errors, assumptions, and outputs. It is important. Therefore, it is important to understand the source. This is important for the possible reduction of uncertainties. For GR4H modelled that has been used in the Menstrie catchment following uncertainties and errors should be highlighted:

- Due to instrumentation breakage, a certain amount of data has been missing from the original data set (see Table 6.1 in Chapter 6)
- Establish boundaries for each monitored plot (P1, P2, P3, P4, P5, P6 and P7) through site surveys, GPS surveys and expert network discussion (TillHIll Forestry, Forestry Research and HWU). Special incurrence can affect the exact location of existing boundaries and estimated contribution area.
- Instrumentation by itself has limitations for operation. This can be a possible source of errors.

4.5 Chapter Summary

This chapter introduces the GR4H model and summaries its inputs and model setup required for sub-catchment areas and other monitoring plots. The calibration and validation process has been evaluated through an objective function that further has been used in Chapter 6.

Output from the GR4H model has been further used for analyses of variable that has been defined in Chapter 3.

Chapter 5 Experimental results

5.1 Introduction

This chapter provides an overview of the results obtained from the field observations and the assessment of different cultivation techniques and their influence on larger sub-catchment scales. The results from the runoff flow experimental study sites provide insight into the hydrological behaviour of different cultivations. The relationship supported by RQ1 (runoff flow, precipitation, and antecedent conditions) and RQ2 (changes in sediment delivery for different cultivations) highlights the key points of the research. It is therefore examined and presented in greater detail. Firstly, we analysed and compared results obtained for three (plough, excavation mounding and hand screefing) different cultivation land techniques and their interrelationships. Differences between unplanted plots and cultivated areas were also examined. Secondly, linear regression analyses were performed for Qp, Qv and P to elucidate hydrological features. Thirdly, precipitation group data were established under each cultivation technique to examine relationships for the set of hydrological features in each plot. The results presented in this chapter expand the current knowledge and understanding regarding the effectiveness of cultivation techniques as NFM measures. This will be thoroughly discussed in Chapter 7.

5.2 Research question 1 results:

RQ1: How do different cultivation techniques influence the runoff volume and timing? Which factors control delivery?

The results in the following section will be pertaining to RQ1 will break down RQ and answer each element:

i. First, the cultivation practices, techniques, observations and categories are described. Runoff flow type is defined for runoff events which occur during wet or dry weather conditions controlled by API30 (explained in Section 3.3.4). The results were presented by delineating rainfall events (>3 mm) through dry/wet weather conditions under each cultivation practice category. These events attribute to their respective statistics for event conditions (e.g. P depth, antecedent conditions) and the experimental variables (e.g. runoff volume, runoff flow peak). The events were grouped by cultivation practices (e.g., plough, excavation mounding and hand-screefing), unplanted plots and sub-catchment areas for the coincidental event.

ii. The findings were presented for both groups and included event weather conditions (e.g., antecedent conditions related to dry and wet weather) and influencing factors (e.g. cultivation practices category and conditioning group). Such an approach enabled the answer regarding how different cultivation techniques affect the runoff and which element controls delivery (RQ1).

iii. Data comparison was also performed for the same precipitation event over the same cultivation practices and between them, where possible. This allowed investigations of different combinations among the studied cultivation techniques with runoff occurrences over different plots.

5.2.1 Event identification

Representative events were selected based on catchment precipitation totals that were equal to or greater than 3 mm, which was found to be the threshold that generated surface runoff. Events were grouped into those that occurred during dry or wet periods, determined according to the API30 value in the catchment before a significant event occurred. Dry periods were defined as those with an API30 value ≤ 20 mm, while wet periods had API30 values >20 mm (see Section 3.5.4). The results distinguished dry and wet event types (see Table 5.1). Furthermore, the boxplot shows a specific difference between P and API30 variables for different event types (see Figure 5.1).

Table 5.1: Event conditions for dry and wet weather periods (P= precipitation; Ed = event duration; I =intensity of precipitation event, API30 = antecedent prescription index)

Variable	Event type	Mean	StDev	Min	Median	Max
P (mm)	Dry	7.6	6	3	5.6	28.4
	Wet	10.6	6.9	3	9	39
Ed (hr)	Dry	20.3	22	3	12	103
	Wet	18.8	15.1	1	15	81
I (mm/hr)	Dry	0.5	0.4	0.1	0.5	2.3
	Wet	0.7	0.5	0.2	0.6	3.6
API30 (mm)	Dry	13.9	3.8	6.8	13.2	19.9
	Wet	31.7	7.8	20.2	30.5	59.5

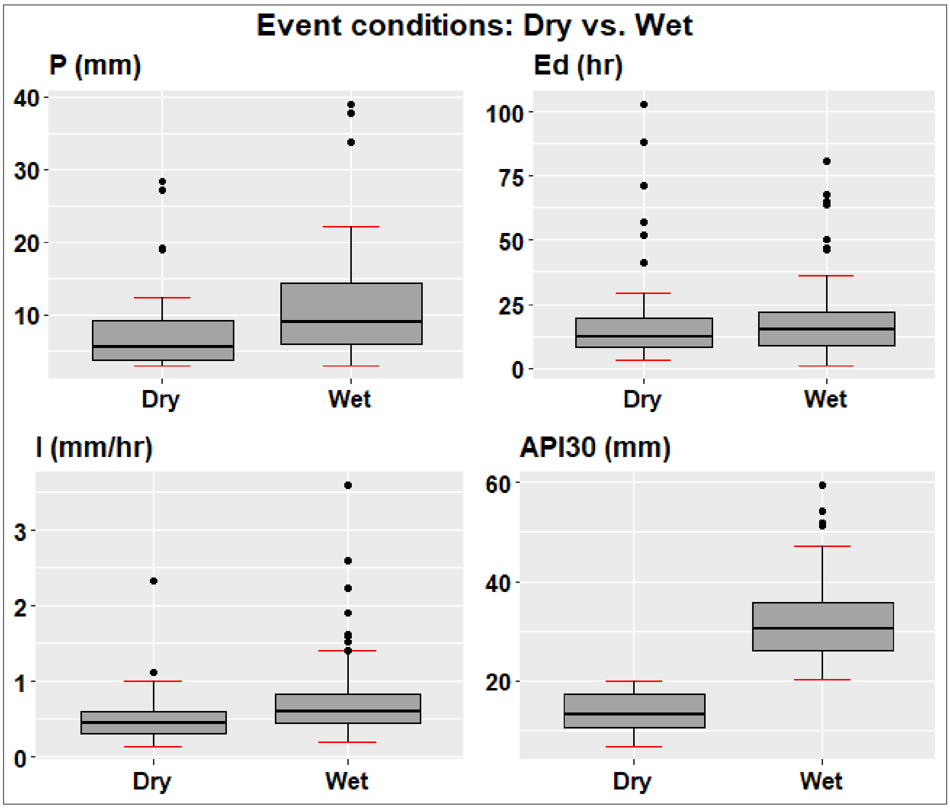


Figure 5.1: Characterisation of event conditions during dry and wet weather periods, as per Table 5.1

5.2.2 Runoff flow determination

Runoff flow occurrence points to establish the events' behaviour over different cultivated areas and unplanted plots. Such observation enabled the determination of events that were used as representatives. For example, according to the position of equipment and channel used for measurements (maximum depth of 0.60 m under the main ground layer), an event that likely resulted in runoff flow was observed precisely in some cultivated regions. The number of events observed during the analysis process for all cultivated areas, unplanted plots and sub-catchment areas is shown in Table 5.2.

Table 5.2: Total number of events that were observed during the monitoring period for unplanted plots, cultivated areas and sub-catchment areas.

	Cultivation practices							**Sub-catchments**	
	Unplanted plot	Hand screefing	Ploughed ground			Excavated ground		Inch 1	Inch 2
Monitoring plot	P1	P2	P3	P4	P5	P6	P7		
Number of events	44	85	85	79	68	70	48	69	63

5.3 Event characteristics for dry and wet weather conditions

Runoff events were grouped for dry and wet weather periods to analyse differences between cultivated and unplanted plots. Division of runoff events into dry and wet weather conditions enabled a more thorough analysis and deeper understanding of the conditions and factors that affect runoff flow occurrence in these areas (RQ1). The conditions of each category are presented in Appendix 1, along with several analysed events per dry/wet weather conditions group. The wet weather conditions have a range of median API30 in an interval of 27.7 mm to 32.68 mm, while the dry weather conditions have a range of API30 in an interval of 10.96 mm to 14.52 mm (see Table A.1.1 in Appendix 1).

The statistical test has been used to assess the effects of runoff volume depth/runoff peak and precipitation events. The summary of statistical significance was assessed using P-value, Pearson correlation and R-square values (see Table 5.3).

Table 5.3: Combination of values or evaluation of the significance of data sets

Correlation	P-value	Pearson correlation	R-square
High	<0.0001	0.51-1	0.7-1
Medium	0.05-0.0001	0.3-0.5	0.4-0.7
Low	<0.05	<0.29	<0.4

The relationships between runoff volume (Qv) and runoff flow peak height (Qp) for unplanted plots, cultivated areas and sub-catchment areas for dry and wet weather conditions and the results of statistical analyses are summarised in Table 5.4. Only two data sets were excluded for further analyses due to low performance (marked in red, Table 5.4). The remaining 18 data sets were analysed further using a linear regression analyses model (LRM) for each monitored plot and are presented in the following section.

Table 5.4: Mann-Whitney Statistical test /Pearson correlation/R evaluation

Monitoring area	**Relationship examined**	**Weather conditions group**	**Achieved confidence**	**P-value for Mann-Whitney statistical**	**Pearson correlation**	**R - Square**	**Combined Significance**
P1 (2016-2017)	Qp/ P	Dry	95%	**0.36**	**0.29**	**0.42**	**Low**
		Wet		**<0.0001**	**0.69**	**0.50**	**Medium**
	Qv/ P	Dry		**0.48**	**0.71**	**0.51**	**Low**
		Wet		**<0.0001**	**0.76**	**0.58**	**Medium**
P1 (2017-2018)	Qp/ P	Dry		0.0022	0.90	0.81	High
		Wet		0.0006	0.86	0.73	High
	Qv/ P	Dry		0.045	0.98	0.96	High
		Wet		0.0006	0.93	0.86	High
P22	Qp/ P	Dry		<0.00001	0.72	0.52	High
		Wet		<0.0001	0.65	0.42	High
	Qv/ P	Dry		<0.0003	0.91	0.82	High
		Wet		<0.0003	0.74	0.54	High
P33	Qp/ P	Dry		< 0.0001	0.72	0.51	High
		Wet		< 0.0001	0.68	0.46	High
	Qv/ P	Dry		< 0.0001	0.89	0.78	High
		Wet		< 0.0001	0.86	0.74	High
P44	Qp/ P	Dry		<0.0001	0.65	0.43	High
		Wet		<0.0001	0.65	0.42	High
	Qv/ P	Dry		<0.0001	0.90	0.80	High
		Wet		<0.0001	0.72	0.52	High
P55	Qp/ P	Dry		<0.0001	0.73	0.53	High
		Wet		<0.0001	0.71	0.51	High
	Qv/P	Dry		0.0003	0.92	0.85	High
		Wet		<0.0001	0.76	0.58	High
P66	Qp/ P	Dry		<0.0001	0.74	0.55	High

		Wet		<0.0001	0.63	0.40	Medium
	Qv/ P	Dry		<0.0001	0.80	0.64	High
		Wet		<0.0001	0.89	0.80	High
P77	Qp/ P	Dry		<0.0001	0.82	0.67	High
		Wet		<0.0001	0.68	0.46	High
	Qv/ P	Dry		<0.0001	0.92	0.84	High
		Wet		0.0002	0.83	0.68	High
Inch 1	Qp/ P	Dry		0.004	0.71	0.51	Medium
		Wet		<0.0001	0.69	0.50	Medium
	Qv/ P	Dry		<0.0001	0.76	0.58	High
		Wet		<0.0001	0.73	0.53	High
Inch 2	Qp/ P	Dry		0.004	0.74	0.55	Medium
		Wet		<0.0001	0.76	0.58	Medium
	Qv/ P	Dry		0.0018	0.73	0.53	Medium
		Wet		<0.0001	0.71	0.50	Medium

5.3.1 LRM for dry and wet weather conditions

relationship between (runoff flow peak (Qp) and runoff flow water volume (Qv) in correlation with precipitation (P))) is shown in Table 5.5. API30 was used for the assessment of weather conditions groups (see .

Table 5.10 shows results for LRM that was formed for the set of variables. LRM signature predicts all monitored plots differently with statistical significance of cross-correlated variables, R2 values, NSE and RSR.

Values of NSE and RSR (see **Error! Reference source not found.**) are in the range of s atisfactory to very good. However, in situations where variables have different performances, the rating must be clearly defined. For example, if one of the unbalanced performance ratings of “very good” and another “good” overall performance should bed escribed as “good” [151].

Similarly, if performance ratings differ for various monitored areas and/or output types, then those differences must be clearly described. Values for both NSE and RSR have a spectrum from very good to satisfactory.

Table 5.5: LRM performances and relationship between variables relationship (runoff flow peak (Qp) and runoff flow water volume (Qv) in correlation with precipitation (P)))

PlotPlot	**Conditioning Group**	**Relationship examined**	**Relationship**	**NSE**	**RSR**	**Model performance**
Pl ot ,	Dry	Qp/ P	Qv= 0.6+ 0.03* P	0.81	0.40	Very good
		Qv/P	Qv=-20.6+6.9 *P	0.96	0.18	Good

	Wet	Qp/ P	Qv= -0.2+0.2 *P	0.73	0.48	Good
		Qv/P	Qv= -12.4 +6.3*P	0.86	0.34	Very good
Plot 2	Dry	Qp/ P	Qp= 0.3+0.01*P	0.53	0.68	Satisfactory
		Qv/P	Qv= 1.1 + 0.1*P	0.83	0.41	Very good
	Wet	Qp/ P	Qp=0.1+0.03*P	0.52	0.69	Satisfactory
		Qv/P	Qv=1.6+0.47*P	0.52	0.68	Satisfactory
Plot 3	Dry	Qp/ P	Qp=0.2 +0.02*P	0.51	0.69	Satisfactory
		Qv/P	Qv=-2.3+1.38*P	0.51	0.46	Very good
	Wet	Qp/ P	Qp= 0.1+0.03*P	0.51	0.70	Satisfactory
		Qv/P	Qv= 1.8+0.9*P	0.51	0.69	Satisfactory
Plot 4	Dry	Qp/ P	Qp=0.07+0.01*P	0.72	0.69	Satisfactory
		Qv/P	Qv=-0.9 +0.5*P	0.85	0.38	Very good
	Wet	Qp/ P	Qp=-0.05+0.02*P	0.54	0.67	Satisfactory
		Qv/P	Qv= -2.8 + 0.6*P	0.59	0.63	Satisfactory
Plot 5	Dry	Qp/ P	Qp=0.1+0.01*P	0.53	0.67	Satisfactory
		Qv/P	Qv=-0.5+0.6*P	0.85	0.38	Very Good
	Wet	Qp/ P	Qp= 0.04+0.02*P	0.51	0.69	Satisfactory
		Qv/P	Qv=-2.8 + 0.75*P	0.58	0.64	Satisfactory
Plot 6	Dry	Qp/ P	Qp=0.02+0.002*P	0.55	0.66	Satisfactory
		Qv/P	Qv=0.2 + 0.08*P	0.64	0.59	Good
	Wet	Qp/ P	Qp= 0.03+0.001*P	0.51	0.69	Satisfactory
		Qv/P	Qv=0.3+0.03*P	0.84	0.40	Very good
Plot 7	Dry	Qp/ P	Qp=0.1+0.03*P	0.67	0.56	Good
		Qv/P	Qv=-4.6 +1.6*P	0.85	0.38	Very good
	Wet	Qp/ P	Qp=0.2+0.01*P	0.54	0.67	Satisfactory
		Qv/P	Qv=-1.3+ 0.7*P	0.70	0.56	Good
Inch 1	Dry	Qp/ P	Qp=0.1+0.02*P	0.51	0.68	Satisfactory
		Qv/P	Qv=-3.9+0.8*P	0.58	0.63	Satisfactory
	Wet	Qp/ P	Qp=-0.6+0.1*P	0.51	0.7	Satisfactory
		Qv/P	Qv=-7.4+1.1*P	0.53	0.68	Satisfactory
Inch 2	Dry	Qp/ P	Qp=0.1+0.04*P	0.55	0.65	Satisfactory
		Qv/P	Qv=-9.1+1.8*P	0.53	0.66	Satisfactory
	Wet	Qp/ P	Qp=-0.4+0.1*P	0.58	0.64	Satisfactory
		Qv/P	Qv=-1.7+0.7*P	0.51	0.70	Satisfactory

Results for LRM analyses related to the correlation of P/Qp and P/Qv are statistically significant in terms of wet and dry conditions group and are presented in Table 5.5. The P-value showed statistical significance ($P<0.001$) for all analysed cross-correlation variables (see Table 5.5). However, LRM formed general trends over cultivated areas, the unplanted plot and sub-catchment areas as all events were used for analyses during the dry and wet phase.

Key findings from the analysis of events between cultivation techniques and unplanted plots showed the following:

Unplanted plot:

The P1 (unplanted plot) experienced the highest amount of runoff in the case of both weather conditions. The median Qp was 76% to 98% lower in the case of cultivated areas compared to P1 for dry weather conditions. Further comparisons for wet weather conditions showed that Qp was 87% to 98% lower than P1(unplanted plot). Median Rt for the P1 (unplanted plot) was the lowest in the case of dry weather conditions, followed by P3 (plough plot), P5 (plough plot), P2 (hand-screefing plot), P4 (plough plot), P6 (excavation mounding plot) and P7 (excavation mounding plot). On the other hand, median Rt for wet weather conditions was the same in the case of P1, P3, P4, P5 and P6, followed by P2 and P7. According to analysed data, it is likely that the P1 (unplanted) plot area will likely have lower Rt with the highest amount of Qp/Qv/Qvt/Qpt for dry and wet weather conditions. Median Qv is 11% and 1% lower than Qvt for dry and wet weather conditions. Hence, events occurring in the P1 (unplanted plot) will have the most prolonged duration for both weather conditions (see Table A.2.1 in Appendix 2 and Figure 5.2).

Plough cultivation:

According to analysed data in three different plough plots, it is likely that the P3 plough plot experienced the highest amount of each variable (Qp, Qv, Qpt and Qvt) compared to another three plots since the lowest amounts occurred in the case of P4 plough plot. Median Qv is 26% and 39% lower than Qvt is case of P3 plough plot, 46% and 44% in case of P4 plough plot and 68% and 69% in case of P5 plough plot for dry and wet weather conditions. Median Rt was 50% and 60% higher in the case of P4 plough plot and P5 plough plot for dry weather conditions compared to P3 plough plot. Furthermore, median tRt was identical for all plough plots in wet weather conditions. Also, Tp was the highest in the case of P3 plough plot for both weather conditions.This leads to the conclusion that water runoff will enter faster P3 plough plot in case of dry weather conditions since, in case of wet weather conditions, water will enter all plough areas simultaneously. On the other hand, P3 will experience the highest amount of runoff water, followed by P5 plough plot and P4 plough plot (see Table A.2.1 in Appendix 2 and Figure 5.2).

Hand screefing cultivation

Hand screefing cultivation is compared to plough and excavation mounding cultivation since only one plot was monitored. Median Qv is 60% and 30% lower than Qvt in the case of the P2 hand-screefing plot for dry and wet weather conditions. Median Rt was the same for dry and wet weather conditions in the case of the P2 hand –screefing plot. Furthermore, the median Rt for P2 hand –screefing plot was higher between 50% and 25% in comparison with the P3 (plough plot) and P5 plough plot and lower than 20% in the case of the P4 plough plot and P7 excavation mounding plot for dry weather conditions. Hence, for wet weather conditions, median Rt was 50% higher for P2 hand – screefing plot than P3 plough plot, P4 plough plot, P5 plough plot and P7 excavation mounding plot since P2 hand-screefing plot and P6 excavation mounding plot had the exact value of median Rt (see Table A.2.1 in Appendix 2 and Figure 5.2). Median Qv was highest in the case of P2 hand-screefing plot for wet weather conditions compared to other cultivated areas.

Excavation mounding cultivation

Observation during weather conditions showed that the P7 excavation mounding plot would experience significantly higher amounts of runoff water than the P6 excavation mounding plot. Median Qv is 56% and 53% lower than Qvt is case of P6 excavation mounding plot, 61% and 60% in case of P7 excavation mounding plot for dry and wet weather conditions. Median Rt was 45% lower for P6 excavation mounding plotplot for dry weather conditions and 50% higher for wet weather conditions. In the case of dry and wet weather conditions, Median Qv was 84% and 88% lower for P6 excavation mounding plot. On the other hand, the P7 excavation mounding plot will likely reach Tp faster and deliver more runoff water in case of any weather conditions. On the other hand, water will enter the P6 excavation mounding plot earlier in case of dry weather conditions since the Ed duration will be reasonably similar between those two monitored areas.

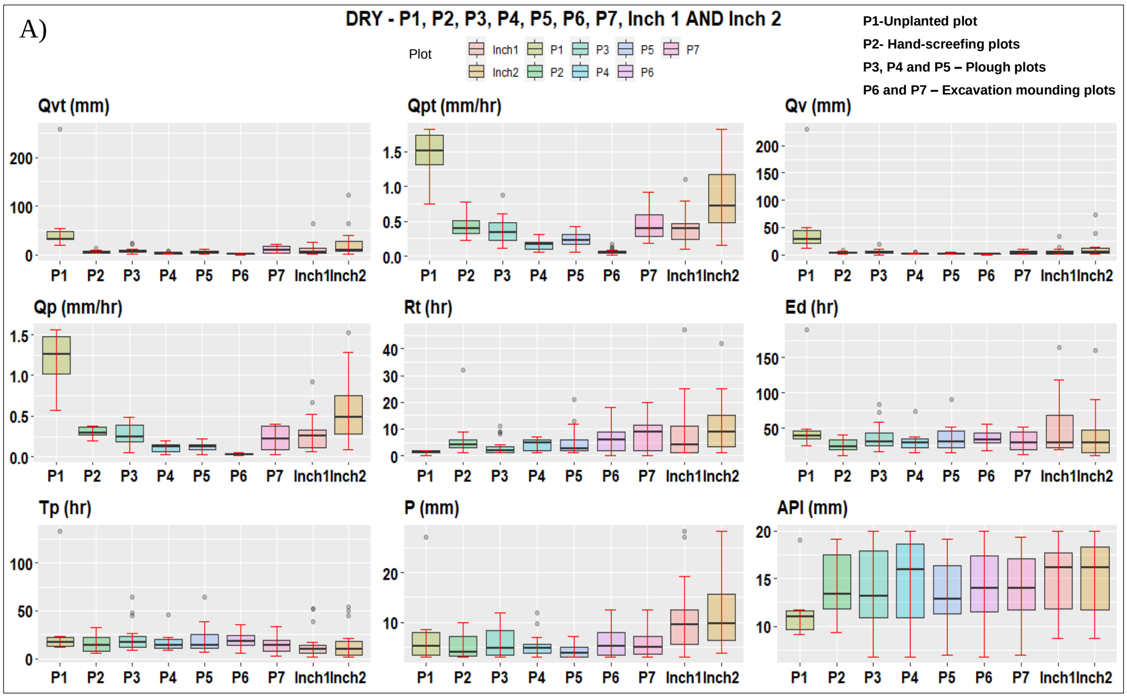
General comparisons:

A general comparison of cultivated areas showed that runoff water will first P1 area, followed by the P3 plough plot, P2 hand-screefing plot, P4 plough plot, P5 plough plot, P6 excavation mounding plot and P7 excavation mounding plot during the dry weather conditions. This finding indicated that upland areas would respond faster to possible rain than lowland cultivated areas for dry weather conditions. On the other hand, the fastest response for wet weather conditions will occur in P1 unplanted plot, P3 plough plot, P4 plough plot, P5 plough plot and P7 excavation mounding plot, followed by P2 hand-screefing plot and P6 excavation mounding plot. Then, the highest Qv for dry weather conditions occurred in the case of P1 unplanted plot), P3 plough plot and P7 excavation mounding plot, since wet weather conditions had P1 unplanted plot, P2 hand-screefing plot and excavationP7 excavation mounding plot.

Key findings from the analysis of sub-catchment events observation key findings showed the following:

The Inch 2 sub-catchment area showed a higher value of Qv for the wet and dry phase than the Inch 1 sub-catchment (see Table A.2.1 in Appendix 2 and Figure 5.2). Median Qv values were lower at 32% and 47% for Inch 1 sub-catchment in case of dry and wet weather conditions. Furthermore, median Qp was lower 40% and 60% lower in the case of Inch 1 sub-catchment for dry and wet weather conditions. Conversely, the Inch 1 sub-catchment had lower Rt for dry and wet phases. For dry and wet weather conditions, the median Rt was lower than 55% and 66% in the case of inch 1. Tp was the same for dry weather conditions and 12% lower for Inch 2 in case of wet weather conditions. Qv values were lower at 32% and 47% for Inch 1 sub-catchment in case of dry and wet weather conditions.

Furthermore, median Qp was lower than 40% and 60% lower in the case of the Inch 1 sub-catchment for dry and wet weather conditions. According to those results, the Inch 1 sub-catchment will likely respond faster to runoff with less runoff volume water and lower runoff peak height. On the other hand, the Inch 2 sub-catchment will reach Tp more quickly in wet weather conditions since, for dry weather conditions, Tp will be the same for both sub-catchments.



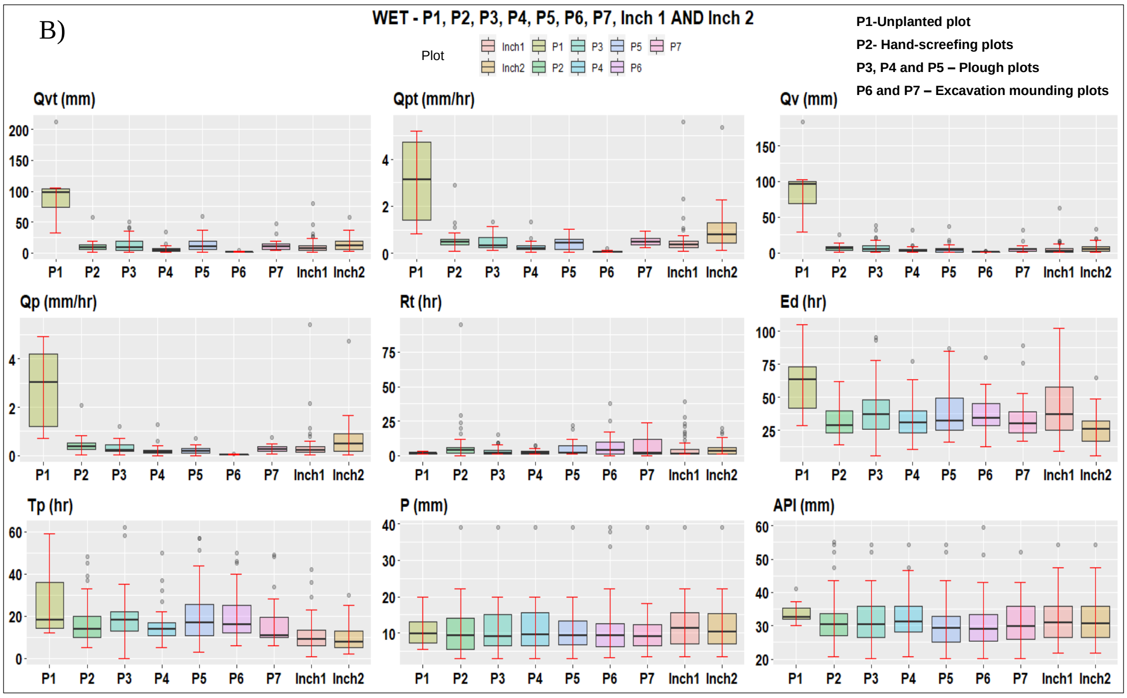


Figure 5.2: Distribution of event variables for all PlotPlots and sub-catchments over A) dry weather conditions and B) wet weather conditions (P1-unplanted plot, P2-hand screening plot, P3, P4 and P5 – plough plots, P6 and P7 – excavator mounding plots).

5.4 Event groups

5.4.1 LRM for grouped events under plough cultivation (P3, P4, P5), excavation mounding cultivation (P6 and P7) and sub-catchment areas (Inch 1 and Inch 2)

The total number of coincidental events that were analysed for sub-catchment areas, plough cultivation, excavation mounding cultivation, hand-screefing cultivation and unplanted plot are: 61, 34, 35, 83 and 13. For the purpose of LRM events that occurred in plough and excavation, mounding cultivation has been a group in the case of P3, P4 and P5 for plough cultivation and for P6 (excavation mounding plot) and P7 (excavation mounding plot) in the case of excavation mounding cultivation. This assessment showed differences between Qp/P and Qv/P relationship under dry/wet weather conditions (see Figure 5.3). Therefore, LRM was performed to establish connections between P/Qv/Qp. Although the same P events and API30 value have occurred, hydrological behaviour showed differences between monitored areas. The assessment of LRM highlighted the greater importance of wet and dry weather conditions over cultivated areas and validated this model (see Table A.3.1. in Appendix 3). NSE and RSR values were satisfactory to very good (see Table A3.1. in Appendix 3).

The R2 values for all variables in LRM were fairly high (0.44<R2<0.95), and the RSR values ranged from 0.18 to 069. This indicates that the performance of all models was very good to satisfactory. For example, LRM analysis for the dry conditioning group revealed a very close fit, with NSE values ranging from 0.48 to 0.96. For wet conditions, NSE values ranged from 0.51 to 0.96 (see Table A.3.1 in Appendix 3).

Hence the performance of all models was very good to satisfactory. Very good to good performance was mainly established for the dry conditioning group in the case of the Qv and P relationship.

The results of the standardised coefficient for the LRM model indicates that precipitation and runoff volume/runoff peak is an important parameter for observed monitoring plots. Further investigation of that parameter under vegetation changes will consider different conditions of those relationships.

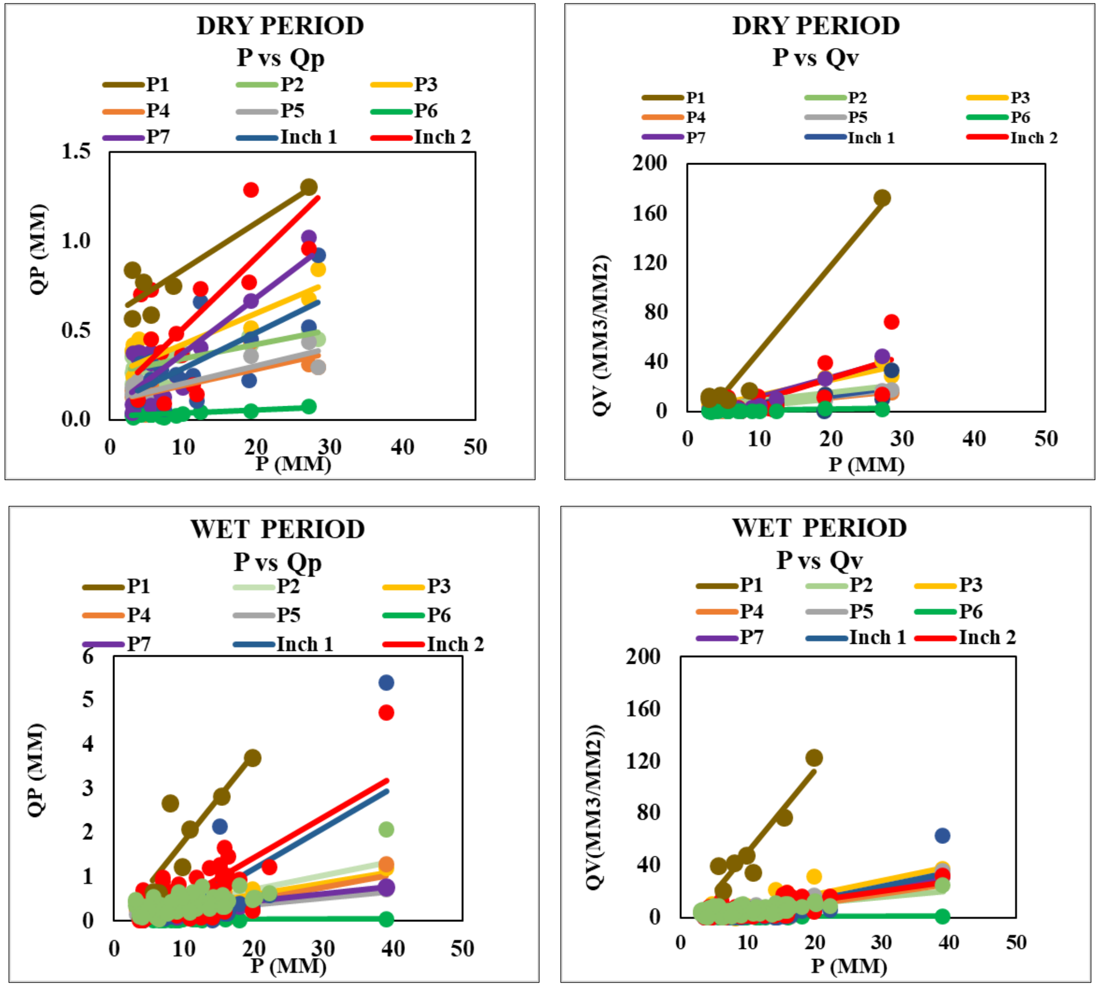


Figure 5.3: LRM presentation Qv/P and Qp/P for dry and wet weather conditions (P1- unplanted plot, P2 – hand-screefing, P3, P4, P5 – plough cultivation technique; P6 and P7-excavation mounding technique; Inch 1 and Inch 2 –sub-catchment areas)

Analysing those data makes it apparent that P1 (unplanted plot), P3 (plough plot) and P7(excavation mounding plot) cultivated areas deliver more runoff water than the other two ploughed cultivated areas (P4 and P5) and one excavation mounding area (P6). Furthermore, Inch 2 sub-catchment showed higher Qp/Qv than Inch 1 sub-catchment area. Those differences are statistically significant. In addition to that, observed data indicated the following:

Dry weather conditions:

The highest values of Qp/Qv can be referred to as P1 unplanted plot(values in the range of 0-1.3 mm for Qp and 0-180 mm^3/mm^2 for Qv). In the case of the LRM model developed for sub-catchments and cultivated areas for Qv vs P, it was possible to group models into three groups. The first group included Inch2, P3 plough plot, and P7 excavation mounding plot (values in the range of 0-40 mm^3/mm^2), the second category included Inch1 P2 hand-screefing plot, P4 plough plot and P5 plough plot (values in the range of 0-15 mm^3/mm^2) and the third group that includes P6 excavation mounding plot (values in the range of 0-2 mm^3/mm^2). Qv will likely have the highest amount during the dry period in the first group of LRM, followed by the second and third groups. On the other hand, the range of Qv for P1 (unplanted plot) was from 0 to 175 mm^3/mm^2. Furthermore, according to LRM that predicted Qp, it is likely that Inch 2 and P7 excavation mounding plot (values in the range of 0-1.2 mm) will have the highest Qp, followed by P3 plough plot (values in the range of 0-0.75mm), Inch1sub-catachmnet (values in the range of 0-0.66 mm), P2 hand-screefing plot (values in the range of 0-0.48 mm), P5/P4 plough plots (values in the range of 0-0.38 mm) and P7 excavation mounding plot (values in the range of 0-0.08 mm) LRM that was developed across Inch 1 sub-catchment, P5 plough plot and P4 plough plot, showed almost a same curve projection, that is in the same range of values for Qv. The same phenomena occurred in the case of Inch 2 sub-catchment, P3 plough plot and P7 excavation mounding plot.

Wet weather conditions:

According to LRM, in the case of Qv vs P, it is likely that P1 will have the highest Qv followed by P3 plough plot, Inch 1 sub-catchment, P5 plough plot, P7 excavation mounding plot, Inch 2 sub-catchment, P4 plough plot, P2 hand-screefing plot and P6 excavation mounding plot. Further analyses can group this projection for the P3 plough plot and Inch1 sub-catchment (values in the range of 0-37 mm3/mm2), then the P5 plough plot and P7 excavation mounding plot (values in the range of 0-30 mm3/mm2), then Inch 2 sub-catchment and P4 plough plot (values in the range of 0-26 mm3/mm2). Also, likely, the P7 excavation mounding plot (values in the range of 0-20 mm3/mm2) and P6 excavation mounding plot (values in the range of 0-1.6 mm3/mm2) will not follow any of the trends of the cultivated area. On the other hand, Qp predictions can be grouped in the case of Inch 1 and Inch 2 (values in the range of 0-3.20 mm), then in the case of P2 hand screefing plot, P3 plough plot and P4 plough plot (values in the range of 0-1.3 mm), then in case of P7 excavation mounding plot and P5 plough plot (values in the range of 0-3.0.76 mm). On the other hand, P6 excavation mounding plot experienced the lowest Qp prediction in the range of 0-0.06 mm.

General trends summary:

Hydrological predictions that LRM can likely be grouped in sub-catchments and cultivated areas related to either Qp (for the wet period) or Qv (for the dry period). Further analyses will take into account different perspectives of data.

5.4.2 Dry and wet weather conditions group event comparison

Sub-catchment areas (Inch 1 and Inch 2) events comparison

To compare the same precipitation events in Inch 1 and 2 sub-catchment areas, 12 and 46 were selected for dry and wet weather conditions, respectively. The pervious section included all possible events. Selected events from this section had the same P event occur in both sub-catchments. Those events were outlined in Appendix 4: under dry/wet weather conditions (see Figure 5.6) and FDS categories (see Figure 5.4 and Figure 5.5). Furthermore, FDS represented with F1 and F3 categories for dry weather conditions and F2, F3, F4 and F5 categories for wet weather conditions. In addition to that, observed data indicated the following:

- Three major P events (P>15 mm) occurred in the case of dry weather conditions, and 14 major P events in wet weather conditions. Despite this, median P values are the same (P=10 mm, see Appendix 4) for dry and wet weather conditions with indicative differences in API30 (see Appendix 4). Further analyses related to FDC

/VSC (see Appendix 4 and Figures 5.4 and 5.5) showed that the highest median P values occurred in the case of the F4 category (see Appendix 4) and the F5 category (see Appendix 4) for wet weather conditions and the F1 category for dry weather conditions (see Table 5.10). FDC with lower median P and lower median API30 experienced lower Qvt/Qpt for both sub-catchments for dry weather conditions (see Appendix 4). On the other hand, FDC, with the highest API30 (see category F5 in Appendix 4), experienced the highest Qv/Qp for sub-catchment during wet weather conditions (see category F5 in Appendix 4).

- It was indicative that the Inch1 sub-catchment had 60% (dry weather conditions) and 70% lower (wet weather conditions) median Qv than the Inch 2 sub-catchment. Further analyses related to FDC/VSC (see Appendix 4 and Figures 5.4 and 5.5) showed higher Qv in the case of Inch 2 sub-catchment for any category under dry and wet weather conditions. The same trend was noticed for Qvt/Qpt/Qp. Further assessment of results showed that the Inch 1 sub-catchment experienced a 14% lower median Qv for wet than dry weather conditions.
- Rt median values were lower in the case of Inch 1 for dry and wet weather events. Furthermore, in the case of dry weather conditions, Inch 1 has 44% lower Rt since, in wet weather conditions, Inch 1 had 33% lower Rt than Inch2 (see Appendix 4 and Figure 5.6). From the FDC/VSC perspective, Inch 1 demonstrated higher Rt for the F1 category and lower Rt for the F3 category than Inch 2 for dry weather conditions (see Appendix 4 and Figure 5.6). On the other hand, Rt was lower in any FDS during the wet period for Inch1 than Inch 2 (see Appendix 4).
- Tp median values were 1 hour higher for Inch 1 than for Inch 2 for events in the dry and wet weather conditions group (see Appendix 4). Furthermore, for FDS, Tp was in a similar range (10-13.5 hr) between Inch 1 and Inch 2 sub-catchments for dry FDS categories. Moreover, FDS categories for wet weather conditions experienced lower values in the case of F4 (Inch 1 and Inch 2 – see Table 5.10) and F5 (for Inch 2 -see Appendix 4). Median Tp and Rt values for dry and wet weather conditions between Inch 1 and Inch 2 were in a similar range (10-11 hours).
- Ed median values were higher in the case of the Inch1 sub-catchment for both weather conditions (see Appendix 4).

Single events comparisons under certain FDC groups and dry/wet weather conditions:

- Dry weather conditions were considered F1 and F3 categories. Major events that occurred in the F1 category (P= 28.4 mm, API30= 8.7 mm occurred on the 20th of December 2016) and in the F3 category (P=27.2 mm and API30=9.2 mm occurred on 19 November 2017). Further analysis showed that events in the F1 category delivered a significantly higher Qv than those in the F3 category. The Qv were higher for 70% and 80% for Inch 1 and Inch2, respectively. Further compared events occurred on the 9th of January 2017 (P=11.80 mm and API30=19.95 mm) and the 5th of March 2018 (P=11.40 mm and API30= 17.72 mm), where again more runoff water occurred in the case of category F1 than in category F3.
- Wet weather conditions are considered F2, F3, F4 and F5 categories and could match major and minor events. For example, events that occurred in the F2 category (P= 15.2 mm and API30= 25.9 mm occurred on 10th September 2017, the F4 category (P=15.4 mm and API30=31.7 mm appeared), and in the F5 category (P= 15.8 mm and API30=54.34 mm occurred on 14th November 2018) showed that event that belongs to F2 category will deliver less runoff water thane events that occurred in F2 and F5 category.

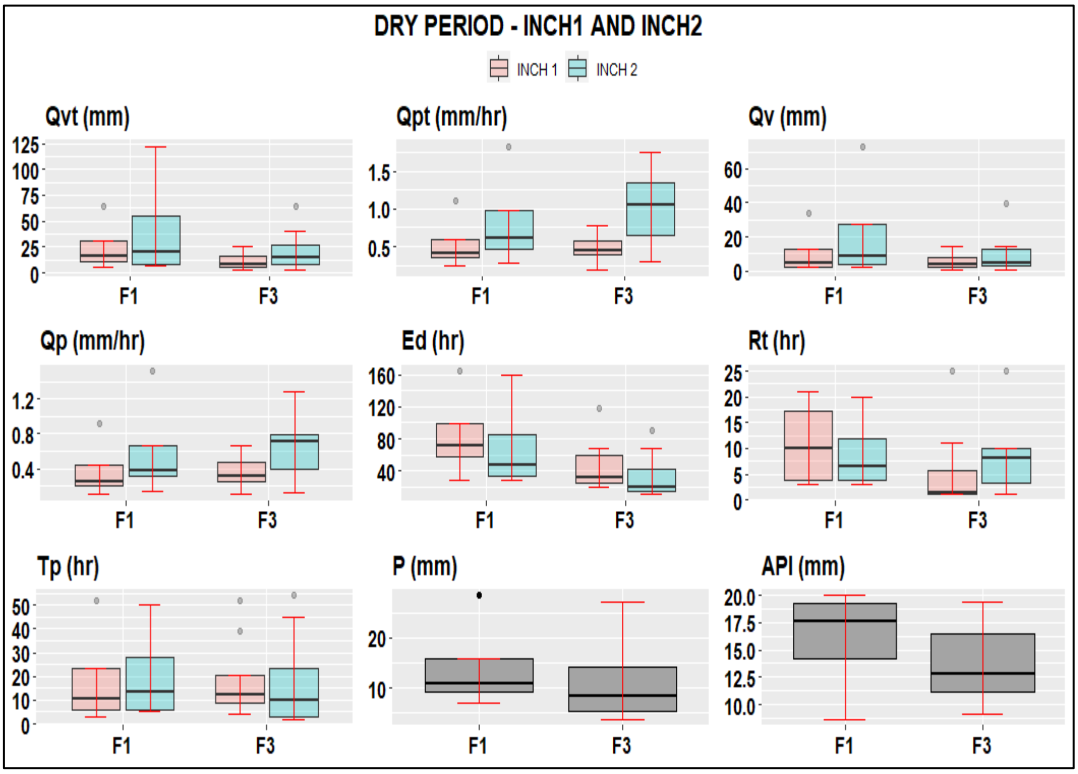


Figure 5.4: Forest development categories (F1, F3) box plot for variables under the group of events in the case of Inch 1 and Inch 2 sub-catchments for the dry weather conditions

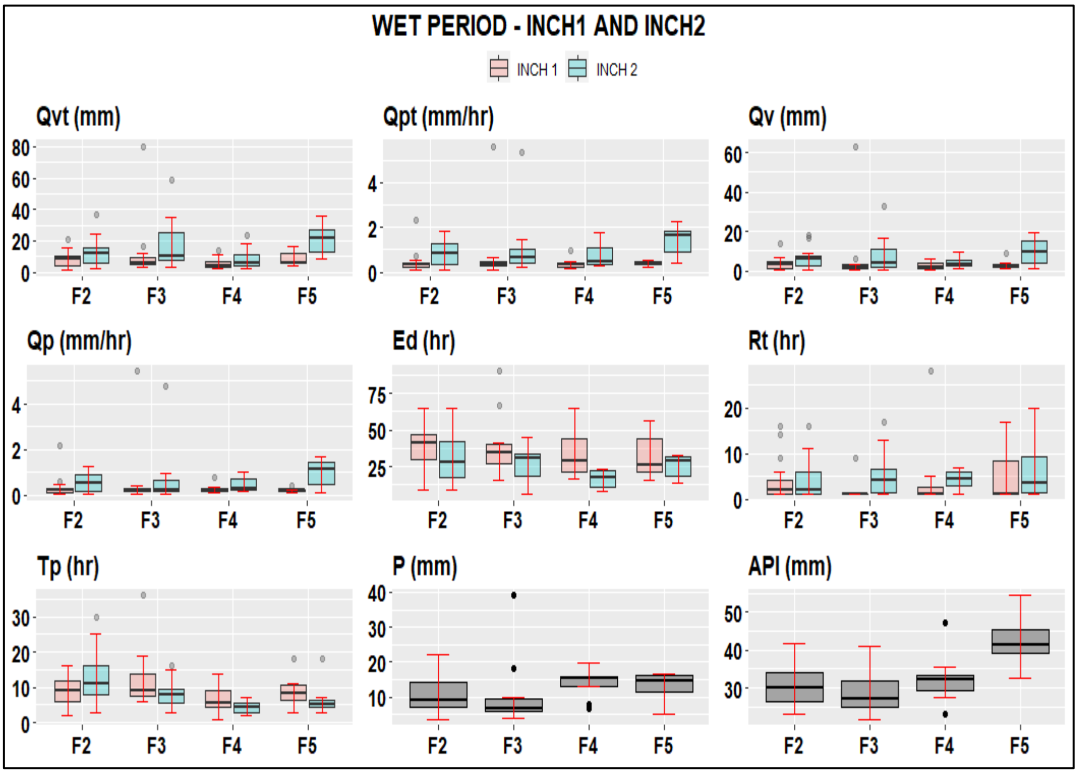


Figure 5.5: Forest development categories (F2, F3, F4 and F5) box plot for variables under the group of events in the case of Inch 1 and Inch 2 sub-catchments for the wet weather conditions

Dry and wet weather conditions findings for Inch 1 and Inch 2 sub-catchment areas:

Figure 5.6 shows that Inch 2 will deliver more runoff water than Inch 1 sub-catchment area.

According to analysed data, it is expected that events that occurred during dry and wet weather conditions in the Inch 1 sub-catchment area will have lower Qvt/Qpt/Qv/Qp compared to the Inch 2 sub-catchment. Furthermore, those events will likely be higher Ed and Tp and shorter Rt than the Inch 2 sub-catchment (see Figure 5.6 and Appendix 4). Dissemination of results under each FDC is likely to follow this trend, with some exceptions explained in the previous section.

A higher percentage of afforestation (see Appendix 4) and the number of trees in the Inch 1 sub-catchment (see Appendix 4) might significantly influence lower runoff water values in this sub-catchment. Furthermore, 18% more trees have been planted by plough cultivating technique in Inch 1 sub-catchment than in Inch 2 sub-catchment.

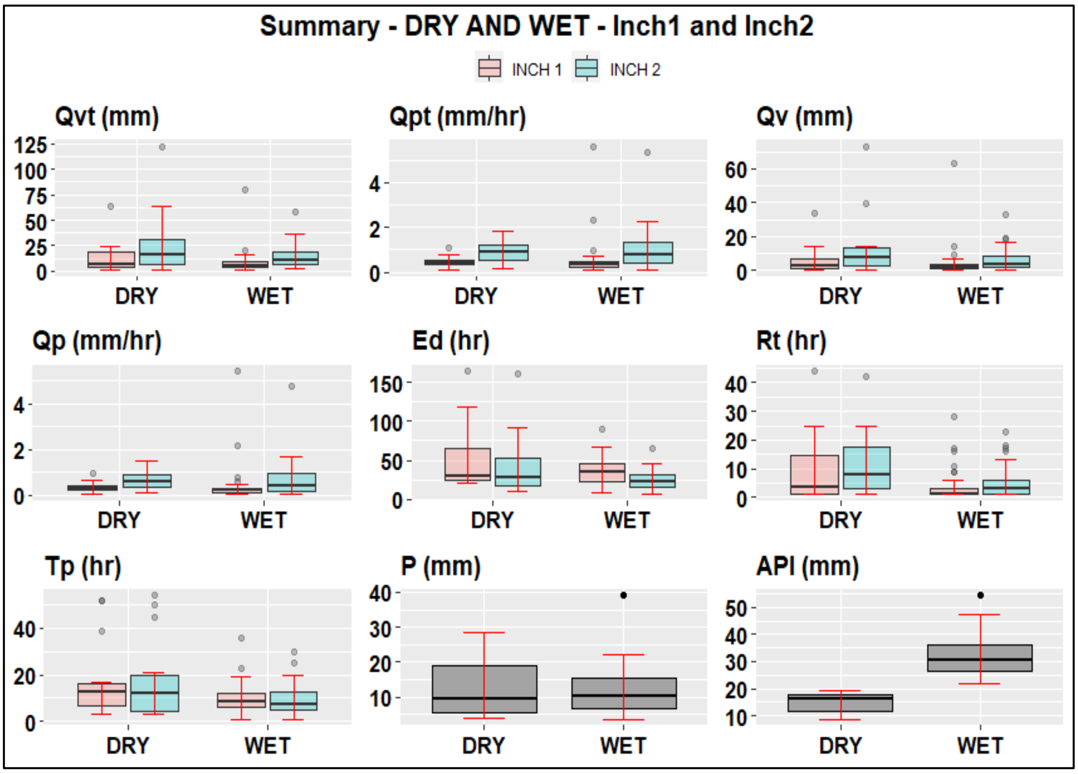


Figure 5.6: Dry and wet weather conditions summary for Inch 1 and Inch 2 under the group of same events

Seasonal influences were visible in the case of spring and summer dominating season events. Those events likely delivered less Qvt/Qpt/Qv/Qp than winter and autumn dominant the season (see Appendix 4). Furthermore, seasonal influence is visible in terms of Rt and showed that Inch 1 has lower Rt for spring and summer dominant seasons since Inch 2 has a higher Rt.

Dissemination of the result above highlights the following trend under different weather conditions:

Dry weather conditions trends:

- Higher median API30 values (>15 mm) in combination with higher median (P ≥ 10mm) values will create higher median runoff water for the Inch 1 and Inch 2 areas (see F1 category in Figure 5.4 and Appendix 4). On the other hand, Qp/Qpt will have lower median values in the case of Inch 2 (see Table 5.10 and Figure 5.7).
- Lower median API30 values (<15 mm) in combination with lower median P (<10mm) values will create lower runoff in the case of Inch 1 and Inch 2 sub-catchment areas (see F3 category in Figure 5.5).

Wet weather conditions trends:

- Lower median API30 values (<30 mm) in combination with lower median P values (<10mm) will still lead to more runoff for early FDC (see category F2 in Appendix 4 and Figure 5.5) since further FDC will deliver less runoff water (see F3 category in Appendix 4 and Figure 5.5).
- Higher API30 values (>=32mm) in combination with higher P (>=10mm) values will create more runoff for the non-growing season (see F5 category in Appendix 4 and Figure 5.5) and less runoff for the growing season see F4 category in Appendix 4 and Figure 5.5.8)

For better distinguishing hydrological signatures between cultivated areas and unplanted plots, high precipitation events were analysed separately in section 5.3.2.3.

Cultivated areas (P2, P3, P4, P5, P6 and P7) events comparison

To enable comparison between events for cultivated areas, 11 and 20 events were selected for dry and wet weather conditions in the case of P2, P3, P4 and P5. Furthermore, 5 and 7 events were chosen for dry and wet weather conditions in the case of P6 and P7. The significantly lower number of events in the case of P6 and P7 occurred due to a lack of matching events related to instrumentation breakdown and resulted in less events for comparison. Analysed events were outlined in Appendix 4 and Figure 5.7 and 5.8 under dry/wet weather conditions. Furthermore, FDC categories for dry/wet weather conditions were outlined in Figures 5.10 and Figure 5.11 showing difrencesdifferences between different cultivations. FDC area is represented by F1, F2, F3 and F4 for P2, P3, P4 and P5 categories and F2 and F3 for P6 and P7 for dry weather conditions. FDS represented F2, F3, F4 and F5 for P2, P3, P4 and P5 categories and F3 for P6 and P7 for wet weather conditions. In addition to that, observed data indicated the following:

- Three major P events occurred in the case of dry weather conditions, and five major P events in wet weather conditions. Further analyses related to FDC categories showed that the highest median P values occurred in the case of the F3 category for dry weather conditions (see Appendix 4) and the F5 category (Appendix 4) for wet weather conditions. Furthermore, FDC with lower median

P experienced lower Qvt/Qpt/Qv/Qp for dry weather conditions. On the other hand, analyses related to wet weather conditions showed that less Qvt/Qpt/Qv/Q is likely to be connected to lower values of median P and API 30 (e.g. see F4 category in Appendix 4) for P4 and P5 areas.

- It indicated that P3 and P7 have the highest amount of Qvt/Qpt/Qv/Qp for dry weather conditions since P2 and P7 deliver the highest Qvt/Qpt/Qv/Qv/Qp during the wet period (see Appendix 4). On the other hand, the lowest Qvt/Qpt/Qv/Qp was P4 and P6 in both weather conditions groups (see Appendix 4). Moreover, the highest amount of Qvt/Qv/Qp corresponds to a high median P (see category F3 in Appendix 4) in the case of dry weather conditions for all monitoring plots. Furthermore, in wet weather conditions, the highest amount of Qvt /Qp/Qv for P2 occurred in the F5 category, which experienced the highest median P and API30 (see Appendix 4). However, the same phenomena occurred in the case of the P3 monitoring plot. Despite this fact, the highest Qp/Qv for P4 and P5 happened in the case of category F2, which cannot be related to the highest P or API30 but likely can be related to the early stage of forest development and vegetation stage.
- It indicates that Qv will be lower at 20%, 70%, 65%, 87%, and 2% for P2, P4, P5, P6, and P7, respectively, compared with P3 for dry weather conditions. Furthermore, it is indicative that Qv will be lower than 11%, 15%, 54%, 40% and 91% for P2, P3, P4, P5, and P6, respectively, compared with P7 for wet weather conditions.
- When comparing CFDC categories that belong to the growing (F2 and F4) and non-growing categories (F3 and F5), it is indicative that more Qpt/Qvt/Qp/Qv will occur in the case of F1 and F3 than F2 and F4 for dry weather conditions in the case of all monitoring plots. Furthermore, in the case of wet weather conditions, the decreasing trend in the case of Qp/Qv was indicative of the P4 and P5 area for all FDS. This comparison is related to the comparison between F2 and F4 or between F1 and F3. Conversely, an increase of Qpt/Qvt/Qp/Qv for P2 and P3 was indicated for non-growing season values in category F4 are higher than in category F2) and growing season (values in category F3 are higher than in category F1).
- The assessment of Rt highlighted that the lowest Rt occurred in the case of P4 for dry weather conditions, and the highest occurred in the case of P6 (see Appendix 4). On the other hand, wet weather conditions experienced the lowest in the case

of P3 since the highest one occurred in the case of P6 (see Appendix 4). Other trends related to FDC indicate that P2, P3, and P4 areas have lower Rt in the case of higher median P (P>10 mm) and higher median API30 (AP30 ≥ 30 mm) for wet weather conditions.

- IfIf we look through the lens of plough cultivation monitoring plots, the highest amount of runoff water will occur in the P3 monitoring plot, followed by P5 and P4 (see Appendix 4). Furthermore, Rt was shorter in the case of P3 for dry weather conditions and the case of P4 and P5 for dry weather conditions.

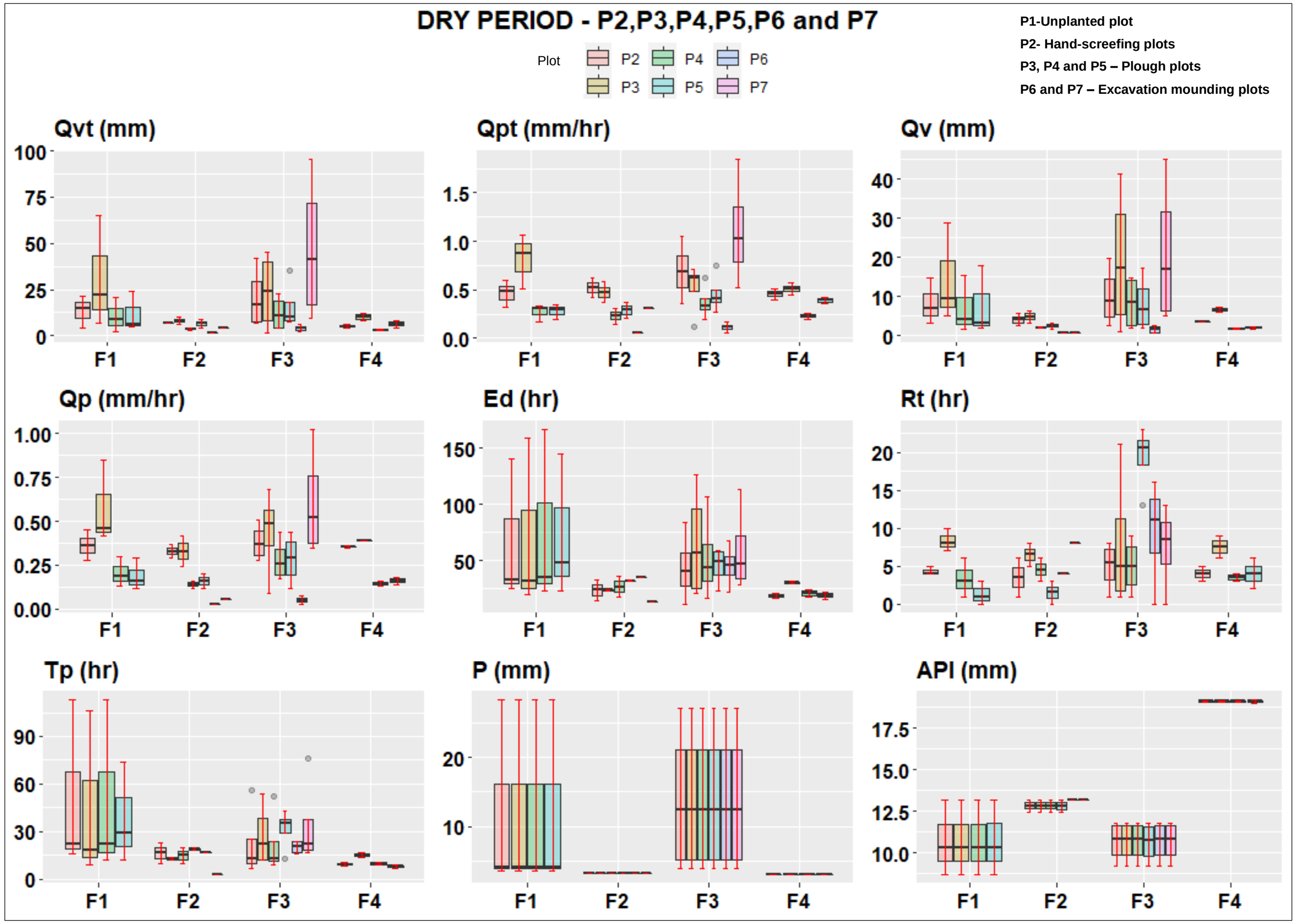


Figure 5.7: Forest development categories (F1, F2, F3 and F4) box plot for variables under the events group for P2, P3, P4, P5, P6 and P7 for the dry weather conditions. Due to missing data in P6 and P7, only categories F2 and F3 were included in the box plot above

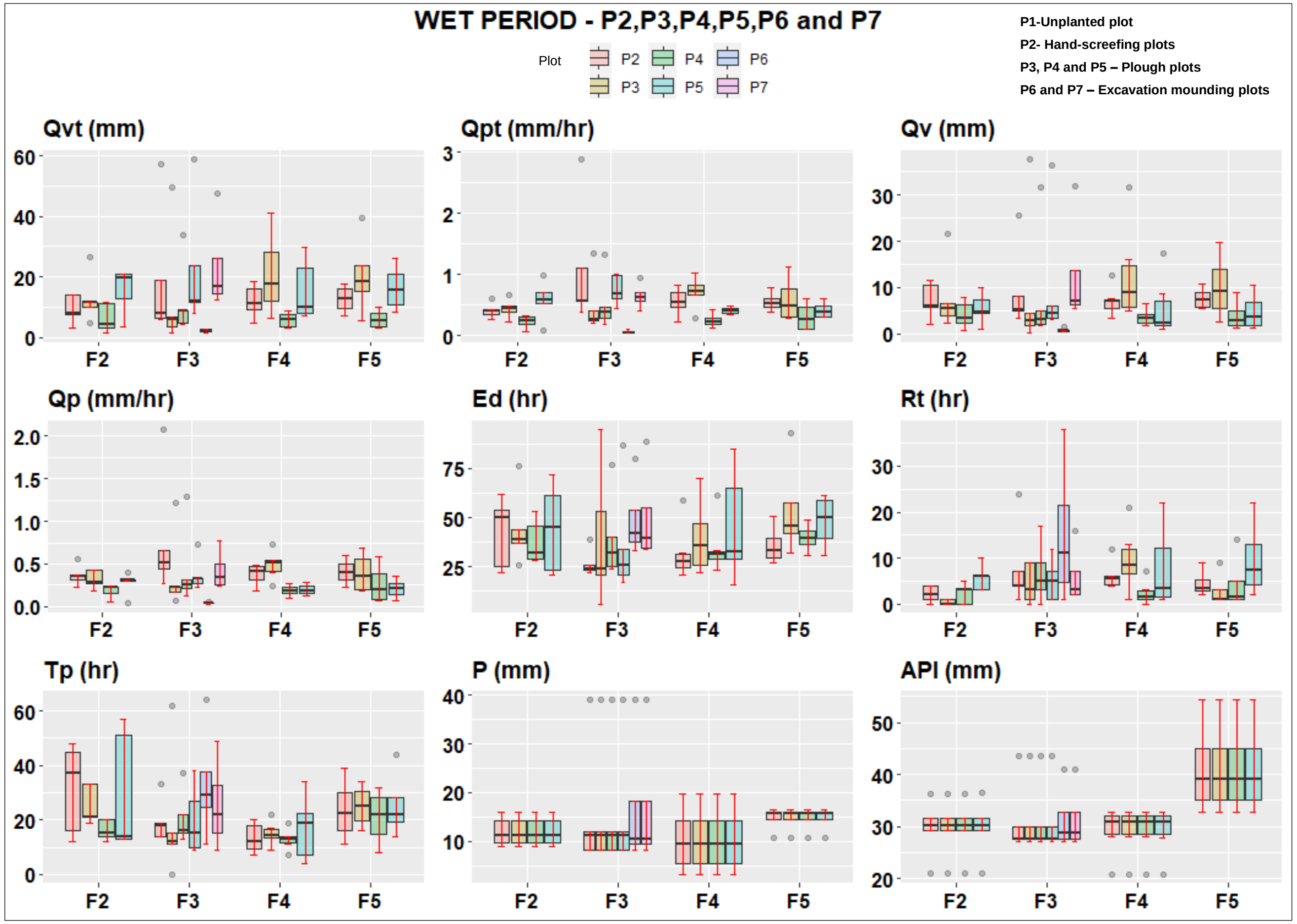


Figure 5.8:Forest development categories (F2, F3, F4 and F5) box plot for variables under the events group for P2, P3, P4, P5, P6 and P7 for the wet weather conditions. Due to a lack of data in the case of P6 and P7, only category F3 was included in the box

- In addition, the assessment of Tp highlighted that lower Tp values occurred in the case of P4 for dry and wet weather conditions (see Appendix 4). In addition to FDC, an increase of Tp for P2, P3, P4 and P5 was indicated for the non-growing season (values in category F5 are higher than in category F3) and a decrease in the growing season (values in category F2 are lower than in category F4) for wet weather conditions.
- The assessment of Ed showed that the highest values of Ed occurred in the case of P6 for both weather conditions.

Single similar events comparisons under certain FDC groups and dry/wet weather conditions:

- Dry weather conditions were considered F1 and F3 categories, where it was possible to observe significant events that occurred in the F1 category (P= 28.4 mm, API30= 8.7 mm happened on the 20th of December 2016) and in the F3 category (P=27.2 mm and API30=9.2 mm occurred on 19 November 2017). Further analysis showed that an event in the F1 category delivered a lower amount of Qv than one in the F3 category in P4 and P5 since the opposite effect occurred in P2 and P3. The Qv were lower by 5% and 3% for P4 and P5, respectively, in category F3, since Qv were higher by 26% and 30% for P2 and P3, respectively. Further compared events occurred on the 18th of March 2017 (P=3.2 mm and API30=13.2 mm) and the 9th of September 2018 (P=3 mm and API30= 19 mm), where again more runoff water occurred in the case of category F1 than in category F3 for P4 and P5, since P2 and P3 experienced opposite phenomena.
- Wet weather conditions considered F1, F2, F3 and F4 categories, and it was possible to match the few significant events in the case of P2, P3, P4 and P5. For example, events that occurred in the F2 category (P= 11.2 mm and API30= 29.2 mm occurred on 20th October 2017, the F3 category (P=11.2 mm and API30=29.9 mm occurred on 10rh March 2018), and the F4 category (P= 10.8 mm and API30=32 mm occurred on 26th August 2018) showed that event that belongs to F4 category will deliver the lowest amount of runoff in case of P2, P4 and P5 since P3 will have the lowest amount in case of 3.

Dissemination of the result above highlights the following trend under different weather conditions:

Dry weather conditions trends:

- Events characterized by higher median P values (>10mm) in combination with higher median values of API30 (>10mm) created more runoff water for any cultivated area (see F3 category in Figure 5.7 and Table 5.11). In addition to this, events with higher median values of API30 (>10mm) that occurred in early non–growing FDC (e.g. F1 category – see Appendix 4) will create more runoff for P2, P3 and P4 areas.
- Events characterized by lower median P values (<10mm) values will create less runoff (see F2 and F4 categories in Figure 5.7 and Appendix 4). This trend is likely not connected to median API30 values

Wet weather conditions trends:

- A group of events characterized by lower API30 values (<32 mm) in combination with lower P values (<12mm) created less runoff water (see F2, F3, and F4 categories in Appendix 4 and Figure 5.8). In this case, dominant values are observed over P2 and P3 cultivated areas.
- A group of events characterized by higher API30 values (>32mm) in combination with higher P (>12mm) values will create more runoff (see F5 category in Table 5.11 and Figure 5.11) in the case of P2 and P3 areas. In addition to this, areas P4 and P5 will likely have higher values of runoff related to the early stage of forest development. It is likely to be associated with F2 or F3 (see Appendix 4 and Figure 5.8)

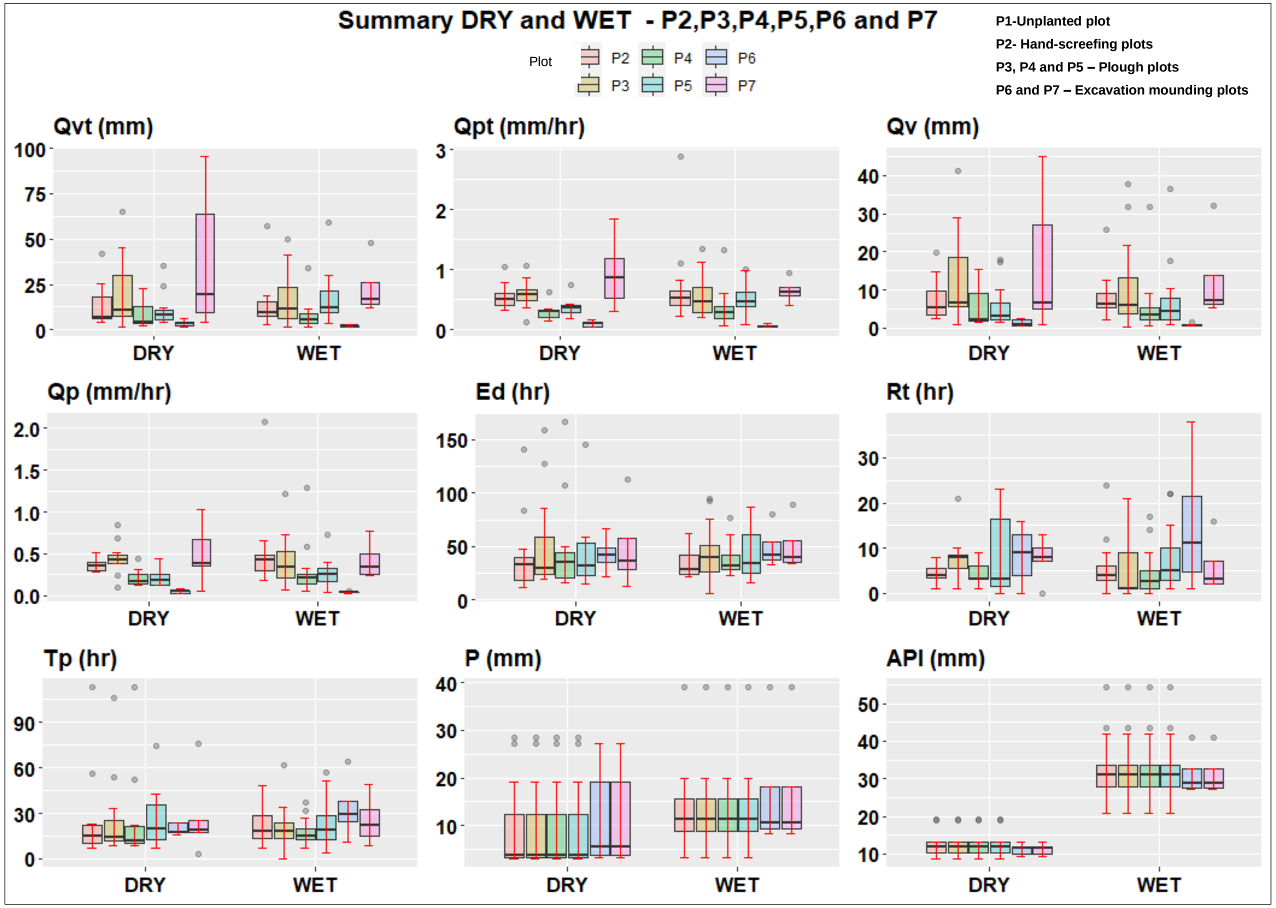


Figure 5.9: Dry and wet weather conditions summary for P2, P3, P4, P5, P6 and P7 under the group of same events. Due to missing data in P6 and P7 monitoring areas, only F2 and F3 categories were included in the box plot above

Dry and wet weather conditions summary for cultivated areas:

The section above discusses possible trends likely to be created around cultivated areas. According to analysed data, it is demonstrated that events that occurred during dry periods will experience the highest Qvt/Qpt/Qv/Qp in the P3 area, and events that occurred during wet weather conditions will experience the highest Qvt/Qpt/Qv/Qp in P3 area. P4 and P6 will likely have the lowest amount of Qvt/Qpt/Qv/Qp for any weather conditions. Those differences are statistically significant.

Furthermore, for dry weather conditions, less runoff water likely occurred in the case of P4 than in P5, P2, P3, P7 and P6, according to Rt data. On the other hand, for wet weather conditions, it is likely that runoff water first occurred in the case of P3, then P4, P7, P2, P5 and P6. Then, the shortest Tp will first occur in the case of P4, then P3, P2, P6, P7 and P5 for dry weather conditions, since in the case of wet weather conditions, it will be the following order: P4, P3, P2, P5, P7 and P6.

Seasonal influences were visible in the case of spring and autumn events. Those events delivered less Qvt/Qpt/Qv/Qp than winter's dominant season (see Appendix 4).

Further analyses presented in the section included the dissemination of P events by creating groups that highlighted changes under specific amounts of precipitation for each sub-catchment.

Cultivated areas (P2, P3, P4, P5, P6 and P7) events comparison with unplanted plot

To compare events for unplanted plots and cultivated areas, 2 and 4 events were selected for dry and wet weather conditions in the case of P1, P2, P3, P4 and P5 since only a limited number of events were available for P1 monitoring plots. Events areas are selected based on the same event occurrence around each plot. Furthermore, 2 and 3 events were chosen for dry and wet weather conditions in the case of P1, P6 and P7. Analysed events are outlined in Appendix 4 and Figure 5.12 under dry/wet weather conditions. Furthermore, FDC categories (related to cultivated areas) for dry/wet weather conditions were outlined in Figures 5.10 and 5.11. F3 represents the FDC area for dry weather conditions, and F3 and F4 for wet weather conditions. In addition to that, observed data indicated the following:

- One major P event occurred in the case of both dry and wet weather conditions. Further analyses showed that the highest amount of Qvt/Qpt/Qv/Q occurred in the case of P1 for both weather conditions.
- Rt was lowest in the case of P1 for dry weather conditions since, in the case of wet weather conditions, the lowest Rt occurred in cases P1 and P3.
- In addition to the distribution of Tp values, the lowest values occurred in the case of P6 for both weather conditions.
- Ed was the highest for P1 in case of both weather conditions

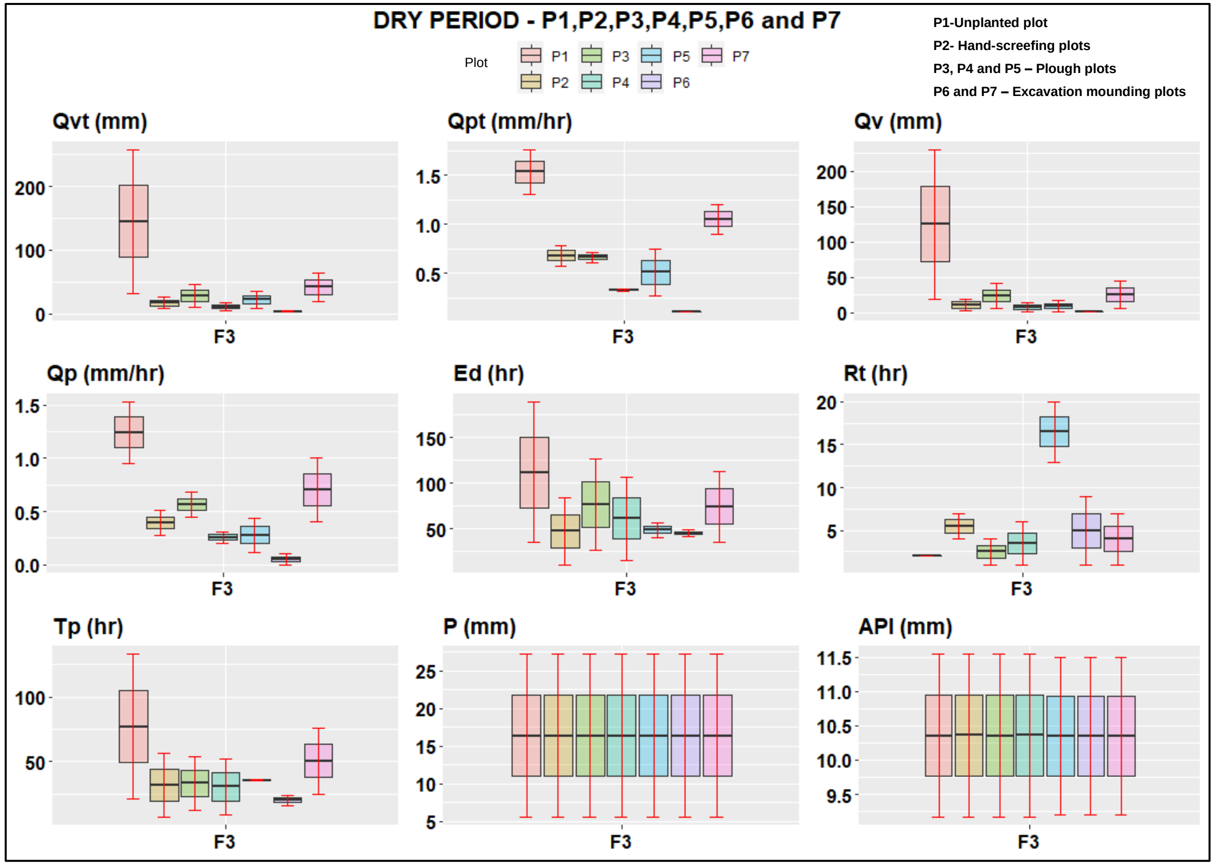


Figure 5.10: Forest development categories F3 box plot for variables under the events group for P1, P2, P3, P4, P5, P6 and P7 for the dry weather conditions.

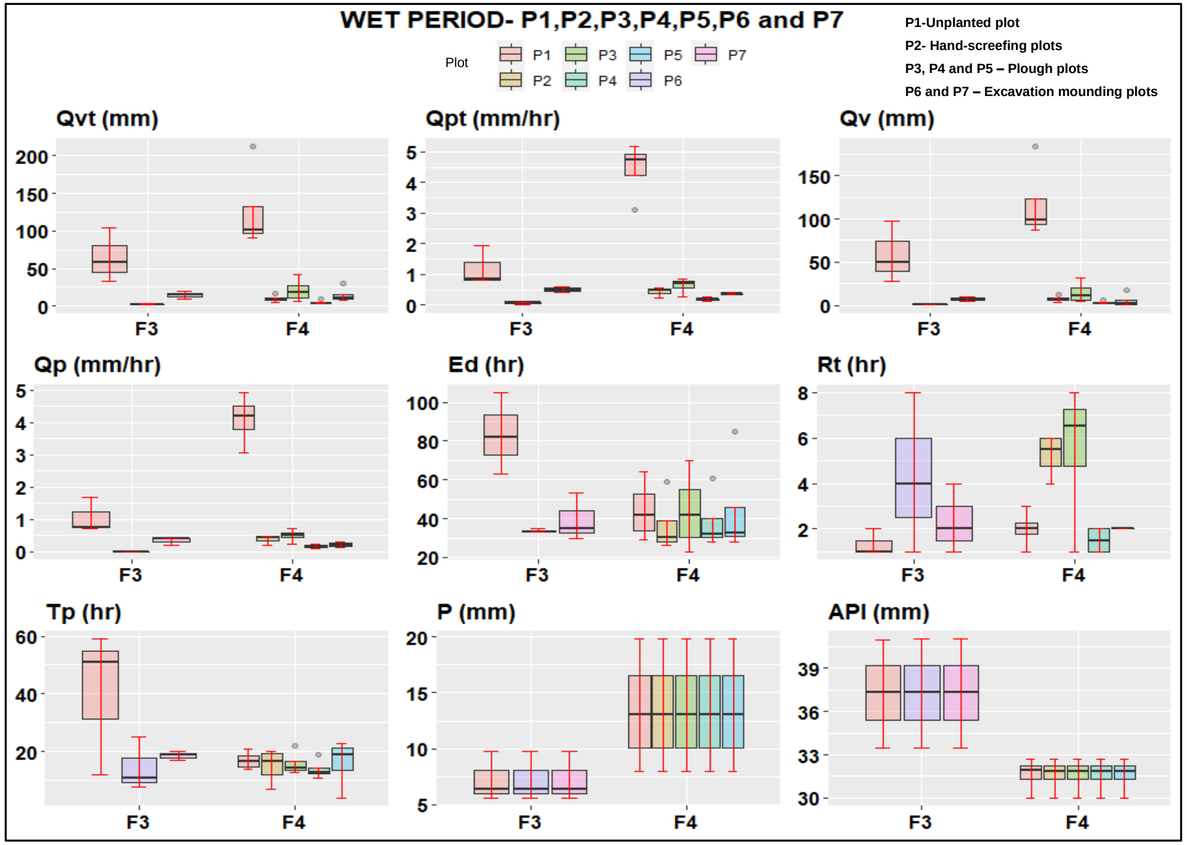


Figure 5.11: Forest development categories (F3 and F4) box plot for variables under the events group for P1, P2, P3, P4, P5, P6* and P7* for the wet weather conditions. *Due to missing data in P6 and P7, only categories F3 were included in the box plot above.

Dry and wet weather conditions summary for cultivated areas and unplanted plots:

The section above discusses events that were compared between cultivated and unplanted plots. According to analysed data, it is indicative expected that events that occurred during dry and wet weather conditions experienced the highest Qvt/Qpt/Qv/Qp in P1. The P1 area will likely have higher Tp and Ed since Rt is lower compared to other cultivations.

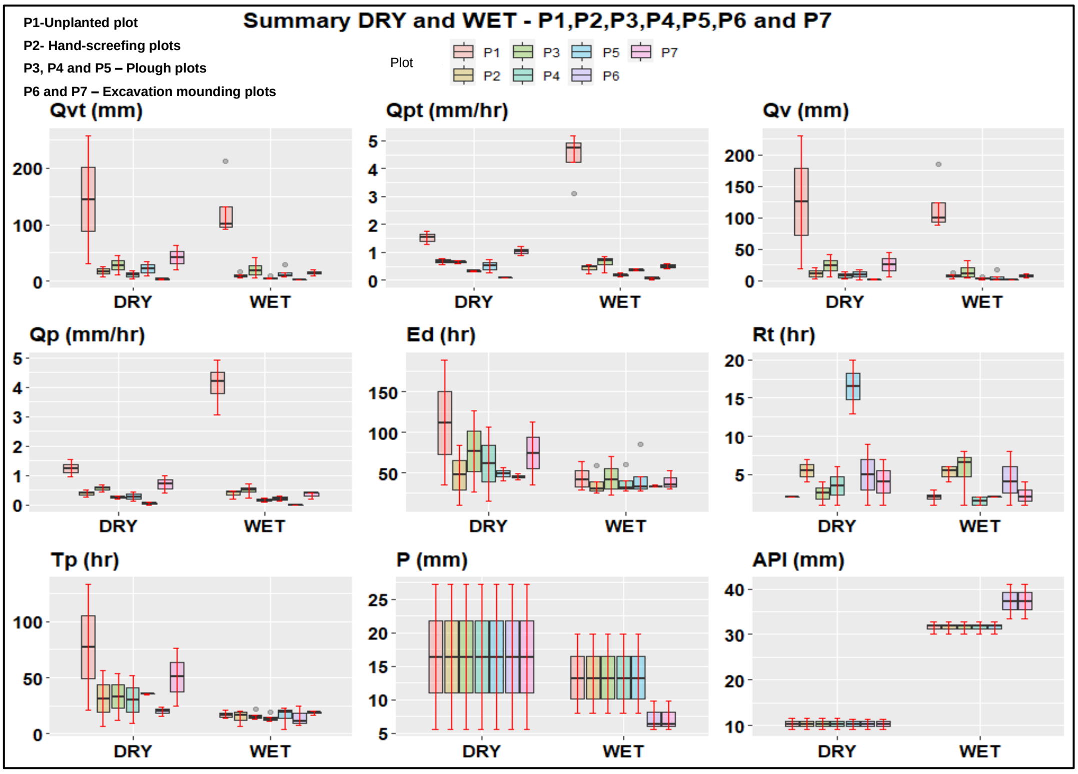


Figure 5.12: Dry and wet weather conditions summary for P1, P2, P3, P4, P5, P6 and P7 under the events group.

5.5 Precipitation groups

For data analysis, precipitation groups are defined (see Section 3.5.2) as events that had similar amounts of precipitation. Group events under a certain amount of rainfall contributed to understating the behaviour of sub-catchment and cultivated areas. This categorization is essential for understanding the field conditions when runoff events will form in different monitoring areas. Those groups were developed under both dry and wet weather conditions. This aimed to provide insight into event conditions and by which runoff occurred over each monitored plot or sub-catchment area, and it aimed to consider variables such as Qp, Qv, Qpt, Qvt, Tp, Rt and Ed.

5.5.1 Dry weather conditions groups (DP)

Inch 1 and Inch 2 sub-catchment areas:

Four groups were included in the dry weather P groups analysis for Inch 1 and 2 sub-catchments (see Table 5.6 and Figure 5.13). Critical differences between those group were:

- The highest Qv values for the Inch 1 and Inch2 sub-catchment were observed for the DP4 group. It was possible to observe the increasing trend of Qvt/Qv for Inch 2 from the DP1 to DP4 group. On the other hand, the DP1 group delivered more runoff water than the DP2 group (see Table 5.6 and Figure 5.13)
- The Lowest Rt occurred in the case of the DP3 group for both Inch 1 and Inch 2 sub-catchments. DP3 group has the highest median API30.
- The lowest Tp occurred in the case of the DP1 group for both sub-catchments.
- Higher values of Qvt for both Inch1 and Inch 2 are likely connected to the early stage of forest development, such as the DP2 group or high precipitation events in the case of the DP4 group (see Table 5.6 and Figure 5.13)
- The highest Qv/Qvt occurred in the case of group DP4 (P>15 mm), and it has a similar Rt for Inch 1 ad Inch2 sub-catchment areas.

Cultivated monitoring plots

Two precipitation group were included for cultivated areas (DP1 and DP4). There were specific differences in variables for those groups:

- Precipitation group DP1 experienced less runoff water than precipitation group DP4 for all cultivated areas (see Table 5.6 and Figure 5.13)
- In precipitation group DP1 and DP4, the highest Qvt has occurred in the following monitoring areas: P3 and P7
- Rt was lowest in the case of P5 for the DP1 group and the case of P4 for group DP4.
- Tp was lowest in the case of P4 for the DP1 group and the case of P6 for group DP4.

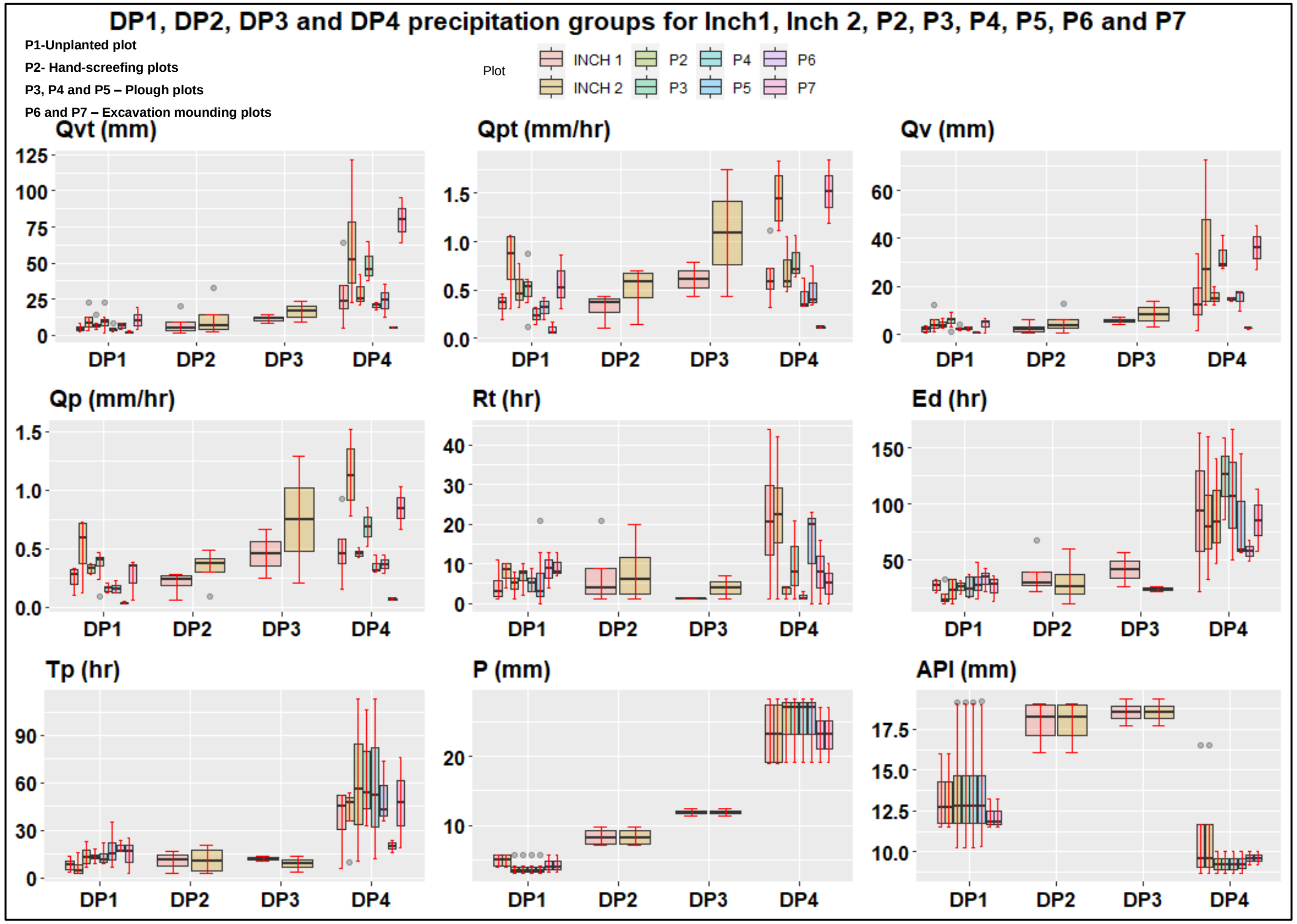


Figure 5.13: Dry weather conditions group box plot that was developed for Inch 1, Inch2, P2, P3, P4, P5, P6 and P7

Table 5.6: Median values of all variables for DP group in case Inch 1, Inch 2, P2, P3, P4, P5, P6 and P7

Plot Plot/Sub-catchment	DP groups name (No of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
Dry weather conditions														
Inch 1	DP1 (4)	Winter	28	8	0.4	4.4	0.1	2.4	0.3	2.0	3	5	0.5	13
	DP2 (4)	Winter	30	12	0.4	4.9	0.1	2.9	0.2	2.0	4	8	0.5	18
	DP3 (2)	Spring	42	13	0.6	11.3	0.1	5.8	0.5	5.6	1	12	0.8	19
	DP4 (4)	Winter	94	46	0.6	23.8	0.2	11.6	0.5	12.2	21	23	0.3	10
Inch 2	DP1 (4)	Winter	15	5	0.9	7.9	0.3	4.3	0.6	3.6	9	5	0.5	13
	DP2 (4)	Winter	26	11	0.6	6.4	0.2	2.9	0.4	3.5	6	8	0.5	18
	DP3 (2)	Spring	24	9	1.1	16.6	0.4	8.2	0.7	8.4	4	12	0.8	19
	DP4 (4)	Winter	80	48	1.4	52.2	0.3	25.3	1.1	26.9	23	23	0.3	10
P2	DP1 (8)	Winter	23	13	0.5	6.8	0.1	1.9	0.3	3.5	5	3	0.5	13
	DP4 (3)	Winter	84	56	0.6	25.5	0.1	6.6	0.5	14.7	4	27	0.3	9
P3	DP1 (8)	Winter	26	13	0.5	9.0	0.1	3.3	0.4	6.2	8	3	0.5	13
	DP4 (3)	Winter	127	54	0.7	45.1	0.1	10.1	0.7	28.9	8	27	0.3	9
P4	DP1 (8)	Winter	24	12	0.2	3.8	0.1	1.5	0.2	2.0	5	3	0.5	13
	DP4 (3)	Winter	107	52	0.3	20.6	0.0	5.2	0.3	14.7	1	27	0.3	9
P5	DP1 (8)	Winter	27	16	0.3	6.9	0.2	3.8	0.2	2.1	3	3	0.5	13
	DP4 (3)	Winter	59	43	0.4	24.1	0.0	6.3	0.4	17.3	20	27	0.3	9
P6	DP1 (3)	Winter	35	17	0.1	1.9	0.03	1.1	0.03	0.5	9	4	0.5	12
	DP4 (2)	Winter	58	20	0.1	5.3	0.05	2.9	0.1	2.4	8	23	0.3	10
P7	DP1 (3)	Winter	28	17	0.5	9.8	0.3	4.8	0.4	5.0	8	4	0.5	12
	DP4 (2)	Winter	86	48	1.5	79.7	0.7	43.6	0.8	36.1	5	23	0.3	10

Summary for DP group **over sub-catchments and cultivated areas:**

More runoff water has been delivered in the case of the DP4 group for cultivated areas and both sub-catchments. Furthermore, the Rt were different. Sub-catchment areas showed lower responses in the DP3 group that coincided with the highest median API30 and I. However, cultivated areas have a shorter Rt for DP4 groups in cases of P2, P4, P6 and P7. On the other hand, Tp values were shorter for the DP1 group in the case of all cultivated areas and sub-catchment areas.

5.5.2 Wet weather conditions groups (WP)

Inch 1 and Inch 2 sub-catchment areas:

Four groups were included in the dry weather P group analysis for Inch 1 and Inch 2 sub-catchments (see Table 5.7 and Figure 5.14).

Differences between WP1, WP2, WP3 and WP4 groups were:

- The highest Qv values for the Inch 2 sub-catchment were observed WP4 group for bot sub-catchments since the lowest occurred in the case of WP1.
- The lowest Rt occurred in the case of Inch 1 for all groups (1-2 hours) since Inch2 had a higher Rt (2-4 hours)
- Higher values of Qvt for both Inch1 and Inch 2 are likely connected to the higher values of P or API30 (see Table 5.14 and Figure 5.16).
- The highest Qv/Qvt occurred in group WP4 (P>15 mm), and it has a low Rt for Inch 1 and higher Rt for Inch2 sub-catchment
- Tp was lower in the case of WP1 and WP4 catchment since Inch 2 had lower values than Inch 1

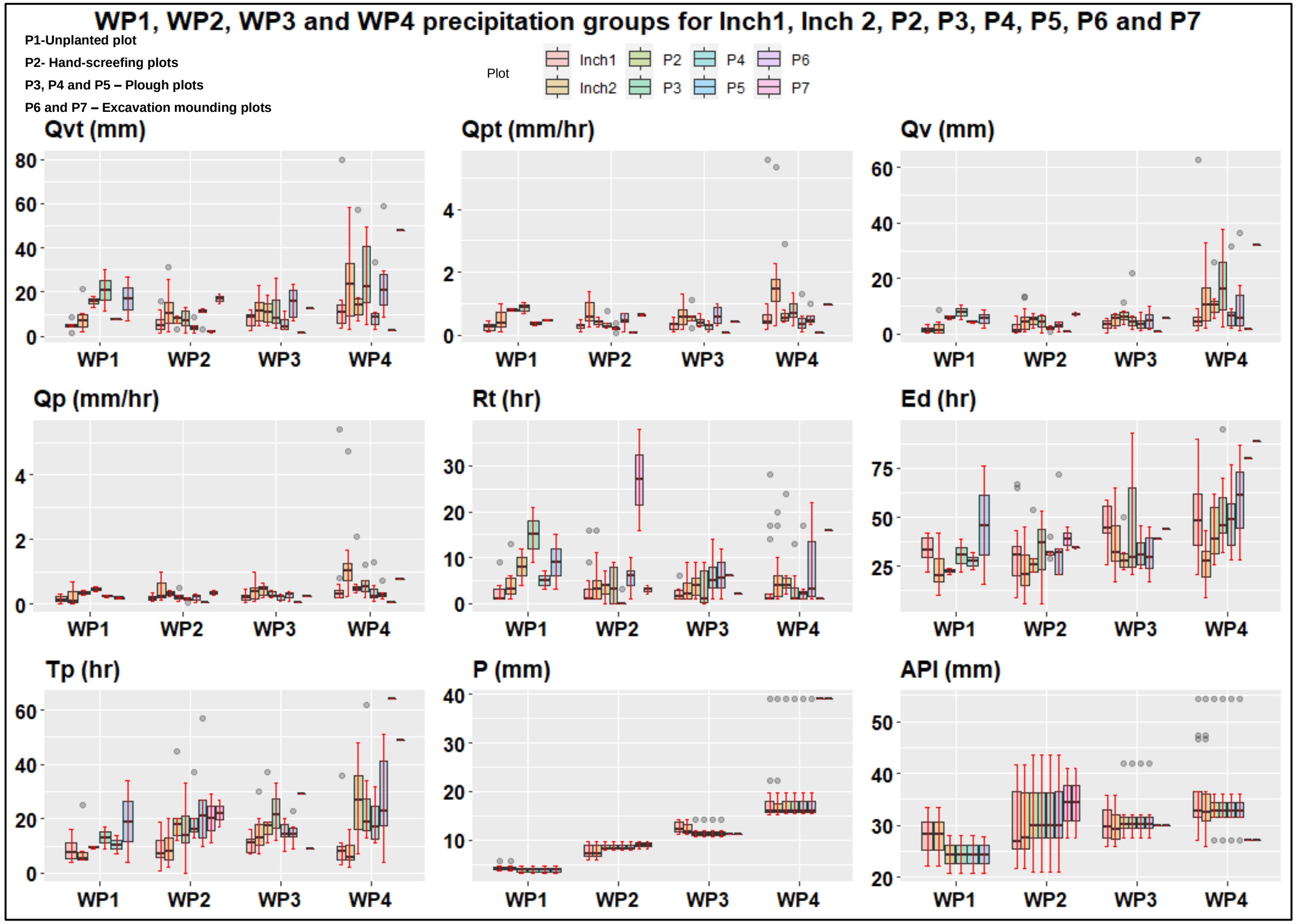


Figure 5.14: WP conditions group box plot that was developed for Inch 1, Inch2, P2, P3, P4, P5, P6 and P7

Table 5.7: Median values of all variables for WP group in case Inch 1, Inch 2, P2, P3, P4, P5, P6 and P7

PlotPlot	Weather conditio No(Noof events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
WP groups														
Inch 1	WP1 (6)	Winter	34	8	0.2	4.8	0.1	3.5	0.1	1.1	1	4	0.4	28
	WP2(16)	Autumn	31	7	0.3	4.7	0.1	3.1	0.2	1.3	1	7	0.5	27
	WP3 (6)	Autumn	45	11	0.3	8.6	0.1	4.8	0.2	3.2	2	12	0.6	30
	WP4(13)	Autumn	48	8	0.4	10.8	0.1	5.2	0.3	4.4	1	16	0.7	33
Inch 2	WP1 (6)	Winter	14	5	0.4	5.0	0.3	4.1	0.1	0.7	4	6	0.3	28
	WP2(16)	Autumn	26	10	0.6	11.1	0.3	6.5	0.3	4.2	3	9	0.5	28
	WP3 (6)	Autumn	36	15	0.7	13.2	0.3	6.6	0.4	6.1	2	13	0.7	29
	WP4(13)	Autumn	27	5	1.4	23.5	0.3	7.6	1.0	9.7	4	16	0.7	33
P2	WP2 (5)	Autumn/ Winter	24	16	0.4	7.0	0.1	2.5	0.3	4.1	3	9	0.4	32
	WP3 (6)	Autumn	28	18	0.6	10.6	0.1	2.0	0.4	5.8	4	11	0.6	30
	WP4 (7)	Autumn	39	27	0.5	14.0	0.1	3.5	0.5	10.5	4	16	0.6	33
P3	WP2 (5)	Autumn/ Winter	41	16	0.2	5.7	0.1	2.3	0.2	3.4	2	9	0.4	32
	WP3 (6)	Autumn	30	22	0.4	8.2	0.1	4.4	0.2	4.4	1	11	0.6	30
	WP4 (7)	Autumn	46	19	0.7	22.3	0.1	6.4	0.5	16.0	1	16	0.6	33
P4	WP2 (5)	Autumn/ Winter	32	18	0.2	3.9	0.1	1.7	0.1	1.9	1	9	0.4	32
	WP3 (6)	Autumn	31	15	0.3	4.2	0.0	1.3	0.2	3.2	5	11	0.6	30
	WP4 (7)	Autumn	49	17	0.3	8.8	0.0	2.0	0.2	6.4	2	16	0.6	33
P5	WP2 (5)	Autumn/ Winter	28	20	0.6	11.8	0.3	7.8	0.3	3.7	7	9	0.4	32
	WP3 (6)	Autumn	30	15	0.6	15.6	0.3	9.6	0.3	4.6	6	11	0.6	30
	WP4 (7)	Autumn	61	23	0.5	20.9	0.2	13.8	0.3	5.4	3	16	0.6	33
P6	WP2 (2)	Autumn	39	20	0.1	2.2	0.04	1.6	0.03	0.6	27	9	0.3	34
	WP3 (1)	Autumn	39	29	0.1	1.7	0.03	1.1	0.04	0.7	6	11	0.5	30
	WP4 (1)	Winter	80	64	0.1	2.4	0.01	0.9	0.1	1.5	1	39	0.6	27
P7	WP2 (2)	Autumn	35	22	0.6	16.9	0.3	9.9	0.3	7.1	3	9	0.3	34
	WP3 (1)	Autumn	44	9	0.4	12.4	0.2	7.1	0.2	5.4	2	11	0.5	30
	WP4 (1)	Winter	89	49	0.9	47.6	0.2	15.6	0.8	32.0	16	39	0.6	27

Cultivated areas:

The highest Qv values were observed in the case of the WP4 group for P7, followed by P3, P2, P4, P5 and P6. If we group data under each cultivation, it is evident that the P3 plough cultivated area experienced higher Qp/Qv than P4 and P5 areas. On the other hand, in the case of excavation, mounding significantly higher values occurred in the case of the P7 cultivated area.

The lowest amounts of Qp/Qv occurred in the case of WP1 for sub-catchments and cultivated areas.

The lowest Rt occurred in the case of the P3 plough plot for the WP3 and WP4 precipitation group since the P2 hand-screefing plot and P4 plough plot had the lowest Rt in the case of the WP1 group and P6 excavation mounding plot and P5 plough plot in the case of the WP4 group.

Summary for WP group over sub-catchments and cultivated areas:

More runoff water has been delivered in the case of the WP4 group for all cultivated areas and sub-catchments. Furthermore, the Inch 1 sub-catchment area responded faster to runoff water than the Inch 2 sub-catchment area in the case of any WP group. At the same time, Ed around Inch 1 sub-catchment will be longer. However, when we look through the lens of cultivated areas, a faster response will occur in the case of P3 (any of the analysed groups – see Table 5.7), P4 and P6 (in the case of WP4 group - see Table 5.7). Furthermore, a response is likely to become shorter in the case of P3, P5 and P6 while median P increases. Also, opposite phenomena were noticed in the case of P2 and P7.

5.6 Research question 2 results: introduction

RQ2: How does sediment delivery from each cultivation technique change over time, and what is the difference in sediment delivery between cultivations?

The following section utilised the results for RQ2. The sediment analyses are determined based on measurements from different cultivated areas. The results in the following section will be pertaining to RQ2 will break down RQ and answer each element:

i. Sediment collection dates (SC1, SC2, SC3, SC4, SC5, SC6, SC7, SC8, SC9 and SC10) were connected to the mean precipitation and mean API30 (see Table 5.8). This refers to events that occurred prior to sediment data collection was done in the field. Those analyses contributed to the understanding of hydrological processes that occurred between each sediment collection date.

ii. LRM presented in section 5.3.1 was used to estimate runoff peak and runoff volume over each cultivated area for selected precipitation events ($P > 3$ mm). That approach was used since experimental data were unavailable in the case of all observed precipitation events (see Section 6.2.1). The results are presented in the section. Runoff data analyses contributed to a further understanding of sediment movement and delivery.

iii. Particle size data analyses were analysed and presented in Section 5.6.3 and give a better insight into particle size (e.g., gravel, sand or silt) that was moved through monitored areas. The methodology of this process is presented in Chapter 3.

The additional findings highlighted the differences in sediment delivery through afforested areas and the implementation of each practice in the Menstrie catchment.

5.6.1 Comparison of sediment delivery from different cultivated areas

The purpose of sediment collection was to establish the status that would contribute to the assessment of the impact of cultivation practices to release sediment referring to specific particle size distribution. The delivery of sediment from cultivated areas and compare delivery between them. According to Section 3.4.5, sediment collection was established around all monitoring plots (see Figure 3.17).

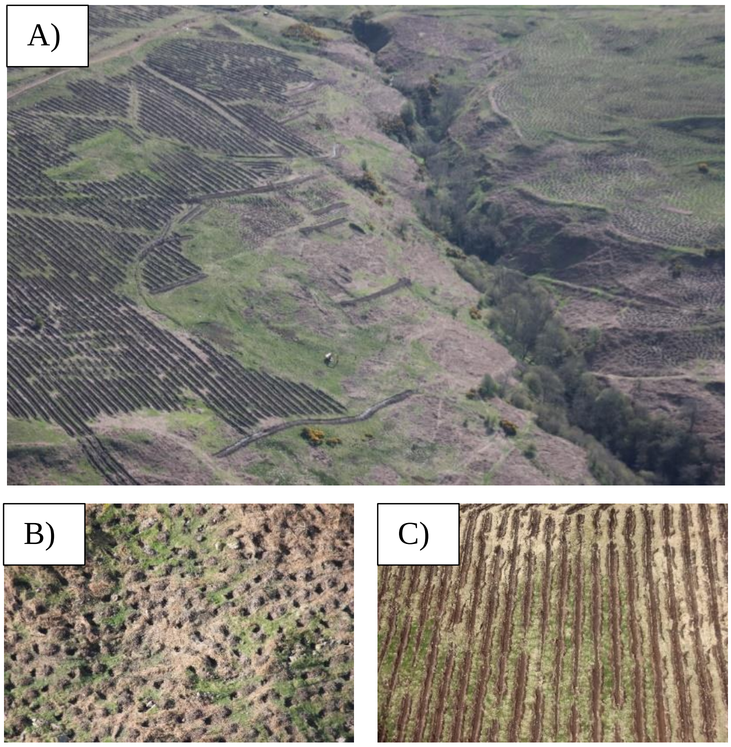
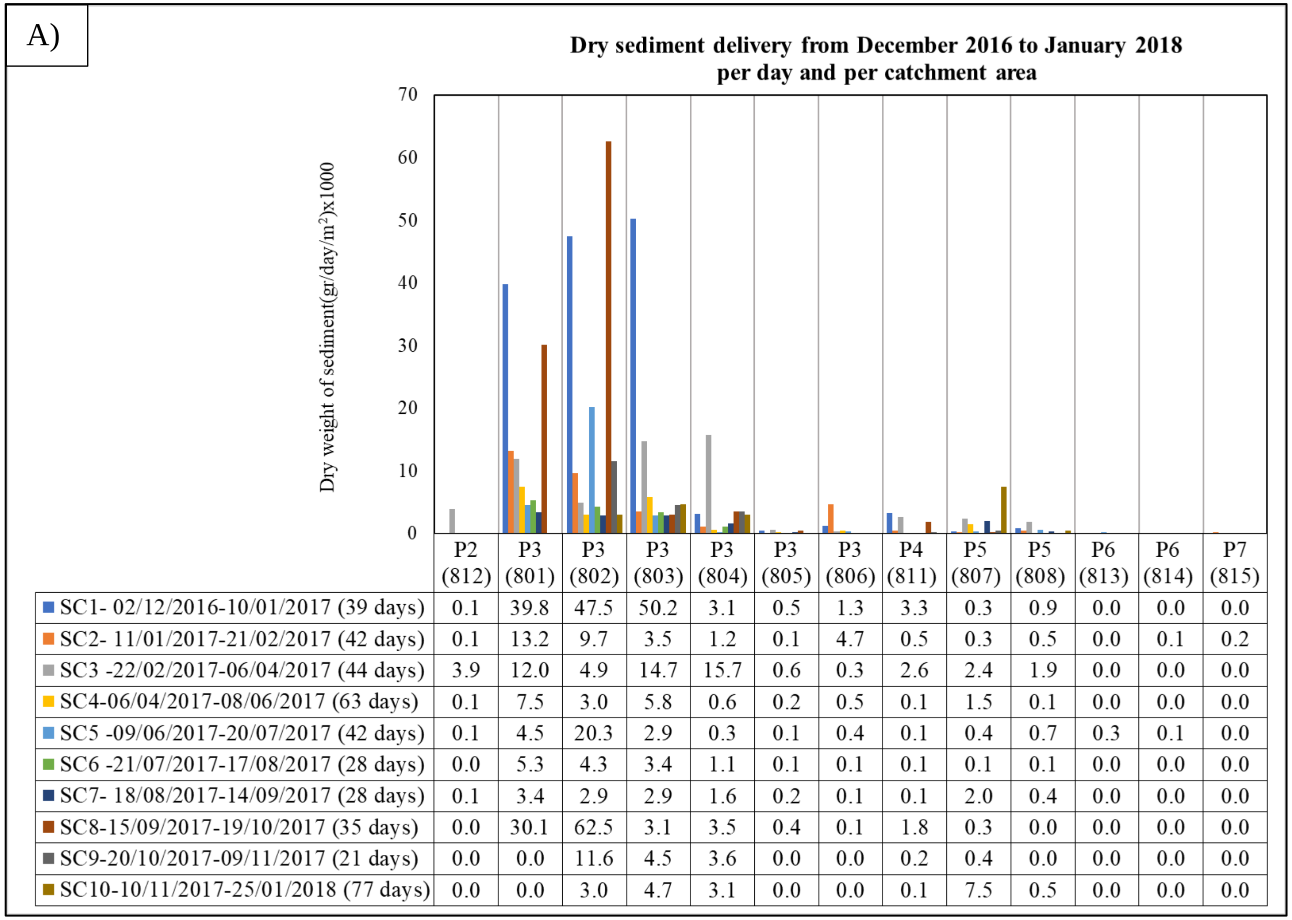
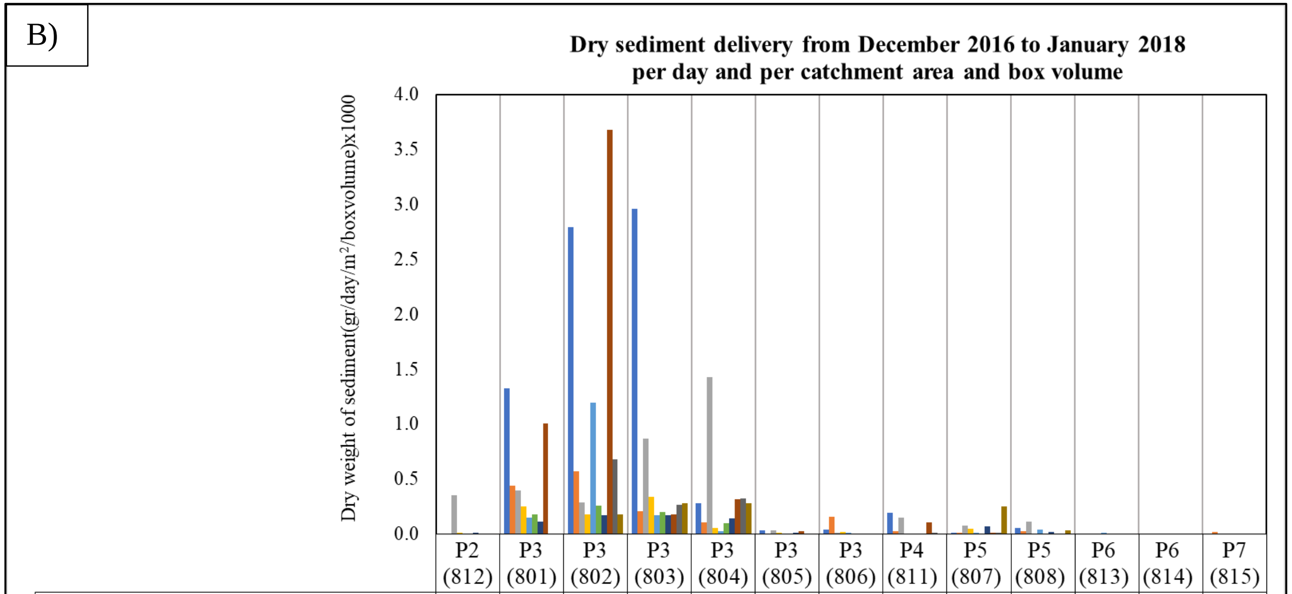


Figure 5.15: A) Plough, excavator mounding, and hand-screefing cultivation at the Menstrie catchment area (TillHill Forestry took a picture in May 2015) B) close image of excavator mounding technique C) close view of plough ridges and furrows

Sediment collection refers to sediment delivery in cultivated areas (ploughing, hand-screefing and excavator mounding) and unplanted plot. The plough-cultivated areas had slightly higher possibilities for sediment measurements due to their field designs consisting of plough lines network (borders) with various cross-drains (see Figure 5.15). On the other hand, excavation mounding and hand-screefing cultivated areas were implemented by simple planting systems (hand digging or excavator mound digging), where a collection of sediment was challenging. This refers to sediment containers that were used for collection. Also, sediment collection from the unplanted plot area was not used for analyses since the installation of the set up was not in a suitable position, which was discovered in November 2017 (close to the end of the monitoring process). This comes from the fact that the monitoring channel was not designed properly, and sediment movement through this area was accurate.



	P2 (812)	P3 (801)	P3 (802)	P3 (803)	P3 (804)	P3 (805)	P3 (806)	P4 (811)	P5 (807)	P5 (808)	P6 (813)	P6 (814)	P7 (815)
SC1- 02/12/2016-10/01/2017 (39 days)	0.1	39.8	47.5	50.2	3.1	0.5	1.3	3.3	0.3	0.9	0.0	0.0	0.0
SC2- 11/01/2017-21/02/2017 (42 days)	0.1	13.2	9.7	3.5	1.2	0.1	4.7	0.5	0.3	0.5	0.0	0.1	0.2
SC3 -22/02/2017-06/04/2017 (44 days)	3.9	12.0	4.9	14.7	15.7	0.6	0.3	2.6	2.4	1.9	0.0	0.0	0.0
SC4-06/04/2017-08/06/2017 (63 days)	0.1	7.5	3.0	5.8	0.6	0.2	0.5	0.1	1.5	0.1	0.0	0.0	0.0
SC5 -09/06/2017-20/07/2017 (42 days)	0.1	4.5	20.3	2.9	0.3	0.1	0.4	0.1	0.4	0.7	0.3	0.1	0.0
SC6 -21/07/2017-17/08/2017 (28 days)	0.0	5.3	4.3	3.4	1.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
SC7- 18/08/2017-14/09/2017 (28 days)	0.1	3.4	2.9	2.9	1.6	0.2	0.1	0.1	2.0	0.4	0.0	0.0	0.0
SC8-15/09/2017-19/10/2017 (35 days)	0.0	30.1	62.5	3.1	3.5	0.4	0.1	1.8	0.3	0.0	0.0	0.0	0.0
SC9-20/10/2017-09/11/2017 (21 days)	0.0	0.0	11.6	4.5	3.6	0.0	0.0	0.2	0.4	0.0	0.0	0.0	0.0
SC10-10/11/2017-25/01/2018 (77 days)	0.0	0.0	3.0	4.7	3.1	0.0	0.0	0.1	7.5	0.5	0.0	0.0	0.0



	P2 (812)	P3 (801)	P3 (802)	P3 (803)	P3 (804)	P3 (805)	P3 (806)	P4 (811)	P5 (807)	P5 (808)	P6 (813)	P6 (814)	P7 (815)
■ SC1- 02/12/2016-10/01/2017 (39 days)	0.01	1.33	2.79	2.96	0.28	0.03	0.04	0.19	0.01	0.05	0.00	0.00	0.00
■ SC2- 11/01/2017-21/02/2017 (42 days)	0.00	0.44	0.57	0.21	0.11	0.00	0.16	0.03	0.01	0.03	0.00	0.01	0.02
■ SC3 -22/02/2017-06/04/2017 (44 days)	0.35	0.40	0.29	0.87	1.43	0.03	0.01	0.15	0.08	0.11	0.00	0.00	0.00
■ SC4-06/04/2017-08/06/2017 (63 days)	0.01	0.25	0.18	0.34	0.05	0.01	0.02	0.01	0.05	0.01	0.00	0.00	0.00
■ SC5 -09/06/2017-20/07/2017 (42 days)	0.01	0.15	1.19	0.17	0.02	0.01	0.01	0.00	0.01	0.04	0.02	0.01	0.00
■ SC6 -21/07/2017-17/08/2017 (28 days)	0.00	0.18	0.26	0.20	0.10	0.01	0.00	0.01	0.00	0.01	0.00	0.00	0.00
■ SC7- 18/08/2017-14/09/2017 (28 days)	0.01	0.11	0.17	0.17	0.14	0.01	0.00	0.01	0.07	0.02	0.00	0.00	0.00
■ SC8-15/09/2017-19/10/2017 (35 days)	0.00	1.00	3.68	0.18	0.32	0.03	0.00	0.11	0.01	0.00	0.00	0.00	0.00
■ SC9-20/10/2017-09/11/2017 (21 days)	0.00	0.00	0.68	0.26	0.33	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00
■ SC10-10/11/2017-25/01/2018 (77 days)	0.00	0.00	0.18	0.28	0.28	0.00	0.00	0.00	0.25	0.03	0.00	0.00	0.00

Figure 5.16: Dry sediment delivery from December 2016 to January 2018: A) normalized daily per catchment area and days B) normalized daily per catchment area and the number of days and sediment container capacity.

Given that the upslope extent of the cultivated area varies between individual sediment containers, it is appropriate to divide the dry sediment weight collected by the contributing site and the number of days (between the dates of sediment collection – see Figure 5.16A). This ensured the daily contribution of sediment from each plot. Furthermore, since container capacity has been different in Figure 5.16B, results are normalized per capacity of each sediment container. Sediment containers have been filled with a mixture of water and sediment. Table 3.3 from Chapter 3 shows the total contributing area, and the table from Figure 5.16A show the number of days within each period. Figure 5.16A indicates that different patterns of sediment movement are evident between cultivation techniques for the collected data. Figure 5.16B suggests the importance of the size of sediment container distribution (there were 11 L, 17 L and 30 L). After normalization, ploughing had (P3, P4 and P5) the highest sediment movement through the SC periods compared to excavator mounding and hand screefing (P2, P6 and P7). Also, ploughing (P3, P4 and P5 plots) had higher sediment mass before normalization. An increased sediment movement is evident for sediment containers labelled by numbers 801,802,803 (located in the P3 plough cultivated area) and 804 (found in the main drain in the P3 area) that measured sediment movement across plough lines since boxes 805 (P3) 806 (P3), 811 (P4), 807 (P5) and 808 (P5) were in the main drain and contained less sediment. Furthermore, P3 and P5 plough areas had implemented a silt trap on the end of the main drain just before sediment containers 804 and 808. Also, sediment containers 805 and 806 in the P3 plough cultivated area have been implemented after the silt trap (see Figure 3.17).

The P3 plough cultivated area has more sediment containers implemented over the area than other cultivated areas. This is related to the fact that implementation in other plough-developed areas was impossible without complex machinery since the underlying geology contained hard rock.

5.6.2 Sediment contribution from cultivated areas

Sediment delivery data has been analysed through the lens of P events and API30 values that occurred during the periods of sediment collection. Table 5.8 indicates that the highest precipitation occurred for the SC10 collection date, and the lowest precipitation occurred in the case of SC3. Furthermore, the wettest period is related to SC6, and the driest period is related to SC3 (see API30 in Table 5.8).

Table 5.8: P and API30 median values connected to sediment collection date (SC1, SC2, SC3, SC4, SC5, SC6, SC7, SC8, SC9 and SC10) with the dominant season, dominant FDC, number of observed P events >3m and number of observed events P >15 mm, mean P, mean API30 and mean T before SC date.

Sediment collection	**Dominant FDC/ Dominant season**	**Dominant weather conditions**	**No of observed P events >3 mm**	**No of observed P events >15 mm**	**Mean P before SC date (mm/day)**	**Mean API30 before SC date (mm)**	**Mean T before SC date (0C)**
SC1	F1/Winter	Dry	6	1	9.9	18	3
SC2			6	0	6.8	20	3
SC3			5	0	3.6	12	9
SC4	F1/Spring	Wet	7	1	11.8	31	14
SC5	F2/Summer		10	2	10.4	28	17
SC6			9	2	9.7	33	16
SC7	F2/Autumn		6	1	10.2	29	14
SC8	F3/Autumn		10	1	9.1	31	11
SC9		Dry	2	0	7.5	20	5
SC10	F3/Winter	Wet	14	3	12.0	26	2

Figure 5.16A indicates that ploughing (P3, P4 and P5 areas) collectively contain a higher dry sediment weight than the other cultivated areas (P2, P6 and P7) during overall monitoring periods. If we compare plough-cultivated areas, it is evident that P3 experienced higher sediment rates than P4 and P5. Also, P4 will have higher sediment delivery than P5, which apparel has the lowest sediment distribution

Correspondingly, it is evident that the highest amount of sediment was observed in the SC1, SC2, SC3 and SC10 periods. SC1, SC2 and SC3 periods are observed between the 2nd of December 2016 and the 6th of April 2017. Those sediment collections belong predominantly to the non-growing vegetation period and winter season (see Table 5.8). Furthermore, ground disturbances (see Figure 3.22 and Figure 3.23) were higher during this period (December 2016 to April 2017) than later in 2017 (after April 2017). For example, the main drain in the P3 (804) cultivated area demonstrated a significant rise in weight in April 2017, with 0.0157 gr/day/m2. This phenomenon might be connected to seasonal temperature changes that were relatively higher in this SC class compared to previous dry periods (see Section 3.5.4). Furthermore, the period between March and April 2017 was very dry (see P and API30 in Table 5.8).

On the other hand, higher sediment delivery during SC10 periods is likely related to the high number of P events that occurred during this period (see Table 5.8). Likewise, a higher sediment mass of 0.0075 gr/day/m^2 was obtained for SC10 in the 807 – P5 area (box 807 was located in the upstream part of the monitoring channel). On the other hand, downstream in main drain box no 808 experienced higher sediment delivery for SC10 but 92% lower than in box 807. The delivery in 807 boxes is possibly related to high precipitation events and the upstream location in the P5 area [143]. In addition, the 804 boxes in the P3 area experienced higher sediment delivery during the S10 period since boxes 805 and 806 had zero sediment delivery. Box 804 was located upstream in the main drain before the silt trap since boxes 805 and 806 were located further downstream from the main drain area after the silt trap.

In addition, hand screefing shows an intermediate amount between P6 and P7, but with an exceptionally high rise during the two months between February and April 2017 with 0.0039 gr/day/m^2, compared to all other periods. Excavation Mounding (P6 and P7) has a considerably lower sediment dry weight throughout the time. Sediment collection from those two plots contained biological content that did not contain any sediment after being processed in a high-temperature oven.

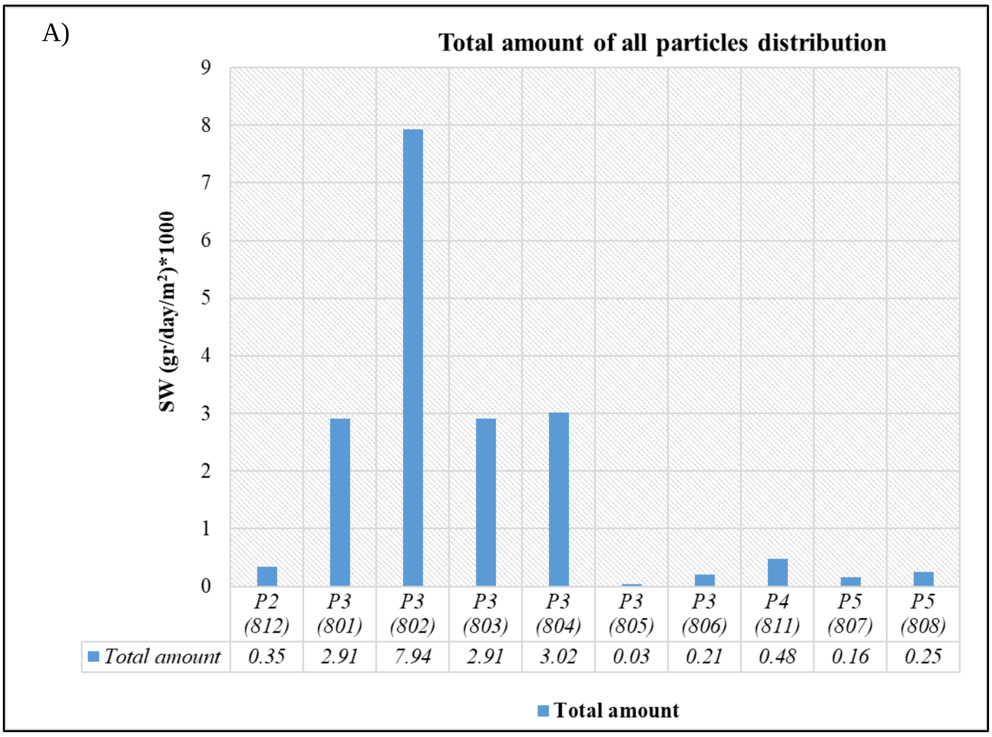
5.6.3 Grain size contribution from different cultivation

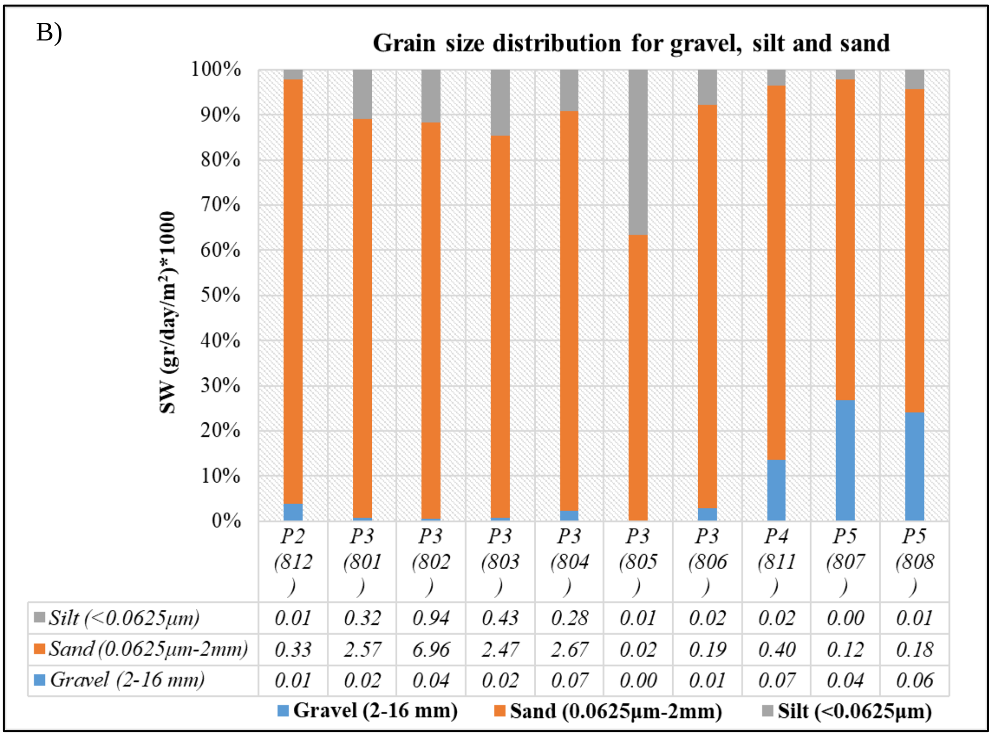
This section addressed particle size analyses for sediment collected in monitored areas. Due to low weight, samples with a total dry weight lower than 30gr were not used for particle size distribution. The used amount was 88%, 75%, 81%, 54%, 98%, 25%, 84%, 92%, 80%, and 74% of total mass for P2 (812), P3 (801), P3 (802), P3 (803), P3 (804), P3 (805), P3 (806), P4 (811), P5 (807) and P5 (808) respectfully.

According to Figure 5.17, the following findings can be highlighted:

- A higher amount of sand was found in the upland area around the P3 (see 801,802,803,804 in Figure 5.2017A) in plough lines and main drain compared with P4 (see 8.11 in Figure 5.17B) and P5 (see 807 and 808 in Figure 5.16B) areas. The highest distribution of sand occurred in the case of plough lines (801, 802, 803), and main drain (804) in the P3 area since the main drain (805 and 806) in the P3 area and main drain (8011,807 and 808) experienced lower amounts of sand
- On the other hand, the same amount of gravel has been disposed of in main drains in P3 (see 804 in Figure 5.118) and P4 areas since P5 (see 811 in Figure 5.16) has lower disposal of gravel (see 807 and 808 in Figure 5.16).

- P3 area had 99%, 98%, and 95 % higher sand amounts than P2, P4 and P5, respectively. Furthermore, the P3 area had 99% higher disposal of silt than the P2, P4 and P5 areas. On the other hand, the P5 area had 98 %, 45 %, and 77 % higher disposal of silt than P2, P3 and P4.
- Sediment containers positioned downstream after the silt trap experienced less sediment grain size distribution (805 and 806 in Figure 5.16A and 5.17B).
- The P5 area experienced the lowest amount of sediment grain size distribution compared to any other plot, as shown in Figure 5.16A. Furthermore, the container positioned just before the silt trap occurred had more sediment than the container positioned further upstream (see 808 in Figure 5.16A and 5.17B).





	P2 (812)	P3 (801)	P3 (802)	P3 (803)	P3 (804)	P3 (805)	P3 (806)	P4 (811)	P5 (807)	P5 (808)
Silt (<0.0625µm)	0.01	0.32	0.94	0.43	0.28	0.01	0.02	0.02	0.00	0.01
Sand (0.0625µm-2mm)	0.33	2.57	6.96	2.47	2.67	0.02	0.19	0.40	0.12	0.18
Gravel (2-16 mm)	0.01	0.02	0.04	0.02	0.07	0.00	0.01	0.07	0.04	0.06

Figure 5.17: Grain size distribution for gravel, sand and silt (A) and all particles (B) for P2 (812), P3 (801), P3 (802), P3 (803), P3 (804), P3 (805), P3 (806), P4 (811), P5 (807) and P5 (808).

Further supplementary results (in Section 5.6.4) will explore any trends in gravel, sediment and silt distribution that could explain differences in the amounts accumulated (found) in different cultivated areas.

5.6.4 <u>Grain size distribution vs P, API30, Qv, Qp</u>

Linear regression analyses showed a relationship between variables (Qp/Qv/P/API30) and sample weight (see Table 5.9). The strongest relationship was found for silt and sand distribution in the P3 (806) area. This relationship refers to considered variables. Furthermore, a strong relationship between Qv and sediment weight has been formed in the case of the P3 (804) area for sand distribution. Also, a strong relationship has been founded in the case of API30 and P5 (808) area for sand distribution. According to trend analyses, the amount of sand and silt will likely decrease in the main drain (804, 806 and 808) since increasing relationships were observed in plough lines (801, 802).

Table 5.9: R2 results for sediment weight (gr/day/m2) and mean Qp, mean Qv mean P (mm) and mean API (mm) for gravel, sand, and silt grain size

Variable	P2 (812)	P3 (801)	P3 (802)	P3 (803)	P3 (804)	P3 (805)	P3 (806)	P4 (811)	P5 (807)	P5 (808)
Gravel										
Qp	-	-	-	-	0.46	-	-	0.83	0.47	-0.73
Qv	-	-	-	-	0.26	-	-	0.67	0.41	-0.07
API30	-	-	-	-	0.00	-	-	0.01	0.15	-0.28
P	-	-	-	-	0.33	-	-	0.46	0.17	-0.35
Sand										
Qp	-	0.69*	0.77*	-	-0.70*	-	-0.95	0.23	0.40	-0.73
Qv	-	0.88*	0.75*	-	-0.78*	-	-1.00*	0.11	0.38	-0.50
API30	-	0.24	0.68*	-	-0.47	-	-0.31	0.18	0.12	-0.84
P	-	0.80	0.61*	-	-0.57	-	-0.97	0.00	0.12	-0.64
Silt (<62.5)										
Qp	-	0.34	0.03	-	-0.04	-	-0.99	0.67	0.23	-0.80*
Qv	-	0.32	0.17	-	-0.03	-	-0.82	0.52	0.10	-0.48
API30	-	0.07	0.03	-	-0.02	-	-0.71	0.05	0.11	-0.47
P	-	0.29	0.10	-	-0.03	-	-0.94	0.29	0.09	-0.09

All p values >0.05 (not siginifact relationship) except for *(p-value <0.05)

5.7 Chapter Summary

This chapter aimed to refer to the differences between different cultivated areas, unplanted plots and sub-catchment areas. This chapter presented results for a field related to runoff occurrence and sediment delivery. The findings are the following:

RQ1: How do different cultivation techniques influence the runoff flow and volume? Which factors control delivery?

- The ruoff occurrence has been determined by selecting events that occurred in dry and wet weather conditions. The selected events have been analysed in detail through different forest development categories.
- Mann-Whitney statistical tests found that there is statistical significance between runoff flow/volume and precipitation for all selected data sets except for the P1 data set related to the first year of monitoring. This applies to LRM.

- A comparison of selected data sets showed that runoff water would first occur in the P1 area, followed by P3, P2, P4, P5, P6 and P7 during dry weather conditions. Furthermore, for wet weather conditions, runoff water will occur in monitored areas as follows: P1, P3, P4, P5, P7, P2 and P6. However, in the case of sub-catchment areas, runoff occurred first in the case of Inch 1 compared to Inch 2.
- LRM showed that Inch 1, P5, and P4 are for dry weather conditions and have the same trend as the LR curve trend since Inch 2, P3 and P7 have the same LR curve trend. However, in wet weather conditions, Inch 1, Inch 2, P2, P3, P4, P5, and P7 showed very similar trends in the LR curve.
- FDC data analysis for Inch 1 and 2 showed that Inch1 had lower Rt during the wet period for any category and F3 category in dry weather conditions, compared to Inch 2. On the other hand, Rt had higher values for Inch 1 only in the case of the F1 category during dry conditions. However, Qp/Qv has been lower in Inch 1 for all FDC and weather conditions than in Inch 2. Interesting findings indicate that the F1 category has higher Qp/Qv for dry weather conditions than the F3 category for both sub-catchments. A similar trend for wet weather conditions for Inch 1, where the highest amount of Qp/Qv has been related to the F2 category. According to those findings, there have been developed trends for dry and wet weather conditions that refer to higher runoff values. Higher runoff values will likely occur for API>15 mm and P>10 mm for dry weather conditions. However, higher runoff values will occur for median API30≥32 mm and P≥10 mm in dry weather conditions.
- FDC data analysis for cultivated areas under matched events showed that runoff water would first occur in P4, followed by P5, P2, P3, P7 and P6 for dry weather conditions. Furthermore, runoff water appeared first in the P3 area for wet weather conditions, followed by P4, P7, P2, P5 and P6. However, Qp/Qv has been highest in cases of P3 and P7 for dry weather conditions, since for wet weather conditions highest values occurred in cases of P2 and P7. If we included FDC category results, it is evident that for non-growing seasons (F1 and F3) for dry weather conditions, Qp/Qv has higher values for all cultivations. On the other hand, this is not the case for wet weather conditions. According to those findings, there have been developed trends for dry and wet weather conditions that refer to higher runoff values. Higher runoff values will likely occur for API>10 mm and P>10

mm for dry weather conditions. However, higher runoff values will occur for median API30>32 mm and P>12 mm in dry weather conditions.

- Matching events between unplanted plots and cultivated areas showed that unplanted plots had the highest Qp/Qv and lowest Rt for dry and wet weather conditions.
- DP group findings showed that the highest amount of runoff water occurred in the case of the DP4 group. However, WP group findings showed that the highest amount of runoff water occurred in the case of the WP4 group.
- Cultivation practices have covered a range of the catchment areas slope and monitoring channel slope. This is likely to be an influencing factor of high runoff water in the case of plough cultivation (the highest slope of the catchment area is detected for the P3 monitored area). Conversely, opposite phenomena occurred in the excavation mounding plot, where P7 has a lower slope of the catchment area and monitoring channel slope. It is assumed that the design of this cultivation has influenced higher runoff water occurrence.
- Cultivation and unplanted areas distribution has been different for Inch 1, and Inch 2 monitored sub-catchments. Inch 2 monitored sub-catchment has 15% less plough cultivated land than Inch 1 sub-catchment. On the other hand, unplanted areas are lower at 25% for Inch 1 monitored sub-catchment compared to Inch 2. However, since the unplanted plot has the highest Qp/Qv compared to cultivated areas, unplanted areas likely have more control over those two variables.

RQ2: How does sediment delivery from each cultivation technique change over time?

- The highest amount of sediment delivery refers to plough cultivation (P3, P4, P5) since hand screefing (P2) and excavation mounding (P6 and P7) monitoring plots have experienced significantly less sediment delivery. Furthermore, the plough-cultivated areas (P3) had higher sediment disposal than the other two plough-cultivated areas (P4 and P5).
- The P3 area had experienced higher sand and silt amounts than P2, P4 and P5. Furthermore, the P5 area had higher disposal of gravel than P2 and P4.

- The highest amount of sediment delivery has been observed during SC1, SC2, SC3 and SC10. It is rather connected to non-growing season (such as SC1, SC2, SC3) or high amount of precipitation (such as SC10)
- The monitoring containers that were positioned closer to the silt trap in the main monitoring channel (containers No. 808 and 804) contained more sediment (particularly sand grains).
- According to LRM analyses, the amount of sand and silt will likely decrease in the main drain–monitoring channel. Furthermore, increasing relationships were observed in plough lines (P3 area – containers No. 801, 802 and 803).

Chapter 6 Modelling results

6.1 Chapter introduction

Modelling the impact of catchment-wide cultivated area hydrology on the reduction of runoff volume and peak was undertaken to address RQ3 (What is the preferred cultivation technique for minimizing flood generation and can this be reliably predicted using hydrological modelling tools?).

The results generated using the GR4H model were analysed to the properties of each cultivation technique. This chapter outlines all events during the monitoring period compared with modelling events. Two monitoring years were used for modelling different cultivation and sub-catchment areas. Those two years were used for calibration and validation of the model (see Table 6.2 and Table 6.3). Model output variables are surmised under other properties, including tree coverage and soil types, to consider why the reduction output parameters differed for different cultivated areas. Those results complement event-based validation of the model for hand-screefing, excavation mounding, plough cultivation, and sub-catchment area. Moreover, all these processes help understand the effectiveness of each cultivation and sub-catchment level change.

6.2 Calibration and validation

The GR4H model is a global rainfall-runoff model developed by the national institute of research in sciences and technologies for environment and agriculture (IRSTEA) [128]. The model is parameterized with only four parameters to calibrate and includes two reservoirs (production and routing) and two transfer functions to represent the watershed processes (see Section 4.3.1). The model needs hourly precipitation and ET (see Chapter 3) to simulate streamflow at the watershed outlet.

The four parameters are:

- The maximum daily capacity of the production store (X1, in mm);
- The groundwater exchange coefficient (X2, in mm/hours) allows water to be imported ($X2>0$) or exported ($X2<0$) from the system
- The maximum hourly capacity of the routing store (X3, in mm)

- The time base of the unit hydrograph (X4, in hours).

Parameters are automatically calibrated by optimized objective function (OF), such as the Kling–Gupta (KGE) coefficient (see Chapter 4). The calibration was performed at an hour scale on the 2016-2018 period for the nine plots independently and with a maximum of five months of the warm-up period. The GR4H calibration has been performed automatically using the airGR package at the hourly time scale for each plot independently from 2016 to 2018. The best performance of this model was achieved by using the KGE coefficient as the objective function and the Nealder-Mead method as the optimizing algorithm (see Chapter 4). Another OF (NSE and RMSE) was evaluated in Figure 6.1 and showed the quality of each solution together with Pearson correlation. Model calibration was automatic. Furthermore, Figure 6.1 shows that the best optimization was achieved through OF presented by the KGE coefficient, which was used as relevant in further analyses of modelled data. The mathematical definition of the OF evaluation metrics is shown in Table 4.3, and there is possibility that missing data percentages (Table 6.1) can influence performance model [170].

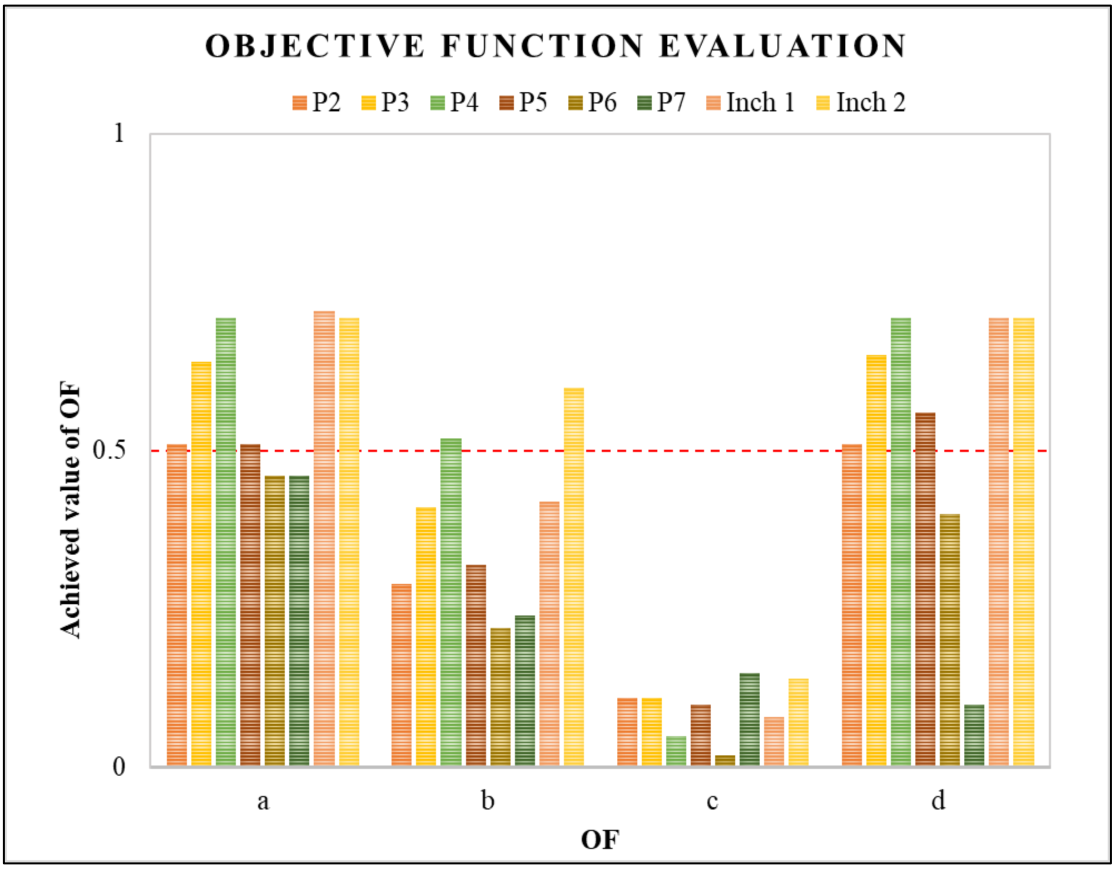


Figure 6.1: Comparison of values used to calculate objective function (OF) during the calibration stage of each case study and seven GR4H models. The figure shows Kling–Gupta (KGE) (a), Nash–Sutcliffe efficiency (NSE) (b), Root mean square error (RMSE) (c) and Pearson correlation (r) (d). The red line represents the 0.5 level of achievement of OF.

6.2.1 <u>Missing data percentages</u>

Prior to modelling, missing data were identified in each data set (see Table 6.1). Missing percentage up to 25% gives a good performance of the model. Modelling performance was validated for all data sets (see Table 6.1). Additionally, the model was done through event-based variables validation, where modelling and observed data have been looked at through the lens of a single event. Furthermore, data from the P6 excavation mounding plot, P7 excavation mounding plot and P1 unplanted plot were analysed in Chapter 5 and complimented the modelling results. Unfortunately, this chapter did not use modelling results from the P1 (unplanted plot) area due to a lack of data from the first year of monitoring, where the monitoring setup was found wrong. Furthermore, the P1 (unplanted plot) measuring instrument experienced a lot of malfunctions during the second year of monitoring, in the total number of events was low (11 events in total) for GR4H modelling.

Table 6.1: Percentage and periods of missing data for Inch 1 and Inch 2 sub-catchments

Sub-catchment area/ Cultivation area/ Unplanted plot area	Missing data periods	Percentage of missing data (%)
Inch 1	• 3rd October 2016 to 23rd October 2016 • 22nd February 2017 to 21st June 2017 • 15th October 2018 to 3rd November 2018	17
Inch 2	• 2nd August 2016 to 8th September 2016 • 31st October 2016 • 10th November 2016 to 17th November 2016 • 24th February 2017 to 15th June 2017 • 16th May 2018 to 10th August 2018* *(excluded due to low flow)	24
P1	• 11th January 2016 to 18th January 2017 • 27th January 2017 to 6th April 2017 • 15th October 2017 to 19th October 2017 • 23rd December 2017 to 27th December 2017 • 29th December 2017 to 10th January 2018 • 13th January 2018 to 25th January 2018 • 8th February 2018 to 9th February 2018 • 12th February 2018 to 25th June 2018 • 27th June 2018 to 4th July 2018 • 1st August 2018 to 26th August 2018 • 24th September 2018 to 15th October 2018 • 21st October 2018 to 9th November 2018 • 16th November 2018	43 (+50)*
P2	• 3rd May 2017 to 12th May 2017 • 15th January 2018 to 21st January 2018 • 23rd March 2018 to 24th March 2018 • 26th March 2018 to 28th March 2018 • 30th March 2018 to 31st March 2018 • 2nd April 2018 to 8th April 2018	6
P3	• 12th February 2018 to 9th March 2018 • 14th March 2018 to 7th June 2018 • 27th July 2018 to 26th August 2018 • 11th October 2018 to 15th October 2018 • 1st November 2018 • 8th November 2018	20

	• 12th December 2018 to 15th December 2018	
P4	• 29th May 2017 to 14th September 2017 • 3rd October to 19th October 2017 • 24th November 2017 to 27th November 2017 • 11th December 2017 to 17th December 2017 • 29th December 2017 to 31st December 2017 • 4th January 2018 to 10th January 2018 • 16th January 2018 to 22nd January 2018 • 31st January 2018 to 2nd February 2018 • 3rd February 218 to 8th February 2018 • 5th March 2018 to 9th March 2018 • 3rd April 2018 to 7th April 2018	22
P5	• 10th January 2017 to 15th January 2017 • 18th July 2017 to 18th August 2017 • 24th August 2017 to 22nd September 2017 • 16th October 2017 to 20th October 2017 • 30th January 2018 to 22nd February 2018 • 3rd March 2018 to 7th March 2018 • 1st June 2018 to 4th June 2018 • 13th June 2018 to 5th July 2018 • 10th August 2018 to 26th August 2018 • 30th September 2018 to 10th November 2018	24
P6	• 24th May 2018 to 26th August 2018 • 5th September 2018 to 10th November 2018 • 17th November to 15th December 2018	26
P7	• 20th July 2017 to 19th August 2017 • 1st March 2018 to 6th March 2018 • 3rd May 2018 to 12th May 2018 • 19th March 2018 to 21st March 2018 • 31st March to 15th December 2018	40

*P1 is missing 41% of data, but the first year of monitoring cannot be used due to the wrong setup of the monitoring area.

6.2.2 Inch 1 and Inch 2 sub-catchment models calibration and validation

Inch 1 and Inch 2

Model calibration is considered for 17 months from July 2016 to December 2017 (see Figure 6.1a and Figure 6.2a). The warm-up period considered data from July 2016 to December 2017, and model validation evaluated the GR4H outputs (see Table 6.2) using optimal parameters from the calibration step. The period from January 2018 to January 2019 (13 months) was used to validate a model for both sub-catchments (see Figure 6.1b and Figure 6.2b).

Table 6.2: GRH4 model performance output (X1, X2, X3, X4, KGE, PBIAS)* for Inch 1 and Inch 2 sub-catchment with war-up, calibration and validation period.

PlotPlot	Warm-up	Calibration period	Validation period	X1	X2	X3	X4	KGE Calibration	KGE Validation	PBIAS Calibration	PBIAS Validation
Inch 1	June –December 2016	January –December 2017	January 2018 - January 2019	5.53	1.39	52.70	1.93	0.72	0.63	0.3	-14.6
Inch 2				4.85	1.08	16.88	4.28	0.71	0.64	-2.1	-2.1

*Parameters as defined in Chapter 4

Flow peaks in the Inch1 and Inch 2 sub-catchments hourly time step calibration (see Figure 6.1) estimated through the GR4H present satisfactory performance (see Figure 6.2). The peaks were responsive in the case of both sub-catchments, and similar trends were noticeable over base flow. Overall KGE values between simulated and observed flows were above the acceptable threshold (KGE>0.5), and PBIAS scored below ±20%, indicating good fitting between observed and simulated values [127]. The sub-catchments of Inch1 KGE showed the highest performance by reaching KGE for calibration of 0.72 since Inch 2 achieved the highest performance for validation of 0.64. The mathematical definition of the evaluation metrics is shown in Table 4.3.

Model parameters performances:

- The X1 parameter has 12% higher values for the Inch 1 sub-catchment, which indicates a higher production store. Furthermore, this parameter is likely to be related to vegetation development in the sub-catchment areas. Generally, there is a more significant production store in the Inch 1 sub-catchment than in the Inch 2 sub-catchment, suggesting that more water is stored in the soil–production store, contributing to vegetation growth.
- The X2 parameter is a function of groundwater exchange. A positive value indicates that the water is imported into the routing store observed for both sub-catchments. However, 22% lower values for the Inch 2 sub-catchment, suggesting that more water stayed in the store for the Inch 1 sub-catchment.
- The X3 has 67% lower values in the Inch 2 sub-catchment, suggesting that Inch 2 area vegetation changes are lower than in the case of the Inch 1 area.
- Finally, X4 higher values of Inch 2 suggest that flow durations are longer in the case of this sub-catchment and suggest higher values of volume of water in general

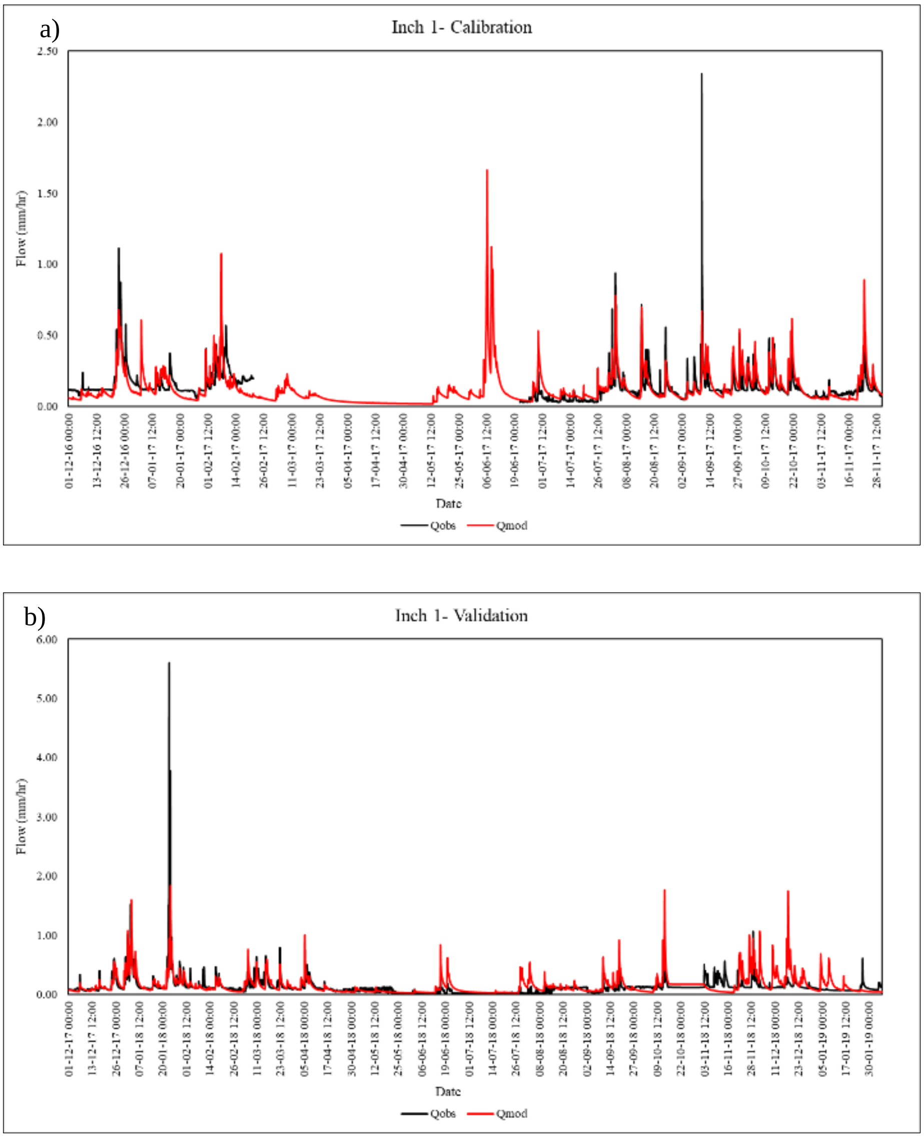


Figure 6.2: Inch 1 hourly observed and modelled flow outputs for a) calibration and b) validation

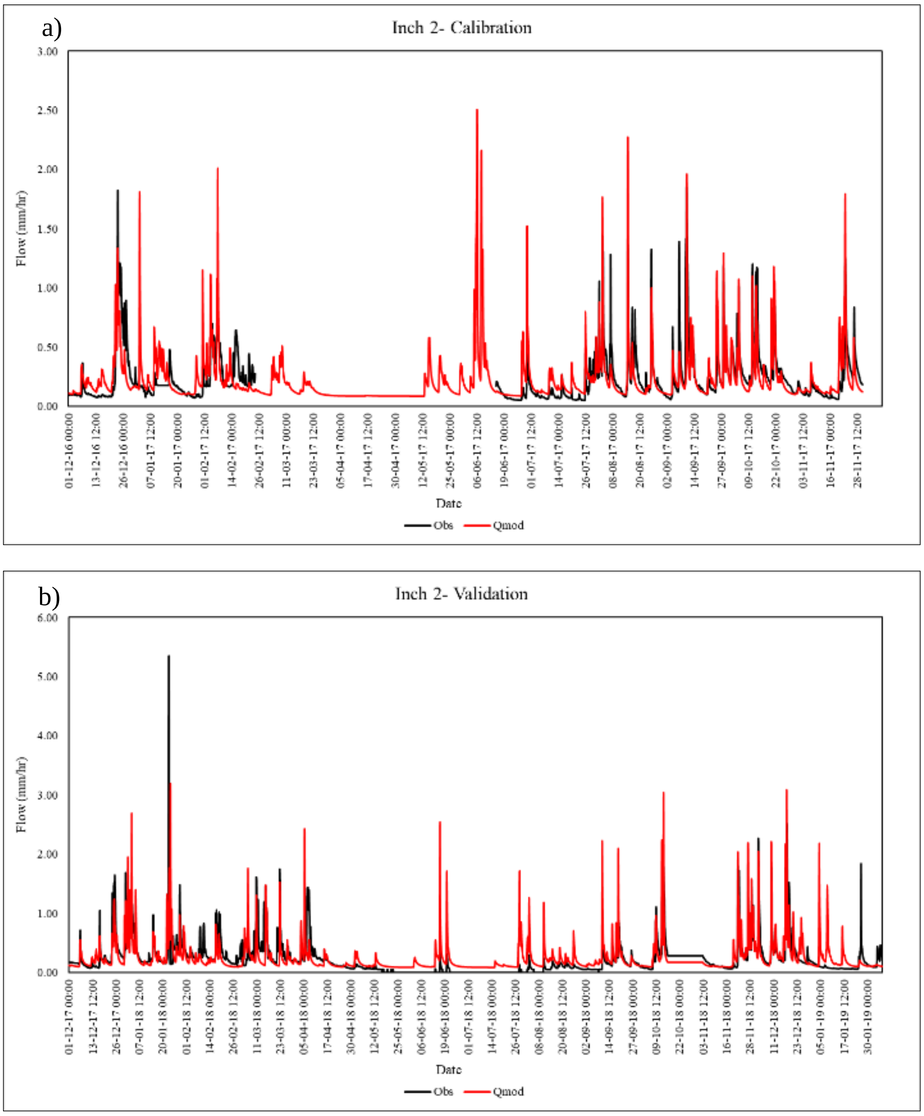


Figure 6.3: Inch 2 hourly observed and modelled flow outputs for a) calibration and b) validation

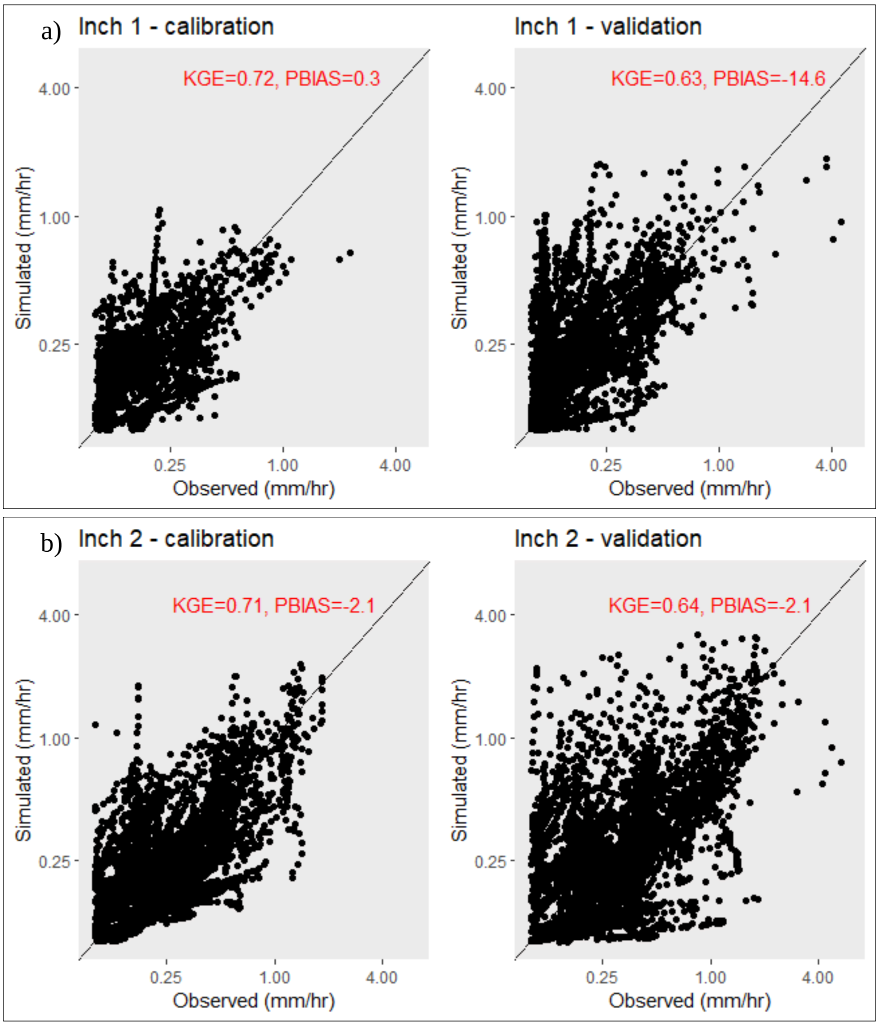


Figure 6.4: Performance of the GR4H model for calibration and validation periods with PBIAS and KGE expression: a) Inch1 and b) Inch2

6.2.3 Cultivation techniques models calibration and validation

The effectiveness of the GR4H model at the scale of cultivation techniques was assessed to determine the linkage between field experiments and the model and understand where GR4H could perform at the small scale (see Section 2.8.1) when it is calibrated and validated at the sub-catchment scale (see Table 6.3). Modelled output from the hourly model was compared in each cultivated area (see Figures 6.5, 6.6, 6.7, 6.8, 6.9, 6.10, 6.11 and 6.12).

Table 6.3: GRH4 model performance output (X1, X2, X3, X4, KGE, PBIAS) for cultivated areas with warm-up, calibration and validation period

Plot**Plot**	**Warp up period**	**Calibration period**	**Validation period**	**X1**	**X2**	**X3**	**X4**	**KGE Calibratio**	**KGE Validation**	**PBIAS Calibratio**	**PBIAS Validation**
P2	December 2016 - January 2017	February 2017 - December 2018	January 2018 - December 2018	74.33	0.13	1.54	11.72	0.51	0.54	-3.5	-7.8
P3				7.78	0.14	1.79	22.52	0.64	0.53	-2.2	2.9
P4				350.80	0.09	1.99	12.82	0.71	0.59	-2.8	-18.2
P5				74.85	0.37	8.03	11.69	0.51	0.62	-5	9.7
P6				457.18	-0.004	0.008	35.48	0.46*	0.28*	-17.3	-68.2
P7				109.95	0.81	10.81	14.42	0.46*	0.34*	4.1	38.2

*Those models were evaluated through variables evaluation in the next section due to missing data

Model performances were tested on each calibrated plot. GR4H has simulated two sub-catchment areas, six cultivated fields and one unplanted plot. Most of the cultivated areas show satisfactory performance (KGE>0.5). Poor performance was highlighted in red in Table 6.3 (see red letters). Despite extensive effort to manually obtain better calibration, the hourly performance outcome did not improve. Lower KGE values for the validation phase compared with the calibration phase occurred in the case of P3, P4, P6 and P7. It is likely that the model has difficulties capturing the complex process related to vegetation changes, significantly local moisture changes and micro-basin variables. Also, lower KGE in the calibration phase was noticed for Inch 1 and Inch 2 sub-catchment. Furthermore, a higher performance decrease was detected in Inch 1, which was subject to more complex vegetation changes [171], [172] than in Inch 2 sub-catchment (see Table 3.1). This might prove that a more complex, specially modelled model needs to be applied over micro-scale catchments for better modelling results.

Furthermore, this GR4H model is not specially based. Therefore, it was impossible to apply a specially based model over cultivated plots since high-resolution DSM was unavailable by the modelling process.

The tested model included two years of monitoring for P3, P4, P5 and P7 cultivated areas since the P6 area was tested only for the first year of monitoring and part of the second year of monitoring due to a lack of available data.

Model parameters performances

According to parameter X1, areas of P4 and P6 can store more water in soil storage compared with other monitored areas (P2, P3, P5 and P7). Furthermore, those areas are predominantly located on brown earth, with a high storage capacity. Areas of the P5 plough plot, P7 excavation mounding plot, and P2 hand-screefing plot have very similar storage capacities since the P3 plough plot showed the lowest parameter values. On the other hand, according to parameter X2, changes are slightly different, indicating that water has been exported from the system for all areas except for P6. For example, the highest values of this parameter are related to P5 plough plot and the P7 excavation mounding plot since P2, P3, and P4 have shown very similar values. The X3 has the highest values for P5 and P7 since P2, P3, and P4 have very similar lower values. This may influence vegetation changes and root system development over plough and excavation mounding. In addition, the hand screefing area experienced a slight increase for this parameter. For example, P3 and P6 had X4 higher values, which indicates a higher volume or prolonged water runoff over monitored areas.

The plough cultivation plots experienced various changes in the production store, where water storage was highest in the P4 plough plot and lowest in the P3 plough plot. On the other hand, the maximum hourly capacity was highest in the P3 area. The number of trees per plough cultivated plot is higher for P5 plough plot (see Table 6.9), which might influence the X3 parameter related directly to the capacity of the routing store. On the other hand, flow duration is highest in the P3 plough plot, suggesting higher runoff water volume. These changes might influence the hydrological signature of sub-catchments over time because plough cultivation is the predominant cultivation in the Menstrie catchment (see Figure 3.8).

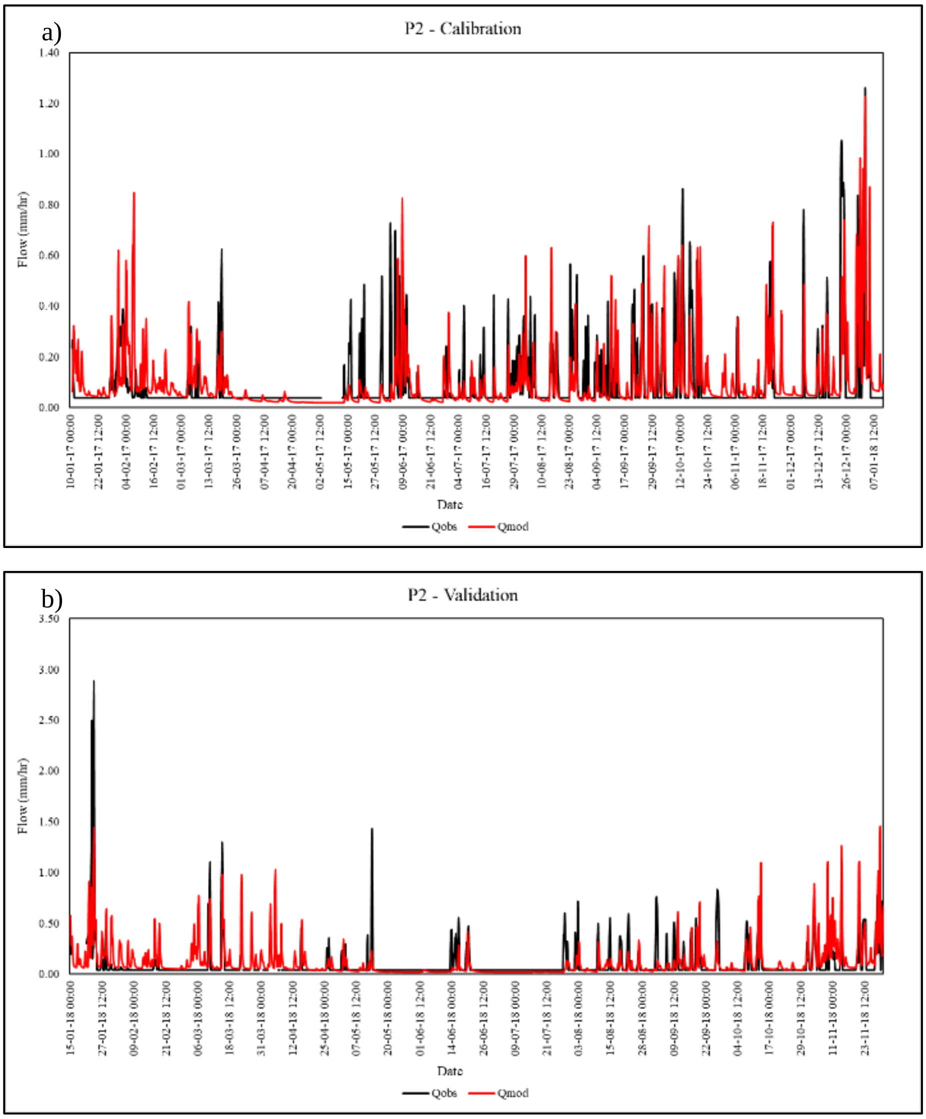


Figure 6.5Plot: Plot 2 hourly observed and modelled runoff flow outputs for a) calibration and b) validation

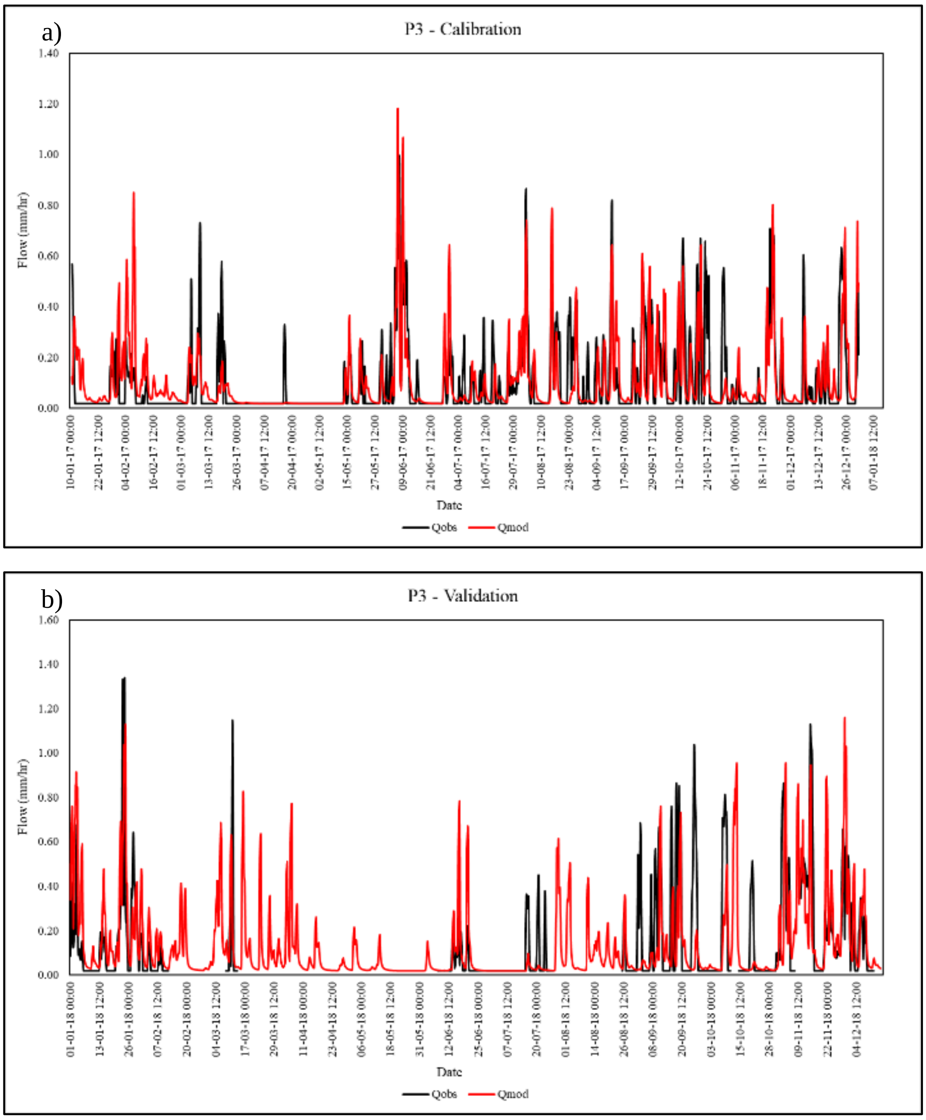


Figure 6.6Plot: Plot 3 hourly observed and modelled runoff flow outputs for a) calibration and b) validation

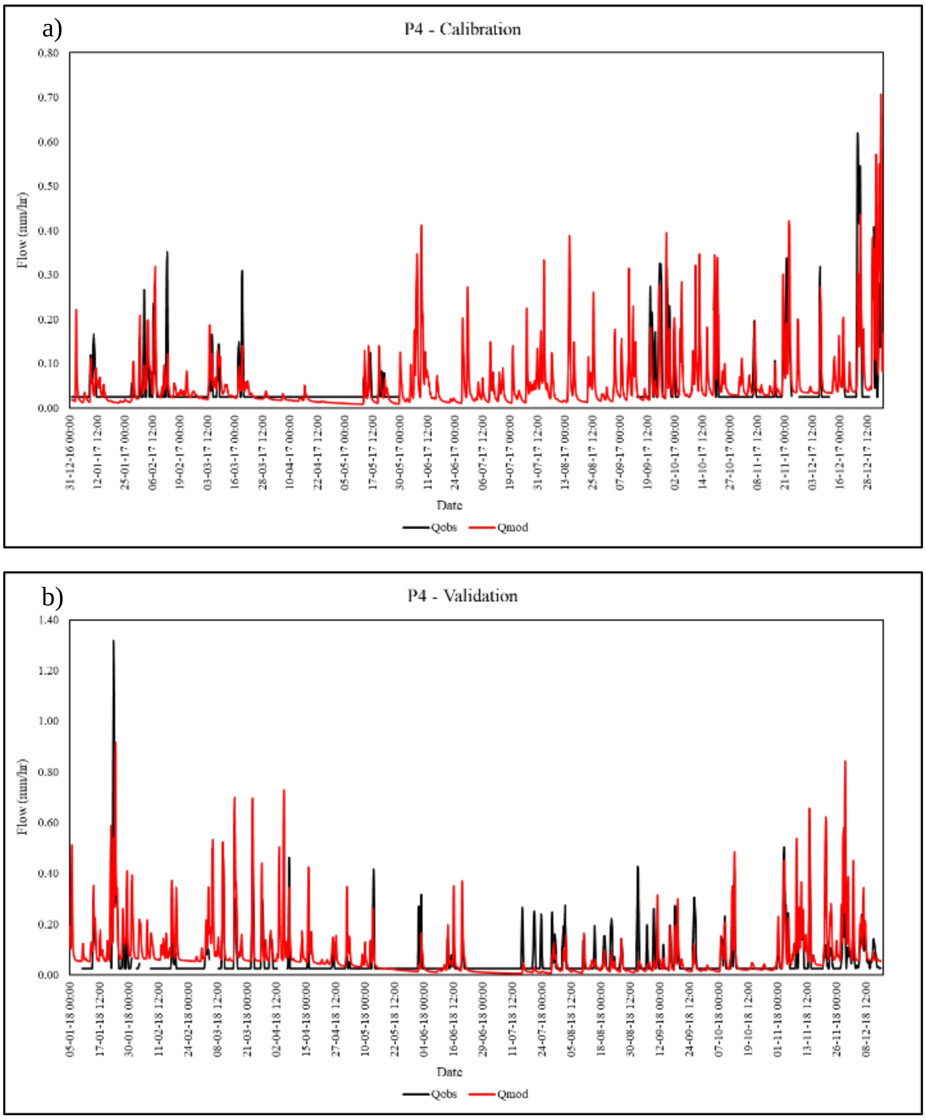


Figure 6.7Plot: Plot 4 hourly observed and modelled runoff flow outputs for a) calibration and b) validation

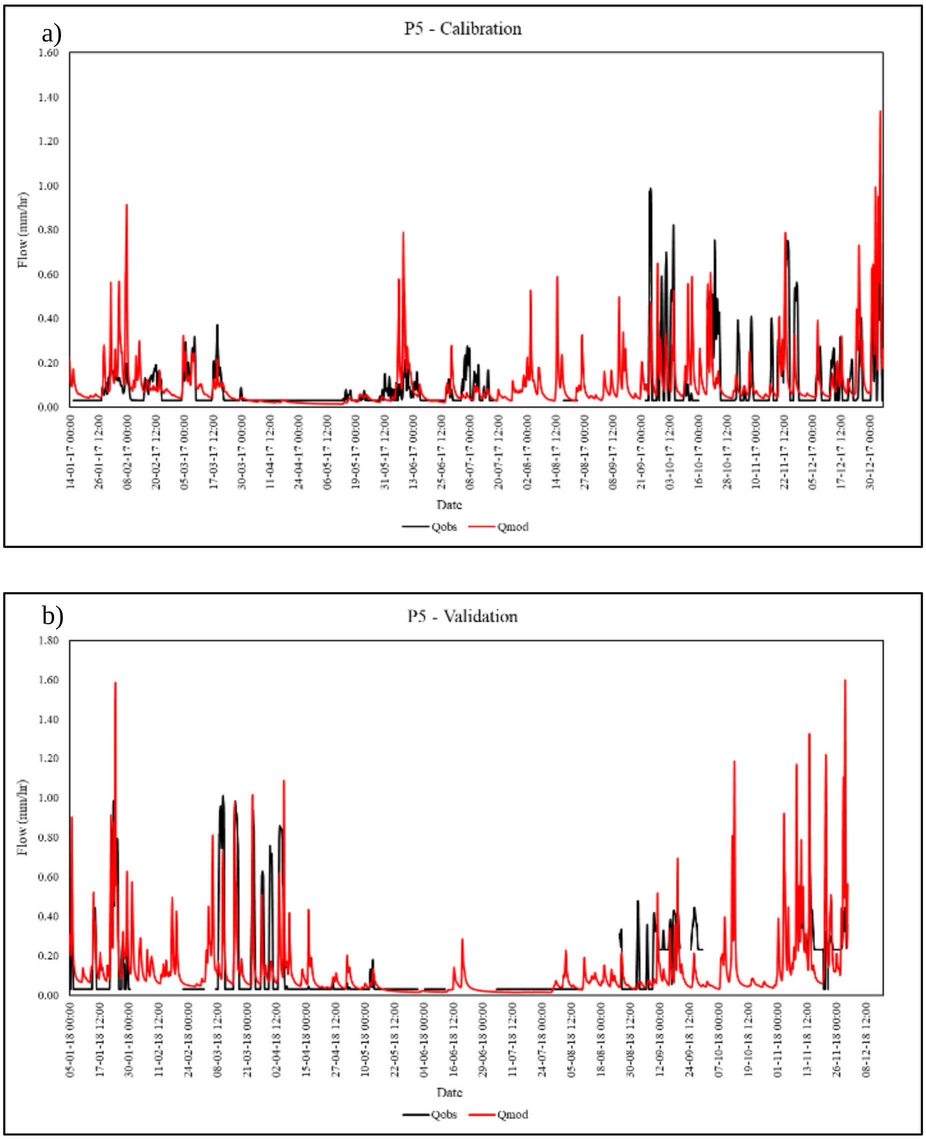


Figure 6.8Plot: Plot 5 hourly observed and modelled runoff flow outputs for a) calibration and b) validation

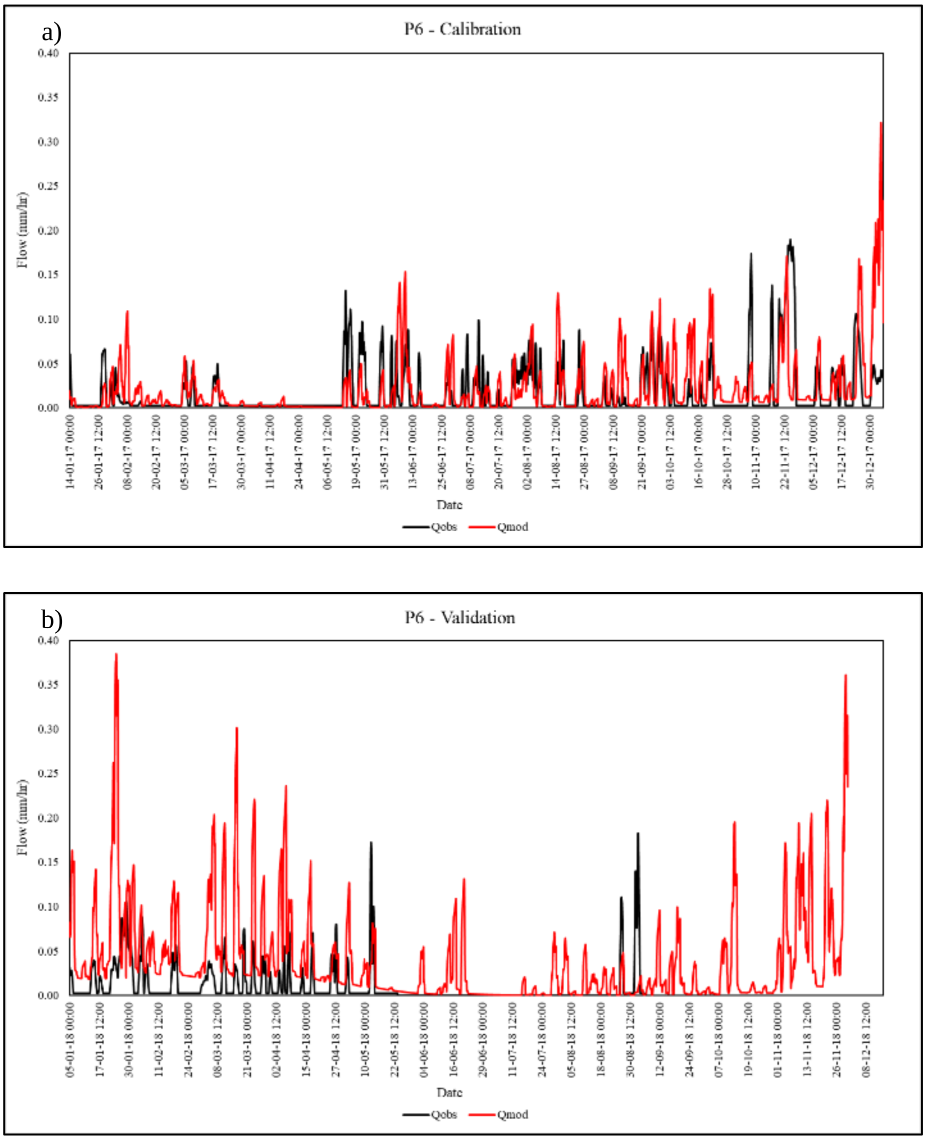


Figure 6.9Plot: Plot 6 hourly observed and modelled runoff flow outputs for a) calibration and b) validation

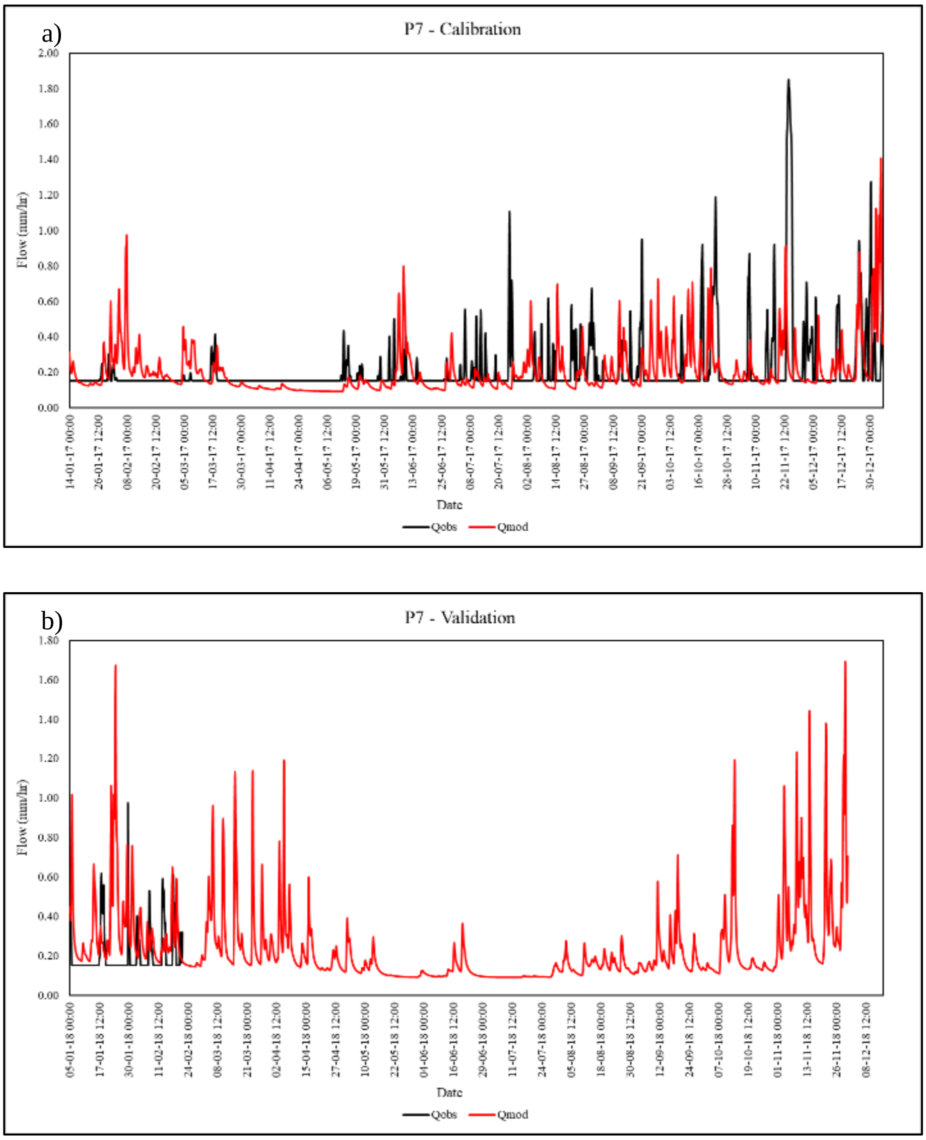
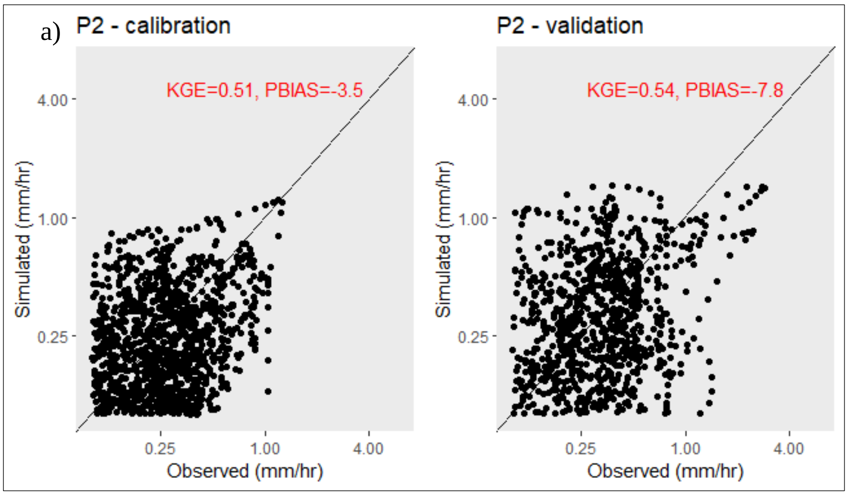
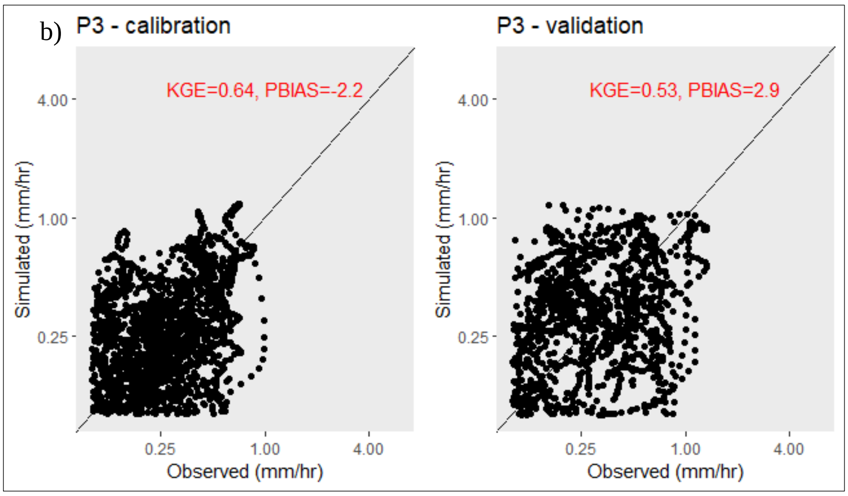
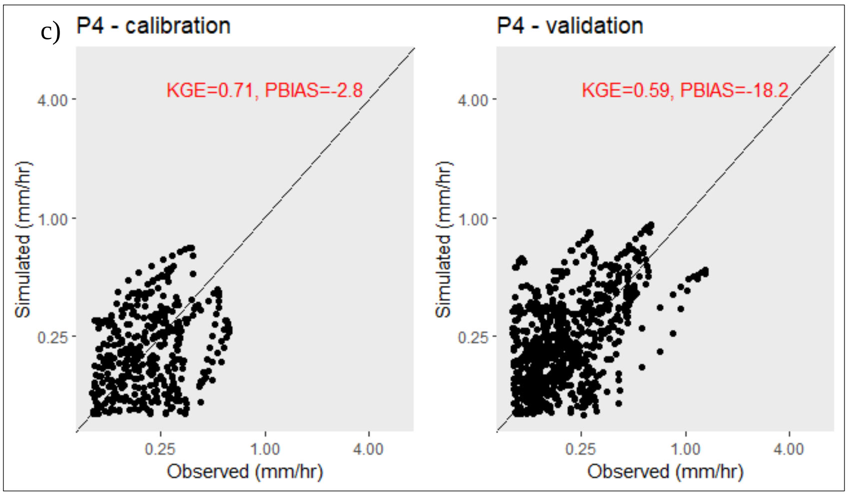


Figure 6.10Plot: Plot 7 hourly observed and modelled runoff flow outputs for a) calibration and b) validation


a)
P2 - calibration
KGE=0.51, PBIAS=-3.5
P2 - validation
KGE=0.54, PBIAS=-7.8
Simulated (mm/hr)
4.00
1.00
0.25
Observed (mm/hr)
0.25
1.00
4.00


b)
P3 - calibration
KGE=0.64, PBIAS=-2.2
P3 - validation
KGE=0.53, PBIAS=2.9
Simulated (mm/hr)
4.00
1.00
0.25
Observed (mm/hr)
0.25
1.00
4.00


c)
P4 - calibration
KGE=0.71, PBIAS=-2.8
P4 - validation
KGE=0.59, PBIAS=-18.2
Simulated (mm/hr)
4.00
1.00
0.25
Observed (mm/hr)
0.25
1.00
4.00

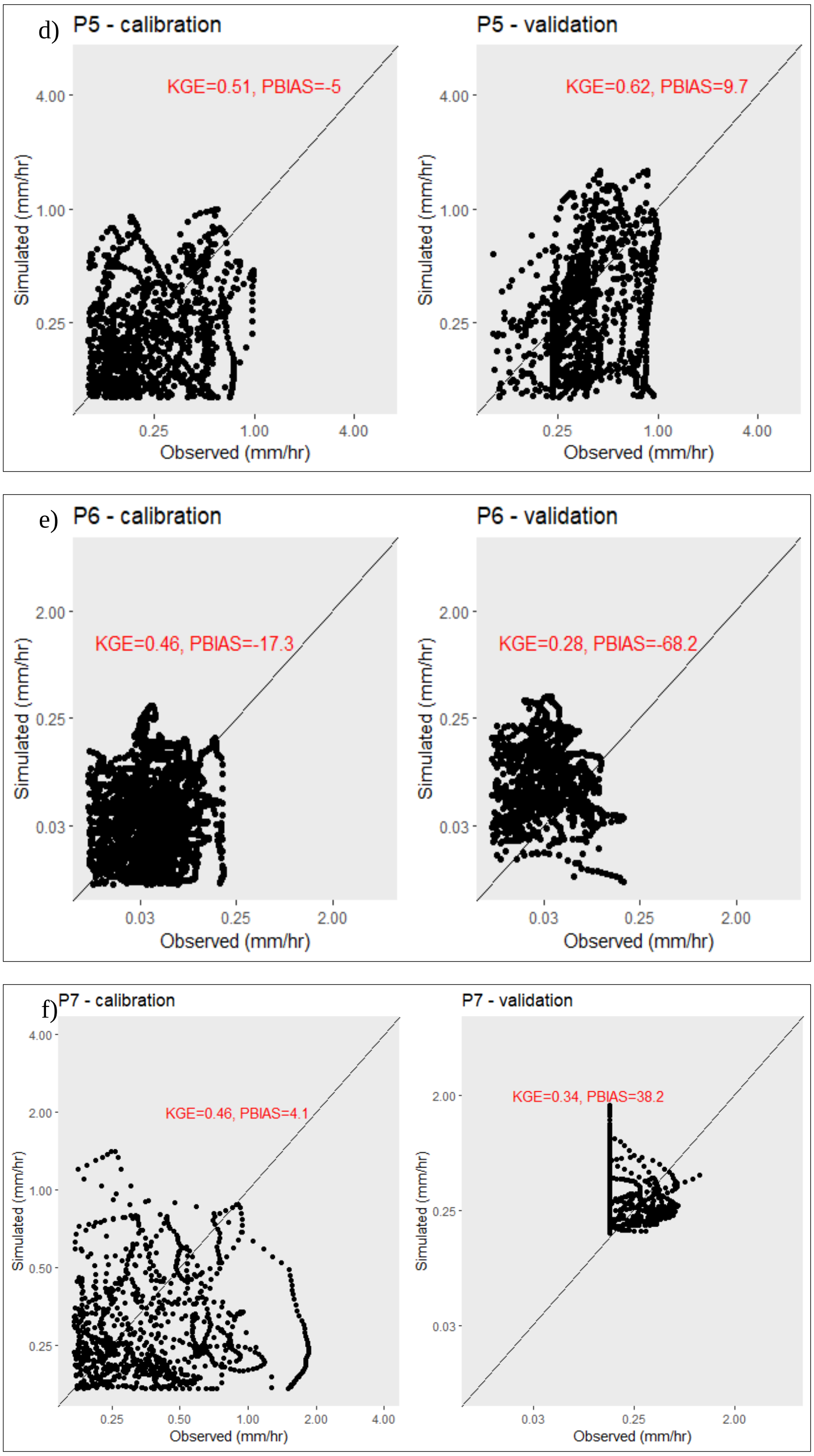


Figure 6.11: Performance of the GR4H model for calibration and validation periods: a) P2 b) P3 c) P4 d) P5 e) P6 f) P7

6.2.4 Model validation through an event-based approach

The effectiveness of the GR4H model was assessed to determine the linkage between modelled and observed events in dry/wet weather conditions. Simulated outputs from the GR4H model were compared to sub-catchment experimental field data. The goodness of fit criteria methods reached a set of variables defined in Chapter 4. This method is presented in Table 4.3. The evaluation criteria used KGE, representing each variable of three statistical components: linear correlation, bias, and flow variability. In addition, (P) - Pearson correlation and PBIAS measures of the average tendency of fitting between simulated and modelled values were used to assess the model further. Performance criteria are presented in Table 6.4 and Figure 6.12. Finally, it showed satisfactory performance for selected variables in the case of sub-catechumens and cultivated areas.

Table 6.4: Values of KGE, PBIAS and Pearson correlation for event-based model validation of Qpt/Qvt/Qp/Qv variables in case of P2, P3, P4, P5, P5, P6, P7, Inch 1 and Inch 2.

KGE	P2	P3	P4	P5	P6	P7	Inch 1	Inch 2
KGE								
Qpt	0.56	0.64	0.59	0.62	0.51	0.50	0.61	0.57
Qvt	0.61	0.71	0.76	0.66	0.51	0.57	0.79	0.74
Qp	0.55	0.70	0.73	0.53	0.50	0.57	0.57	0.57
Qv	0.77	0.63	0.76	0.67	0.65	0.65	0.71	0.77
PBIAS								
Qpt	-14.37	2.00	6.02	3.23	16.77	-4.41	3.52	-12.91
Qvt	-15.19	-4.18	0.00	-18.46	12.43	5.36	-2.27	0.62
Qp	-12.33	-4.81	7.96	13.42	1.94	-4.66	15.06	-12.89
Qv	-12.27	-14.22	-11.45	17.59	15.00	-4.70	8.69	3.28
Pearson correlation								
Qpt	0.69	0.70	0.69	0.71	0.52	0.74	0.71	0.61
Qvt	0.73	0.81	0.87	0.76	0.63	0.86	0.90	0.89
Qp	0.72	0.74	0.80	0.88	0.69	0.79	0.73	0.60
Qv	0.90	0.78	0.95	0.86	0.94	0.83	0.88	0.87

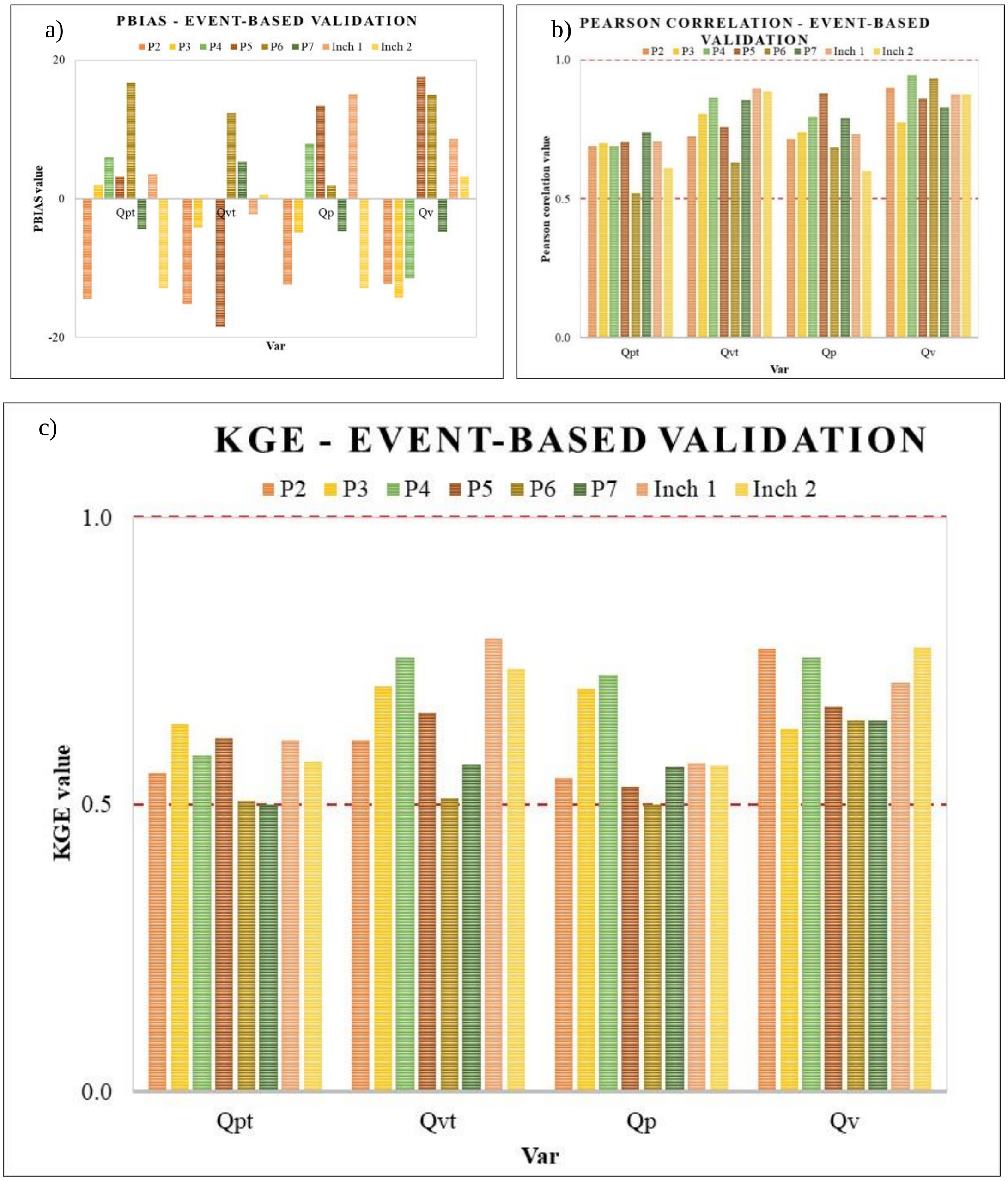


Figure 6.12: Event-based model validation of Qpt/Qvt/Qp/Qv variables (var at the figure) through a) PBIAS, b) Pearson correlation, and c) KGE in case of P2, P3, P4, P5, P5, P6, P7, Inch 1 and Inch 2.

6.3 Dry and wet weather conditions group of events perspective for modelled data

6.3.1 Sub-catchment areas (Inch 1 and Inch 2) and cultivated areas (P2, P3, P4, P5, P6 and P7) events comparison

To compare the events across sub-catchments and cultivated areas, 34 and 72 events were selected for dry and wet weather conditions to compare the events across sub-catchments and cultivated areas. Those events were outlined in Table 6.5 and Table 6.6 under dry/wet weather conditions and FDS categories for dry/wet weather conditions (see Figure 6.13 and Figure 6.14). Furthermore, FDS represented the F1, F2, F3, F4 and F5 categories for dry and wet weather conditions. In addition to that, observed data indicated the following:

- Three major P events (P>15 mm) occurred in the case of dry weather conditions since 14 major P events occurred in wet weather conditions. Despite this, median values of P were reasonably similar for dry weather conditions (from 6-8 mm – see Table 6.5) and variable for wet weather conditions (8-16 mm – see Table 6.6). Further analyses related to FDC/VSC showed that the highest median P values occurred in the case of F2 and F3 for dry weather conditions and F1 and F5 for wet weather conditions (see Table 6.5 and Table 6.6). It is likely that the F1, F2 and F3 categories will experience higher Qp/Qv than F2 and F4 categories. Also, for wet weather conditions, higher Qp/Qv for categories F1 and F5 possible can be related to higher P values (see categories F1 and F5 for wet weather conditions in Table 6.6)
- It was indicative that the Inch 1 sub-catchment had approximately 84% (dry weather conditions) to 64% lower (wet weather conditions) median Qv than the Inch 2 sub-catchment. Further analyses related to FDC/VSC showed higher Qv in the case of Inch 2 for any category under dry and wet weather conditions. The same trend was noticed for Qvt/Qpt/Qp. There is likely a higher percentage of afforestation in the Inch 1 sub-catchment. Further analyses related to cultivated

areas showed that Qp/Qv/Qvt/Q is likely to be highest in the case of P3 and P7 for both weather conditions (see Tables 6.5 and 6.6). It indicates that Qv will be lower at 35%, 49%, 32%, 76%, and 14% for P2, P4, P5, P6, and P7, respectively, compared with P3 for dry weather conditions. Furthermore, it is indicative that Qv will be lower than 33%, 2%, 54%, 23% and 75% for P2, P3, P4, P5, and P6, respectively, compared with P7 for dry weather conditions.

- The assessment of Rt highlighted that the lowest Rt occurred in the case of Inch 1 sub-catchment and P6 for dry weather conditions (see Table 6.5). On the other hand, Inch 1 and P2, P6 and P7 had the lowest Rt in the case of wet weather conditions (see Table 6.6).
- The lowest Tp occurred in the case of Inch 1 and P4 for dry weather conditions (see Table 6.5) since for wet weather conditions, it occurred in the case of Inch1, P2 and P4 (see Table 6.6).

Dissemination of the result above highlights the following trend under different weather conditions:

Dry weather conditions:

- Events characterized by higher median P values (>8mm) in combination with higher median values of API30 (>10mm) will create more runoff water for any sub-catchment areas cultivated area in case of non-growing categories (see F1, F3 and F5 categories in Figure 6.13 and Table 6.5). In addition to this, events that are characterized by higher median P values (>8mm) in combination with higher median values of API30 (>10mm) will create less runoff water for any sub-catchment areas cultivated area in the case of non-growing categories (see F2 and F4 categories in Figure 6.13 and Table 6.5)

Wet weather conditions:

- A Group of events characterized by lower P values (<12mm) will create less runoff water (see F2 and F4 categories in Table 6.6 and Figure 6.14).
- A group of events characterized by higher P (>12mm) values will create more runoff (see F1 and F5 categories in Table 6.6 and Figure 6.14).

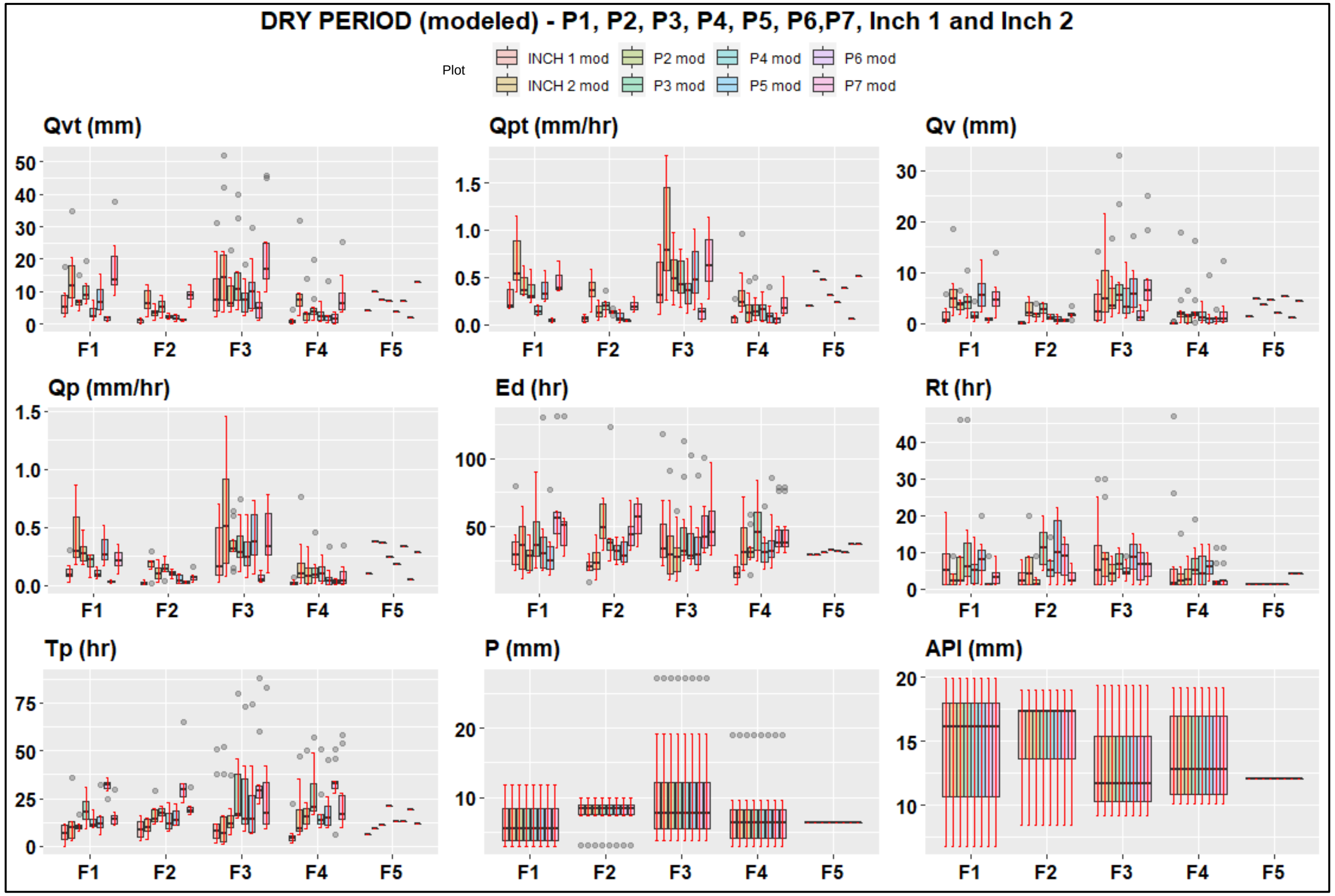


Figure 6.13: Forest development categories (F2, F3, F4 and F5) box plot for variables under the group of events in the case of Inch 1 and Inch 2 sub-catchments and cultivated areas (P2, P3, P4, P5, P6 and P7) for the dry weather condition

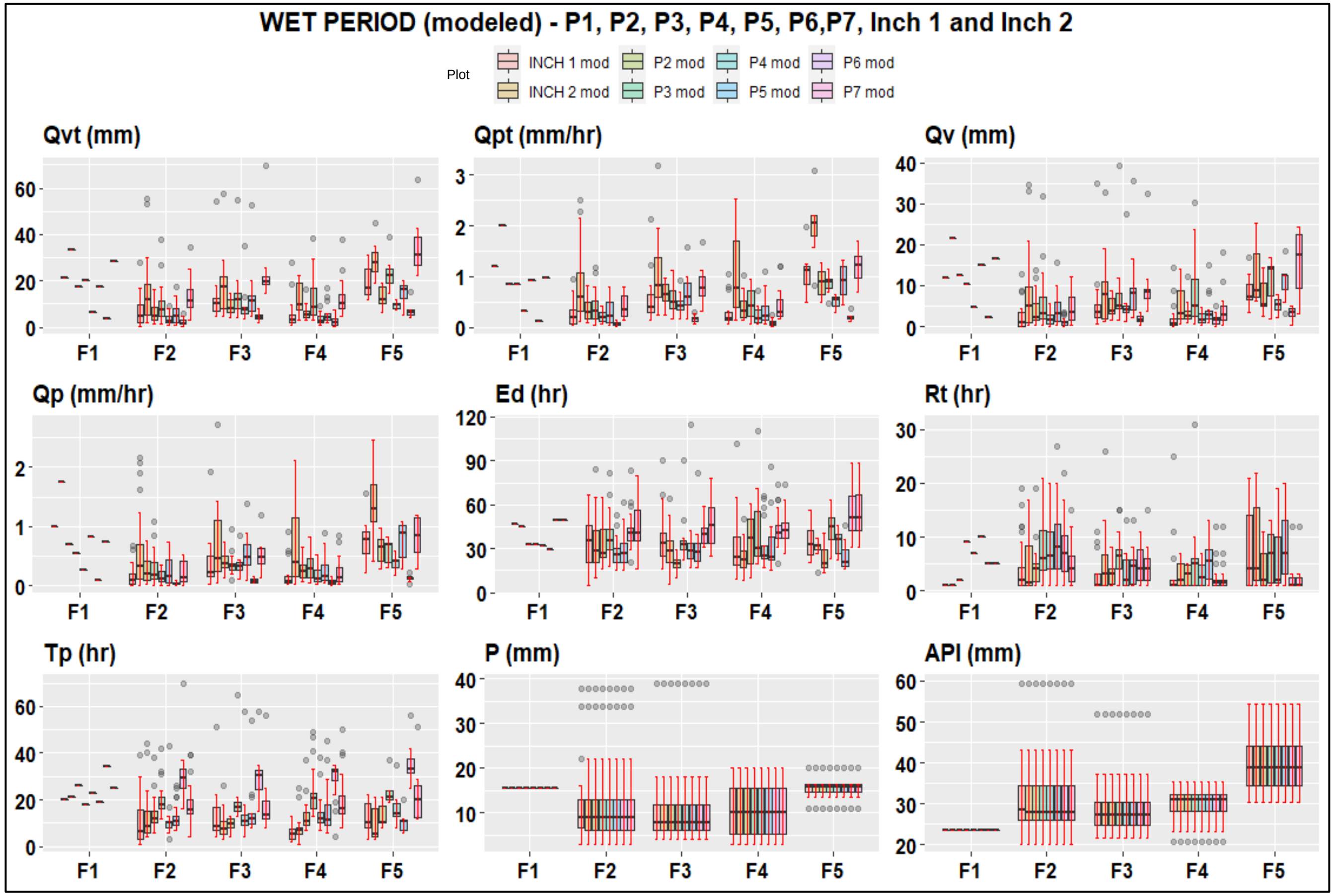


Figure 6.14: Forest development categories (F2, F3, F4 and F5) box plot for variables under the group of events in the case of Inch 1 and Inch 2 sub-catchments and cultivated areas (P2, P3, P4, P5, P6 and P7) for the wet weather conditions

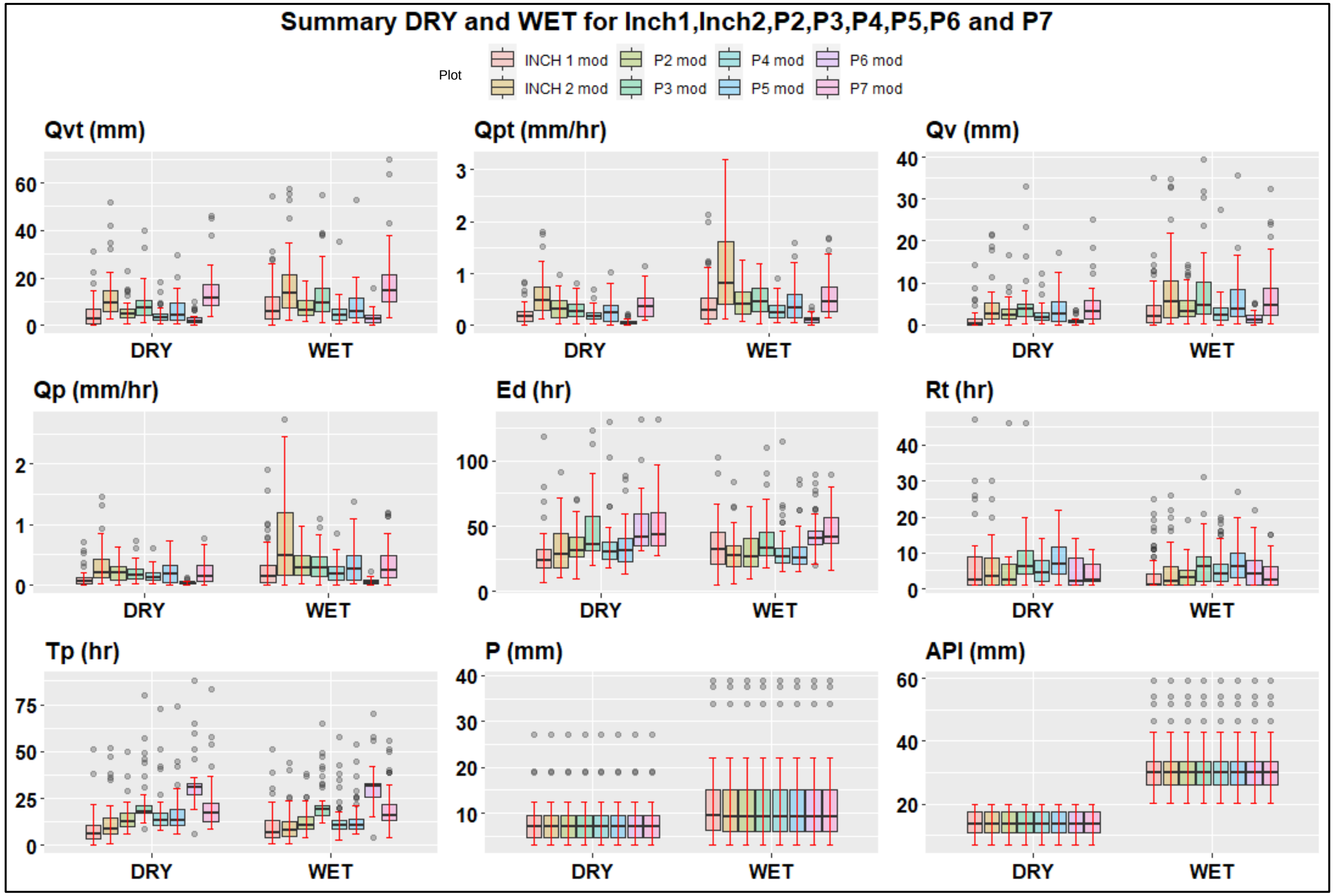


Figure 6.15: Dry and wet weather conditions summary for Inch 1, Inch 2, P2, P3, P4, P5, P6 and P7 under the group of same events.

Dry and wet weather conditions summary for sub-catchment areas and cultivated areas: The section above discusses possible trends likely to be created around cultivated areas. According to analysed data, it is expected that events that occurred during dry will experience the highest Qvt/Qpt/Qv/Qp in the P3 area and events that occurred during wet weather conditions Qvt/Qpt/Qv/Qp in P7. P4 and P6 will likely have the lowest Qvt/Qpt/Qv/Qp for weather conditions. Furthermore, for dry weather conditions, runoff water probably occurred in the case first in P6, then P2, P7, P4, P3 and P5, according to Rt data. On the other hand, it is likely that runoff water first occurred in the case of P2, then P6, P7, P4, P5 and P3 for wet weather conditions. Then, Tp will first happen in the case of P2, then P4, P5, P7, P3 and P6 for dry weather conditions, since it will be the following order: P4, P5, P2, P7, P3 and P6.

Table 6.5: Median values of all variables for dry weather conditions group and each FDC in case Inch1, Inch 2 and P2, P3, P4, P5, P6 and P7

Sub-catchment	Weather conditions /FDS (number of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
Dry weather conditions														
Inch 1	Dry All events(34)	Winter	24	6	0.16	2.6	0.1	2.2	0.1	0.4	3	7	0.5	14
	F1 (7)	Winter	29	7	0.2	5.3	0.1	4	0.09	0.7	5	6	0.4	16
	F2 (6)	Spring	20	9	0.1	1.0	0.04	0.9	0.02	0.2	2	8	0.5	17
	F3 (10)	Winter	33	8	0.3	7.3	0.1	4.9	0.2	2.4	5	8	0.4	12
	F4 (10)	Autumn	15	5	0.1	0.5	0.1	0.4	0.01	0.1	2	6	0.5	13
	F5 (1)	Autumn	29	6	0.2	4.0	0.1	3	0.10	1.3	1	6	0.8	12
Inch 2	Dry All events(34)	Winter	29	9	0.5	9.3	0.2	6.3	0.2	2.6	4	7	0.5	14
	F1 (7)	Winter	36	10	0.5	11.7	0.3	6.9	0.3	4.9	2	6	0.4	16
	F2 (6)	Spring	23	10	0.4	6.3	0.2	4.2	0.2	2.1	4	8	0.5	17
	F3 (10)	Winter	30	7	0.8	14.3	0.3	9.3	0.5	4.9	8	8	0.4	12
	F4 (10)	Autumn	31	9	0.2	7.6	0.1	4.6	0.1	1.8	2	6	0.5	13
	F5 (1)	Autumn	29	9	0.6	10.1	0.2	5.2	0.4	4.8	1	6	0.8	12
P2	Dry All events(34)	Winter	31	12	0.3	4.9	0.1	2.4	0.2	2.4	3	7	0.5	14
	F1 (7)	Winter	28	10	0.4	6.6	0.1	2.6	0.3	3.8	2	6	0.4	16
	F2 (6)	Spring	50	15	0.1	3.5	0.0	1.6	0.1	1.9	1	8	0.5	17
	F3 (10)	Winter	27	12	0.5	6.4	0.1	3.1	0.3	3.4	4	8	0.4	12
	F4 (10)	Autumn	31	16	0.1	2.9	0.0	1.4	0.1	1.3	3	6	0.5	13
	F5 (1)	Autumn	31	11	0.5	7.3	0.1	3.5	0.4	3.7	1	6	0.8	12
P3	Dry All events(34)	Winter	36	18	0.3	7.3	0.1	2.8	0.2	3.7	6	7	0.5	14
	F1 (7)	Winter	36	18	0.3	8.8	0.1	6.3	0.2	4.2	6	6	0.4	16
	F2 (6)	Spring	38	18	0.2	5.0	0.1	2.2	0.1	2.8	11	8	0.5	17
	F3 (10)	Winter	32	17	0.4	10.6	0.1	4.7	0.3	5.6	7	8	0.4	12
	F4 (10)	Autumn	46	21	0.1	3.8	0.0	2.0	0.1	1.9	5.	6	0.5	13
	F5 (1)	Autumn	33	21	0.3	7.0	0.1	2.4	0.2	4.6	1	6	0.8	12
P4	Dry All events(34)	Winter	30	13	0.2	3.2	0.0	1.4	0.1	1.9	5	7	0.5	14
	F1 (7)	Winter	30	11	0.1	2.4	0.0	1.1	0.1	1.4	5	6	0.4	16
	F2 (6)	Spring	32	12	0.1	2.1	0.0	1.0	0.1	1.2	5	8	0.5	17
	F3 (10)	Winter	29	14	0.4	7.3	0.1	2.4	0.2	3.2	5	8	0.4	12
	F4 (10)	Autumn	30	13	0.2	2.5	0.0	1.2	0.1	1.2	4	6	0.5	13
	F5 (1)	Autumn	32	13	0.2	3.9	0.1	1.7	0.2	2.2	1	6	0.8	12

P5	Dry All events(34)	Winter	31	14	0.2	4.0	0.1	1.6	0.2	2.5	7	7	0.5	14
	F1 (7)	Winter	25	12	0.3	6.6	0.1	1.1	0.3	5.6	8	6	0.4	16
	F2 (6)	Spring	28	14	0.1	1.8	0.0	1.1	0.0	0.7	10	8	0.5	17
	F3 (10)	Winter	30	15	0.5	10	0.1	3.5	0.4	5.7	9	8	0.4	12
	F4 (10)	Autumn	32	15	0.1	2.1	0.0	1.2	0.0	0.9	6	6	0.5	13
	F5 (1)	Autumn	31	13	0.4	7.1	0.1	1.8	0.3	5.3	1	6	0.8	12
P6	Dry All events(34)	Winter	42	31	0.1	1.9	0.0	0.9	0.0	0.9	2	7	0.5	14
	F1 (7)	Winter	56	32	0.0	2.0	0.0	1.0	0.0	0.9	1	6	0.4	16
	F2 (6)	Spring	44	30	0.0	1.2	0.0	0.5	0.0	0.6	9	8	0.5	17
	F3 (10)	Winter	42	29	0.1	4.9	0.1	3.2	0.1	1.2	7	8	0.4	12
	F4 (10)	Autumn	37	32	0.1	1.7	0.0	0.7	0.0	0.9	2	6	0.5	13
	F5 (1)	Autumn	37	19	0.1	1.9	0.0	0.8	0.0	1.2	4	6	0.8	12
P7	Dry All events(34)	Winter	44	17	0.4	11.6	0.2	8.4	0.2	3.2	3	7	0.5	14
	F1 (7)	Winter	51	14	0.4	13.5	0.2	9.8	0.2	4.7	3	6	0.4	16
	F2 (6)	Spring	57	18	0.2	8.8	0.1	6.9	0.1	1.8	2	8	0.5	17
	F3 (10)	Winter	45	17	0.6	17.1	0.2	10.5	0.3	6.5	7	8	0.4	12
	F4 (10)	Autumn	37	17	0.2	6.4	0.1	5.3	0.0	0.9	2	6	0.5	13
	F5 (1)	Autumn	37	12	0.5	12.8	0.2	8.4	0.3	4.4	4	6	0.8	12

Table 6.6: Median values of all variables for wet weather conditions group and each FDC in case Inch1, Inch 2 and P2, P3, P4, P5, P6 and P7

Sub-catchment	Weather conditions /FDS (number of	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
Wet weather conditions														
Inch 1	Wet All events(72)	Summer	32	7	0.3	5.7	0.1	4.1	0.1	2.0	1	9	0.6	30
	F1 (1)	Winter	47	20	1.2	21.5	0.2	9.6	1.0	12.0	1	16	0.5	24
	F2 (32)	Summer	35	6	0.2	4.9	0.1	3.3	0.1	1.1	2	9	0.5	29
	F3 (14)	Winter	33	8	0.4	10.0	0.2	6.4	0.2	3.6	1	8	0.6	27
	F4 (18)	Summer	24	5	0.2	3.2	0.1	2.5	0.1	0.6	1	10	0.8	31
	F5 (7)	Autumn	33	10	1.1	16.6	0.3	8.6	0.8	7.2	4	16	0.6	39
Inch 2	Wet All events(72)	Summer	28	8	0.8	13.6	0.3	7.6	0.5	5.6	2	9	0.6	30
	F1 (1)	Winter	45	21	2.0	33.4	0.3	11.9	1.7	21.5	1	16	0.5	24
	F2 (32)	Summer	29	9	0.6	11.8	0.2	7.0	0.3	5.0	1	9	0.5	28
	F3 (14)	Winter	29	8	0.8	17.2	0.3	9.6	0.5	7.7	3	8	0.6	27
	F4 (18)	Summer	22	7	0.8	9.7	0.3	6.1	0.4	3.3	2	10	0.8	31
	F5 (7)	Autumn	32	5	2.0	27.8	0.6	15.6	1.3	8.7	4	16	0.6	39
P2	Wet All events(72)	Summer	27	11	0.4	6.2	0.1	2.6	0.3	3.2	3	9	0.6	30
	F1 (1)	Winter	33	26	0.8	17.1	0.1	4.7	0.7	12.4	2	16	0.5	24
	F2 (32)	Summer	27	12	0.3	4.5	0.1	2.2	0.2	2.2	4	9	0.5	28
	F3 (14)	Winter	20	10	0.6	8.1	0.2	4.1	0.4	3.7	3	8	0.6	27
	F4 (18)	Summer	38	11	0.3	5.0	0.1	2.2	0.2	2.6	3	10	0.8	31
	F5 (7)	Autumn	20	10	0.9	11.8	0.2	5.6	0.6	5.4	2	16	0.6	39
P3	Wet All events(72)	Summer	33	19	0.4	9.5	0.1	3.9	0.3	4.7	6	9	0.6	30
	F1 (1)	Winter	33	18	0.8	20.0	0.3	9.8	0.6	10.2	9	16	0.5	24
	F2 (32)	Summer	35	18	0.3	7.3	0.1	3.2	0.2	3.1	6	9	0.5	28
	F3 (14)	Winter	33	17	0.5	12.1	0.1	5.0	0.3	5.0	6	8	0.6	27
	F4 (18)	Summer	31	21	0.4	8.7	0.1	3.8	0.3	4.9	5	10	0.8	31
	F5 (7)	Autumn	45	21	0.9	22.2	0.2	8.8	0.7	14.1	7	16	0.6	39
P4	Wet All events(72)	Summer	27	11	0.3	4.4	0.1	1.8	0.2	2.2	4	9	0.6	30
	F1 (1)	Winter	32	23	0.3	6.6	0.1	2.1	0.3	4.6	7	16	0.5	24
	F2 (32)	Summer	26	10	0.2	2.7	0.1	1.3	0.1	1.4	6	9	0.5	28
	F3 (14)	Winter	29	11	0.4	7.3	0.1	3.1	0.3	4.2	2	8	0.6	27

	F4 (18)	Summer	25	12	0.2	2.6	0.0	1.3	0.1	1.7	3	10	0.8	31
	F5 (7)	Autumn	36	14	0.5	9.7	0.1	4.0	0.4	5.4	2	16	0.6	39
P5	Wet All events(72)	Summer	26	11	0.3	5.8	0.1	1.9	0.3	3.7	6	9	0.6	30
	F1 (1)	Winter	29	19	0.9	17.6	0.1	2.6	0.8	15.0	10	16	0.5	24
	F2 (32)	Summer	27	11	0.2	4.6	0.1	1.3	0.1	3.0	8	9	0.5	28
	F3 (14)	Winter	28	12	0.6	11.2	0.1	3.1	0.5	8.2	5	8	0.6	27
	F4 (18)	Summer	24	12	0.2	4.3	0.1	1.4	0.2	2.9	5	10	0.8	31
	F5 (7)	Autumn	21	11	0.9	16.4	0.2	3.8	0.9	12.4	7	16	0.6	39
P6	Wet All events(72)	Summer	41	32	0.1	2.9	0.0	1.0	0.1	1.2	3	9	0.6	30
	F1 (1)	Winter	49	34	0.1	3.5	0.03	1.2	0.1	2.2	5	16	0.5	24
	F2 (32)	Summer	41	30	0.1	1.7	0.01	0.6	0.04	0.9	6	9	0.5	28
	F3 (14)	Winter	39	30	0.2	4.3	0.1	2.6	0.1	1.5	4	8	0.6	27
	F4 (18)	Summer	41	32	0.1	2.1	0.01	0.5	0.1	1.5	2	10	0.8	31
	F5 (7)	Autumn	51	33	0.2	6.3	0.1	2.7	0.1	3.3	1	16	0.6	39
P7	Wet All events(72)	Summer	42	16	0.5	14.7	0.2	9.0	0.3	4.8	3	9	0.6	30
	F1 (1)	Winter	49	25	1.0	28.2	0.2	11.7	0.7	16.5	5	16	0.5	24
	F2 (32)	Summer	41	15	0.3	11.5	0.2	7.8	0.1	3.6	4	9	0.5	28
	F3 (14)	Winter	45	13	0.8	19.7	0.3	11.8	0.5	8.4	4	8	0.6	27
	F4 (18)	Summer	42	16	0.3	10.0	0.2	6.8	0.1	2.8	2	10	0.8	31
	F5 (7)	Autumn	51	20	1.2	30.9	0.3	18.5	0.9	17.4	1	16	0.6	39

6.4 Precipitation groups modelled data comparison

For data analysis, precipitation groups are defined (see Section **Error! Reference source not found.**) as events with similar amounts of precipitation. This categorization is important for understanding the field conditions when runoff events form in different monitoring areas. Those groups were developed under both dry and wet weather conditions. This helped in creating hydrological behaviour of runoff over each monitored plot or sub-catchment area, and it desired to consider variables such as Qp, Qv, Qpt, Qvt, Tp, Rt and Ed.

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6.4.1 Dry weather conditions groups (DP) for modelled data

Four groups were included in the dry weather P group analysis for modelled data (see Table 6.7 and Figure 6.16). Critical differences between those groups were:

- The highest Qv values for all monitored areas were observed for the DP4 group. It was possible to observe the increasing trend of Qvt/Qv for Inch1, Inch 2, P3, P4 and P6 from the DP1 to DP4 group (see Table 6.7). On the other hand, a slight decrease of Qvt/Qv occurred in the DP2 group for P2, P5 and P7.
- The Lowest Rt occurred in the case of the DP3 group for both Inch 1 and Inch 2 sub-catchments. DP3 group has the highest median API30. Furthermore, the lowest Rt in the case of cultivated areas occurred for excavation mounding (P6 and P7) for the DP1 group, in the case of hand screefing (P2) for the DP2 group, in the case of P4 and P5 for the DP3 group and the case of P7 for DP4 group
- The lowest Tp occurred in the case of the DP1 group for both sub-catchments. This mainly was the same for cultivated areas

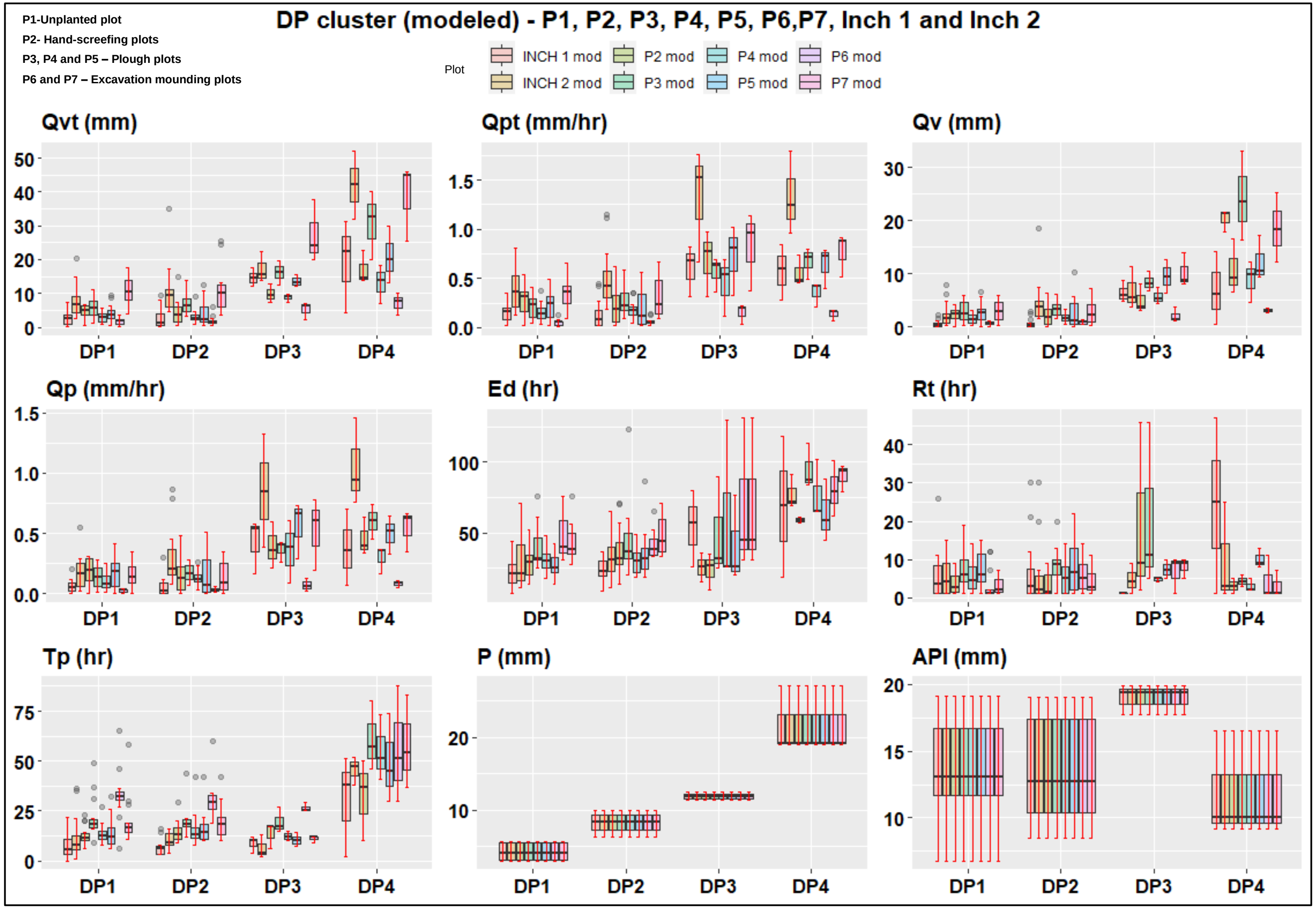

Figure 6.16: Dry weather (DP) conditions group box plot that was developed for Inch 1, Inch2, P2, P3, P4, P5, P6 and P

Table 6.7: Median values of all variables for DP group in case Inch 1, Inch2, P2, P3, P4, P5, P6 and P7 for modelled data

PlotPlot	Weather conditions /FDS	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I	API30 (mm)
DP groups														
Inch 1	DP1 (14)	Winter	21	6	0.2	2.4	0.1	1.9	0.0	0.3	3	4	0.4	13
	DP2 (13)	Summer/Spring	24	6	0.1	1.5	0.1	1.1	0.0	0.3	4	8	0.5	12
	DP3 (4)	Spring	42	11	0.5	13.2	0.1	6.6	0.4	5.3	1	12	0.6	19
	DP4 (3)	Autumn	69	38	0.6	22.5	0.2	16.4	0.4	6.1	25	19	0.3	10
Inch 2	DP1 (14)	Winter	21	8	0.4	6.7	0.2	4.7	0.2	1.7	4	4	0.4	13
	DP2 (13)	Summer/Spring	33	9	0.4	9.2	0.2	4.8	0.2	2.7	3	8	0.5	12
	DP3 (4)	Spring	25	9	1.1	14.7	0.4	10.1	0.6	5.1	2	12	0.6	19
	DP4 (3)	Autumn	72	47	1.2	42.0	0.3	20.4	0.9	21.3	3	19	0.3	10
P2	DP1 (14)	Winter	29	11	0.3	4.9	0.1	2.2	0.2	2.4	3	4	0.4	13
	DP2 (13)	Summer/Spring	31	13	0.2	3.7	0.0	1.6	0.1	1.8	1	8	0.5	12
	DP3 (4)	Spring	31	15	0.5	8.4	0.1	4.2	0.3	3.5	6	12	0.6	19
	DP4 (3)	Autumn	59	37	0.5	14.4	0.1	6.1	0.4	9.2	3	19	0.3	10
P3	DP1 (14)	Winter	31	18	0.2	5.7	0.1	2.3	0.1	2.4	6	4	0.4	13
	DP2 (13)	Summer/Spring	36	18	0.2	5.6	0.1	2.5	0.2	3.3	8	8	0.5	12
	DP3 (4)	Spring	36	16	0.5	14.4	0.2	6.9	0.3	7.4	10	12	0.6	19
	DP4 (3)	Autumn	87	57	0.7	32.5	0.1	7.0	0.6	23.5	4	19	0.3	10
P4	DP1 (14)	Winter	30	12	0.1	2.8	0.0	1.2	0.1	1.3	4	4	0.4	13
	DP2 (13)	Summer/Spring	28	13	0.2	2.5	0.0	1.3	0.1	1.4	6	8	0.5	12
	DP3 (4)	Spring	34	12	0.3	8.2	0.1	2.7	0.2	4.7	5	12	0.6	19
	DP4 (3)	Autumn	65	51	0.4	13.9	0.1	4.1	0.4	9.7	2	19	0.3	10
P5	DP1 (14)	Winter	26	12	0.2	3.6	0.1	1.2	0.2	2.5	5	4	0.4	13
	DP2 (13)	Summer/Spring	31	13	0.2	2.8	0.1	1.4	0.1	1.2	6	8	0.5	12
	DP3 (4)	Spring	34	12	0.6	12.6	0.1	3.5	0.5	7.9	5	12	0.6	19
	DP4 (3)	Autumn	59	45	0.7	20.0	0.1	9.7	0.5	10.4	9	19	0.3	10
P6	DP1 (14)	Winter	40	32	0.1	1.8	0.0	0.9	0.0	0.8	2	4	0.4	13
	DP2 (13)	Summer/Spring	37	29	0.1	1.6	0.0	0.7	0.0	0.8	6	8	0.5	12
	DP3 (4)	Spring	45	27	0.1	4.3	0.0	2.3	0.0	1.2	7	12	0.6	19

	DP4 (3)	Autumn	79	51	0.2	7.6	0.1	4.6	0.1	3.0	8	19	0.3	10
P7	DP1 (14)	Winter	38	16	0.4	10.5	0.2	7.4	0.1	2.8	2	4	0.4	13
	DP2 (13)	Summer/Spring	42	18	0.3	10.1	0.1	7.7	0.1	2.3	3	8	0.5	12
	DP3 (4)	Spring	58	12	0.7	22.0	0.3	13.6	0.4	8.4	7	12	0.6	19
	DP4 (3)	Autumn	94	54	0.9	44.9	0.2	19.7	0.6	18.3	1	19	0.3	10

Summary for DP group over sub-catchments and cultivated areas:
More runoff water will likely be delivered in the case of the DP4 group for cultivated areas and both sub-catchments in the case of modelled data. Furthermore, the response around those areas was different, and sub-catchment areas showed lower responses in the DP3 group that coincided with the highest median API30. However, cultivated areas have a lower response in the case of P2 and P7 for the DP2 and DP4 groups.

6.4.2 Wet weather conditions group (WP) for modelled data

Four groups were included in the dry weather P group analysis for Inch 1 and Inch 2 sub-catchments (see Table 6.8 and Figure 6.17).
Critical differences between those groups were:

- The highest Qv values for the Inch 2 sub-catchment were observed WP4 group for bot sub-catchments since the lowest occurred in the case of WP1.
- The lowest Rt occurred in the case of Inch 1 for all groups (1-2 hours) since Inch2 had a higher Rt (2-4 hours)
- Higher values of Qvt for both Inch1 and Inch 2 are likely connected to the higher values of P or API30 (see Table 6.8 and Figure 6.17)
- The highest Qv/Qvt occurred in group WP4 (P>15 mm), and it has a low Rt for Inch 1 and higher Rt for Inch2 sub-catchment
- Tp was lower in the case of WP1 and WP4 catchment since Inch 2 had lower values than Inch

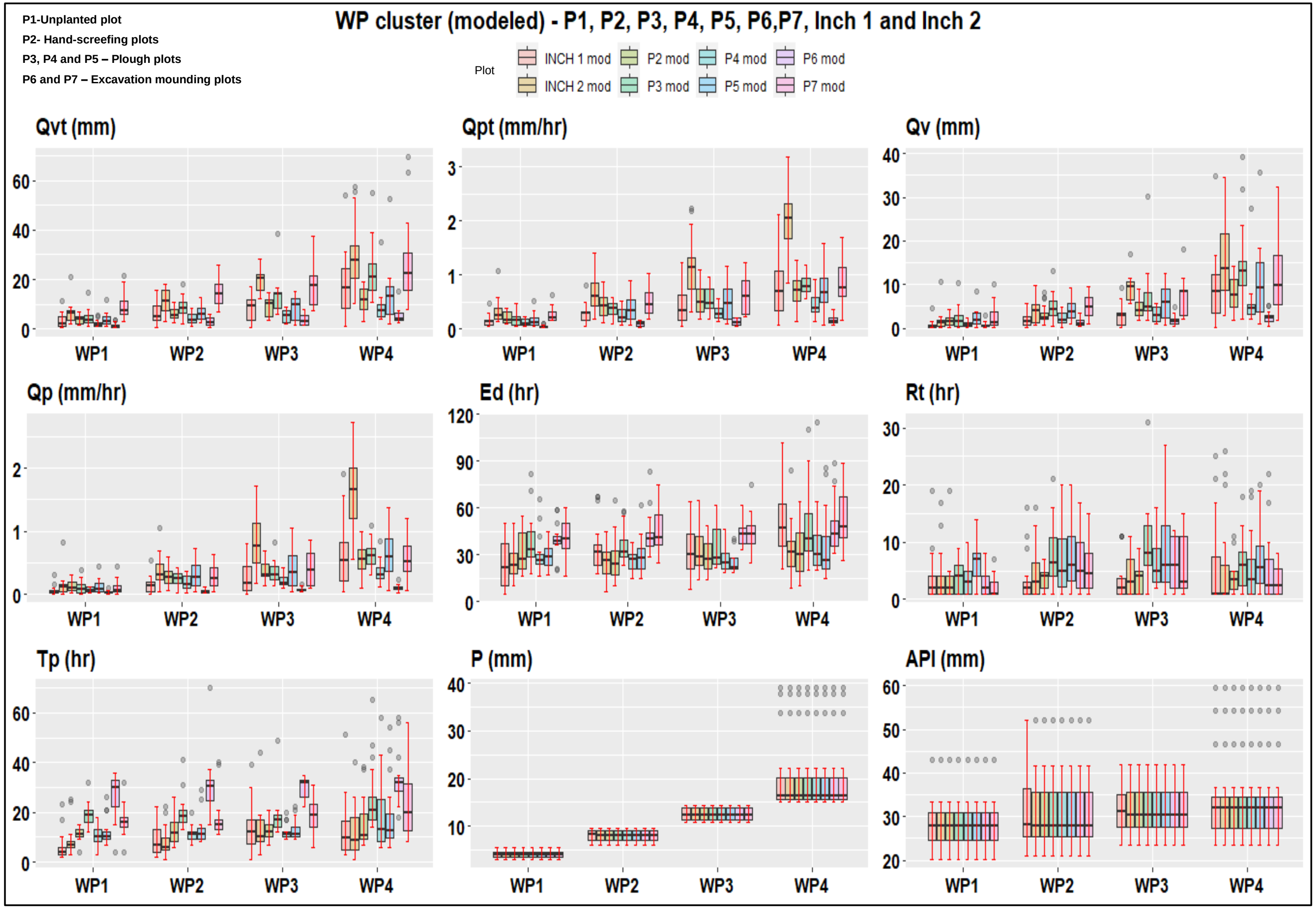

Figure 6.17: Wet weather (WP) conditions group box plot that was developed for Inch 1, Inch2, P2, P3, P4, P5, P6 and P7

Table 6.8: Median values of all variables for WP group in case Inch 1, Inch2, P2, P3, P4, P5, P6 and P7 for modelled data

PlotPlot	Weather conditions /FDS (number	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I	API30 (mm)
WP groups														
Inch 1	WP1 (17)	Summer	22	4	0.1	2.0	0.1	1.7	0.0	0.3	2	4	0.5	28
	WP2 (18)	Summer	29	7	0.2	4.8	0.1	3.2	0.1	1.3	2	8	0.5	28
	WP3 (14)	Autumn	30	12	0.4	10.0	0.2	6.6	0.2	2.8	2	12	0.6	31
	WP4 (20)	Autumn	48	9	0.7	16.7	0.1	7.9	0.5	8.3	1	16	0.6	32
Inch 2	WP1 (17)	Summer	23	7	0.3	6.3	0.2	4.4	0.1	1.2	2	4	0.5	28
	WP2 (18)	Summer	26	6	0.6	11.0	0.3	6.9	0.3	4.0	3	8	0.5	28
	WP3 (14)	Autumn	29	10	1.1	19.7	0.3	10.7	0.7	9.2	3	12	0.6	31
	WP4 (20)	Autumn	32	9	2.0	27.6	0.4	11.6	1.7	13.6	1	16	0.6	32
P2	WP1 (17)	Summer	27	11	0.2	3.8	0.1	2.2	0.1	1.6	2	4	0.5	28
	WP2 (18)	Summer	24	11	0.4	5.0	0.1	2.2	0.2	2.5	4	8	0.5	28
	WP3 (14)	Autumn	28	12	0.5	10.4	0.1	2.6	0.4	4.5	3	12	0.6	31
	WP4 (20)	Autumn	31	11	0.7	11.7	0.1	3.7	0.6	7.5	3	16	0.6	32
P3	WP1 (17)	Summer	33	19	0.2	3.4	0.1	2.3	0.1	1.4	4	4	0.5	28
	WP2 (18)	Summer	32	19	0.4	8.0	0.1	3.8	0.3	4.3	7	8	0.5	28
	WP3 (14)	Autumn	30	17	0.5	13.4	0.1	5.3	0.3	5.3	8	12	0.6	31
	WP4 (20)	Autumn	40	21	0.8	20.8	0.2	6.9	0.6	13.0	6	16	0.6	32
P4	WP1 (17)	Summer	26	10	0.1	1.5	0.0	0.9	0.1	0.8	3	4	0.5	28
	WP2 (18)	Summer	27	11	0.2	3.4	0.1	1.6	0.1	1.8	6	8	0.5	28
	WP3 (14)	Autumn	26	11	0.3	5.6	0.1	1.6	0.2	3.1	5	12	0.6	31
	WP4 (20)	Autumn	30	13	0.4	7.5	0.1	2.2	0.3	4.5	3	16	0.6	32
P5	WP1 (17)	Summer	29	10	0.1	2.8	0.0	0.9	0.1	1.9	7	4	0.5	28
	WP2 (18)	Summer	28	11	0.3	5.9	0.1	1.9	0.3	3.8	6	8	0.5	28
	WP3 (14)	Autumn	24	11	0.5	10.4	0.1	2.1	0.4	7.1	6	12	0.6	31
	WP4 (20)	Autumn	27	12	0.7	13.1	0.1	2.3	0.6	9.1	6	16	0.6	32
P6	WP1 (17)	Summer	39	30	0.03	0.7	0.01	0.3	0.02	0.4	2	4	0.5	28
	WP2 (18)	Summer	41	31	0.1	2.4	0.02	1.1	0.04	1.0	4	8	0.5	28
	WP3 (14)	Autumn	43	32	0.1	2.9	0.05	2.0	0.1	1.5	6	12	0.6	31

	WP4 (20)	Autumn	43	32	0.1	4.0	0.1	2.4	0.1	2.3	2	16	0.6	32
P7	WP1 (17)	Summer	40	16	0.2	7.5	0.2	6.2	0.1	1.2	1	4	0.5	28
	WP2 (18)	Summer	41	15	0.5	12.8	0.2	8.5	0.2	4.3	5	8	0.5	28
	WP3 (14)	Autumn	41	17	0.6	17.3	0.3	9.8	0.4	8.0	3	12	0.6	31
	WP4 (20)	Autumn	48	20	0.8	22.4	0.2	12.5	0.5	9.7	3	16	0.6	32

Summary for WP group over sub-catchments and cultivated areas:
More runoff water will likely be delivered in the case of the WP4 group for cultivated areas and both sub-catchments in the case of modelled data compared to other groups.

6.5 Impact on Qp and Qv from a different perspectives

6.5.1 Tree coverage impact

In Table 6.9, it was calculated tree coverage per each monitored plot (P2, P3, P4, P5, P6, P7) according to the Till Hill forestry survey and according to HWU survey in cultivated areas, where the average value between those two surveys was used as relevant for further analyses.

Table 6.9: Number of trees per cultivated each monitored plot

Number of trees per each monitored plot	P2	P3	P4	P5	P6	P7
I) Till Hill Forestry database	694	943	1039	2821	413	434
II) HWU survey database	722	950	1047	2842	416	436
Average (I+II)	708	946	1043	2832	415	435

According to Table 6.9 number of trees was compared to variables for each cultivated plot. Plough plots were combined into one plot (median values for variable expressions were used). However, the same rule was applied to excavation mounding plots.
The area of the sub-catchment covered by trees was compared to all variables for the dry and wet periods with a distinction between a growing and non-growing category. A definite increasing trend (with R2=1) was formed in the case of Qv/Qvt/Qp/Qvp for both sub-catchments. Furthermore, Rt experienced decreasing correlation with the higher number of trees for the growing phase since the non-growing phase had the same Rt in both sub-catchments. All variable cross-correlation outcomes were presented in Table

6.10 since the graphical presentation is outlined in Appendix 14 (see Figure A.14.1 and Figure A.14.2) and forming a relationship with tree coverage presented in Appendix 14 (see Table A.14.1 and Table A.14.2). There was a solid positive relationship between Qpt/Qvt/Qp/Qv and tree coverage (R2 between 0.53 to 1) (see Table 6.6). A clear trend (Table 6.6) indicates that tree coverage impacts the decrease in Qvt (see graphs outlined in Appendix 14) than Qpt. An important relationship was formed between tree coverage and Qp/Qv, where it is possible to understand the following: However, the summary of those data emphasised that Rt was higher in areas with higher tree coverage since Tp and Ed followed opposite trends.

Qpt/Qp created the highest value in the case of the P2 area for dry (non-growing) and Wet (non-growing and growing) weather conditions. This aims to ascertain the behaviour of cultivated areas if we combine 2 of them. For example, suppose plough cultivation combined with hand-screefing. In that case, Qp/Qpt will likely have decreasing trend for dry (non-growing) and wet (non-growing and growing) weather conditions since, in the case of excavation mounding and plough cultivation, this trend will be the opposite.

Qvt trends increased in wet (non-growing) weather conditions since all others showed decreasing trends. Furthermore, Qv will have increasing trends in the case of wet (growing) and dry (non-growing) weather conditions. On the other hand, Qv, in the case of dry (growing) and wet (non-growing), has similar trends. For example, the highest value occurs in the case of the hand screefing area since plough and excavation mounding had identical values in the dry/wet period. All variable's cross-correlation outcomes were presented in Table 6.10.

Table 6.10:Pearson correlation, R2, P-value for the relationship between different variables (Ed, Tp, Qpt, Qvt, Qbp, Qvb, Qp, Qv, Rt) and the number of trees in cultivated areas.

Weather conditions	Statistical Analyses	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)
DRY Period (non-growing)	Pearson	-0.77	-0.72	0.38	-0.57	-0.94	-0.94	0.52	0.99	0.78
	R2	0.60	0.52	1*	1*	0.89	-0.88	1*	0.99	0.60
	P-value	0.009	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
DRY Period (growing)	Pearson	-0.98	-0.69	0.95	-0.99	-0.90	-0.91	0.93	0.04	0.64
	R2	0.96	0.51	0.91	0.98	0.82	0.84	0.87	1*	0.41
	P-value	0.009	0.008	0.008	0.0078	0.008	0.008	0.008	0.008	0.008
WET Period (non-growing)	Pearson	-0.62	-0.81	0.80	0.94	-0.64	-0.99	0.28	-0.05	0.37
	R2	0.38	0.65	0.63	0.89	0.51	0.99	1*	1*	0.14
	P-value	0.009	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008
WET Period (growing)	Pearson	-0.99	-0.88	0.32	-1	-0.93	-0.95	0.53	0.97	0.93
	R2	0.98	0.77	1*	1*	0.87	0.89	1*	0.95	0.87

	P-value	0.009	0.008	0.008	0.008	0.008	0.008	0.008	0.008	0.008

*Those correlations didn’t follow linear regression; polynomial regression was more beneficial for those data.

6.5.2 Reduction of Qp/Qv between forest categories

Comparing variables Qp and Qv reduction between forest development categories for different cultivated and sub-catchment areas showed a clear distinction between growing (F2 and F4) and non-growing conditions (F1, F3 and F5). The comparison was made in the following order: the F2 category was compared to the F1 category, the F3 category was compared to the F2 category, the F4 category was compared to the F3 category, and the F5 was compared to the F4 category (see Table 6.11).

Table 6.11: Reduction/increase of Qp and Qv between different forest categories for sub-catchments (Inch 1 and Inch 2) and cultivated areas (P2, P3, P4, P5, P6 and P7). Red numbers highlighted the highest values for each compared category.

Conditions	**Dry weather conditions**								**Median increase/reduction (%)**	
Category	F2 (compared to F1)		F3 (compared to F2)		F4 (compared to F3)		F5 (compared to F4)			
Variables change (%)	Qp	Qv	Qp	Qv	Qp	Qv	Qp	Qv	Qp	Qv
Inch1	-82	-74	+90	+93	-94	-97	+90	+94	+4	+10
Inch2	-32	-56	+61	+58	-81	-63	+75	+63	+15	+1
P2	-63	-48	+68	+43	-76	-61	+79	+65	+3	-3
P3	-35	-33	+50	+50	-69	-65	+64	+58	+8	9
P4	+12	-13	+59	+61	-62	-64	+47	+46	+30	+17
P5	-87	-88	+91	+88	-90	-84	+88	+83	+1	-1
P6	-2	-26	+50	+47	-41	-29	+32	+28	+15	+1
P7	-68	-61	+80	+72	-89	-85	+87	+78	+6	+6
Conditions	Wet weather conditions								Median increase/reduction (%)	
Category	F2 (compared to F1)		F3 (compared to F2)		F4 (compared to F3)		F5 (compared to F4)			
Variables change (%)	Qp	Qv	Qp	Qv	Qp	Qv	Qp	Qv	Qp	Qv
Inch1	-91	-61	+58	+69	-72	-83	+92	+91	-7	+4
Inch2	-82	-77	+31	+35	-14	-57	+69	+62	+9	-11
P2	-72	-83	+46	+41	-33	-28	+62	+52	+7	+7
P3	-67	-70	+45	+39	-12	-2	+58	+65	+17	+19
P4	-55	-69	+65	+66	-63	-59	+72	+68	+5	+4
P5	-82	-80	+69	+63	-65	-65	+81	+77	+2	-1
P6	-58	-62	+55	+44	-29	-3	+60	+55	+13	+21
P7	-81	-78	+70	+57	-72	-66	-84	+84	-1	-5

This comparison highlighted the following:

- There was a specific increase in Qp and Qv for the F1 and F3 categories since F2 and F4 experienced a decrease.
- The most significant increases/decreases during the dry period were noticed in the P5 plough plot and P7 excavation mounding plot,
- The most significant increase/decrease during the wet period was very variable, showing the most remarkable change in the case of the P7 excavation mounding plot for the F4 and F5 categories since the F2 and F3 types showed the most significant changes for Qp in the case of P5 plough plot and the Highest change in Qv for P2 hand-screefing plot and P4 plough plot.

According to the number of trees, monitored change slope, soil type and observed plot slope of cultivated area, each cultivated area will likely develop different hydrological reactions that can be summaries in the following (see

- Figure 6.18) :
- Inch 1 and Inch 2 changes experienced a decrease in both Qp and Qv. Moreover, Inch 1 experienced more significant changes in the case of, since Inch 2 experienced more substantial changes in the case of Qv. According to the number of trees, more significant changes between dry and wet periods relate to the Inch 2 area with fewer trees implemented.
- Plough cultivation monitored areas had similar channel slopes and catchment areas slopes. Therefore, it is likely that area of the P5 plough plot with the highest number of trees (see Table 6.9) will have identical changes between dry and wet weather conditions. This change is very stable and in the range of 1%. Moreover, the area of P4 will experience quite a significant decrease in Qp and Qv between dry and wet periods since P3 plough plot will experience increases between dry and wet periods. This change can lead to underlying soil properties that are different in the case of P3 plough plot that in the case of P5 plough plot and P4 plough plot. Excavation mounding (P6 and P7) cultivated areas showed different hydrological signatures. For example, P6 experienced an increase in Qv and a decrease in Qp, while P7 experienced a reduction in Qp and Qv. In addition, the hand screefing (P2) cultivated area experienced an increase in Qp and Qv compared with P3 plough plot and P7 excavation mounding plot; this increase was lower (see Figure 6.18).

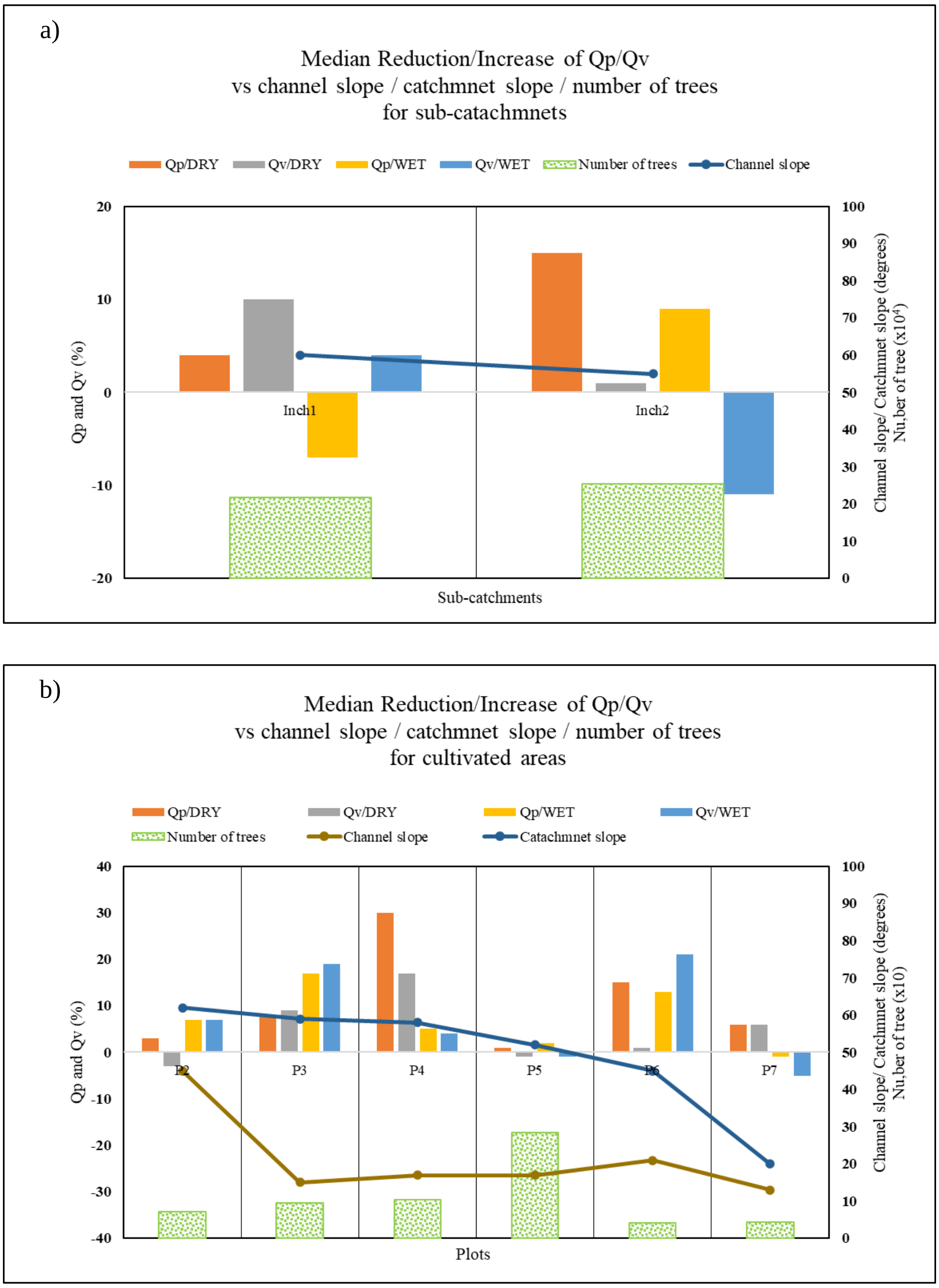

Figure 6.18: Median reduction/increase of Qv/Qp vs channel slope/catchment slope /number of trees in monitored area in case of A) sub-catchment areas (Inch 1 and Inch 2) and B) cultivated areas (P2, P3, P4, P5, P6, P7)

6.6 Chapter Summary

The chapter summarises findings for RQ3. The modelling period identified 106 events for cultivated and sub-catchment areas. The 34 events belonged to dry weather conditions, while 72 events belonged to wet weather conditions. The results are summaries as follows:

- The GR4H model has been developed and validated for sub-catchment and cultivated areas. This modelling data has been used for further analyses.
- According to the modelling result, it has been confirmed that the Inch 1 sub-coachmen will have less Qp/Qv than the Inch 2 sub-catchment. This finding complements findings from experimental results.
- According to analysed data from modelling results, it is expected that events that occurred during dry will experience the highest Qvt/Qv/Qp in the P3 area and events that occurred during wet weather conditions Qvt/Qv/Qp in P7. P4 and P6 will likely have the lowest amount of Qvt/Qv/Qp for any weather conditions. Furthermore, for dry weather conditions, runoff water probably occurred in the case first in P6, then P2, P7, P4, P3 and P5, according to Rt data. On the other hand, it is likely that runoff water first occurred in the case of P2, then P6, P7, P4, P5 and P3 for wet weather conditions. Then, Tp will first happen in the case of P2, then P4, P5, P7, P3 and P6 for dry weather conditions, since it will be the following order: P4, P5, P2, P7, P3 and P6. In addition, more runoffs will occur in the case of the median API30>10mm and P>8mm for dry weather conditions since events with P>12mm will deliver more runoff for wet weather conditions for the non-growing seasons.
- More runoff water will likely be delivered in the case of the DP4 group for cultivated areas and both sub-catchments in the case of modelled data. Furthermore, the response around those areas was different, and sub-catchment areas showed lower responses in the DP3 group that coincided with the highest median API30. However, cultivated areas have a lower response in the case of P2 and P7 for the DP2 and DP4 groups.
- A decreasing relationship between Tp/Ed/Qpb/Qbv and tree coverage for cultivated areas has been discovered. The same relationship applies to Qvt in the case of the growing season.

Higher tree coverage on the sub-catchment level is associated with a higher number of Rt. This is the case for cultivated areas with dry weather conditions and wet weather conditions (growing season).

Chapter 7 Discussion

7.1 Chapter introduction

This PhD study aimed to map, analyse, quantify and understand how large-scale woodland planting affect dynamics in water storage movement/sediment supply and the interrelationships of these processes at the catchment level and cultivation practices level .

Also, sub-catchment areas have been looked at through the lens of hydrology. A set of variables (see Section 3.5.1) were assessed from field measurements (this refers to RQ1 and RQ2) to understand how different cultivation create hydrological signatures (runoff and sediment delivery). Results from field experiments monitoring runoff (RQ1) and sediment delivery (RQ2) have been presented in (Chapter 5) and discussed in this chapter (Chapter 7). Finally, Chapter 5 confirmed the importance of dry and wet weather conditions for forest development categories and related to vegetation development categories (those changes are visible in Google Earth imagery). Chapters 5 and 6 combined sub-catchments and cultivation areas and demonstrated the critical importance of growing and non-growing seasons from different perspectives (dry and wet weather conditions, P group, forest development categories).

Different cultivation practices were considered at the sub-catchment scale to estimate the more significant spatial scale implication of other cultivated areas on hydrology (RQ3) and presented in Chapter 6. GR4H model was utilized to evaluate the impact of different cultivated areas on runoff at the sub-catchment scale. This chapter discusses these results in more detail (Chapter 7). Building on the understanding of forest hydrology from a cultivation perspective, Chapter 5 and Chapter 6 critically examined the impact of each cultivation in the case of the Inch 1 sub-catchment. According to this understanding, Inch 2 hydrology behaviour had complemented cultivations hydrology findings.

7.2 Event conditions under different forest development stages

The RQ1 analyzed detailed runoff water occurrence in the cultivated areas, unplanted plots, and sub-catchment areas, therefore engaging the ability to change over time. This includes events analysis during different forest development stages (see Section 3.5.7) when runoff volume/runoff peak occurred in monitored cultivated and sub-catchment areas. Furthermore, all other variables (see Chapter 6) were analyzed in the case of experimental and modelled data. However, those analyses are in accordance with the research gap that has been established in Section 2.9. Key literature suggests that empirical studies area is lacking on catchment and sub-catchment levels [23]. Lastly, micro-level studies area very rare, mainly refereeing to modelling [130], [131]. Determining conditions when water enters cultivated plots contributes to defined gaps. Establishing which event conditions and cultivated techniques enhance or inhibit the runoff volume/peak will inform future cultivation placement, design, planning, and maximize benefits of its. Forest and vegetation development categories can be better understood under each cultivation and each sub-catchment, which was a unique case study by itself.

A vital research discovery related to FDC is explained in Section 6.5, looking into increasing and decreasing Qp and Qv in percentage. For the sub-catchment level, it was discovered decreasing in Qp and Qv comparing dry and wet weather conditions of different FDCs. Furthermore, in the case of Inch1, more significant changes occurred in the case of Qp and in the case of Inch 2, more significant changes occurred in the case of Qv. According to the literature review for Section 2.6.1, key references mainly refer to changes of Qp for woodland areas, so higher decrees of Qp in case of Inch 1 are in line with those changes. Also, changes in Qv in the case of Inch 2 might be connected to water yield development that is in the beginning stage and still can be connected to the number of trees in sub-catchment areas [50].

Furthermore, in the case of Cultivation plots, those changes are likely to be connected to soil properties infiltration in the case of plough cultivation, where the P5 plot has very stable changes and the P4 plough plot experiences decreasing Qp and Qv [173]. On the other hand, the P3 plough plot based on peat has experienced an increase in both variables. Another factor that can be considered influential in the slope of the catchment areas was the highest in the case of the P3 plough plot (Table 3.5) [174]. Furthermore, P6 and P7 excavation mounding plot experience different behaviour of decreasing Qp for both but increasing Qv just for P6 excavation mounding. Since P6 and P7 excavation mounding plots are based on the same soil type and contain a similar area of research, opposite changes of Qv be reeled to the fact that the P6 excavation mounding plot has a higher slope of the catchment area and a higher slope of the channel than the P7 excavation mounding plot (Table 3.5).

LRM helped in understanding Qp/Qv in relationship with P events. Statistical Mann-Whitney testing identified significance in data sets that have been used further. However, the more negligible significance may be due to a low sample number (e.g., P1 unplanted plot). Thus, differences in runoff occurrence during dry/wet weather conditions could explain why runoff entered cultivated areas under certain conditions, particularly for the young forest.

Conversely, the distribution of values for dry/wet conditions was different, and these results suggested a distinction between events that occurred during dry and wet weather conditions related. Those conditions were discussed in other sections.

Sub-catchment areas perspective

Inch 1 sub-catchment experienced a lower amount of Qp and Qv in comparison with Inch 2 sub-catchment area for any of FCD (see Section 0). If we look through the perspective of different FDC, it was evident that both sub-catchments experienced a higher amount of runoff water for FDC category in the first year of monitoring. This was the case in experimental and modelling data (see Section). A similar case study was discussed in Chapter 2, which applies to the Colburn catchment [105]. Furthermore, this case study experienced increased runoff water after cultivations were implemented.

Also, exciting findings from modelling data showed that less runoff water occurred in the F2 and F4 categories connected to the vegetation growing season. On the other hand, the Inch 1 sub-catchment has 25% fewer grassland areas than the Inch 2 sub-catchment (see Section 3.2.1), and according to Buechel, afforestation influences the decrease of median and low flows by its increase [175]. This research study has been applied to United Kingdom catchment areas, including Scottish catchments as well. Furthermore, grassland areas in the Inch 2 sub-catchment are predominantly based on peat soil, since in the case of the Inch 1 sub-catchment, grassland areas are based on peaty podzol. This is an important fact in we look through the lenses of infiltration rate, where peat soil has very low infiltration.

Unplanted plots and cultivation plots

According to experimental data, FDC analyses made differences between cultivation practices. From the perspective of dry weather conditions, experimental results showed that F2 and F4 categories experienced lower runoff than F1 and F3 categories. This finding applies to the P2 hand-screefing plot, P3 plough plot, P4 plough plot and P5 plough plot where experimental data has been available for analysis. Also, analysis that has been done in case of wet weather conditions showed that decreasing runoff water trend from F2 to F5 category occurred in the case of the P4 plough pot and P5 plough plot since the P3 plough plot and P2 hand-screefing plot experienced the opposite. On the other hand, categories that included P1 unplanted plot showed that this plot has higher runoff water than any other monitored plot. If we make a percentage comparison between

According to modelling data, FDC analyses followed the trend of lower runoff for F2 and F4 for all monitored plots and the same phenomena occurred in wet weather conditions.

7.3 Dry and wet weather conditions for runoff events

Field observations that have been recorded to address RQ1 will follow the discussion of this Section. An assessment of the trends indicated circumstances when runoff flow could enter the monitored area. The LRM model (see Section 5.3.1) assessed different cultivated and sub-catchment areas performances. It was evident that the highest runoff values refer to the P1 unplanted plot, P3 plough plot, P7 excavation mounding plot and Inch 2 sub-catchment during dry weather conditions and P1 unplanted plot, P3 plough plot, P7 excavation mounding plot, respectively, Inch 1 sub-catchment and Inch 2 sub-catchment during wet weather conditions (see Section 5.3.1). However, higher values have been confirmed through modelling data (see Section 6.3).

Experimental analyses confirmed that response time was lowest in the case of the P1 unplanted plot (see Section 5.3.1). Furthermore, it was evident that the excavation mounding (P6 and P7 plots) plot has the highest response time in dry and wet weather conditions.

7.3.1 Dry and wet weather conditions

Antecedent conditions influence [176], generating more or less runoff. Developed significances between variables suggest that P correlated very good with all other variables at the sub-catchment level—Pearson correlation, R2, and P-values are high for all variables except Rt. Rt time-correlated was better with API30 values. Furthermore, event-based analyses identified site-specific thresholds for sub-catchments, cultivated areas, and unplanted plots using calculations from Chapters 5 and 6. Those thresholds are based on values of API30 and P and have been defined in Section 0 and Section 6.3.1. and evaluated in Table 7.1. Modelling results suggested a lower threshold for rainfall. This might be related higher amount of runoff events included in developing those thresholds.

Table 7.1: Identified trend for runoff in the sub-catchment areas, cultivated plots and unplanted plot. Values are obtained in the Section 0 and Section 6.3.1.

Data	Plot/ Sub-catchments	Identified trend	Comments
Experimental data	Inch 1/ Inch 2	API >=32 mm and P >= 10 mm for wet weather conations	Inch 1 and Inch 2
		API >15 mm and P >= 10 mm for dry weather conditions	
	Cultivated areas	API>32mm and P>12 mm For wet weather conditions	P2, P3,P4 and P5
		API> 10 mm and P>10 mm For dry weather conditions	All cultivation plots
Modelled data	Inch 1/ Inch 2 and cultivation plots	P > 12 mm for wet weather conations	All cultivation plots and sub-catchment areas
		API> 10 mm and P>8 mm For dry weather conditions	

7.3.2 Runoff Qp and Qv occurrence in monitoring areas and their characteristics

Each runoff event had specific conditions resulting from monitoring location, event conditions and seasonal properties. However, the most significant event's contributions occurred during a high P amount, which is evident for experimental data (Section 0) and modelling (Section 6.3.1.) results. Furthermore, as P event-based values influence all variables, this was proven through statistical significance (see Appendixes 3).

However, forest development category F1 (belonging to the establishment stage of forest development) in winter coincidence with one high rainfall event (>15 mm). Furthermore, the F3 category coincided with four high precipitations precipitation events and delivered less runoff water. These findings suggest that forest development (that has bare soil at the beginning of the development) and wetter soil conditions increase runoff water delivery [74]. Forest development categories F2 and F4 experienced high rainfall events and indicated that later stages of forest development deliver less runoff water in all areas under weather conditions.

Evidently, there was a simultaneous coincidence in different cultivated areas and event conditions, resulting in greater runoff volume study. However, the study [177] emphasized the role of seasonality in forested development and runoff occurrences during dry and wet weather conditions. Furthermore, since these studies treated broader catchment properties, they could not elaborate on detailed growing and non-growing season categories.

It was evident that the non-growing and growing seasons under the same weather conditions will result in different magnitudes of Qp/Qv in monitoring areas. The complex interactions between event conditions that account for weather conditions, amount of precipitation and precipitation intensity can result in higher runoff in some cases due to its unique conditions. For example, the dominant summer season was likely to have a lower runoff in monitoring areas when highly developed vegetation. On the other hand, high rainfall events still influence monitored areas, even though the grassland areas were developed. In this case, clearly distinguishing between each cultivation technique was possible. Observation of this study illustrated the following in the case of Qp/Qv from micro-location, channel/catchment slope, and soil type for cultivations:

Plough cultivation

The P3 plough cultivation has been located predominantly on peaty gleys soils (73% of the total area) and experienced more runoff volume of water than P4 plough monitoring plots in brown soil areas. Also, those two plots are in the reasonably same area regarding elevation (320 to 420 m). Furthermore, the slope of the channel and catchment area were very similar (see Table 3.3) between those two monitoring plots, but the P3 plough plot has the highest slope of the channel. However, according to a recent study by Jourgholami [174] where different plots across different slope gradient (from 5% to 40%) has been monitored, it was discovered that runoff increases as the gradient increases. This finding can explain higher water runoff values in the case of the P3 plough plot. According to experimental data, the P4 plough plot experienced 70% lower Qv than the P3 plough plot for dry weather conditions since the P5 plough plot experienced 65% lower Qv than the P3 plough plot.

On the other hand, Qv was 48% and 30% lower for P4 and P5 plough plots compared with P3 plough plots for wet weather conditions. However, However plough cultivation monitoring plot P5, situated at a lower altitude than P3 and P4 plots, experienced higher Qp/Qv than the P4 plots and lower Ap/Qv than the P3 plots plough plot. This finding can be related to higher drainage areas (see Table in Section), which were much larger in the case of the P5 plough plot.

According to modelling and experimental results (see Section 0 and Section 6.3.1.), if we narrow down those results, higher Qp/Qv values will likely occur during the non-growing period for the F1 and F3 forest development categories for dry and wet weather conditions. Those evidence has been provided in Chapter 5 and Chapter 6, where matching events have been compared between all cultivated areas. Also, there were more events in Appendix 5 (see Table A.5.1, Table A.5.2, Figure A.5.1 and Figure A.5.2), where more events were included in the case of plough cultivation. Those data showed the same trends, where more runoffs will occur in non-growing conditions (such as F1, F3 and F5). Furthermore, a comparison between modelled and observed data in Appendix 8 (see Table A.9.1, Table A.9.2, Figure A.9.1 and Figure A.9.2), Appendix 10 (see Table A.10.1, Table A.10.2, Figure A.10.1 and Figure A.10.2), and Appendix 11 (see Table A.11.1, Table A.11.2, Figure A.11.1 and Figure A.11.2) show the same trend as previously analyzed data.

Excavation mounding cultivation

The excavation mounding cultivation monitoring plot P6 is located at a slightly higher altitude (see Figure 3.8) than other excavation mounding monitoring plots P7. Plot P6 experienced less runoff water. Both plots have been situated in brown soil (see Table 3.5). On the other hand, the slope of the catchment area and the slope of the monitoring channel were higher in the case of P6 (see Table 3.3). However, recent literature found opposite results on the slope influence of runoff water, which cannot be applied to excavation mounding Cultivation since the case study did not treat cultivated areas [163].

Further explanation of this phenomenon can be founded in the design of excavation mounding cultivation that includes many mounds in the monitored area. Those mounds collets water and sediment at the same time. Also, this means that areas with more mounds will experience more runoff water, which complements findings around the P7 excavation mounding plot.

According to experimental data, the P6 excavation mounding plot experienced 87% lower Qv than the P7 excavation mounding plot for dry weather conditions since Qv was lower by 91% for wet weather conditions. According to analyzed data from Chapter 5, it is evident that the F3 category has higher Qp/Qv for dry weather conditions. Also, events that have been provided in Appendix 7 (see Table A.7.1, Table A.7.2, Figure A.7.1 and Figure A.7.2), where more events were included in the case of excavation mounding cultivation, showed that the F3 category has a higher amount of runoff water for dry and wet weather conditions. Furthermore, according to modelling, the occurrence of runoff water will likely be most increased in the case of the F3 category for dry weather conditions and F5 for wet weather conditions (see Chapter 6).

Hand-screefing cultivation

The hand-screefing monitoring plot has been located at higher elevations and the brow soil. Higher Qp/Qv occurred in the case of the F3 category for dry weather conditions and the F5 category for wet weather conditions. Because the hand-screefing plot does not have repetition, the discussion is made in comparison to other plots. For example, it was evident that the P2 hand-screefing plot experienced higher Qv than the P4 plough plot, P5 plough plot and P7 excavation mounding plot for dry weather conditions since for wet weather conditions on this list is added P3 plough plot. The P2 hand-screefing plot has a higher channel and catchment slope than any plough plot, which might result result in higher values of Qv [178].

Sub-catchment areas

The inch 2 sub-catchment area experienced higher Qp/Qv than the Inch 1 sub-catchment. Those values will likely be higher in the case of the F1 forest development category. According to the soil map (see Figure 3.7), Inch 1 and Inch 2 had predominantly brown soils (46% in the case of the Inch 1 sub-catchment and 49% in the case of the Inch 2 sub-catchment). On the other hand, peat is more dominant in the case of the Inch 2 sub-catchment since Inch 1 consists of peaty podzols. According to experimental data, higher Qp/Qv occurred in the F1 category for dry weather conditions for both sub-catchments, which can be in line with findings on the Colburn catchment [105]. However, higher Qp/Qv for modelling data happened in the case of F3 for both sub-catchments.

On the other hand, for wet weather conditions, experimental data showed the highest Qp/Qv for the F2 category case of the Inch 1 sub-catchment and the F5 category in the case of the Inch 2 sub-catchment. The same pattern has been confirmed in modelling data, but more categories have been observed than in experimental. This refers to the high Qp/Qv occurring in cases of category F1 for both sub-catchments for modelling data. However, according to experimental data, the Inch 1 sub-catchment experienced 31% lower Qv for dry weather conditions and 51% lower Qv for wet weather conditions. Those results confirmed findings from other studies that have been referring to less runoff on more afforested catchments [23], [25].

Unplanted plot

According to experimental data, the unplanted plot experienced the highest amount of Qp/Qv for events that occurred in the F3 category for dry weather conditions and the case of the F4 category for wet weather conditions. That comparison refers to cultivation plots (see Section 0). Also, some of the recent studies by Monger [179], [180] uncover the behaviour of grassland areas compared to forest areas. However, this research confirmed that grassland has a lower capacity to store water. Furthermore, LRM confirmed that unplanted plots have higher values of Qp and Qv for weather conditions. Unfortunately, due to the lack of that, this trend has been analyzed only for the first year of monitoring.

General discussion for Qp/Qv

According to analyzed experimental and modelling data, each monitored plot's interaction has been formed with sub-catchment areas. Runoff water was higher in the case of P3 (plough cultivation) and P7 (excavation mounding cultivation) monitoring plots and the Inch 2 sub-catchment. A previous study [160]indicated the importance of soil type and microtopography for runoff occurrence. Besides this, there is still little evidence of runoff generation in forested areas [103]. However, it can be argued that runoff in the monitored area depends on the cultivation design. Therefore, any precipitation event during dry and wet weather conditions results in high values in the P3 and P7 monitoring plots, which differ in cultivation by design and underlying soil.

However, if we look through the lens of the same cultivation, the P3 monitoring plot experienced higher runoff values compared with P4 and P5. An interesting finding is that P4 and P5 monitoring plots have been placed on the same soil type, and the P4 area experienced lower values than the P5 area. On the other hand, compared to excavation mounding plots, the P6 area experienced less runoff than the P7 area. P7 site is located in the valley under the hill, which might influence the occurrence of runoff water from surrounding areas (see Figure 3.14).

Moreover, looking through soil type distribution and cultivation distribution over the Inch 1 and Inch 2 sub-catchment monitored area (see **Error! Reference source not found.**), there is the possibility that soil type influences higher Qp/Qv at the Inch 2 sub-catchment. This mainly can be referred to as grassland areas that are predominantly located at the peat for Inch 2 sub-catchment. Furthermore, other factors that might control higher Qp and Qv in cultivated areas can be referred to as the slope of the catchment and channel area, especially in plough cultivation. However, other sections discuss the design of cultivated areas and can give deeper conclusions on cultivation hydrology.

7.3.3 Response time around monitored areas

Field observation recorded to address RQ1 provided evidence about Rt across different sub-catchment areas, cultivation plots and unplanted plot. According to a previous study in the Coalburn catchment, a change in response is provided when compared to pre- and post-planting periods [105]. On the other hand, a study [170] that investigated changes in the response after forest harvesting detected significant changes in response. Also, a study that considered 312 catchments [53] studied responses from different perspectives but were not cultivation related. There are examples from many other studies [25], [116] that researched changes at the catchment level but not on the cultivation level plots.

However, this study has been used for the establishment of patterns around cultivated areas for Rt. Moreover, this study indicates that the Rt of runoff generation during dry and wet weather was an essential variable.

According to experimental data (where comparison was made for matching events across all cultivations), plough cultivation plots that are developed on brown soil (P4 and P5) have lower Rt (2-3 hours) in case of dry weather conditions. On the other hand, the P3 plot developed on predominately peat soil has a higher Rt (8 hours) for dry weather conditions. Furthermore, lower Rt (1-3 hours) occurred during the wet period in the case of P3 and P4 since P5 had higher Rt (11 hours). On the other hand, according to data presented in Appendix 5 (see Table A.5.1, Table A.5.2, Figure A.5.1 and Figure A.55.2), where more events were included in the case of plough cultivation, trends are found differently. The P3 plot has lower values for Rt in dry and wet weather conditions (2-3 hours). On the other hand, P4 and P5 followed the same pattern as it has with a lower amount of data

Moreover, the P6 excavation mounding plot had higher Rt (9-11 hours) during the dry and wet periods compared to the P7 plot (8-3 hours) for events presented in Chapter 5. However, the hand-screefing monitoring plot had the same Rt for dry and wet weather conditions. (4 hours). Lower values of Rt (2 hours) refer to the F2 category during wet weather conditions since dry weather conditions have constant Rt. Then, more events were presented in Appendix 6 (see Table A.66.1, Table A.6.2, Figure A.66.1 and Figure A.66.2) and showed the same patterns for Rt.

Also, on the sub-catchment level, both sub-catchments experienced higher Rt in dry weather conditions than in wet weather conditions. Comparison between sub-catchments showed that Inch 1 has lower Rt than Inch 2. This also can be related to rainfall intensity variables that show a significant relationship to Rt in the case of sub-catchments (see Appendix 17).

Further analyses related to modelled data in Chapter 6 proved that in the case of plough cultivation, Rt was lowest in the case of the P4, followed by P3 and P5. On the other hand, Rt was lowest for P3 in wet weather conditions, followed by P4 and P5. Furthermore, the excavation mounding plot will likely have the same response time for dry and wet weather conditions. This is the same for the hand-screefing plot (P2). These findings are fascinating. The diversity of Rt indicates that some cultivations have different behaviour in terms of responses that function for additional features behind them.

Analysis related to the P2 plot showed that Rt time is the same for dry and wet weather conditions (4 hours). On the hand, modelling results showed lower Rt for dry weather conditions.

Monitoring catchment properties and Rt

Looking through the lens of the slope of the catchment area and the slope of the channel (see Table 3.5), P3 and P4 plough plots have higher values of the slope of the catchment area than the P5 plough plot. This might influence Rt during wet weather conditions. At the same time, slope of the channel area is the same (17 degrees) for the P4 and P5 areas, which might influence response time during dry weather conditions since the P3 area has a lower slope than the channel (15 degrees). Also, the P2 hand screefing monitoring plot had a very high slope of catchment area (45 degrees), and the slope of the channel and response time have been the same in dry and wet weather conditions according to experimental results. Numerous studies researched the connection between slope and runoff, and they support this finding as well [174], [178].

Furthermore, the P7 excavation mounding plot had a lower channel, and the catchment slope and Rt were lower than in the P6 excavation mounding plot. Those plots have particular cultivation development with many mounds that might be critical factors for Rt. However, a recent study by Mindham showed that a range of Rt in micro catchment areas could be connected to soil properties, size of the observed basin and flow pathways [181]. This confirmed that many different factors need to be observed to understand Rt in more detail.

Furthermore, the higher slope of the channel in the case of Inch 1 has been higher, which might have influenced the lower Rt in the case of the Inch 1 sub-catchment. Then, in the case of cultivations percentages and grassland areas, Inch 2 has a more complex picture that needs more research for a better understating of responses.

7.3.4 Time of peak around monitored areas

One of the critical variables experienced different values during the monitoring period in Tp. Since the range of Tp was discovered, it is possible to illustrate them through experimental and modelled data. According to experimental data from Chapter 5, plough cultivation practices P3 and P4, located at a higher elevation, have similar/same Tp (9-14 hours) since P5 plough cultivation monitoring plots had higher Tp (35 hours) for dry weather conditions. Furthermore, Tp was lowest for the P4 plough plot (15 hours) during wet weather conditions since the P3 plough plot, and the P5 plough plot had higher Tp (18 and 19 hours). However, in Appendix 5 (see Table A.5.1, Table A.5.2, Figure A.5.1 and Figure A.55.2), where more events have been analyzed, Tp were similar for wet weather conditions for all tree plots (17-18 hours). Furthermore, for dry weather conditions, P4 had the lowest Tp (14 hours) since the P3, and P5 plough plots had similar Tp (20-21 hours). Conversely, the P2 hand-screefing plot had lower Tp for dry weather conditions (15 hours) and higher Tp for wet weather conditions (18 hours).

During dry weather, the P7 excavation mounding plot had a higher Tp (19 hours) than the P6 excavation mounding plot (17 hours). Conversely, Tp was higher for the P6 excavation mounding plot (29 hours) than the P7 excavation mounding plot (22 hours) during wet weather conditions. Then, suppose we use data from Appendix 6 (see Table A.6.1, Table A.6.2, Figure A.6.1 and Figure A.6.2), where more data has been analyzed. In that case, the P6 excavation mounding plot inevitably has higher Tp in the case of both weather conditions.

Monitoring catchment properties and Tp

According to those results, it is evident that Tp has lower values for higher elevation values in the case of plough cultivation. This means that the lowest Tp will occur in the case of P4, then P3 and P5. However, in the case of excavation mounding plots, higher Tp occurred at a higher elevation in excavation mounding plots. A recent study by Bond confirmed the importance of catchment properties for the Tp by investigating seasonality in different catchments across the UK [182]. The main conclusion is related to fact-controlled land management practices that can reduce Tp.

7.3.5 Influence of design of cultivated areas

Tree growth is likely to be connected to transpiration rates increase. However, transpiration rates can differ for different species (and reflect on growing and non-growing seasons [183].
Despite the initial increase in runoff water for the non-growing season and the initial decrease of runoff water for growing, this study found different behaviours in cultivated and unplanted plots.

Different cultivated areas had been designed differently in terms of actual plantation technique, presented in Chapter 3. Plantation type influences the density of the tree network over each type, and the highest density of trees was achieved for plough cultivation (see Table 3.6). This suggested different runoff flow mechanisms that occurred in those areas. For example:

- Lower Rt around plough cultivated in upper catchment areas occurred in the case of P3 plough cultivation. This is likely related to the fact that this cultivation is designed as channel-based (e.g., plough lines and buffer strips can be connected to the channel). Although this type of design help to attenuate the runoff flow, that is related to longer Tp.
- Longer Rt on P events over-excavation mounding areas is likely to be related to the mounding network integrated with over-excavation mounding cultivation techniques. This design possibly influences higher Rt and higher Tp. On the other hand, when API30 values are high, runoff water will likely occur around those areas since the mounding network is saturated. Furthermore, there is a clear distinction between P6 and P7 excavation mounding areas (where P6 was monitored on the small hill and P7 was monitored in the valley), where the P6 area had fewer mounds, and the P7 excavation mounding area had approximately 50% more mounds. Furthermore, surrounding areas can have a more significant influence on the P7 area due to micro-location.
- Medium Rt on P events in the P2 hand-screefing monitoring plot is likely to be connected to the micro-location and higher channel slope. Also, the limitation of just one monitoring plot around these areas limited understanding and decision of controlling factors. Further, this cultivation has some similarities with excavation mounding cultivation but with no mounding system around areas.

Those findings are fascinating for future application of cultivation techniques in similar catchments in Scotland and future Application Guides for the productive forest. However, the micro-locations required more research that might be challenging as the forest development stage progress. For example, the cultivation for soil for Forestry guide from 1999 can inform forest managers on how to formulate cultivation [184]. Still, the range of factors is defined as an unknown effect on forestry development. Furthermore, the new Guidance named cultivation for upland productive woodland creation site, established in July 2021 [185], provided minimal information on the hydrology of cultivated areas based on soil properties (see Chapter 2). Despite this fact, the reflection of actual study in the Menstrie catchment can inform future forestry development in the Scotland region.

7.4 Sediment delivery for different cultivated areas

Field observations that have been recorded for addressing RQ2 provided evidence of sediment movement through cultivated areas will follow the discussion of this section. It was possible to observe differences in sediment movement through developed areas. According to Worrell that investigated cultivation sedimentology it has been confirmed that plough cultivation delivered more sediment that another cultivation [117]. This provided baseline for research in Menstrie.

Results for Menstrie case study informed us about different particle sizes during the monitoring period (see Figure 5.17) related to gravel, sand and silt. It was discovered that most of the gravel occurred in plough cultivation areas (P3, P4 and P5 plots). On another had, higher distribution of the sand and silt occurred only in case of P3 plough cultivation. Those results might be connected to the micro location (upland of catchment) of the plough catchment and fact that P3 catchment has been based on peaty soil. Current literature concentrates on sediment delivery related to mainstream and lowland areas [186].

Interesting further finding refers to relationships that have been discovered between the set of variables and sediment weight (see Table 5.9). Those finding pinpointed decreasing relationship between Qv and sediment weight in the main drain for P3 and P5 plough plots (this is in the case of containers 804, 806, and 808). Moreover, this finding refers to sand and silt particle size. This finding is particularly promising in decreasing sediment movement trough cultivated areas in the main drain. On the other hand, it has been discovered that sediment delivery has an increasing relationship in plough lines in the P3 area (in relationship with Qp/Qv/P). One of the studies [187] researching sediment loss in vegetated furrows has discovered an increasing relationship between flow and sediment movement. Also, there are findings (see Figure 5.16 and Table 3.5) related to sediment loss increasing by increasing slope [188]. This might connect to sediment delivery in the P3 area with the highest catchment slope from all tree plough plots. On the other hand, the slope for the catchment area was lowest in the P5 area, where the total amount of sediment has been recorded as the lowest. This study found this finding interesting since it is likely that sediment settled in plough lines and did not move further through the catchment. On the other hand, sediment was not monitored in plough lines for P4 and P5 monitoring areas, but it has been obvious that those areas had delivered less deposit in the main drain.

Finally, sediment movement was highest in plough cultivation areas since excavation mounding, and hand-screefing cultivations delivered significantly lower amounts.

7.5 Limitation of experiments

According to this PhD study, detailed site monitoring was done to the maximum extent to gather as much data as possible. Possible monitoring improvements can be applied to remote monitoring for future research. That will allow easier data access (even during bad weather conditions), use of sustainable energy (such as solar panels or wind energy) for instrumentation and decrease unnecessary visits to the site. Yet, this learning can also be applied to other sites that can adapt learning from the Menstrie catchment.

The investigation of cultivated areas has limited literature (see Chapter 2), and this finding should make an important empirical database for further research in this field. More research can be conducted regarding vegetation changes that will inform us on roughens coefficient in better understanding. However, field observations are an essential part of the hydrological behaviour of each cultivation that would make a ground-breaking lead in future work in the same field. Moreover, it would be necessary to cover different slopes, and more plots is future research.

Uncertainties of equipment are highlighted in Chapter 3. They suggest that more delay can be expected in the case of ultrasonic sensors (see Section 3.4.2) used for monitoring cultivation techniques and unplanted plots. Alternatively, new monitoring methods proposed by Schallener used in rangeland areas can be applied in cultivated areas [189].

Available data from precipitation do estimations related to the API30 coefficient. API30 were used as a proxy of the wettest catchment since soil moisture data was unavailable. Those data would help quantify how much water was used by soil [172]. This method's quantification required the measuring equipment's implementation in the monitoring plots areas. Because this type of monitoring is costly, this study did not consider its costs.

Chapter 8 Research summary, conclusions and recommendations m

In past years, it emphasized the importance of forest development worldwide, and a lot of efforts have been put into the research related to forest development, efficiently producing empirical data. Therefore, understanding empirical data on forest development is essential to future research case studies and its effects on climate change. In particular, understanding hydrological cultivation patterns could improve understanding sediment delivery, changes in runoff volume, peak flow etc. According to previous research studies[76], [105], [179], [181] it was identified lack of understanding related to cultivation. This especially applies in the case of complex hydrological behaviour.

8.1 Research Summary

The thesis aimed to establish how different cultivation techniques affect hydrological dynamics over the monitoring plots and sub-catchments and understand their variables for two years (from December 2016 to December 2018).

8.2 Conclusions

The conclusions of this research study are developed under each RQ and connected to the aims and objectives.

RQ1: How do different cultivation techniques influence the runoff flow and volume? Which factors control delivery?

This study was able to identify identified the runoff amount from each monitored plot and associated it with the plot's specific properties (slope, soil, catchment size, etc.) (Objectives 1 and 2 accomplished). The runoff occurrence has been determined by selecting dry and wet weather events. The selected events have been analysed in detail through different forest development categories. Furthermore, a comparison of FDC for cultivated areas refers to the highest amount of Qp and Qv that occurred to peaty based plough plot and lowland excavation mound plot in the case of dry weather conditions since for wet weather conditions highest values occurred in cases of hand-screefing and lowland

excavation mound plot . Higher amounts of runoff water in the case of plough cultivation are likely to be related to the slope of the monitoring channel and soil properties since excavation mounds those values are associated with cultivation design (Objectives 3 accomplished).
However, in the case of sub-catchment areas, higher values of Qp/Qv occurred for the Inch 2 sub-catchment. For example, the inch 2 sub-catchment has 25% more grassland than the Inch 1 sub-catchment. In complementing this finding, it was discovered that unplanted plot experienced a higher amount of runoff water than any other monitored cultivation plot (Objective 4 accomplished).
Finally, according to analysis data, it has been found that the design of cultivation matters to the runoff occurrence and amount.

RQ2: How does sediment delivery from each cultivation technique change over time?

The highest amount of sediment delivery correlates to plough cultivation plots since hand screefing plot and excavation mounding monitoring plots have experienced significantly less sediment delivery (Objectives 1 and 2 accomplished). However, this finding has Furthermore, the peat-based plough cultivated areas had higher sediment delivery than the other two brow soil-based plough cultivated areas. If we look through the lens of soil particle size, the peaty-based plough plot experienced higher sand and silt amounts than the hand-screefing plot and brown soil-based plough plots. Furthermore, one of the brown soil plough plots had higher disposal of gravel than the hand-screefing plot and the plough plot. Moreover, according to LRM analyses, the amount of sand and silt will likely decrease in the main drain–monitoring channel. Furthermore, increasing relationships were observed in plough lines. This led to the conclusion that plough lines collected more sediment than disposed of there (Objectives 3 and 4 accomplished).
On a broad scale for catchment research, this study provided guidelines for future research in this field since limited literature has been available.

RQ3: What is the preferred cultivation technique for minimizing flood generation, and can this be reliably predicted using hydrological modelling tools?

According to the modelling result, it has been confirmed that the Inch 1 sub-catchment will have less Qp/Qv than the Inch 2 sub-catchment. This finding complements findings from experimental results and modelling results. Furthermore, according to analysed data from modelling results, it is expected that events that occurred during dry will experience the highest Qvt/Qv/Qp in the peat base area and events that occurred during wet weather conditions Qvt/Qv/Qp in lowland-based excavation mound plot . Upland base plough plot and upland excavation mounding plot will likely have the lowest amount of Qvt/Qv/Qp for any weather conditions. Furthermore, for dry weather conditions, runoff water probably occurred in the case first in upland excavation mounding plot, hand-screefing plot, lowland excavation mound plot and plough plots, according to Rt data. On the other hand, for wet weather conditions, it is likely that runoff water first occurred in the case of hand-screefing plot, then excavation mounding plots and plough plots (Objectives 4 and likely 5 accomplished).

A decreasing relationship between Tp/Ed/Qpb/Qbv and tree coverage for cultivated areas has been discovered. Furthermore, higher tree coverage on the sub-catchment level is associated with a higher number of Rt. This is the case for cultivated areas with dry and wet weather conditions (growing season).

8.3 Future research recommendations

Recommendations for further research can include the following:

- Field experiments from this case study could be replicated in various locations covering various parameters (e.g., slope, elevation, measuring channel slope, different soil types, etc.). This is an excellent basis for future similar research in the same area.
- This study could be replicated in similar catchments to quantify processes measured over cultivated areas. This will link more empirical evidence on cultivation techniques, hydrology, and sediment delivery.
- This study highlighted the importance of measurement of sediment delivery across plough cultivation, where implementation of sediment traps was more accessible due to the plough cultivation design. Moreover, measuring sediment in the ploughed area would be essential for future research to improve understanding of its delivery during tree development.
- The existing experimental setup needs to be more operational for future measurement with the possibility of improvement (such as using a different source of power with remote access to data)

8.4 Possible improvements for further research

The most important lessons that have been learned during this study are related to possible improvements that can include:

- A higher number of time-lapse cameras can cover larger monitoring areas and reduce uncertainties related to flow paths (this mainly refers to excavation mounding cultivated areas).
- Development of surface model with scanner or drone, including detailed aerial analysis. This could be related to growing and non-growing seasons.
- Installing the water level meter at the beginning of the monitoring channel would allow a better understanding of runoff occurrence in the monitored areas.

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Appendices

Appendix 1.

Table A.1.1: Dry and wet conditioning group median API30 values with the number of observed events

Monitoring plots	Plot/ Inches	Weather conditions	No. of events	30 days median antecedent rainfall (mm) for Menstrie catchment	
				Menstrie catchment applied criteria (mm)	API30 values (mm)
Unplanted plot	P1 (2016-2017)	Dry	8	<20	14.5
		Wet	23	>20	27.7
	P1 (2017-2018)	Dry	6	<20	10.9
		Wet	7	>20	32.7
Cultivation practices	P2	Dry	27	<20	13.2
		Wet	58	>20	30.3
	P3	Dry	27	<20	12.5
		Wet	58	>20	30.1
	P4	Dry	29	<20	12.5
		Wet	50	>20	31.3
	P5	Dry	25	<20	12.3
		Wet	43	>20	29.2
	P6	Dry	26	<20	12.8
		Wet	44	>20	28.3
	P7	Dry	18	<20	13.5
		Wet	30	>20	28.8
Sub-catchments	Inch 1	Dry	17	<20	16.1
		Wet	52	>20	30.9
	Inch 2	Dry	15	<20	16.1
		Wet	48	>20	30.7

Appendix 2.

Table A.2.1: Median values of the variable for dry and wet weather conditions for all observed events

Weather conditions	Plot (no of events)	Dominant FDC	Season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
Dry	P1 2017 (6)	F3/F4 (3/3)	Autumn/ Summer/Winter (2/2/2)	39	18	1.5	31.9	0.2	6.2	1.3	28.1	1.5	5.1	0.4	11
	P2 (26)	F4 (8)	Winter (9)	28	15	0.4	6.7	0.1	1.9	0.3	4.0	4	4.9	0.4	13
	P3 (27)	F1 (8)	Winter (12)	36	18	0.4	8.2	0.1	3	0.3	6.1	2	5.6	0.4	12
	P4 (21)	F1 (8	Winter (11)	34	17	0.2	3.7	0.03	1.3	0.1	2	5	5.6	0.4	13
	P5 (25)	F1 (12)	Winter (15)	31	17	0.2	6.3	0.1	3.1	0.1	2	3	4	0.4	12
	P6 (26)	F1 (8)	Winter (14)	35	19	0.1	1.6	0.02	0.7	0.03	0.7	5	5.6	0.4	13
	P7 (18)	F3 (8)	Winter (11)	31	17	0.5	11.3	0.2	6.5	0.3	4.3	9	5.6	0.5	13
	Inch 1	F3 (8)	Winter (10)	30	10	0.4	5.8	0.1	3.7	0.3	2.8	4	9.6	0.5	16
	Inch 2	F3 (8)	Winter (9)	29	10	0.7	9.3	0.3	6.4	0.5	4.1	9	9.8	0.4	16
Wet	P1 2017 (7)	F4 (4)	Autumn/ Winter (3/3)	63	18	3.1	97.9	0.2	4.6	3	95.8	2	9.8	0.6	33
	P2 (57)	F2 (21)	Autumn (26)	29	14	0.5	8.4	0.1	2	0.4	5.9	4	9.2	0.6	31
	P3 (45)	F3 (23)	Autumn (23)	37	18	0.3	8.1	0.1	3.3	0.2	4.9	2	9	0.6	30
	P4 (47)	F4 (18)	Autumn (22)	31	14	0.2	4.1	0.04	1.5	0.2	2.3	2	9.6	0.6	31
	P5 (43)	F1 (16)	Autumn (18)	32	17	0.4	10	0.2	7.3	0.2	3.2	2	9.2	0.6	29
	P6 (37)	F2 (21)	Summer (1)	34	16	0.1	1.5	0.02	0.8	0.04	0.6	4	9.2	0.5	29
	P7 (27)	F2 (15)	Autumn/ Winter (9/9)	30	11	0.5	10.6	0.2	5.5	0.3	5	2	9	0.5	30
	Inch 1	F2 (22)	Autumn (25)	37	9	0.4	6.5	0.1	4.2	0.2	2.6	1	11.2	0.6	31
	Inch 2	F2 (23)	Autumn (17)	26	8	0.8	11.7	0.3	6.4	0.5	4.9	3	10.3	0.6	30.31

Appendix 3.

Table A.3.1: Summary of linear regression model validation for sub-catchments, unplanted plot and cultivated areas with a set of performance criteria

Inch/Plot	Weather conditions	Relationship examined	P-value	Adjusted R-square	Relationship	NSE	RSR	Model performance
Inch 1 and inch 2 - Sub-catchment areas								
Inch1	Dry	Qp/ P	0.004	0.44	Qp= 0.08+0.02*P	0.48	0.69	Satisfactory
		Qv/P	0.001	0.54	Qv=-3.8+0.8*P	0.57	0.63	
	Wet	Qp/ P	< 0.0001	0.50	Qp= -0.7+0.1*P	0.51	0.69	
		Qv/P	< 0.0001	0.53	Qv=-7.9+1.1*P	0.54	0.67	
Inch2	Dry	Qp/ P	0.002	0.51	Qp= 0.1+0.04*P	0.55	0.65	
		Qv/P	0.002	0.50	Qv=-9.1+1.8*P	0.53	0.66	
	Wet	Qp/ P	< 0.0001	0.58	Qp=-0.4 +0.1*P	0.59	0.64	
		Qv/P	< 0.0001	0.51	Qv=-1.8+0.7*P	0.52	0.68	
Unplanted plot								
P1	Dry	Qp/ P	0.014	0.77	Qv= 0.6+ 0.03* P	0.81	0.40	Very good
		Qv/P	0.0006	0.95	Qv=-20.6+6.9 *P	0.96	0.18	Good
	Wet	Qp/ P	0.01360	0.68	Qv= -0.2+0.2 *P	0.73	0.48	Good
		Qv/P	0.0025	0.84	Qv= -12.4 +6.3*P	0.86	0.34	Very good
Hand screefing cultivation technique								
P2	Dry	Qp/ P	< 0.0001	0.50	Qp= 0.3+0.01*P	0.53	0.68	Satisfactory
		Qv/P	< 0.0001	0.82	Qv= 1.1 + 0.*P	0.83	0.41	Very good
	Wet	Qp/ P	< 0.0001	0.51	Qp=0.1+0.03*P	0.52	0.69	Satisfactory
		Qv/P	< 0.0001	0.52	Qv=1.6+0.47*P	0.52	0.68	Satisfactory
Plough cultivation technique								
P3	Dry	Qp/ P	< 0.0001	0.57	Qp=0.24 +0.02*P	0.61	0.60	Satisfactory
		Qv/P	< 0.0001	0.89	Qv=0.29+1.28*P	0.90	0.30	Very good
	Wet	Qp/ P	< 0.0001	0.51	Qp=0.07 +0.03*P	0.59	0.66	Satisfactory
		Qv/P	< 0.0001	0.56	Qv=-3.4+1.1*P	0.54	0.63	
P4	Dry	Qp/ P	<0.0001	0.51	Qp=0.10+0.01*P	0.55	0.64	Satisfactory
		Qv/P	<0.0001	0.92	Qv=-0.27+0.58*P	0.93	0.26	Very good
	Wet	Qp/ P	<0.0001	0.61	Qp=-0.1+0.03*P	0.63	0.59	Satisfactory
		Qv/P	<0.0001	0.71	Qv=-4.63+0.76*P	0.73	0.51	
P5	Dry	Qp/ P	<0.0001	0.64	Qp=0.15+0.01*P	0.68	0.54	Satisfactory
		Qv/P	<0.0001	0.95	Qv=-0.39+0.62*P	0.96	0.20	Very good
	Wet	Qp/ P	<0.0001	0.57	Qp= 0.07+0.01*P	0.59	0.62	Satisfactory
		Qv/P	<0.0001	0.66	Qv=-4.9 + 0.9*P	0.68	0.55	
Excavation mounding cultivation technique								
P6	Dry	Qp/ P	<0.0001	0.55	Qp=0.02+0.002*P	0.64	0.63	Satisfactory
		Qv/P	<0.0001	0.62	Qv=0.20+0.08 *P	0.72	0.58	Good
	Wet	Qp/ P	<0.0001	0.50	Qp=0.02+0.001*P	0.51	0.67	Satisfactory
		Qv/P	<0.0001	0.87	Qv= 0.3+0.03*P	0.51	0.34	Good
P7	Dry	Qp/ P	<0.0001	0.64	Qp=0.07+0.03*P	0.72	0.56	Satisfactory
		Qv/P	<0.0001	0.86	Qv= -4.51+1.61*P	0.91	0.38	Good
	Wet	Qp/ P	<0.0001	0.68	Qp=0.12+0.02*P	0.56	0.53	Satisfactory
		Qv/P	<0.0001	0.78	Qv=-1.9+0.80*P	0.66	0.44	Good

Appendix 4.

Table A.4.1: Median values of all variables for dry and wet weather conditions group and each FDC in case of Inch 1 and Inch 2 sub-catchment

Sub-catchment area	**Weather conditions /FDS (number of events)**	**Dominant season**	**Ed (hr)**	**Tp (hr)**	**Qpt (mm/hr)**	**Qvt (mm)**	**Qpb (mm/hr)**	**Qvb (mm)**	**Qp (mm/hr)**	**Qv (mm)**	**Rt (hr)**	**P (mm)**	**I (mm/hr)**	**API30 (mm)**
Dry weather conditions														
Inch1	***Dry All events (12)***	***Winter***	***31***	***11***	***0.4***	***8.2***	***0.1***	***4.5***	***0.3***	***2.8***	***4***	***10***	***0.4***	***16***
	F1 (4)	Winter	73	11	0.4	16.3	0.2	11.9	0.3	4.4	10	11	0.4	18
	F3 (8)		32	13	0.4	8.4	0.1	4.5	0.3	3.9	2	9	0.5	13
Inch 2	***Dry All events (12)***	***Winter***	***29***	***10***	***0.7***	***9.3***	***0.3***	***6.4***	***0.5***	***4.1***	***9***	***10***	***0.4***	***16***
	F1 (4)	Winter	48	14	0.6	20.4	0.2	12.6	0.4	8.4	7	11	0.4	18
	F3 (8)		21	10	1.1	14.6	0.3	8.6	0.7	4.5	8	9	0.5	13
Wet weather conditions														
Inch 1	***Wet All events (46)***	***Autumn***	***36***	***9***	***0.3***	***5.9***	***0.1***	***4***	***0.2***	***2.4***	***1***	***10***	***0.6***	***31***
	F2 (21)	Autumn	41	9	0.3	**8.4**	0.1	4.2	0.2	3.4	2	9	0.5	30
	F3 (11)	Spring	35	9	0.3	5.6	0.1	4.1	0.2	1.9	1	7	0.4	27
	F4 (8)	Summer	29	6	0.3	4.5	0.1	2.7	0.2	1.7	1	**16**	**1.4**	32
	F5 (6)	Winter	26	9	0.4	6.3	0.2	**4.6**	0.2	1.9	1	14	0.7	**42**
Inch2	***Wet All events (46)***	***Autumn***	***25***	***8.0***	***0.8***	***11.7***	***0.3***	***6.4***	***0.5***	***4.9***	***3***	***10***	***0.6***	***31***
	F2 (21)	Autumn	28	**11**	0.8	12.3	0.3	6.1	0.5	5.7	2	9	0.5	30
	F3 (11)	Spring	**31**	8	0.6	10.3	0.4	6.4	0.2	4	4	7	0.4	27
	F4 (8)	Summer	18	5	0.5	5.6	0.2	2.7	0.3	3	5	**16**	**1.4**	32
	F5 (6)	Winter	29	5	**1.7**	**21.4**	**0.5**	**10.3**	**1.1**	**9.3**	4	14	0.7	**42**

Table A.4.2: Median values of all variables for dry and wet weather conditions group and each FDC in case P2, P3, P4, P5, P6 and P7

Sub-catchment area	**Weather conditions /FDS (number of events)**	**Dominant season**	**Ed (hr)**	**Tp (hr)**	**Qpt (mm/hr)**	**Qvt (mm)**	**Qpb (mm/hr)**	**Qvb (mm)**	**Qp (mm/hr)**	**Qv (mm)**	**Rt (hr)**	**P (mm)**	**I (mm/hr)**	**API30 (mm)**
Dry weather conditions														
P2	*Dry All events(11)*	*Winter*	*33*	*15*	*0.5*	*7.1*	*0.1*	*4.7*	*0.4*	*5.3*	*4*	*6*	*0.4*	*12*
	F1 (3)	Winter	33	**22**	0.5	14.6	0.04	**6.6**	0.4	6.8	4	4	0.4	11
	F2 (2)	Spring	24	17	0.5	7.0	0.2	3.0	0.3	4	4	3	0.3	13
	F3 (4)	Winter	**40**	13	**0.7**	**16.7**	**0.3**	5.6	0.4	**8.8**	**6**	**12**	0.4	11
	F4 (2)	Autumn	18	9	0.5	5.1	0.1	1.6	0.4	3.5	4	3	**0.5**	**19**
P3	*Dry All events(11)*	*Winter*	*29*	*14*	*0.6*	*10.7*	*0.1*	*3.9*	*0.4*	*6.6*	*8*	*6*	*0.4*	*12*
	F1 (3)	Winter	31	18	**0.9**	22.3	**0.2**	**13**	0.5	9.3	8	4	0.4	11
	F2 (2)	Spring	24	13	0.5	8.1	0.1	3.3	0.3	4.8	6	3	0.3	13
	F3 (4)	Winter	**56**	**23**	0.6	**24**.2	0.1	4.0	0.5	**17.1**	5	**12**	0.4	11
	F4 (2)	Autumn	30	16	0.5	10.2	0.1	3.6	0.4	6.6	8	3	**0.5**	**19**
P4	*Dry All events(11)*	*Winter*	*17*	*9*	*0.3*	*3.9*	*0.1*	*2.2*	*0.2*	*2*	*2*	*6*	*0.4*	*12*
	F1 (3)	Winter	35	**22**	**0.3**	8.5	0.0	**4.4**	0.2	4	3	4	0.4	11
	F2 (2)	Spring	27	15	0.2	3.7	0.1	1.7	0.1	2	5	3	0.3	13
	F3 (4)	Winter	**44**	13	0.3	**10.7**	0.1	2.4	0.3	**8.3**	5	**12**	0.4	11
	F4 (2)	Autumn	20	10	0.2	3.2	0.1	1.5	0.1	2	4	3	**0.5**	**19**
P5	*Dry All events(11)*	*Winter*	*41*	*35*	*0.4*	*8.4*	*0.3*	*6.4*	*0.1*	*2.3*	*3*	*6*	*0.4*	*12*
	F1 (3)	Winter	48	29	0.3	6.4	0.1	3.2	0.2	3.2	1	4	0.4	11
	F2 (2)	Spring	31	19	0.3	6.5	0.1	4.1	0.2	2.5	2	3	0.3	13
	F3 (4)	Winter	**49**	**35**	**0.4**	**10.4**	**0.2**	**5.4**	0.3	**6.5**	20	**12**	0.4	11
	F4 (2)	Autumn	19	8	**0.4**	6.3	0.2	4.4	0.2	2.0	4	3	**0.5**	**19**
P6	*Dry All events (5)*	*Winter*	*42*	*17*	*0.1*	*3.2*	*0.0*	*2.3*	*0.05*	*0.8*	*9*	*6*	*0.4*	*12*
	F2 (1)	Spring	35	17	0.0	1.2	0.0	0.7	0.03	0.5	4	3	0.3	**13**
	F3 (4)	Winter	**46**	**21**	**0.1**	**3.9**	**0.0**	**2.5**	**0.1**	**1.5**	**11**	**12**	**0.4**	11
P7	*Dry All events (5)*	*Winter*	*36*	*19*	*0.9*	*19.2*	*0.3*	*12.7*	*0.4*	*6.5*	*8*	*6*	*0.4*	*12*
	F2 (1)	Spring	13	17	0.3	4.0	0.3	3.3	0.1	0.7	8	3	0.3	**13**
	F3 (4)	Winter	**47**	22	**1**	**41.5**	**0.3**	**15.7**	**0.5**	**16.8**	**9**	**12**	**0.4**	11
Wet weather conditions														
P2	*Wet All events(20)*	*Winter*	*28*	*18*	*0.5*	*9.8*	*0.1*	*2.6*	*0.4*	*6.3*	*4*	*11*	*0.6*	*31*
	F2 (5)	Winter	**50**	**37**	0.4	8.1	0.0	2.2	0.4	5.9	2	11	0.5	30
	F3 (5)	Spring	24	18	**0.6**	7.9	0.1	3	**0.5**	5.1	4	11	0.5	28
	F4 (6)	Winter	27	12	0.5	11.2	0.1	2.9	0.4	7.0	**5**	9	**0.7**	30
	F5 (4)	Autumn	33	23	0.5	**12.9**	0.1	**4.3**	0.4	**7.2**	3	**16**	0.6	**39**
P3	*Wet All events(20)*	*Winter*	*39*	*18*	*0.5*	*11.7*	*0.1*	*6.1*	*0.3*	*6.1*	*1*	*11*	*0.6*	*31*
	F2 (5)	Winter	39	21	0.4	11.4	0.1	4.9	0.3	5.6	1	11	0.5	30
	F3 (5)	Spring	24	12	0.3	5.7	0.1	2.4	0.2	2.9	3	11	0.5	28
	F4 (6)	Winter	36	15	**0.7**	17.7	**0.2**	6.4	**0.5**	8.8	**8**	9	**0.7**	30
	F5 (4)	Autumn	**45**	**25**	0.5	**18.5**	0.1	**9.2**	0.4	**9.3**	1	**16**	0.6	**39**
P4	*Wet All events(20)*	*Winter*	*32*	*15*	*0.3*	*5.8*	*0.04*	*1.8*	*0.2*	*3.2*	*3*	*11*	*0.6*	*31*
	F2 (5)	Winter	32	15	0.3	4.1	0.03	0.9	0.2	**3.3**	3	11	0.5	30
	F3 (5)	Spring	32	16	**0.4**	**8.7**	**0.1**	2.5	**0.3**	3.2	**5**	11	0.5	28
	F4 (6)	Winter	32	13	0.2	5.7	0.03	**2.6**	0.2	3.1	2	9	**0.7**	30
	F5 (4)	Autumn	**39**	**22**	0.3	5.3	0.04	1.6	0.2	2.8	1	**16**	0.6	**39**
P5	*Wet All events(20)*	*Winter*	*34*	*19*	*0.5*	*12.4*	*0.2*	*9.1*	*0.3*	*4.3*	*5*	*11*	*0.6*	*31*
	F2 (5)	Winter	45	14	0.6	**19.5**	**0.3**	9.4	0.3	**4.6**	6	11	0.5	30
	F3 (5)	Spring	26	15	**0.7**	12.0	**0.3**	8.9	0.3	4.3	5	11	0.5	28
	F4 (6)	Winter	33	19	0.4	10.0	0.2	8.3	0.2	2.2	3	9	**0.7**	30
	F5 (4)	Autumn	**50**	**22**	0.4	15.4	0.2	**11.8**	0.2	3.6	**8**	**16**	0.6	**39**
P6	*Wet All events (7)*	*Winter*	*42*	*29*	*0.1*	*2.1*	*0.0*	*1.0*	*0.0*	*0.6*	*11*	*11*	*0.5*	*28*
	F3 (4)	Winter	42	29	0.1	2.1	0.0	1.0	0.0	0.6	11	11	0.5	28
P7	*Wet All events (7)*	*Winter*	*40*	*22*	*0.6*	*16.9*	*0.2*	*9.9*	*0.3*	*7.1*	*3*	*11*	*0.5*	*28*
	F3 (4)	Winter	40	22	0.6	16.9	0.2	9.9	0.3	7.1	3	11	0.5	28

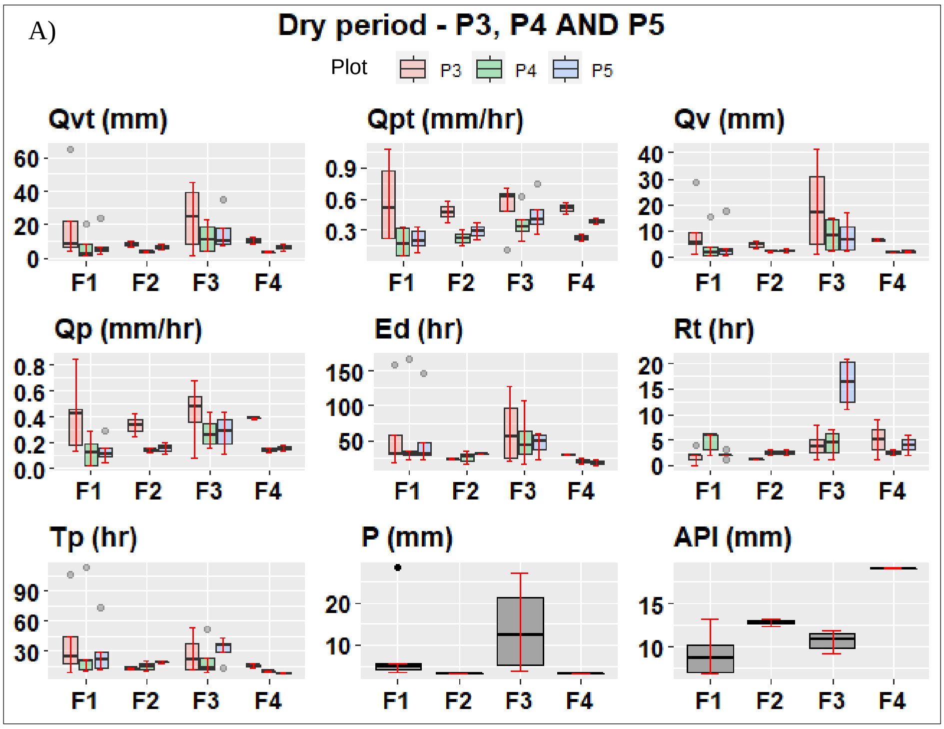
Table A.4.3: Median values of all variables for dry and wet weather conditions group and each FDC in case P1, P2, P3, P4, P5, P6 and P7

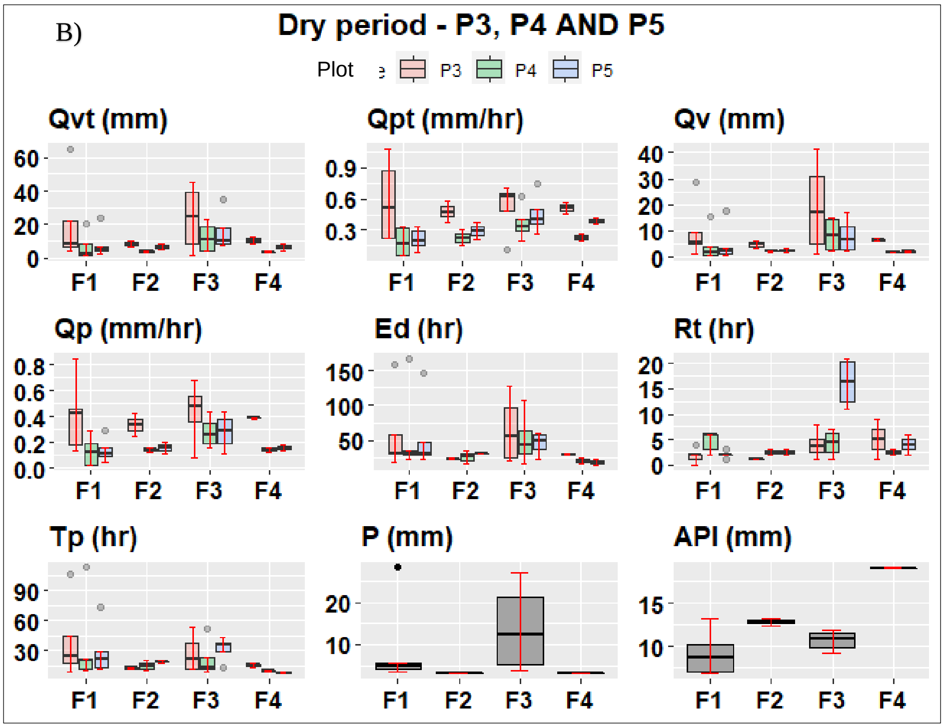
Plot	Weather conditions	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
Dry weather conditions														
P1	Dry events (2)	Winter	112	77	1.5	145	0.24	20	1.2	125	2	16	0.4	10
P2	Dry events (2)		47	32	0.7	16.7	0.29	5.6	0.4	11.1	6			
	F3 (2)													
P3	Dry events (2)		77	33	0.7	27.9	0.1	4.0	0.6	23.9	3			
	F3 (2)													
P4	Dry events (2)		62	30	0.3	10.7	0.07	2.4	0.3	8.3	4			
	F3 (2)													
P5	Dry events (2)		49	36	0.5	21.8	0.2	12.2	0.3	9.7	16			
	F3 (2)													
P6	Dry events (2)		46	20	0.1	3.2	0.04	1.7	0.1	1.5	5			
	F3 (2)													
P7	Dry events (2)		75	51	1.0	41.5	0.3	15.7	0.7	25.8	4			
	F3 (2)													
Wet weather conditions														
P1	Wet events (4)	Autumn	82	59	1.9	103.5	0.3	5.9	1.7	97.6	1	13	1.1	32
P2	Wet events (4)		31	17	0.5	9	0.1	1.5	0.4	7.4	6			
	F4 (4)													
P3	Wet events (4)		57	24	0.6	23.6	0.3	14.5	0.3	9.0	1			
	F4 (4)													
P4	Wet events (4)		63	50	0.4	8.7	0.1	3.4	0.3	5.3	2			
	F4 (4)													
P5	Wet events (4)		30	11	0.3	6.0	0.1	1.3	0.2	4.7	2			
	F4 (4)													
P6	Wet		33	11	0.1	1.8	0.04	1.3	0.0	0.4	4	6	0.3	37

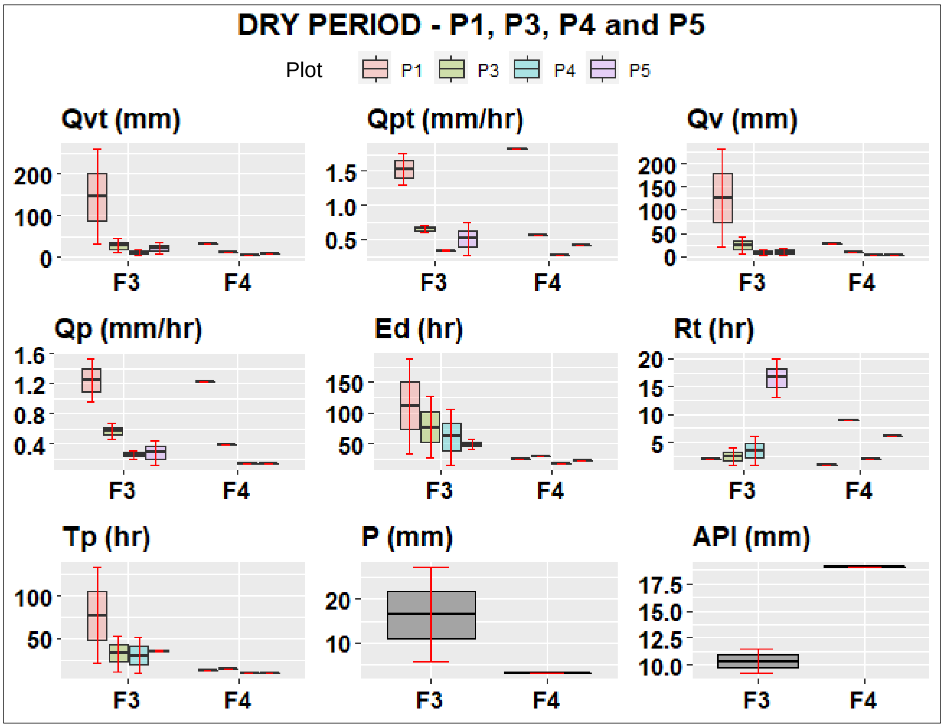
	events (4) F3 (3)	Winter												
P6	Wet events (4) F3 (3)		35	19	0.5	15.0	0.2	7.3	0.4	7.7	2			

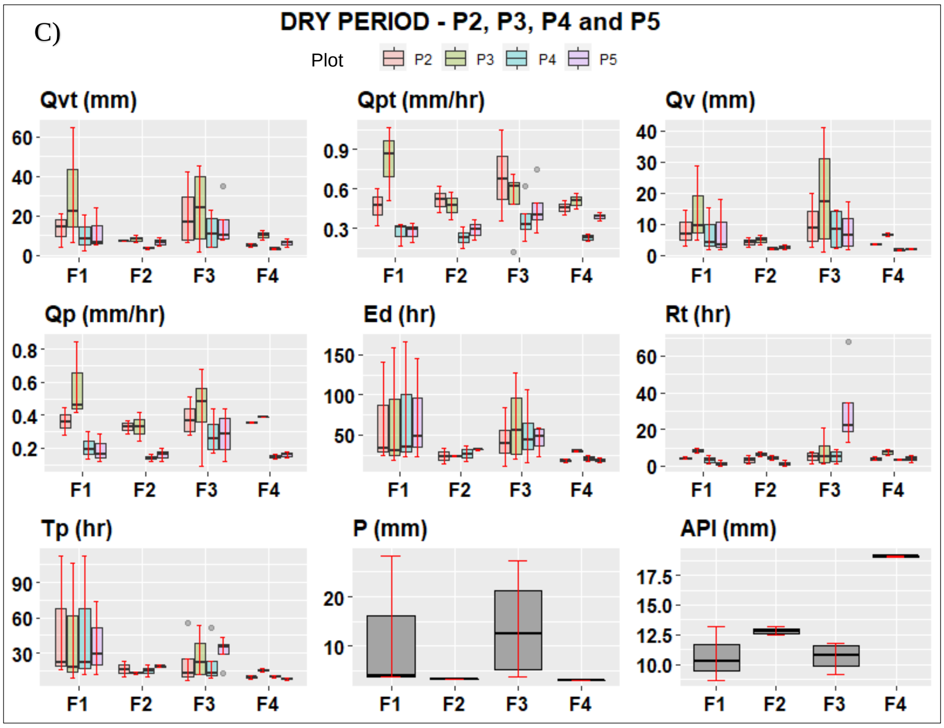
Appendix 5.

Table A.55.1: Forest development categories (F1, F2, F3, F4, F5) box plots for variables under a group of coincidental events in case of A) Plough cultivation (P3, P4, P5), B) Plough cultivation (P3, P4, P5) and unplanted plot (P1) C) Plough cultivation (P3, P4, P5) and hand screefing (P2) and D) Plough cultivation (P3, P4, P5) and excavation mounding (P6, P7) for dry weather conditions




B)
Dry period - P3, P4 AND P5
Plot
P3
P4
P5
Qvt (mm)
0
20
40
60
Qpt (mm/hr)
0.3
0.6
0.9
Qv (mm)
0
10
20
30
40
Qp (mm/hr)
0.0
0.2
0.4
0.6
0.8
Ed (hr)
50
100
150
Rt (hr)
0
5
10
15
20
Tp (hr)
30
60
90
P (mm)
10
20
API (mm)
10
15
F1
F2
F3
F4


DRY PERIOD - P1, P3, P4 and P5
Plot
P1
P3
P4
P5
Qvt (mm)
0
100
200
Qpt (mm/hr)
0.5
1.0
1.5
Qv (mm)
0
50
100
150
200
Qp (mm/hr)
0.4
0.8
1.2
1.6
Ed (hr)
50
100
150
Rt (hr)
5
10
15
20
Tp (hr)
50
100
P (mm)
10
20
API (mm)
10.0
12.5
15.0
17.5
F3
F4


C)
DRY PERIOD - P2, P3, P4 and P5
Plot
P2
P3
P4
P5
Qvt (mm)
Qpt (mm/hr)
Qv (mm)
Qp (mm/hr)
Ed (hr)
Rt (hr)
Tp (hr)
P (mm)
API (mm)
F1
F2
F3
F4
0
20
40
60
0.3
0.6
0.9
10
30
0.2
0.4
0.6
0.8
50
100
150
90
10.0
12.5
15.0
17.5

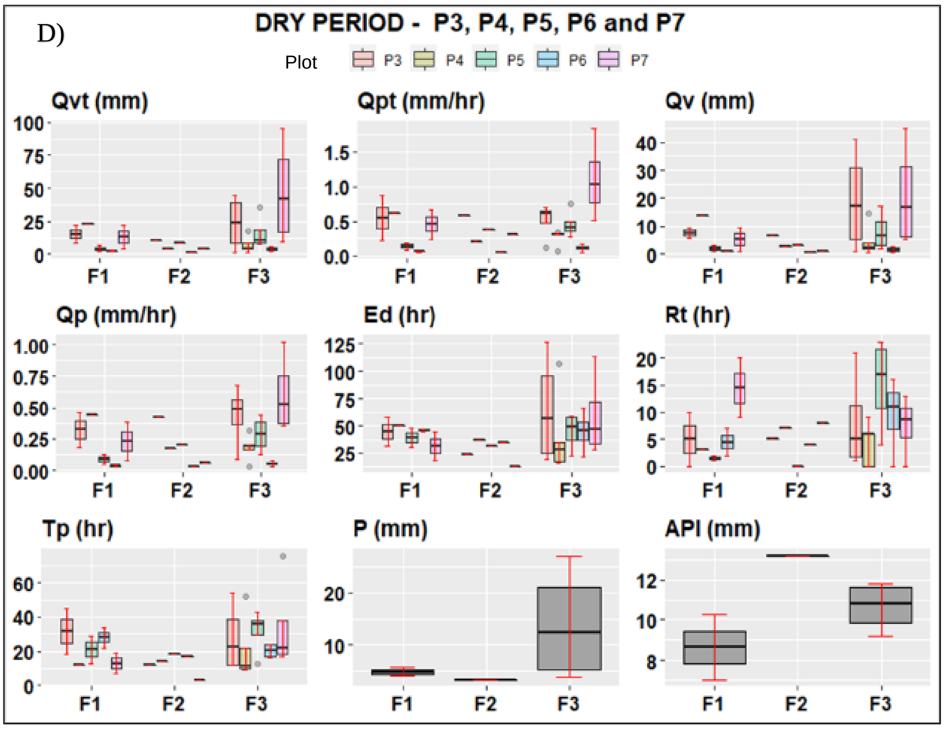
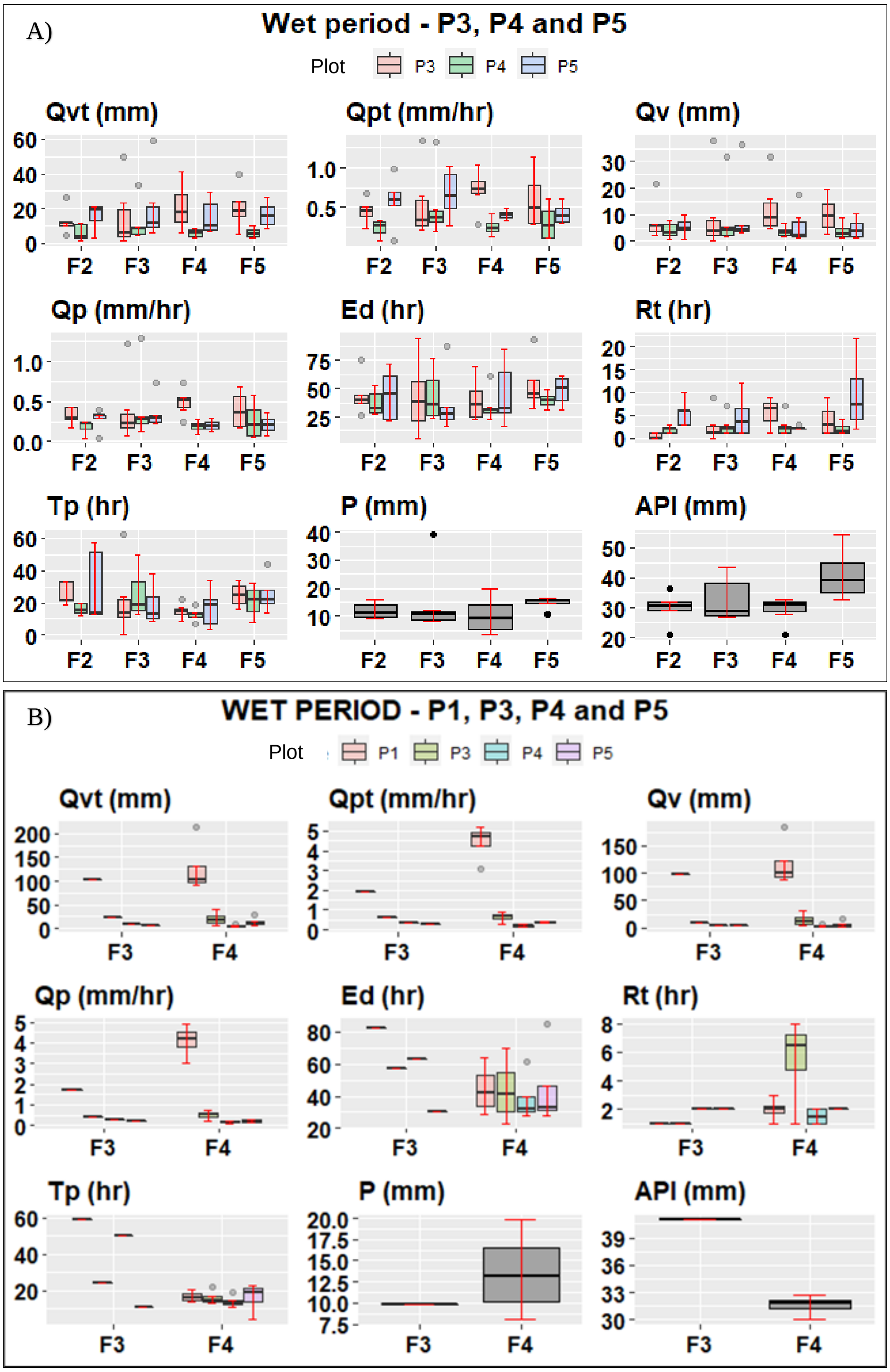

D)
DRY PERIOD - P3, P4, P5, P6 and P7
Plot
P3
P4
P5
P6
P7
Qvt (mm)
Qpt (mm/hr)
Qv (mm)
Qp (mm/hr)
Ed (hr)
Rt (hr)
Tp (hr)
P (mm)
API (mm)
F1
F2
F3
0
25
50
75
100
0.0
0.5
1.0
1.5
10
20
30
40
0.00
0.25
0.50
0.75
1.00
125
5
15
60
8
12

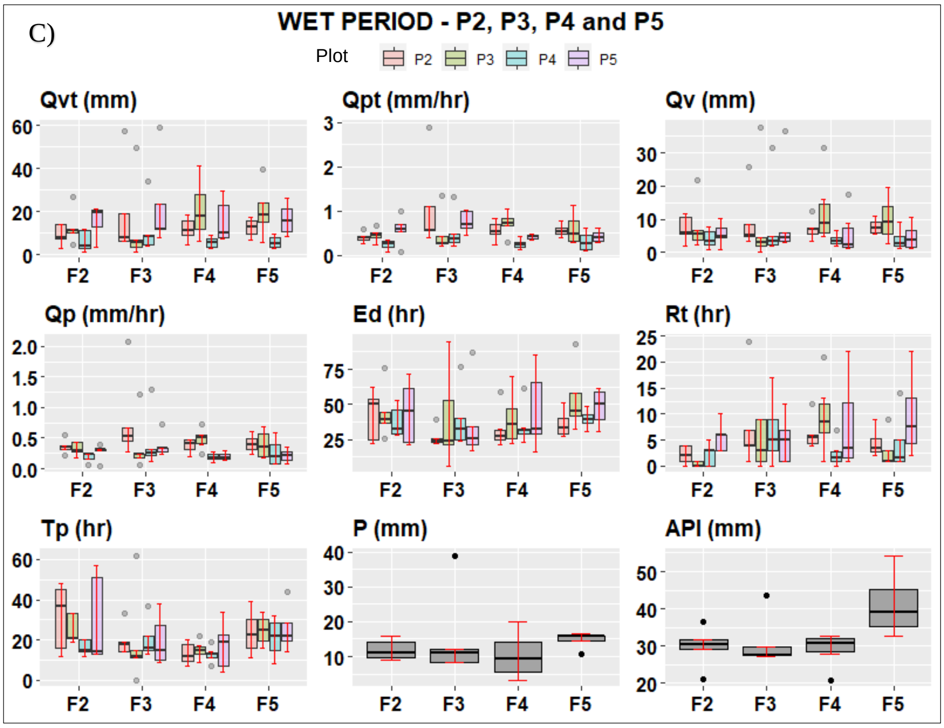
Table A.55.1: Median values of all variables for each forest development category (F1, F2, F3, F4, F5) for a group of coincidental events in case of i) Plough cultivation (P3, P4, P5) ii) Plough cultivation (P3, P4, P5) and unplanted plot (P1) iii) Plough cultivation (P3, P4, P5) and hand screefing (P2) and iv) Plough cultivation (P3, P4, P5) and excavation mounding (P6, P7) for dry weather conditions

Cultivation (No of events)	Plot	FDC (No of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30(mm)
i) Plough (13)	P3	F1 (5)	Winter	31	25	0.5	8.2	0.1	2.7	0.4	5.7	2	5	0.4	9
	P4			31	20	0.2	2.4	0.0	1.0	0.1	1.6	6			
	P5			31	22	0.2	5.1	0.1	3.1	0.1	2.0	2			
	P3	F2 (2)	Spring	24	13	0.5	8.1	0.1	3.3	0.3	4.8	1	3	0.3	13
	P4			27	15	0.2	3.7	0.1	1.7	0.1	2.0	3			
	P5			32	19	0.3	6.5	0.1	4.1	0.2	2.5	3			
	P3	F3 (4)	Winter	57	23	0.6	24.2	0.1	4.0	0.5	17.1	4	12	0.4	11
	P4			44	13	0.3	10.7	0.1	2.4	0.3	8.4	5			
	P5			49	36	0.4	10.4	0.2	5.4	0.3	6.5	17			
	P3	F4 (4)	Winter	30	16	0.5	10.2	0.1	3.6	0.4	6.6	5	3	0.5	19
	P4			21	10	0.2	3.2	0.1	1.5	0.1	1.7	3			
	P5			19	8	0.4	6.3	0.2	4.4	0.2	2	4			
	Summary														
	P3	15	Winter	31	20	0.5	9.2	0.1	3.5	0.4	6.2	3	4	0.4	12
	P4			29	14	0.2	3.5	0.1	1.6	0.1	1.9	4			
	P5			32	21	0.4	6.4	0.2	4.3	0.2	2.3	3.5			
ii) Plough and unplanted (3)	P1	F3 (2)	Autumn	112	77	1.5	144.7	0.2	19.9	1.2	124.8	2	16	0.4	10
	P3			77	33	0.7	27.9	0.1	4.0	0.6	23.9	2.5			
	P4			62	31	0.3	10.7	0.1	2.4	0.3	8.3	3.5			
	P5			49	36	0.5	21.8	0.2	12.2	0.3	9.6	16.5			
	P1	F4 (1)	Autumn	25	13	1.8	31.0	0.4	4.5	1.2	26.5	1	3	0.6	19
	P3			29	14	0.6	12.4	0.2	5.3	0.4	7.1	9			
	P4			17	9	0.3	3.7	0.1	2.2	0.1	1.4	2			
	P5			22	9	0.4	8.3	0.3	6.0	0.1	2.3	6			
	Summary														
	P1	3	Autumn	69	45	1.65	87.85	0.3	12.2	1.2	75.7	2	10	0.5	16
	P3			53	24	0.65	20.15	0.15	4.65	0.5	15.5	6			
	P4			40	20	0.3	7.2	0.1	2.3	0.2	4.9	3			
	P5			36	23	0.45	15.05	0.25	9.1	0.2	6	11			
iii) Plough and hand screefing (11)	P2	F1 (3)	Winter	33	22	0.5	14.6	0.0	6.6	0.4	6.8	4	4	0.4	11
	P3			31	18	0.9	22.3	0.2	13	0.5	9.3	8			
	P4			35	22	0.3	8.5	0.0	4.4	0.2	4.1	3			
	P5			48	29	0.3	6.4	0.1	3.2	0.2	3.2	1			
	P2	F2 (2)	Spring	24	16	0.5	7.0	0.2	3	0.3	4	3.5	3	0.3	13
	P3			24	13	0.5	8.1	0.1	3.3	0.3	4.8	6.5			
	P4			27	15	0.2	3.7	0.1	1.7	0.1	2	4.5			
	P5			32	19	0.3	6.5	0.1	4.1	0.2	2.5	1.5			
	P2	F3 (4)	Winter	40	1	0.7	16.7	0.3	5.6	0.4	8.8	5.5	12	0.4	11
	P3			57	22	0.6	24.2	0.1	4	0.5	17.1	5			
	P4			44	13	0.3	10.7	0.1	2.4	0.3	8.4	5			
	P5			49	35	0.4	10.4	0.2	5.4	0.3	6.5	22			
	P2	F4 (2)	Autumn	18	10	0.5	5.1	0.1	1.6	0.4	3.5	4	3	0.5	19
	P3			30	15	0.5	10.2	0.1	3.6	0.4	6.6	7.5			
	P4			21	10	0.2	3.2	0.1	1.5	0.1	1.7	3.5			
	P5			19	8	0.4	6.3	0.2	4.4	0.2	2	4			
	Summary														
	P2	11	Winter	28	13	0.6	11.9	0.2	4.3	0.4	6.4	5	3	0.4	13
	P3			33	19	0.5	9.4	0.1	3.8	0.4	5.7	6			
	P4			36	14	0.3	5.1	0.1	2.1	0.2	2.6	4			
	P5			28	18	0.4	6.8	0.2	4.3	0.3	3.3	4			
iv) Plough and	P3	F1 (2)	Winter	45	31	0.5	15.2	0.2	7.7	0.3	7.5	5	5	0.3	9
	P4			32	16	0.2	4.8	0.1	2.6	0.1	2.3	3.5			
	P5			39	21	0.1	4.2	0.1	2.3	0.1	2.0	1.5			
	P6			46	28	0.1	2.4	0.0	1.3	0.03	1.1	4.5			

	P7			31	13	0.5	13.1	0.2	7.9	0.2	5.2	14.5			
	P3	F2 (1)	Spring	24	12	0.6	10.1	0.2	3.7	0.4	6.4	5	3	0.5	13
	P4			17	10	0.3	4.4	0.1	2.5	0.2	1.9	6			
	P5			31	18	0.4	8.7	0.2	5.4	0.2	3.2	1			
	P6			35	17	0.0	1.2	0.0	0.7	0.03	0.5	4			
	P7			13	3	0.3	4.0	0.3	3.3	0.1	0.7	8			
	P3	F3 (4)	Winter	57	22	0.6	24.2	0.1	4.0	0.5	17.1	5	12	0.4	11
	P4			44	13	0.3	10.7	0.1	2.4	0.3	8.4	5			
	P5			49	35	0.4	10.4	0.2	5.4	0.3	6.5	17			
	P6			46	20	0.1	3.9	0.0	2.5	0.1	1.5	11			
	P7			47	22	1.0	41.5	0.3	15.7	0.5	16.8	8.5			
	Summary														
	P3	7	Winter	45	22	0.6	15.2	0.2	4	0.4	7.5	5	5	0.4	11
	P4			32	13	0.3	4.8	0.1	2.5	0.2	2.3	5			
	P5			39	21	0.4	8.7	0.2	5.4	0.2	3.2	2			
	P6			46	20	0.1	2.4	0.0	1.3	0.03	1.1	5			
	P7			31	13	0.5	13.1	0.3	7.9	0.2	5.2	9			

Figure A.55.2: Forest development categories (F1, F2, F3, F4, F5) box plots for variables under a group of coincidental events in case of A) Plough cultivation (P3, P4, P5), B) Plough cultivation (P3, P4, P5) and unplanted plot (P1) C) Plough cultivation (P3, P4, P5) and hand screefing (P2) and D) Plough cultivation (P3, P4, P5) and excavation mounding (P6, P7) for wet weather conditions




C)
WET PERIOD - P2, P3, P4 and P5
Plot P2 P3 P4 P5
Qvt (mm)
Qpt (mm/hr)
Qv (mm)
Qp (mm/hr)
Ed (hr)
Rt (hr)
Tp (hr)
P (mm)
API (mm)
F2 F3 F4 F5

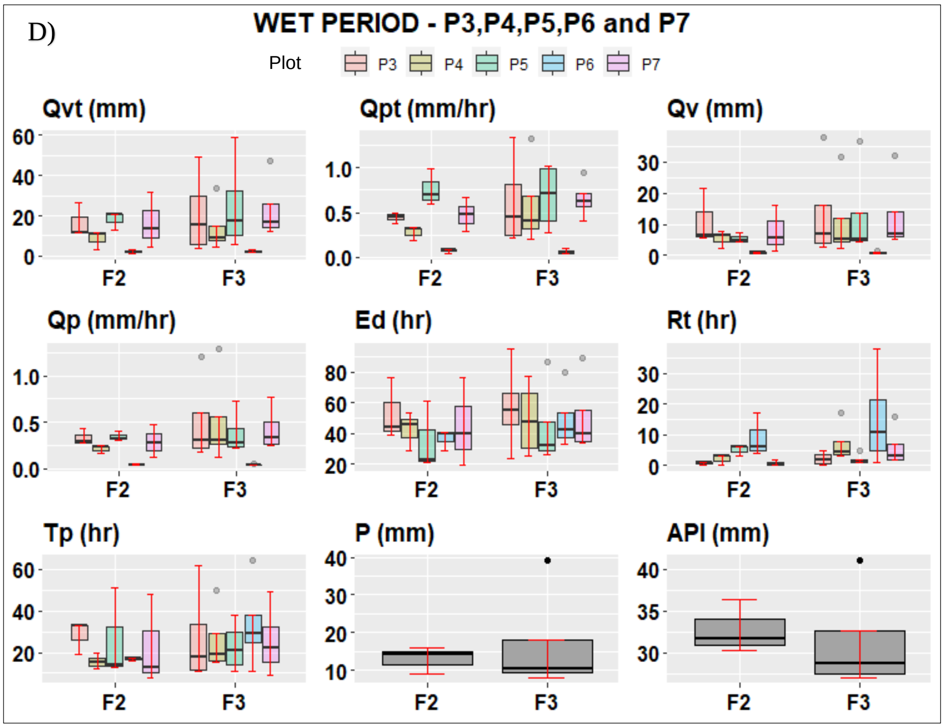

D)
WET PERIOD - P3,P4,P5,P6 and P7
Plot P3 P4 P5 P6 P7
Qvt (mm)
Qpt (mm/hr)
Qv (mm)
Qp (mm/hr)
Ed (hr)
Rt (hr)
Tp (hr)
P (mm)
API (mm)
F2 F3

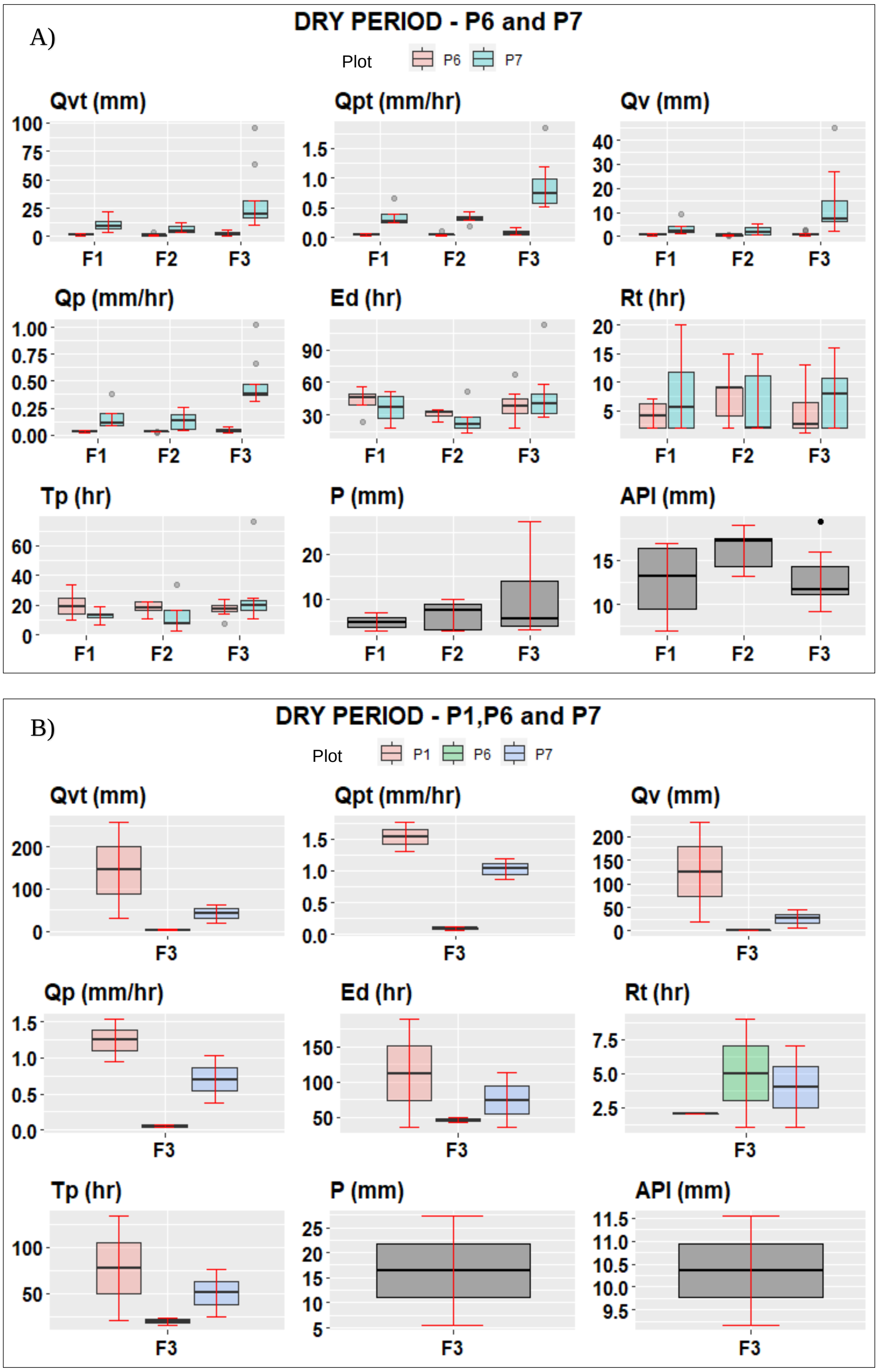
Table A.55.2: Median values of all variables for each forest development category (F1, F2, F3, F4, F5) for a group of coincidental events in case of i) Plough cultivation (P3, P4, P5) ii) Plough cultivation (P3, P4, P5) and unplanted plot (P1) iii) Plough cultivation (P3, P4, P5) and hand screefing (P2) and iv) Plough cultivation (P3, P4, P5) and excavation mounding (P6, P7) for wet weather conditions

Cultivation (No of events)	Plot	FDC (no of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
i) Plough (21)	P3	F2 (5)	Autumn	39	21	0.4	11.4	0.1	4.9	0.3	5.6	1	11	0.5	30
	P4			32	15	0.3	4.1	0.1	0.9	0.2	3.3	2			
	P5			45	14	0.6	19.5	0.3	9.4	0.3	4.6	6			
	P3	F3 (6)	Winter	39	14	0.3	6.3	0.2	3.2	0.2	3.6	1	11		29
	P4			36	19	0.4	8.7	0.1	2.9	0.3	4.1	2			
	P5			28	13	0.6	11.8	0.3	8.0	0.3	4.5	4			
	P3	F4 (6)	Autumn	36	15	0.7	17.7	0.2	6.4	0.5	8.8	7	9	0.7	31
	P4			32	13	0.2	5.7	0.0	1.6	0.2	3.4	2			
	P5			33	19	0.4	10.0	0.2	8.3	0.2	2.2	2			
	P3	F5 (4)	Autumn	46	25	0.5	18.5	0.1	9.2	0.4	9.3	3	16	0.6	39
	P4			40	22	0.3	5.3	0.0	1.6	0.2	2.8	2			
	P5			50	22	0.4	15.4	0.2	11.8	0.2	3.6	8			
	Summary														
	P3	21	Autumn	39	18	0.5	14.6	0.2	5.7	0.4	7.2	2	11	0.6	31
	P4			34	17	0.3	5.5	0.1	1.6	0.2	3.4	2			
	P5			39	17	0.5	13.6	0.3	8.9	0.3	4.1	5			
ii) Plough and unplanted (5)	P1	F3 (4)	Autumn	42	17	4.7	101.7	0.3	3.0	4.2	99.3	2	10	0.2	41
	P3			42	15	0.7	17.7	0.1	6.2	0.5	11.5	7			
	P4			32	13	0.2	3.6	0.0	1.0	0.2	2.6	2			
	P5			33	19	0.4	10.0	0.2	8.3	0.2	2.0	2			
	P1	F4 (1)	Winter	82	59	1.9	103.5	0.3	5.9	1.7	97.6	1	13	1.1	32
	P3			57	24	0.6	23.6	0.3	14.5	0.4	9.0	1			
	P4			63	50	0.4	8.7	0.1	3.4	0.3	5.3	2			
	P5			30	11	0.3	6.0	0.0	1.3	0.2	4.7	2			
	Summary														
	P1	5	Autumn	62	38	3.3	102.6	0.3	4.5	3.0	98.5	2	12	0.7	37
	P3			50	20	0.7	20.7	0.2	10.4	0.5	10.3	4			
	P4			48	32	0.3	6.2	0.1	2.2	0.3	4.0	2			
	P5			32	15	0.4	8.0	0.1	4.8	0.2	3.4	2			
iii) Plough and hand screefing (20)	P2	F2 (5)	Autumn	50	37	0.4	8.1	0.0	2.2	0.4	5.9	2	11	0.5	30
	P3			39	21	0.4	11.4	0.1	4.9	0.3	5.6	1			
	P4			32	15	0.3	4.1	0.0	0.9	0.2	3.3	3			
	P5			45	14	0.6	19.5	0.3	9.4	0.3	4.6	6			
	P2	F3 (5)	Winter	24	18	0.6	7.9	0.1	3.0	0.5	5.1	4	11	0.6	28
	P3			24	12	0.3	5.7	0.1	2.4	0.2	2.9	3			
	P4			32	16	0.4	8.7	0.1	2.5	0.3	3.2	5			
	P5			26	15	0.7	12.0	0.3	8.9	0.3	4.3	5			
	P2	F4 (6)	Autumn	28	12	0.5	11.2	0.1	2.9	0.4	7.0	6	9	0.7	31
	P3			36	14	0.7	17.7	0.2	6.4	0.5	8.8	9			
	P4			32	13	0.2	5.7	0.0	1.6	0.2	3.4	2			
	P5			33	19	0.4	10.0	0.2	8.3	0.2	2.2	4			
	P2	F5 (4)	Autumn	33	23	0.5	12.9	0.1	4.3	0.4	7.2	4	15	0.6	39
	P3			46	25	0.5	18.5	0.1	9.2	0.4	9.3	1			
	P4			40	22	0.3	5.3	0.0	1.6	0.2	2.8	2			
	P5			50	22	0.4	15.4	0.2	11.8	0.2	3.6	8			
	Summary														
	P2	F1 (20)	Autumn	31	21	0.5	9.7	0.1	3.0	0.4	6.5	4	11	0.6	31
	P3			38	18	0.5	14.6	0.1	5.7	0.4	7.2	2			
	P4			32	16	0.3	5.5	0.0	1.6	0.2	3.3	3			
	P5			39	17	0.5	13.7	0.3	9.2	0.3	4.0	6			
iv) Plough and	P3	F2 (3)	Autumn	44	33	0.4	11.7	0.1	4.9	0.3	6.6	1	14	0.4	32
	P4			46	15	0.3	11.0	0.1	3.9	0.2	6.4	3			
	P5			23	14	0.7	20.9	0.4	13.5	0.3	4.6	6			
	P6			40	17	0.1	2.0	0.0	1.1	0.0	0.9	6			
	P7			40	13	0.5	13.8	0.2	8.0	0.3	5.8	1			

	P3	F3 (4)	Winter	55	18	0.5	15.2	0.1	7.1	0.3	6.7	2	11	0.4	29
	P4			48	19	0.4	8.7	0.1	2.9	0.3	5.1	5			
	P5			32	21	0.7	17.6	0.2	12.4	0.3	5.3	1			
	P6			42	29	0.1	2.1	0.0	1.0	0.0	0.6	11			
	P7			40	22	0.6	16.9	0.2	9.9	0.3	7.1	3			
	Summary														
	P3	27	Autumn	50	26	0.5	13.5	0.1	6.0	0.3	**6.7**	2	13	0.4	31
	P4			47	17	0.4	9.9	0.1	3.4	0.3	5.8	4			
	P5			28	18	0.7	19.3	0.3	13.0	0.3	5	4			
	P6			41	23	0.1	2.1	0.0	1.1	0.0	0.8	**9**			
	P7			40	18	0.6	15.4	0.2	9.0	0.3	6.5	2			

Appendix 6.

Figure A.66.1: Forest development categories (F1, F2, F3, F4, F5) box plots for variables under a group of coincidental events in case of A) Excavation mounding (P6, P7), B) Excavation mounding (P6, P7), and unplanted plot (P1) C) Excavation mounding (P6, P7) and hand screefing (P2) for dry weather conditions



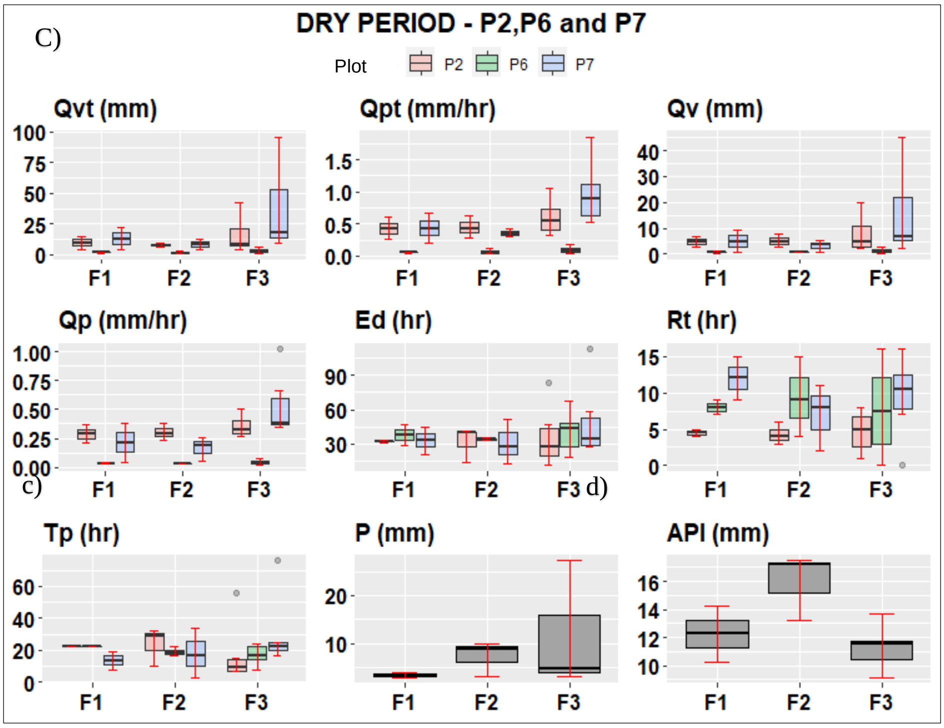
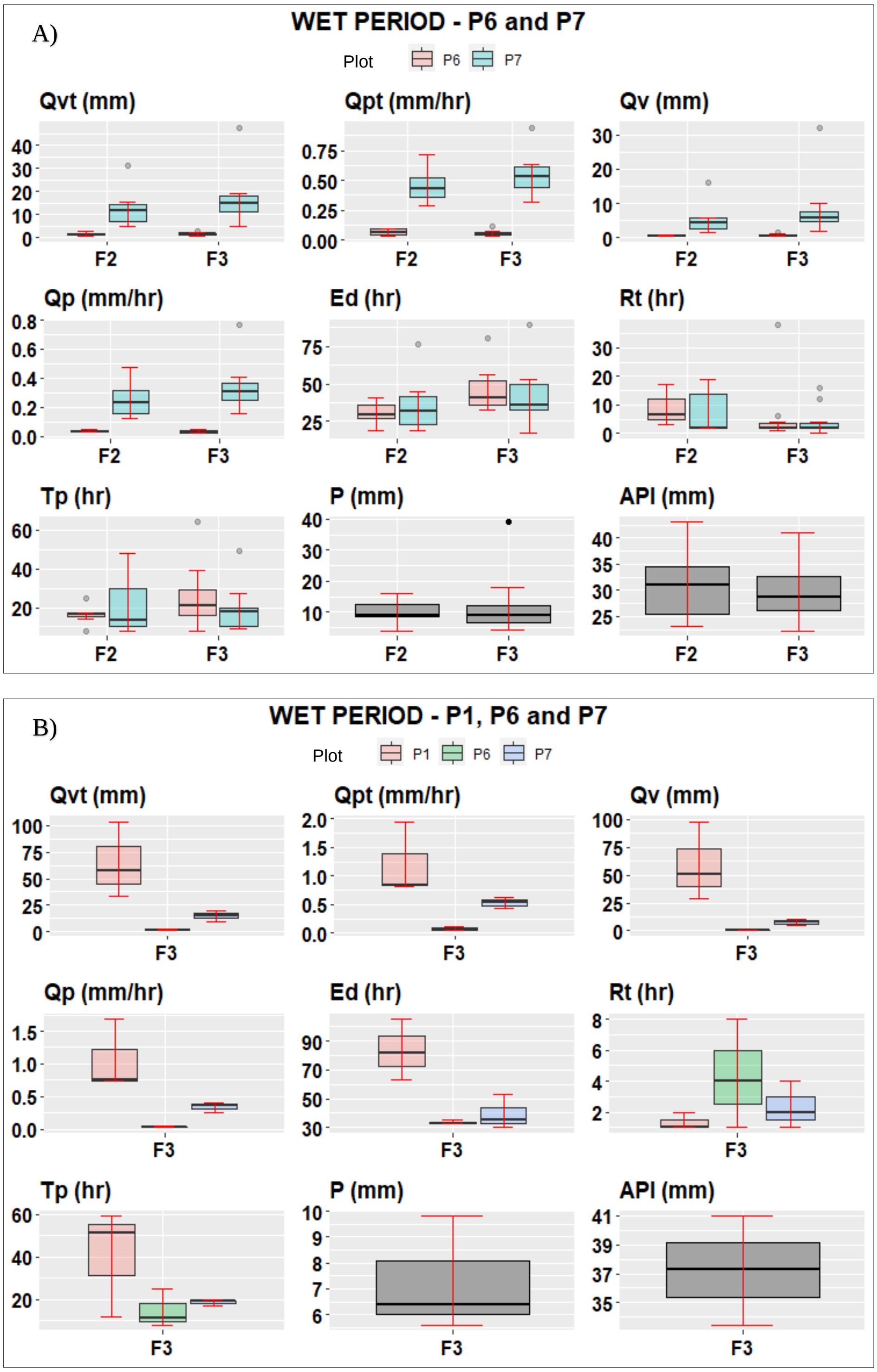

C)
DRY PERIOD - P2,P6 and P7
Plot
P2
P6
P7
Qvt (mm)
100
75
50
25
0
F1
F2
F3
Qpt (mm/hr)
1.5
1.0
0.5
0.0
F1
F2
F3
Qv (mm)
40
30
20
10
0
F1
F2
F3
Qp (mm/hr)
1.00
0.75
0.50
0.25
0.00
F1
F2
F3
c)
Ed (hr)
90
60
30
F1
F2
F3
d)
Rt (hr)
15
10
5
0
F1
F2
F3
Tp (hr)
60
40
20
0
F1
F2
F3
P (mm)
20
10
F1
F2
F3
API (mm)
16
14
12
10
F1
F2
F3

Table A.66.1: Median values of all variables for each forest development category (F1, F2, F3, F4, F5) for a group of coincidental events in case of i) Excavation mounding (P6, P7), ii) Excavation mounding (P6, P7) and unplanted plot (P1) iii) Excavation mounding (P6, P7) and hand screefing (P2) for dry weather conditions

Cultivation (No of events)	Plot	FDC (no of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
i) E. mounding (17)	P6	F1 (5)	Winter	45	22	0.05	1.3	0.02	0.7	0.0	0.8	6	4	0.4	14
	P7			30	13	0.2	7.6	0.2	4.9	0.1	**2.0**	9			
	P6	F2 (4)	Autumn	34	18	0.04	1.0	0.01	0.5	0.0	0.5	7	8	0.5	17
	P7			23	13	0.3	6.6	0.2	4.2	0.2	**2.1**	2			
	P6	F3 (8)	Winter	38	18	0.1	1.9	0.03	1.1	0.0	0.8	3	6	0.4	11
	P7			40	20	0.7	19.3	0.2	13	0.4	**7.2**	6			
	Summary														
	P6	17	Wint	38	18	0.1	1.3	0.02	0.7	0.0	0.8	6	6	0.4	14
	P7			30	13	0.3	7.6	0.2	4.9	0.2	2.1	6			
ii) E. mounding and Unplanted plot (2)	P1	F3 (2)	Winter	112	77	1.5	144.7	0.2	19.9	1.2	124.8	2	16	0.4	10
	P6			46	20	0.1	3.2	0.04	1.7	0.1	1.5	5			
	P7			75	5	1.0	41.5	0.3	15.7	0.7	25.8	4			
iii) E. mounding and h. screefing (11)	P2	F1 (2)	Winter	32	22	0.4	9.4	0.1	4.7	0.3	4.7	5	3	0.4	12
	P6			38	22	0.1	1.6	0.02	0.8	0.0	0.8	8			
	P7			33	14	0.4	**13.0**	0.2	8.0	0.2	**5.0**	12			
	P2	F2 (3)	spring	40	29	0.4	7.1	0.1	2.1	0.3	**4.5**	4	9	0.5	17
	P6			34	18	0.0	1.2	0.02	0.7	0.0	0.5	9			
	P7			28	17	0.4	**8.6**	0.2	5.0	0.2	3.6	8			
	P2	F3 (6)	Winter	28	9	0.5	8.2	0.1	4.9	0.3	4.6	5	5	0.4	12
	P6			43	17	0.1	2.6	0.04	1.7	0.0	0.8	8			
	P7			34	22	0.9	**18.3**	0.3	14.0	0.4	**6.6**	11			
	Summary														
	P2	11	Winter	32	22	0.4	8.2	0.1	4.7	0.3	4.6	5	5	0.4	12
	P6			38	18	0.1	1.6	0.0	0.8	0.0	0.8	8			
	P7			33	17	0.4	13.0	0.2	8.0	0.2	5.0	11			

Figure A.66.2: Forest development categories (F1, F2, F3, F4, F5) box plots for variables under a group of coincidental events in case of A) Excavation mounding (P6, P7), B) Excavation mounding (P6, P7) and unplanted plot (P1) C) Excavation mounding (P6, P7) and hand screefing (P2)



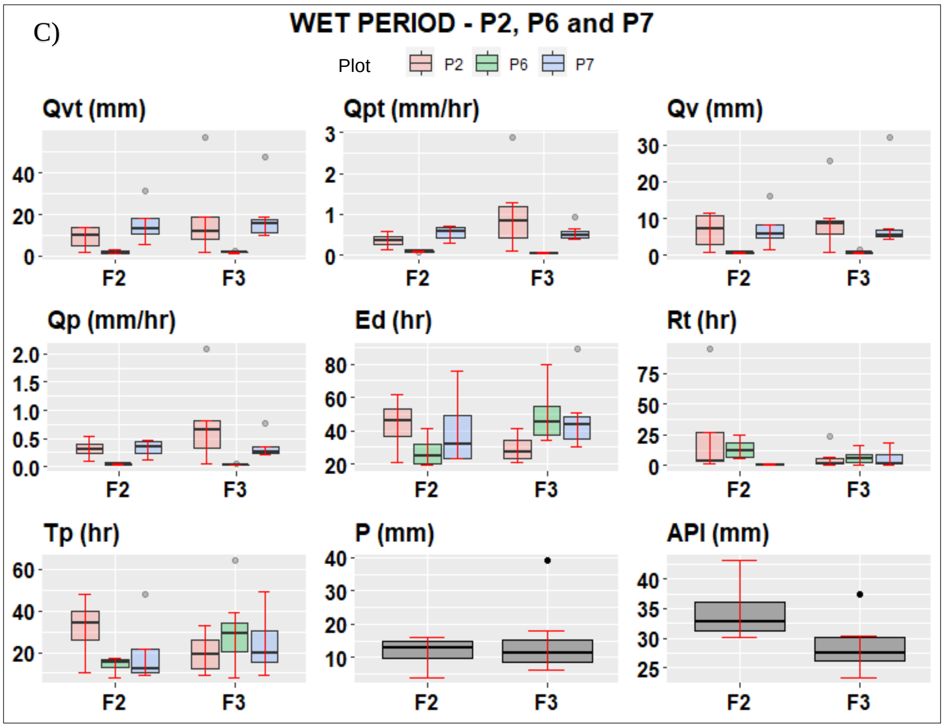

C)
WET PERIOD - P2, P6 and P7
Plot
P2
P6
P7
Qvt (mm)
0
20
40
Qpt (mm/hr)
0
1
2
3
Qv (mm)
0
10
20
30
Qp (mm/hr)
0.0
0.5
1.0
1.5
2.0
Ed (hr)
20
40
60
80
Rt (hr)
0
25
50
75
Tp (hr)
20
40
60
P (mm)
10
20
30
40
API (mm)
25
30
35
40
F2
F3

Table A.66.2: Median values of all variables for each forest development category (F1, F2, F3, F4, F5) for a group of coincidental events in case of i) Excavation mounding (P6, P7), ii) Excavation mounding (P6, P7) and unplanted plot (P1) iii) Excavation mounding (P6, P7) and hand screefing (P2) iv) Excavation mounding (P6, P7) and plough cultivation (P3, P4, P5) for wet weather conditions

Cultivation (No of events)	Plot	FDC (no of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
i) E. mounding (18)	P6	F2 (8)	Autumn	30	16.5	0.1	1.2	0.04	0.7	0.0	0.6	7	9	0.5	31
	P7			32	13.5	0.4	11.7	0.2	7.2	0.2	4.2	2			
	P6	F3(10)	Winter/ Spring	41	21	0.05	1.6	0.02	1.0	0.03	0.6	2	9	0.4	29
	P7			36	18.0	0.5	15.0	0.2	7.9	0.3	5.9	2			
	Summary														
	P6	18	Win	36	19	0.1	1.4	0.0	0.9	0.0	0.6	5	9	0.5	30
	P7			34	16	0.5	13.4	0.2	7.6	0.3	5.1	2			
ii) E. mounding and unplanted plot (3)	P1	F3 (3)	Winter	82	51	0.8	57.7	0.1	5.9	0.7	50.1	1	6	0.3	38
	P6			33	11	0.1	1.8	0.04	1.3	0.0	0.4	4			
	P7			35	19	0.5	15.0	0.2	7.3	0.4	7.7	2			
iii) E. mounding and h. screefing (11)	P2	F2 (5)	Autumn	46	34	0.4	9.8	0.05	2.1	0.3	**7.2**	4	13	0.5	33
	P6			25	15	0.1	1.7	0.04	0.9	0.0	0.7	**12**			
	P7			32	12	0.6	12.9	0.2	7.2	0.4	5.8	1			
	P2	F3 (6)	Winter	27	19	**0.8**	12.1	0.1	2.8	0.7	**8.6**	2	11	0.5	28
	P6			**45**	**29**	0.1	1.8	0.02	1.1	0.0	0.7	**6**			
	P7			44	20	0.5	**15.3**	0.2	**8.6**	0.3	5.4	2			
	Summary														
	P2	11	Winter	37	27	0.6	11.0	0.1	2.5	0.5	7.9	3	12	0.5	31
	P6			35	22	0.1	1.8	0.0	1.0	0.0	0.7	9			
	P7			38	16	0.6	14.1	0.2	7.9	0.4	5.6	2			

Appendix 7.

Figure A.77.1: Forest development categories (F1, F3) box plots for variables under a group of coincidental events in case of A) Inch 1 modelled and observed data B) Inch 2 modelled and observed data for dry weather conditions

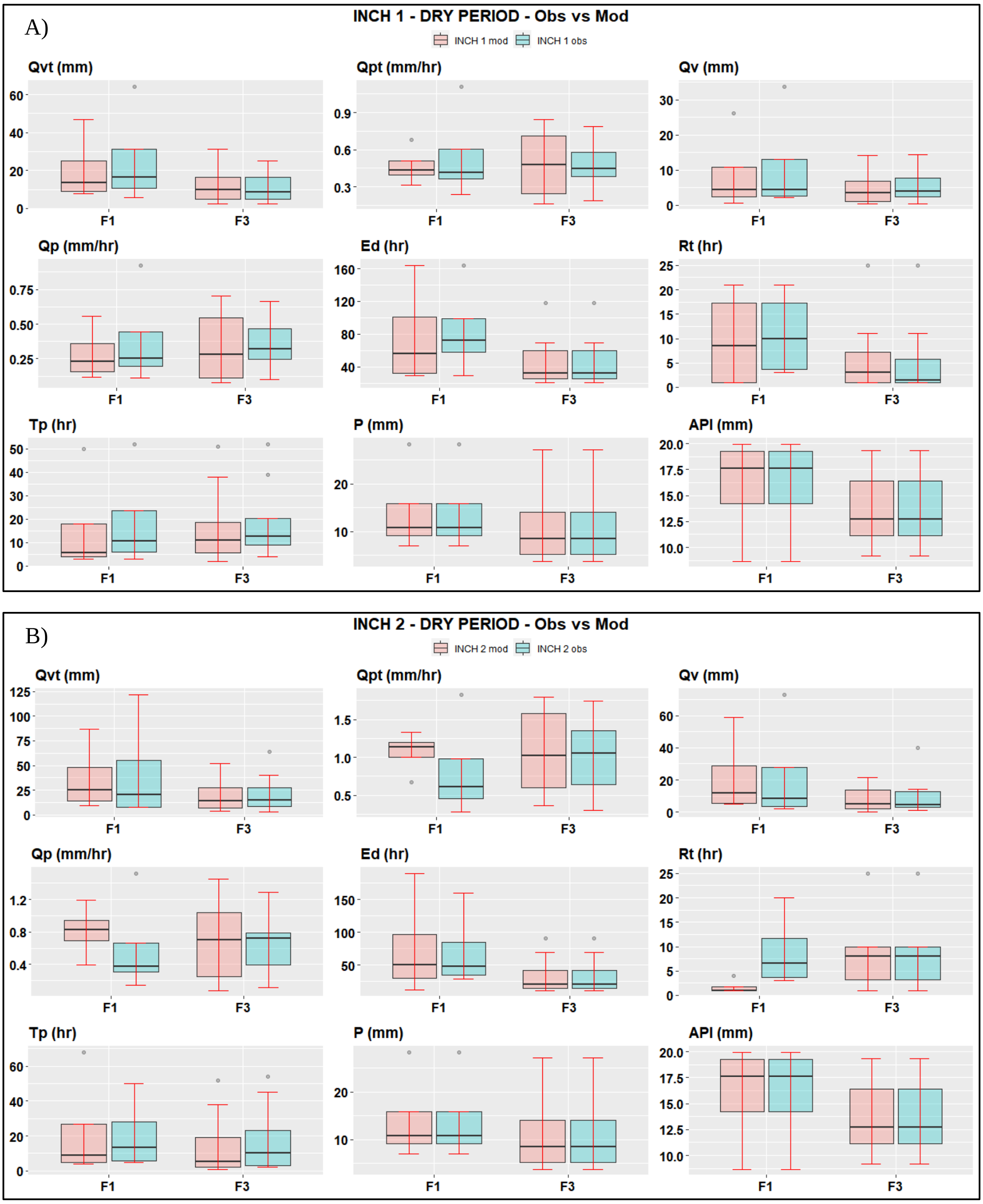


Table A.77.1: Median values of all variables for each forest development category (F1, F3) for a group of coincidental events in case of modelled and observed data for Inch 1 and Inch 2 for dry weather conditions with a summary of the end of the table

Sub-catchment	FDC (no of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
Inch 1- mod	F1 (4)	Winter	57	6	0.4	13.5	0.1	10.3	0.2	4.4	9	11	0.4	18
Inch 1-obs			**63**	**11**	**0.4**	**16.3**	**0.2**	**11.9**	**0.3**	**4.4**	**10**			
Inch 2 -mod			**51**	9	**1.1**	**25.2**	**0.3**	**13.2**	**0.8**	**12**	1			
Inch 2-obs			48	14	0.6	20.4	0.2	12.6	0.4	8.4	**7**			
Inch 1- mod	F3 (8)	Winter	32	11	**0.5**	**9.6**	**0.1**	**5.4**	**0.3**	3.5	**3**	9	0.5	12
Inch 1-obs			**32**	**13**	0.4	8.4	0.1	4.5	0.3	**3.9**	2			
Inch 2- mod			21	6	1	14.3	0.3	**9.4**	0.7	**4.9**	9			
Inch 2-obs			21	10	**1.1**	**14.6**	0.3	8.6	0.7	4.5	8			
Summary (modelled and observed data)														
Inch 1- mod	12	Winter	44	8	0.5	11.6	0.1	7.9	0.3	4.0	6	10	0.5	15
Inch 1-obs			47	12	0.4	12.4	0.2	8.2	0.3	4.2	6			
Inch 2- mod			36	7	1.1	19.8	0.3	11.3	0.8	8.5	5			
Inch 2-obs			34	12	0.9	17.5	0.3	10.6	0.6	6.5	7			

Figure A.77.2: Forest development categories (F1, F2, F3, F4, F5) box plots for variables under a group of coincidental events in case of A) Inch 1 modelled and observed data B) Inch 2 modelled and observed data for wet weather conditions

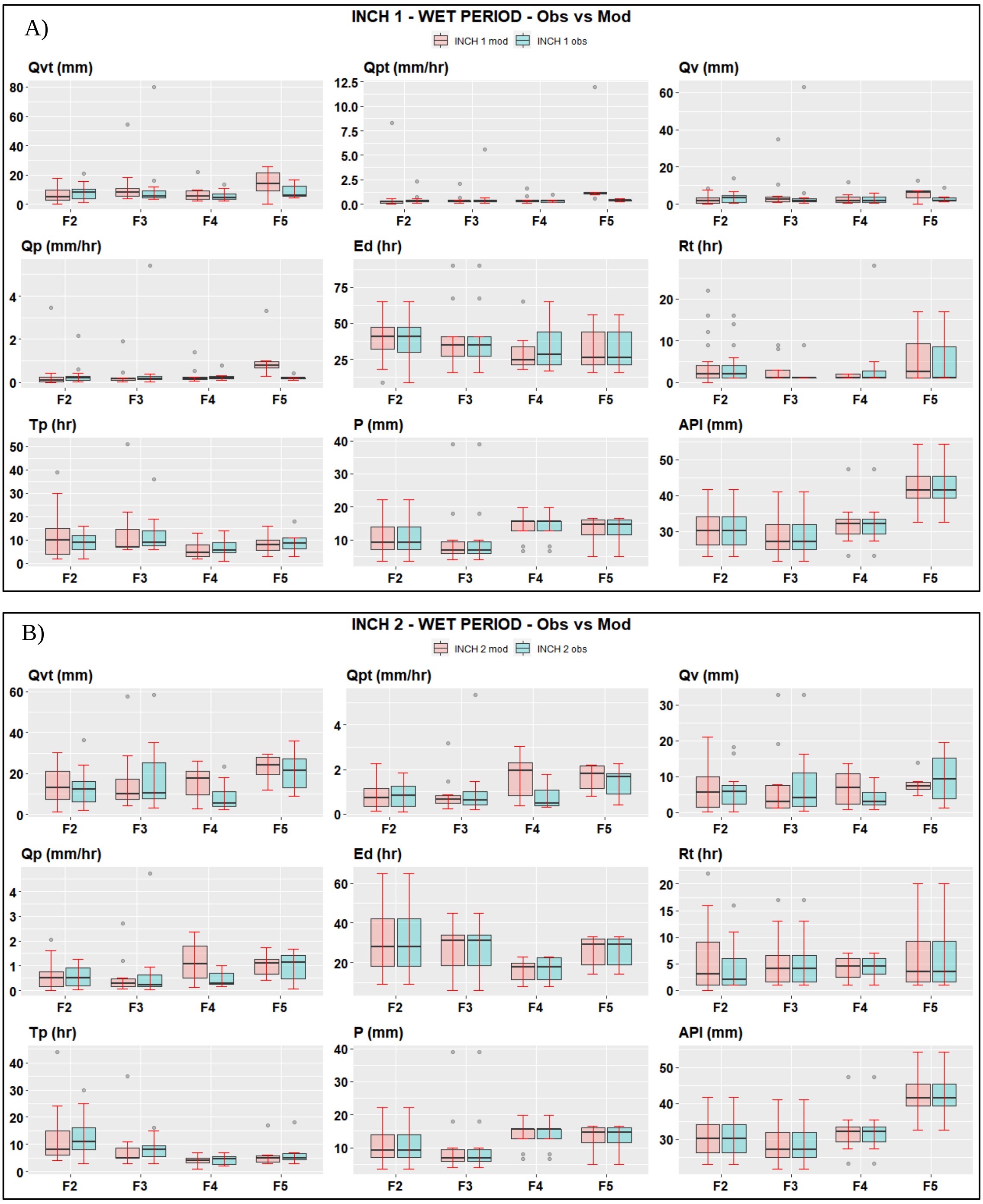


Table A.77.2: Median values of all variables for each forest development category (F1, F2, F3, F4, F5) for a group of coincidental events in case of modelled and observed data for Inch 1 and Inch 2 for wet weather conditions with a summary at the of the table.

Sub-catchment	FDC (no of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
Inch 1- mod	F2 (21)	Autumn	41	10	0.2	5.2	0.1	4.1	0.1	1.8	2	9.2	0.5	30.2
Inch 1-obs			41	9	0.3	8.4	0.1	4.2	0.2	3.4	2			
Inch 2 -mod			28	8	1	13	0.3	8	0.5	6	3			
Inch 2-obs			28	11	0.8	12.3	0.3	6.1	0.5	5.7	2			
Inch 1- mod	F3 (11)	Winter	35	7	0.3	8.2	0.2	5.3	0.2	2.6	1	6.8	0.4	27
Inch 1-obs			35	9	0.3	5.6	0.1	4.1	0.2	1.9	1			
Inch 2- mod			31	5	0.7	9.9	0.3	7.0	0.3	2.9	4			
Inch 2-obs			31	8	0.6	10.3	0.4	6.4	0.2	4	4			
Inch 1- mod	F4 (8)	Autumn	25	5	0.3	5.3	0.2	3.9	0.2	1.6	1	15.5	1.4	32.1
Inch 1-obs			29	6	0.3	4.5	0.1	2.7	0.2	1.7	1			
Inch 2- mod			18	4	2.0	17.5	0.5	10.4	1.1	6.9	5			
Inch 2-obs			18	5	0.5	5.6	0.2	2.7	0.3	3	5			
Inch 1- mod	F5 (6)	Autumn	26	8	1.1	14.1	0.3	8	0.8	6.5	3	14.7	0.7	41.5
Inch 1-obs			26	9	0.4	6.3	0.2	5	0.2	1.9	1			
Inch 2- mod			29	5	2	24	1	15	1	7	3			
Inch 2-obs			29	5	1.7	21.4	0.5	10.3	1.1	9.3	4			
Summary (modelled and observed data)														
Inch 1- mod	46	Autumn	31	8	0.3	6.8	0.2	4.7	0.2	2	2	12	0.6	31
Inch 2- mod			29	5	1.5	15.3	0.4	9.2	0.8	6	4			
Inch 1- obs			32	9	0.3	6.0	0.1	4.2	0.2	2	1			
Inch 2- obs			29	7	0.7	11.3	0.4	6.3	0.4	5	4			

Appendix 8.

Table A.88.1: Forest development categories (F1, F3) box plots for variables under a group of coincidental events in case of hand screefing (P2) modelled and observed data for dry weather conditions

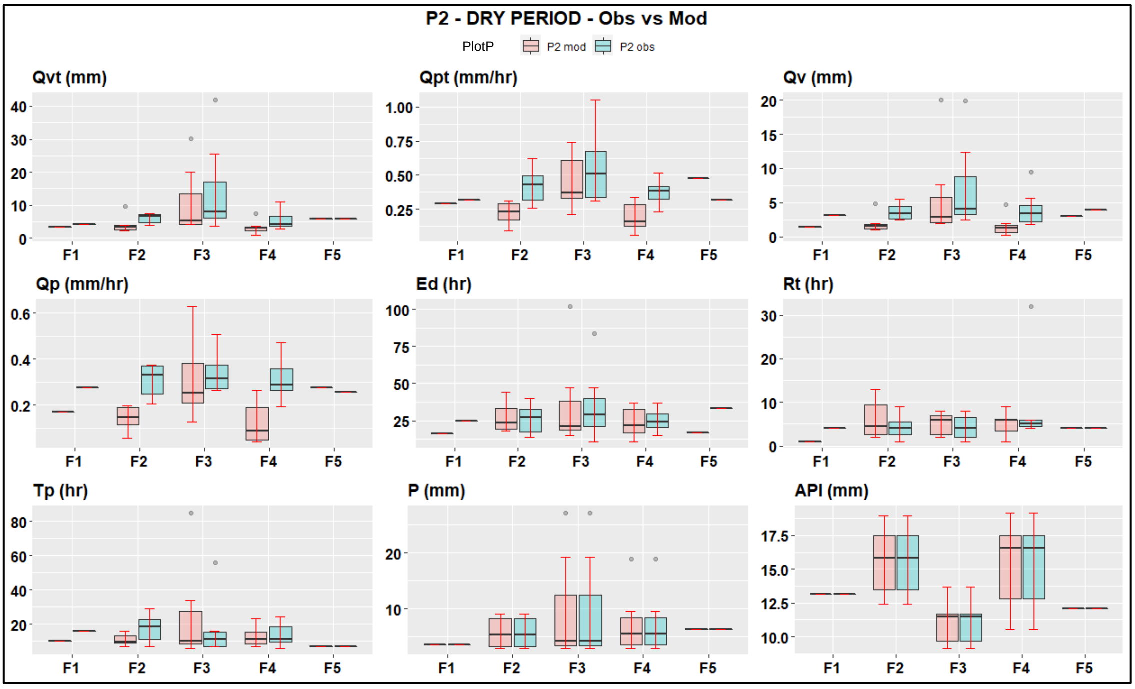


Table A.88.1: Median values of all variables for each forest development category (F1, F2, F3, F4, F5) for a group of coincidental events in case of modelled and observed data for hand screefing (P2) for dry weather conditions with a summary of the end of the table

Plot	FDC (no of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
P2 - mod	F1 (1)	Spring	58	10	0.3	8.1	0.1	5.4	0.2	2.7	1	3.6	0.5	13
P2- obs			25	16	0.3	4.2	0.04	1.1	0.3	3.1	4			
P2 - mod	F2 (5)	Spring	42	16	0.3	4.6	0.1	2.4	0.2	2.7	1	3	0.4	14
P2- obs			31	22	0.4	6.6	0.1	1.6	0.3	2.8	4			
P2 - mod	F3 (7)	Winter	35	14	0.4	6	0.1	2.8	0.3	3.7	3	4	0.4	12
P2- obs			29	11	0.5	8	0.1	4.3	0.3	4.1	4			
P2 - mod	F4 (6)	Spring	32	11	0.3	3.9	0.05	2.0	0.2	2.5	6	5	0.4	17
P2- obs			23	11	0.4	4	0.05	1.2	0.3	3.0	6			
P2 - mod	F5 (1)	Autumn	31	11	0.5	7.3	0.1	3.5	0.4	3.7	1	6	0.8	12
P2- obs			33	7	0.3	6	0.1	2.0	0.3	3.9	4			
Summary (modelled and observed data)														
P2 - mod	20	Spring	35	11	0.3	6	0.1	2.8	0.2	2.7	1	4	0.4	13
P2- obs			29	11	0.4	6	0.1	1.6	0.3	3.1	4			

Figure A.88.2: Forest development categories (F2, F3, F4, F5) box plots for variables under a group of coincidental events in case of hand screefing (P2) modelled and observed data for wet weather conditions

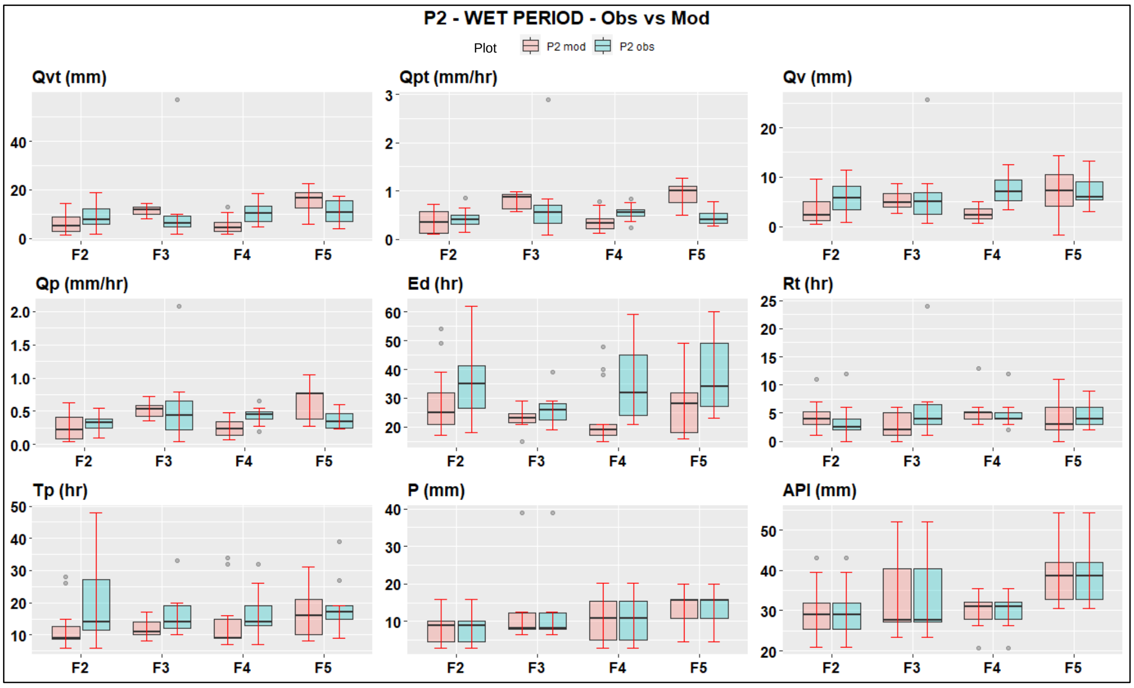


Table A.88.2: Median values of all variables for each forest development category (F2, F3, F4, F5) for a group of coincidental events in case of modelled and observed data for hand screefing (P2) for wet weather conditions with a summary of the end of the table

Plot	FDC (no of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
P2 - mod	F2 (21)	Au tu	27.5	11	0.3	5.7	0.1	2.2	0.2	2.6	3.5	9	0.5	29
P2- obs			35	14	0.4	7.7	0.05	1.9	0.3	5.8	2.5			
P2 - mod	F3 (8)	Wi nte	18.5	9	0.8	9.6	0.3	5.5	0.4	4.1	7	8	0.6	33
P2- obs			24.5	14	0.5	6.1	0.1	1.5	0.4	4.1	4			
P2 - mod	F4 (8)	Au tu	44	13	0.3	6.5	0.1	2.3	0.3	3.9	1	11	0.7	32
P2- obs			29	13	0.5	9.0	0.1	1.6	0.4	6.7	4			
P2 - mod	F5 (5)	Au tu	28	16	1	12.2	0.3	6.7	0.7	6.3	3	16	0.8	39
P2- obs			34	17	0.4	10.5	0.05	2.1	0.3	6.0	4			
Summary (modelled and observed data)														
P2 - mod	42	Autumn	28	12	0.6	8.1	0.2	3.9	0.4	4	3	10	0.7	32
P2- obs			32	14	0.5	8.4	0.1	1.8	0.4	5.9	4			

Appendix 9.

Figure A.99.1: Forest development categories (F1, F2, F3, F4) box plots for variables under a group of coincidental events in case of plough (P3) modelled and observed data for dry weather conditions

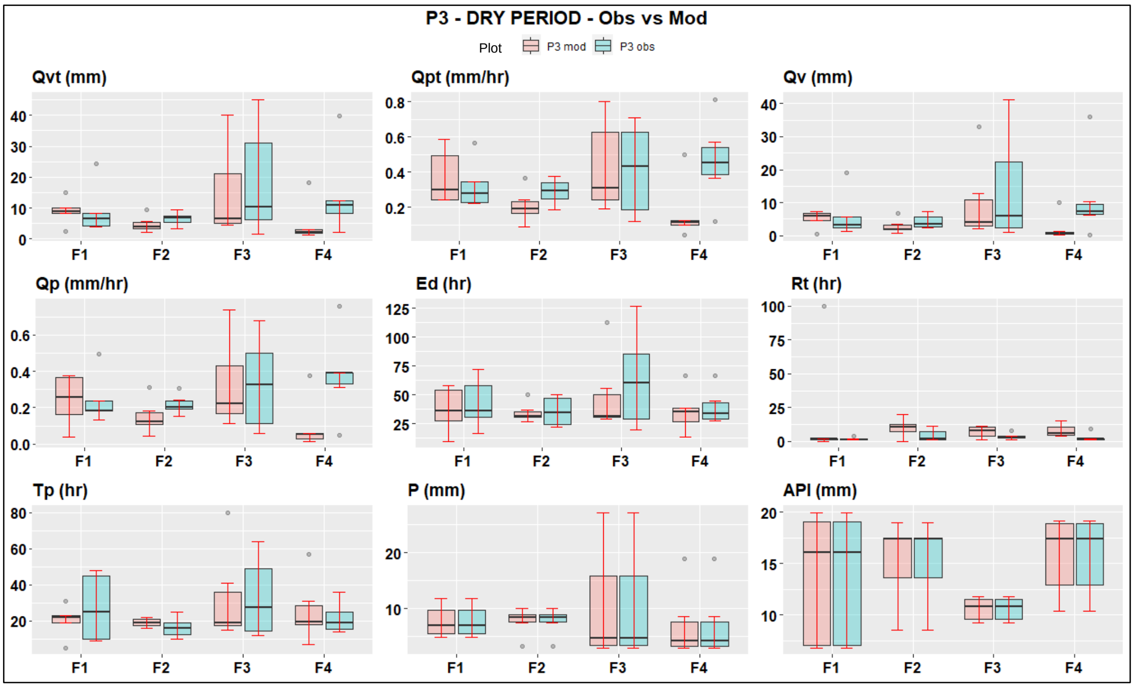


Table A.99.1: Median values of all variables for each forest development category (F1, F2, F3, F4) for a group of coincidental events in case of modelled and observed data for plough (P3) for dry weather conditions with a summary of the end of the table

Plot	FDC (no of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
P3 - mod	F1 (4)	Winter	31	15	0.4	8.5	0.2	6.0	0.2	3.7	8	6	0.5	12
P3- obs			34	18	0.3	5.3	0.1	2.6	0.2	2.7	2			
P3 - mod	F2 (6)	Spring	44	19	0.2	5.9	0.1	2.6	0.1	2.9	10	8	0.5	17
P3- obs			35	16	0.3	6.8	0.1	2.3	0.2	3.5	2			
P3 - mod	F3 (6)	Winter	32	19	0.3	6.6	0.1	2.7	0.2	4.0	7	5	0.4	11
P3- obs			60	28	0.4	10.3	0.1	4.0	0.3	5.9	3			
P3 - mod	F4 (6)	Autumn /	50	21	0.1	3.4	0.0	1.9	0.1	1.6	5	4	0.4	17
P3- obs			34	19	0.5	11.0	0.1	2.3	0.4	7.2	2			
Summary (modelled and observed data)														
P3 - mod	22	Winer	38	19	0.3	6.3	0.1	2.7	0.2	3.3	8	6	0.5	15
P3- obs			35	19	0.4	8.6	0.1	2.5	0.3	4.7	2			

Figure A.99.2: Forest development categories (F2, F3, F4, F5) box plots for variables under a group of coincidental events in case of plough (P3) modelled and observed data for wet weather conditions

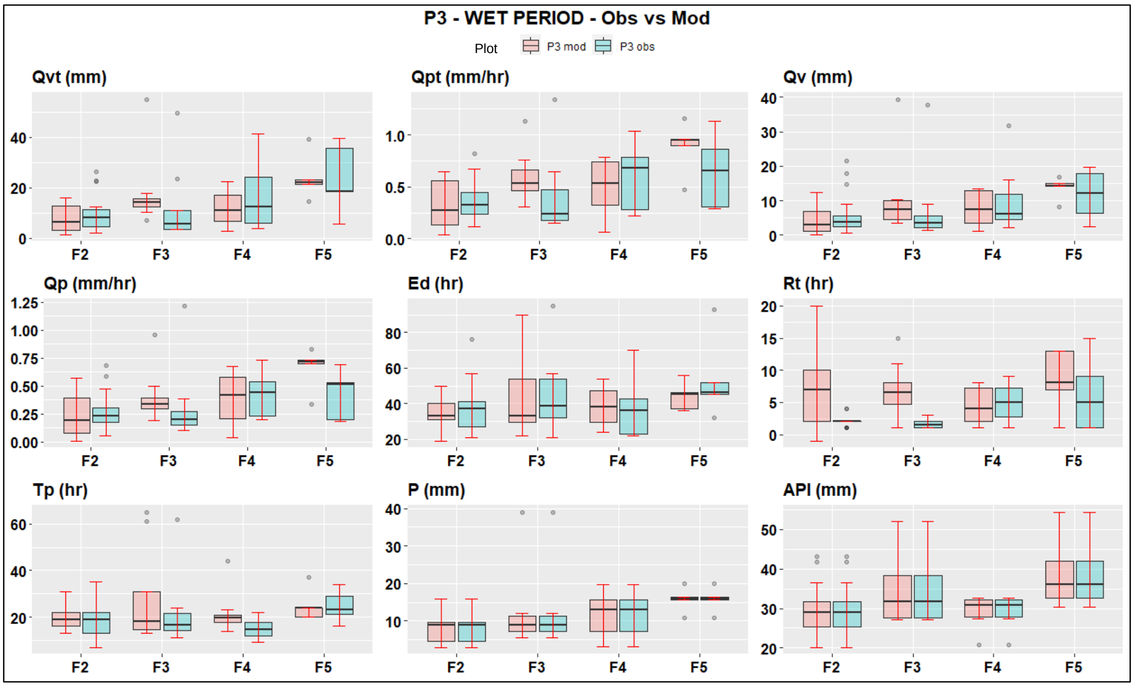


Table A.99.2: Median values of all variables for each forest development category (F1, F2, F3, F4) for a group of coincidental events in case of modelled and observed data for plough (P3) for wet weather conditions with a summary of the end of the table

Plot	FDC (no of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
P3 - mod	F2 (21)	Autumn	35	19	0.3	6.2	0.1	2.9	0.2	3.0	6	9	0.5	29
P3-obs			37	19	0.3	8.1	0.1	3.2	0.2	3.9	1			
P3 - mod	F3 (8)	Winter	33	18	0.5	14.2	0.2	6.5	0.3	7.3	7	9	0.4	31.7
P3-obs			39	17	0.2	5.4	0.0	2.1	0.2	3.5	2			
P3 - mod	F4 (8)	Autumn	37	19	0.5	10.5	0.1	4.2	0.3	5.9	4	13	1.1	31
P3-obs			36	15	0.7	12.4	0.1	6.2	0.4	6.2	7			
P3 - mod	F5 (5)	Autumn	45	24	0.9	22.2	0.2	7.1	0.7	14.3	8	16	0.6	36
P3-obs			46	23	0.7	18.5	0.1	11.9	0.5	12.1	1			
Summary (modelled and observed data)														
P3 - mod	42	Autumn	36	19	0.5	12.4	0.2	5.4	0.3	6.6	7	11	0.6	31
P3-obs			38	18	0.5	10.3	0.1	4.7	0.3	5.1	2			

Appendix 10.

Figure A.1010.1: Forest development categories (F1, F2, F3, F4) box plots for variables under a group of coincidental events in case of plough (P4) modelled and observed data for dry weather conditions

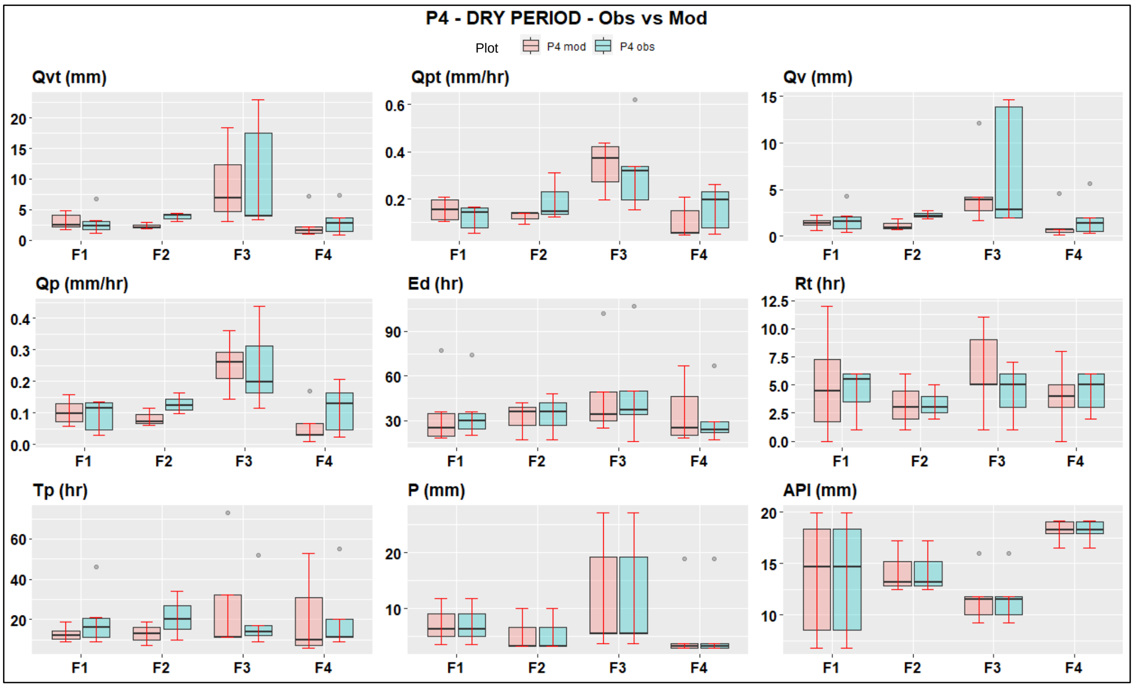


Table A.1010.1: Median values of all variables for each forest development category (F1, F2, F3, F4) for a group of coincidental events in case of modelled and observed data for plough (P4) for dry weather conditions with a summary of the end of the table

Plot	FDC (no of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
P4 - mod	F1 (6)	Winter	25	12	0.2	2.4	0.1	1.2	0.1	1.4	5	6	0.5	15
P4-obs			30	16	0.1	2.3	0.03	0.9	0.1	1.6	6			
P4 - mod	F2 (3)	Spring	36	13	0.1	2.1	0.03	1.2	0.1	0.9	3	3	0.5	13
P4-obs			36	20	0.1	4.0	0.03	1.3	0.1	2.2	3			
P4 - mod	F3 (5)	Autumn	30	11	0.4	5.7	0.1	2.5	0.3	3.1	5	6	0.4	12
P4-obs			37	14	0.3	3.9	0.04	1.9	0.2	2.8	5			
P4 - mod	F4 (5)	Autumn	25	10	0.1	1.7	0.04	1	0.0	0.7	4	3	0.3	18
P4-obs			24	11	0.2	2.7	0.03	1	0.1	1.4	5			
Summary (modelled and observed data)														
P4 - mod	19	Autumn	28	12	0.2	2.3	0.07	1.2	0.1	1.2	5	5	0.5	14
P4-obs			33	15	0.2	3.3	0.03	1.2	0.1	1.9	5			

Figure A.1010.2: Forest development categories (F2, F3, F4, F5) box plots for variables under a group of coincidental events in case of plough (P4) modelled and observed data for wet weather conditions

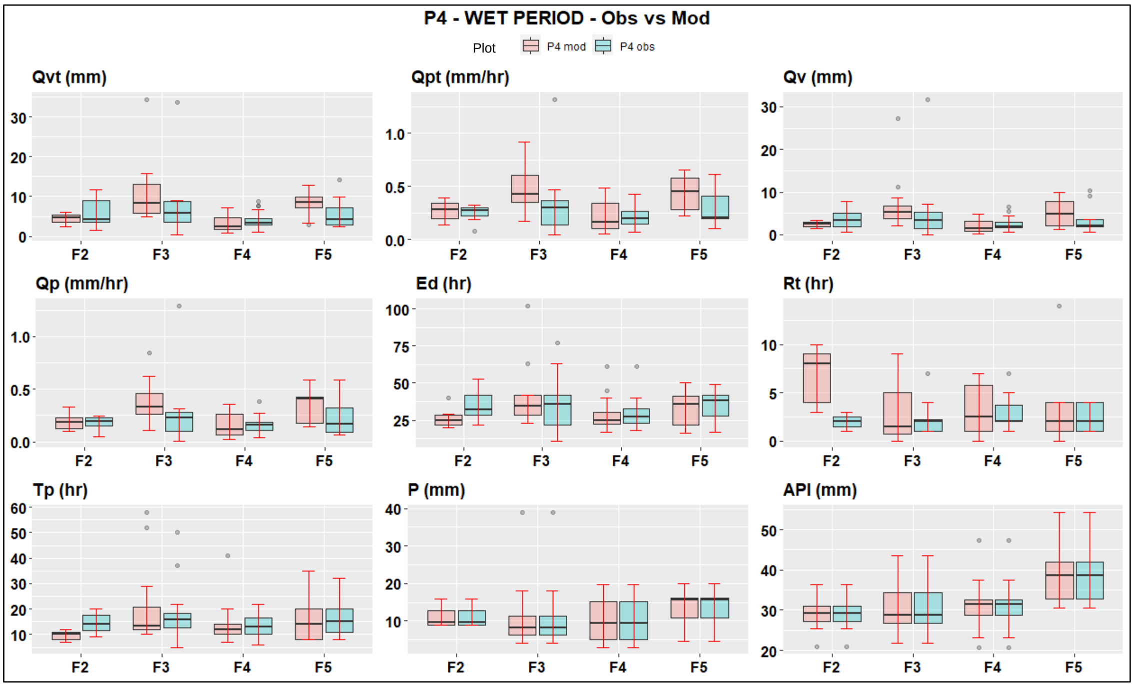


Table A.1010.2: Median values of all variables for each forest development category (F2, F3, F4, F5) for a group of coincidental events in case of modelled and observed data for plough (P4) for wet weather conditions with a summary of the end of the table

Plot	FDC (no of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
P4 - mod	F2 (7)	Autumn	25	10	0.3	4.6	0.1	1.6	0.2	2.5	4	10	0.5	29
P4-obs			32	14	0.3	4.3	0.1	2.7	0.2	3.3	2			
P4 - mod	F3 (12)	Winter	30	13	0.4	8.1	0.1	3.2	0.3	4.5	3	8	0.4	29
P4-obs			36	16	0.3	5.7	0.04	1.5	0.2	3.3	2			
P4 - mod	F4 (18)	Autumn	26	12	0.2	2.6	0.04	1.3	0.1	1.5	2	9	0.9	31
P4-obs			28	13	0.2	3.3	0.03	1.1	0.2	1.9	2			
P4 - mod	F5 (9)	Autumn	31	14	0.5	8.5	0.1	2.5	0.4	4.8	4	16	0.7	39
P4-obs			38	15	0.2	4.2	0.1	1.9	0.2	2.1	2			
Summary (modelled and observed data)														
P4 - mod	46	Autumn	28	13	0.4	6.4	0.1	2.1	0.3	3.5	4	10	0.6	30
P4-obs			34	15	0.3	4.3	0.1	1.7	0.2	2.7	2			

Appendix 11.

Figure A.1111.1: Forest development categories (F1, F2, F3, F4) box plots for variables under a group of coincidental events in case of plough (P5) modelled and observed data for dry weather conditions

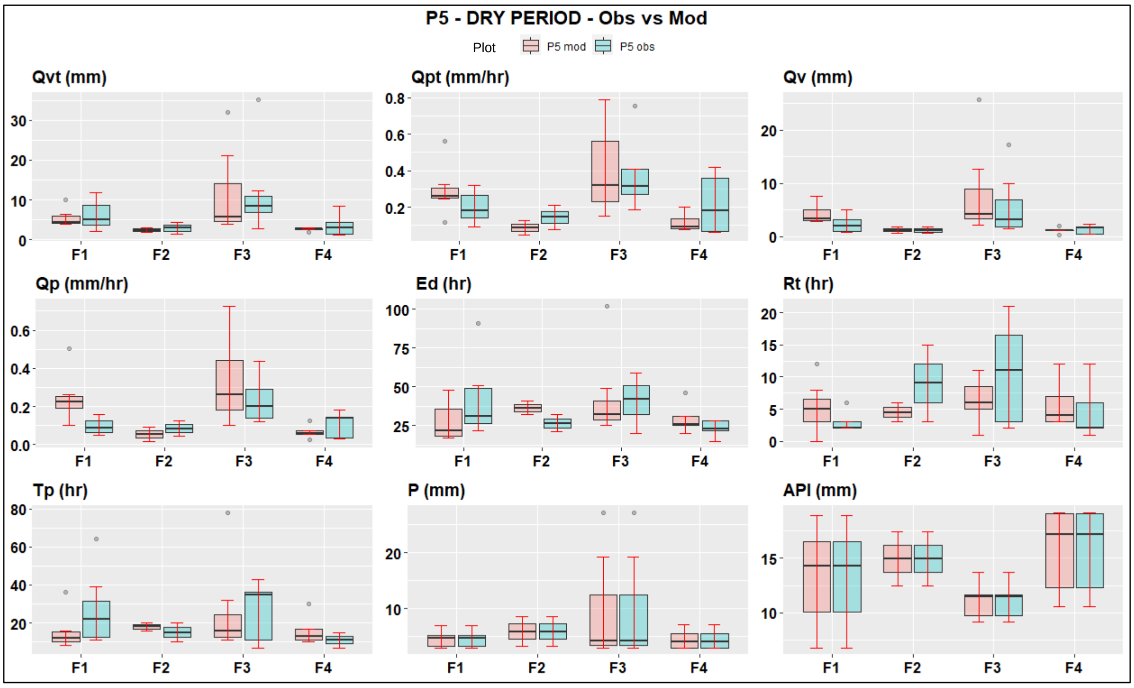


Table A.1111.1: Median values of all variables for each forest development category (F1, F2, F3, F4) for a group of coincidental events in case of modelled and observed data for plough (P5) for dry weather conditions with a summary of the end of the table

Plot	FDC (no of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
P5 - mod	F1 (7)	Winter	16	8	0.3	4.3	0.1	1.1	0.2	3.2	5	5	0.5	14
P5- obs			31	22	0.2	5.1	0.1	3.1	0.1	2.0	2			
P5 - mod	F2 (2)	Spring	37	18	0.1	2.4	0.03	1.2	0.1	1.2	5	6	0.3	15
P5- obs			27	15	0.1	2.9	0.1	1.8	0.1	1.1	9			
P5 - mod	F3 (6)	Winter	25	11	0.3	4.6	0.1	1.9	0.2	3.0	9	4	0.4	12
P5- obs			42	35	0.3	8.4	0.1	4.8	0.2	3.1	11			
P5 - mod	F4 (6)	Spring	26	13	0.1	2.7	0.1	1.6	0.1	1.2	4	4	0.5	17
P5- obs			23	11	0.2	2.9	0.04	1.1	0.1	1.6	2			
Summary (modelled and observed data)														
P5 - mod	21	Spring	26	12	0.2	3.5	0.1	1.4	0.2	2.1	5	5	0.5	15
P5- obs			29	19	0.2	4.0	0.1	2.5	0.1	1.8	6			

Figure A.1111.2: Forest development categories (F2, F3, F4, F5) box plots for variables under a group of coincidental events in the case of plough (P5) modelled and observed data for wet weather conditions

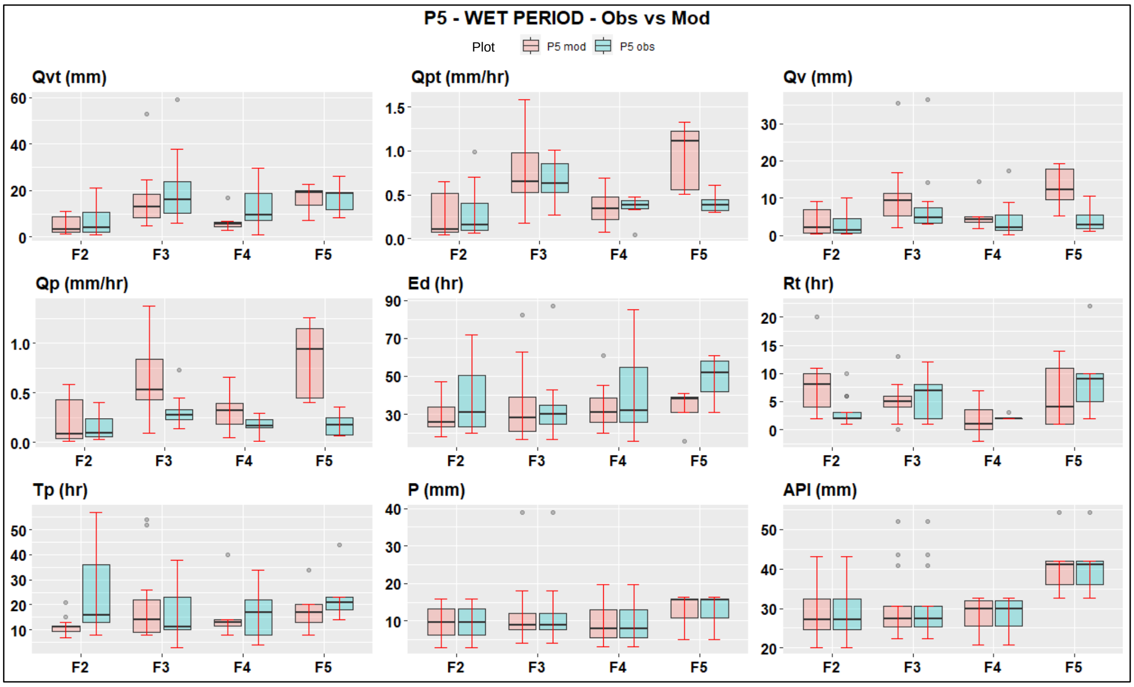


Table A.1111.2: Median values of all variables for each forest development category (F2, F3, F4, F5) for a group of coincidental events in case of modelled and observed data for plough (P5) for wet weather conditions with a summary of the end of the table

Plot	FDC (no of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
P5 - mod	F2 (12)	Summer	26	11	0.1	3.1	0.04	1.2	0.1	2.0	7	9	0.6	28
P5 - obs			38	16	0.2	4.3	0.1	2.7	0.1	1.6	3			
P5 - mod	F3 (13)	Winter	28	14	0.6	13.1	0.1	3.2	0.5	9.4	5	9	0.6	28
P5 - obs			30	11	0.6	16.0	0.4	8.9	0.3	4.7	7			
P5 - mod	F4 (6)	Autumn	28	10	0.3	5.0	0.05	1.3	0.2	3.7	2	9	0.7	31
P5 - obs			33	19	0.4	10.0	0.2	8.3	0.2	2.2	2			
P5 - mod	F5 (4)	Autumn	17	10	0.5	7.7	0.2	3.1	0.4	4.7	3	13	0.7	42
P5 - obs			55	22	0.4	19.0	0.2	14.8	0.2	4.1	7			
Summary (modelled and observed data)														
P5 - mod	35	Autumn	27	11	0.4	6.4	0.1	2.2	0.3	4.2	4	9	0.7	30
P5 - obs			36	18	0.4	13.0	0.2	8.6	0.2	3.2	5			

Appendix 12.

Figure A.1212.1: Forest development categories (F1, F2, F3, F4) box plots for variables under a group of coincidental events in case of excavation mounding (P6) modelled and observed data for dry weather conditions

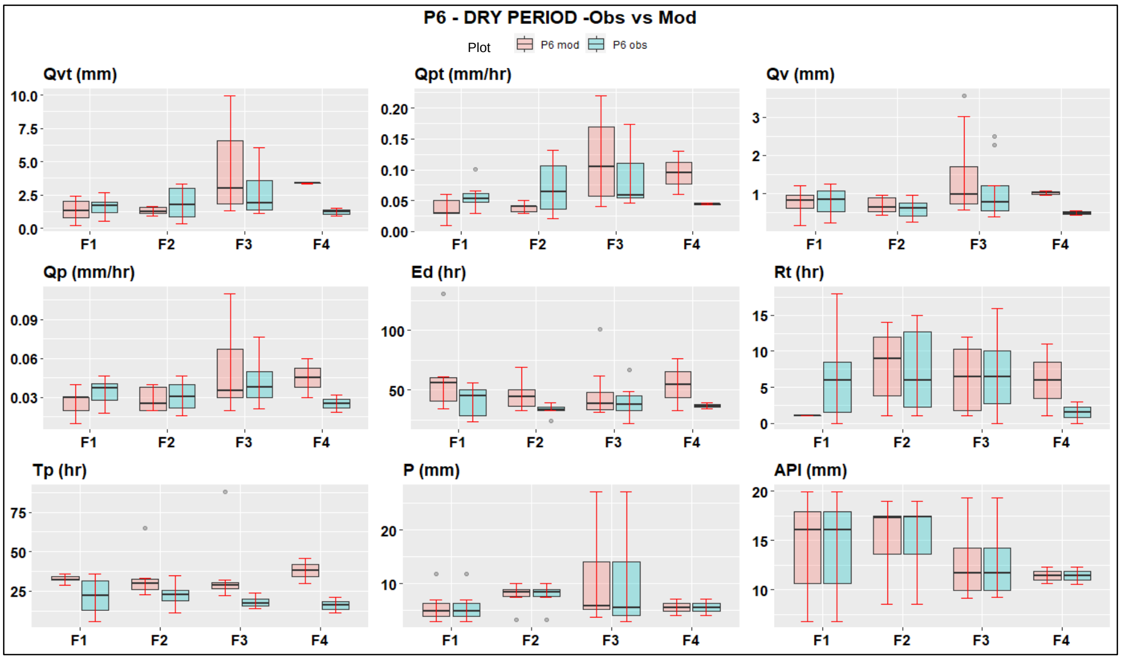


Table A.1212.1: Median values of all variables for each forest development category (F1, F2, F3, F4) for a group of coincidental events in case of modelled and observed data for excavation mounding (P6) for dry weather conditions with a summary of the end of the table

Plot	FDC (no of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
P6 - mod	F1 (8)	Winter	56	32	0.03	1.3	0.01	0.7	0.03	0.8	1	5	0.4	16
P6 - obs			45	22	0.05	1.7	0.01	0.6	0.04	0.8	6			
P6 - mod	F2 (5)	Spring	44	30	0.04	1.2	0.01	0.5	0.03	0.6	9	8	0.5	17
P6 - obs			34	23	0.06	1.8	0.03	1.1	0.03	0.6	6			
P6 - mod	F3 (8)	Winter	39	29	0.10	3	0.05	2.3	0.04	1	7	6	0.4	11
P6 - obs			38	18	0.06	1.9	0.03	1.1	0.04	0.8	7			
P6 - mod	F4 (2)	Spring	55	38	0.09	3.4	0.05	2.4	0.04	1	6	6	0.3	11
P6 - obs			37	16	0.04	1.2	0.02	0.7	0.03	0.5	2			
Summary (modelled and observed data)														
P6 - mod	23	Winter	50	31	0.1	2.2	0.0	1.5	0.04	0.9	7	6	0.4	14
P6 - obs			38	20	0.1	1.8	0.0	0.9	0.04	0.7	6			

Figure A.1212.2: Forest development categories (F2, F3, F4) box plots for variables under a group of coincidental events in case of excavation mounding (P6) modelled and observed data for wet weather conditions

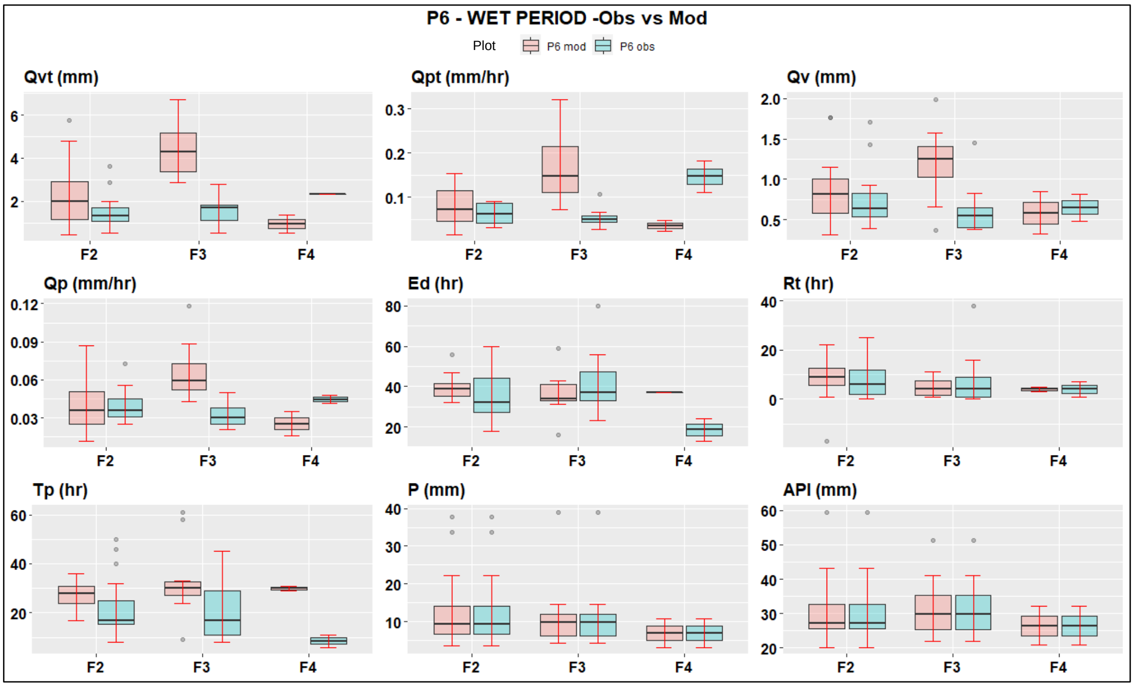


Table A.1212.2: Median values of all variables for each forest development category (F2, F3, F4) for a group of coincidental events in case of modelled and observed data for excavation mounding (P6) for wet weather conditions with a summary of the end of the table

Plot	FDC (no of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
P6 - mod	F2 (19)	Summer	39	28	0.1	2.0	0.02	1	0.04	0.8	9	9	0.5	27
P6 - obs			32	17	0.1	1.3	0.02	0.7	0.04	0.6	6			
P6 - mod	F3 (11)	Winter	34	30	0.1	4.3	0.1	3	0.1	1.3	4	10	0.3	30
P6 - obs			37	17	0.1	1.7	0.02	1	0.03	0.6	4			
P6 - mod	F4 (2)	Spring	37	30	0.04	0.9	0.01	0.4	0.03	0.6	4	7	0.7	26
P6 - obs			19	9	0.1	2.3	0.1	1.7	0.04	0.7	4			
Summary (modelled and observed data)														
P6 - mod	32	Summer	37	30	0.1	2.0	0.02	1	0.04	0.8	4	9	0.5	27
P6 - obs			32	17	0.1	1.7	0.02	1	0.04	0.6	4			

Appendix 13.

Figure A.1313.1: Forest development categories (F1, F2, F3) box plots for variables under a group of coincidental events in case of excavation mounding (P7) modelled and observed data for dry weather conditions

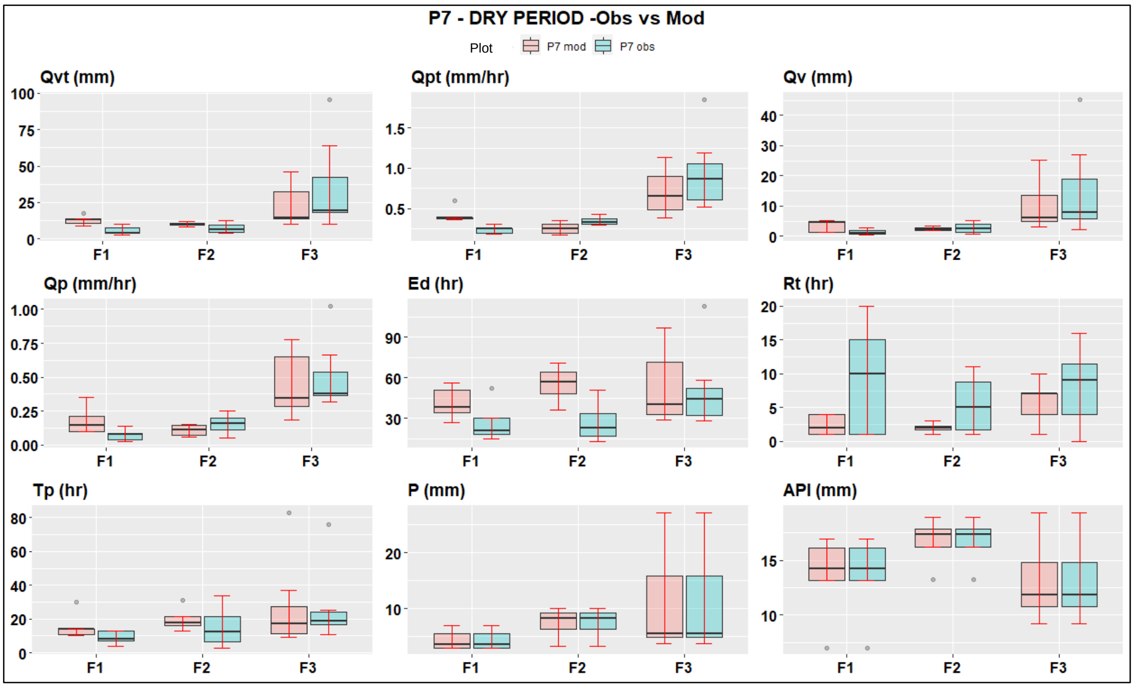


Table A.1313.1: Median values of all variables for each forest development category (F1, F2, F3) for a group of coincidental events in case of modelled and observed data for excavation mounding (P7) for dry weather conditions

Plot	FDC (no of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
P7 - mod	F1 (5)	Winter	38	14	0.4	13.2	0.2	9.0	0.1	4.5	2	4	0.5	14
P7 - obs			21	8	0.2	4.1	0.2	3.3	0.1	1	10			
P7 - mod	F2 (4)	Spring	57	18	0.2	10.1	0.1	8.0	0.1	2.2	2	8	0.5	17
P7 - obs			23	13	0.3	6.6	0.2	4.2	0.2	2.6	5			
P7 - mod	F3 (7)	Winter	40	17	0.7	14.3	0.2	9.8	0.3	6	7	6	0.4	12
P7 - obs			44	19	0.9	19.3	0.3	13.3	0.4	7.7	9			
Summary (modelled and observed data)														
P7 - mod	18	Winter	40	17	0.4	13.2	0.2	9	0.1	4.5	2	6	0.5	14
P7 - obs			23	13	0.3	6.6	0.2	4	0.2	2.6	9			

Figure A.1313.2: Forest development categories (F2, F3) box plots for variables under a group of coincidental events in case of excavation mounding (P7) modelled and observed data for wet weather conditions

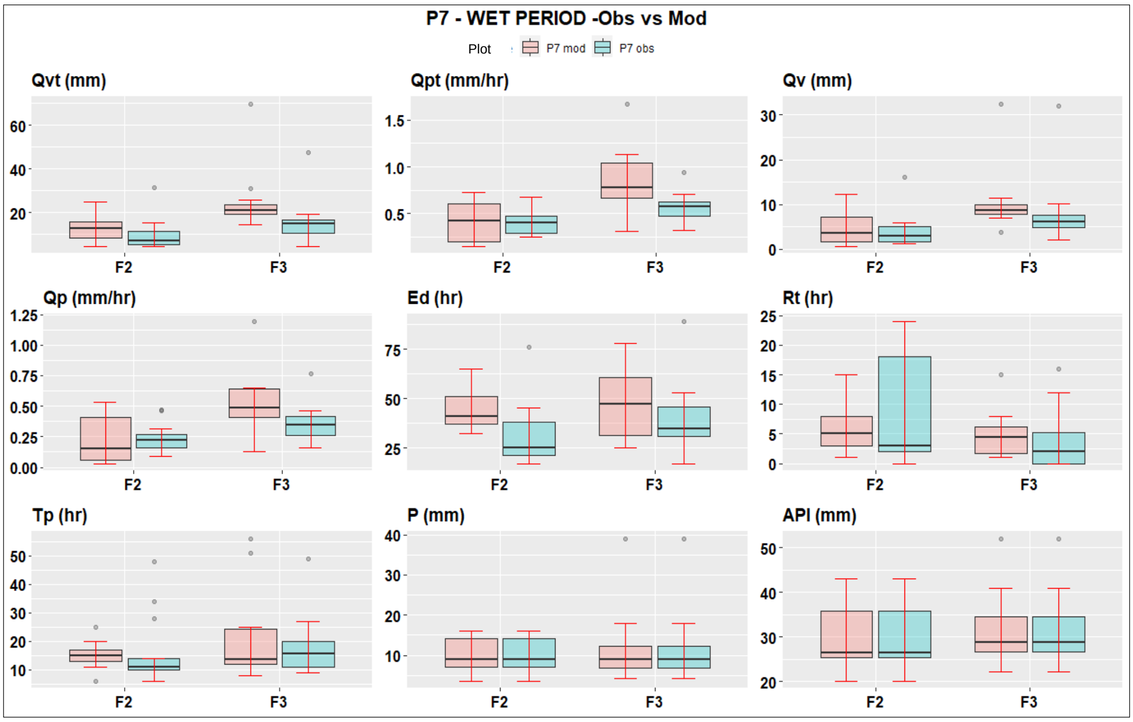
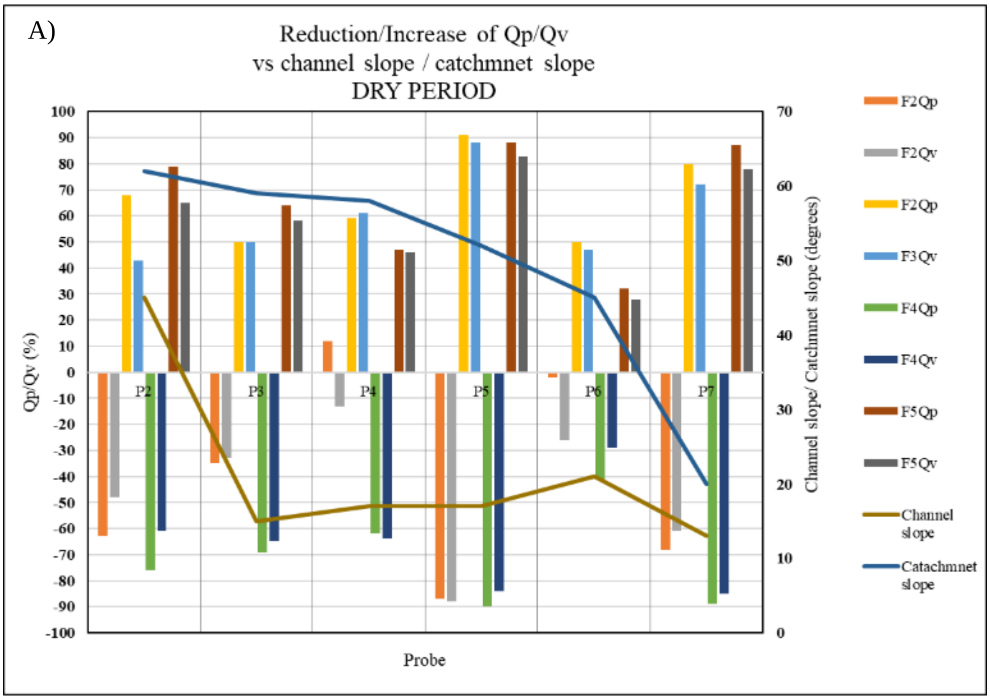


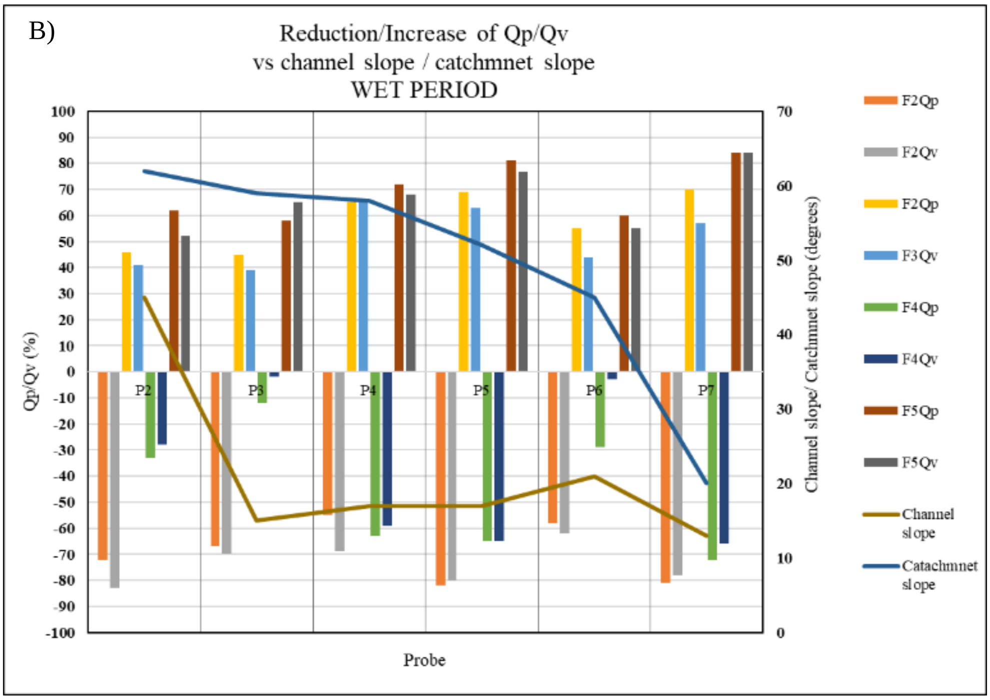
Table A.1313.2: Median values of all variables for each forest development category (F2, F3) for a group of coincidental events in case of modelled and observed data for excavation mounding (P7) for wet weather conditions with a summary of the end of the table

Plot	FDC (no of events)	Dominant season	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)	P (mm)	I (mm/hr)	API30 (mm)
P6 - mod	F2 (13)	Autumn	41	15	0.4	12.8	0.2	8.5	0.2	3.6	5	9	0.5	27
P6 - obs			25	11	0.4	7.2	0.2	3.8	0.2	2.9	3			
P6 - mod	F3 (12)	Winter	47	14	0.8	20.9	0.3	12	0.5	8.6	5	9	0.5	29
P6 - obs			35	16	0.6	15	0.2	7.4	0.3	6.2	2			
Summary (modelled and observed data)														
P6 - mod	25	Autumn	44	15	0.6	16.9	0.3	10	0.4	6.1	5	9	0.5	28
P6 - obs			30	14	0.5	11.1	0.2	6	0.3	4.6	3			

Appendix 14.

Figure A.1414.1: The plot of increase /decrease of Qp/Qv for P2, P3, P4, P5, P6 and P7 in the case of A) Dry weather conditions and B)Wet weather conditions





Appendix 15.

Figure A.1515.1: The plot of a linear relationship between tree cover and A) Ed B) Tp C) Qpt D) Qvt E) Qbp F) Qvb G) Qp H) Qv I) Rt for dry (growing and non-growing) and wet (growing and non-growing) weather conditions for sub-catchment areas

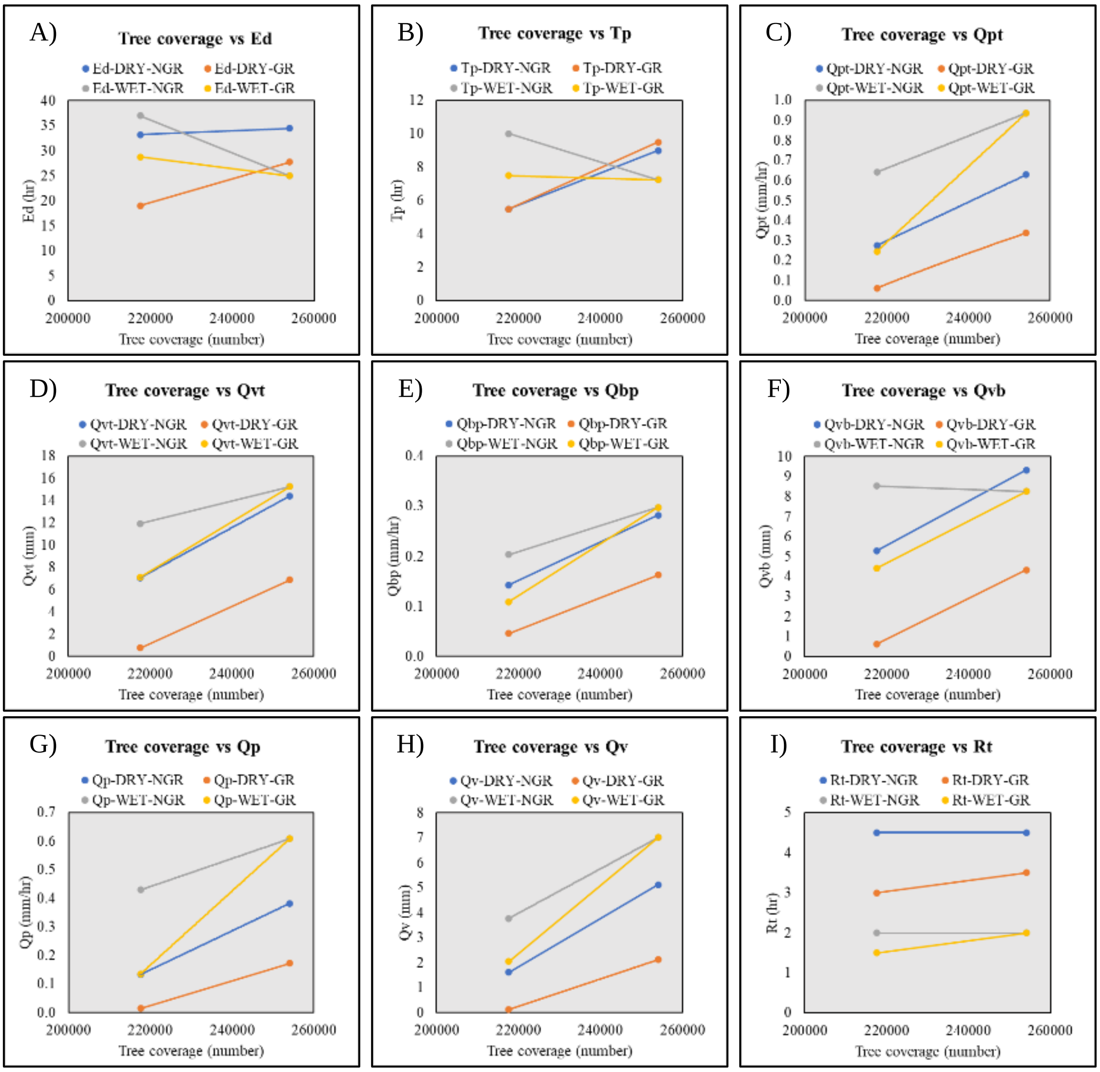


Table A.1515.1: Liner relationship expression between tree coverage (TC) and variables (Ed, Tp, Qpt, Qvt, Qbp, Qvb, Qp, Qv and Rt for dry (growing and non-growing) and wet (growing and non-growing) weather conditions for sub-catchment areas

Variable	Dry (non-growing)	Dry (growing)	Wet (non-growing)	Wet (growing)
Ed (hr)	Ed=0.0003*TC+25.8	Ed=0.0002*TC-33.2	Ed=0.0003*TC+108.5	Ed=0.0001*TC+51.1
Tp (hr)	Tp = 0.0001*TC-15.4	Tp=0.0001*TC-18.3	Tp=0.00008*TC+26.4	Tp=-0.00007*TC+8.99
Qpt (mm/hr)	Qpt=0.0002*TC-3.9	Qpt=0.000008*TC-1.6	Qpt=0.000008*TC-1.1	Qpt=0.00005*TC-1.8
Qvt (mm)	Qvt=0.0002*TC-36.7	Qvt=0.0002*TC-35.6	Qvt=0.00009*TC7.8	Qvt=0.0002*TC-41.38
Qpb (mm/hr)	Qpb=0.000004*TC-0.7	Qpb=*0.000003TC-0.7	Qpb=0.000003*TC-0.4	Qpb=0.000005*TC-1
Qvb (mm)	Qvb=0.0001*TC-18.8	Qvb=0.0001*TC-21.5	Qvb=0.000007*TC+10.1	Qvb=0.0001*TC-18.5
Qp (mm/hr)	Qp=0.000007*TC-1.4	Qp=0.000004*TC-0.9	Qp=0.000005*TC-0.6	Qp=0.00001*TC-2.7
Qv (mm)	Qv=0.00001*TC-19.3	Qv=0.00005*TC-11.8	Qv=0.00009*TC-15.5	Qv=0.0001*TC-27.5
Rt (hr)	Rt=-4E-16*TC+4.5	Rt=1E-05*TC+0.02	Rt=2E-15*TC+2	Rt=1E-05*TC-1.5

Figure A.1515.2: The plot of a linear relationship between tree coverage (TC) and A) Ed B) Tp C) Qpt D) Qvt E) Qbp F) Qvb G) Qp H) Qv I) Rt for dry (growing and non-growing) and wet (growing and non-growing) weather conditions for cultivated areas

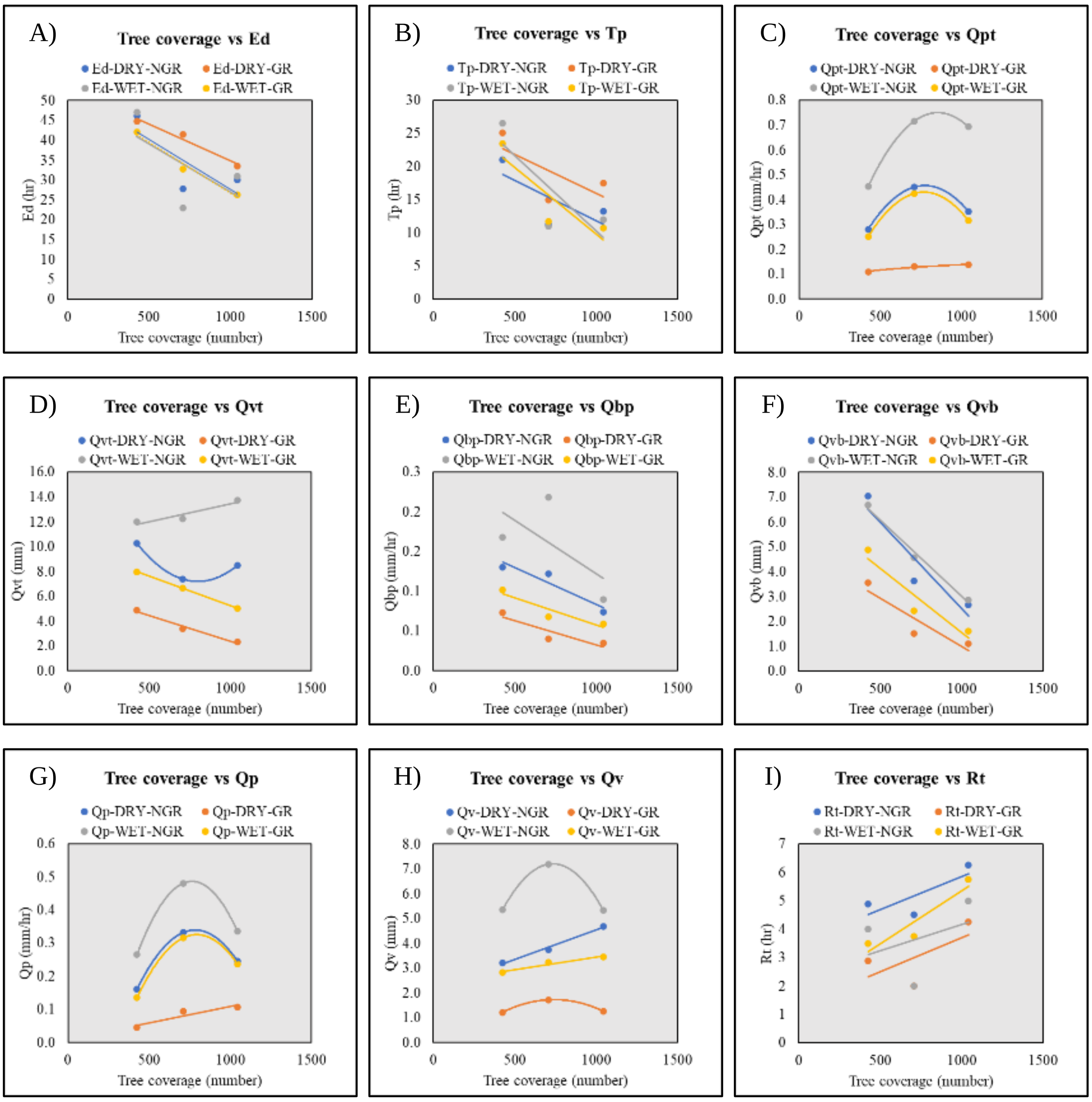


Table A.1515.2: Liner relationship expression between tree coverage (TC) and variables (Ed, Tp, Qpt, Qvt, Qbp, Qvb, Qp, Qv and Rt for dry (growing and non-growing) and wet (growing and non-growing) weather conditions for cultivated areas

Variable	Dry (non-growing)	Dry (growing)	Wet (non-growing)	Wet(growing)
Ed (hr)	Ed=-0.03*TC+52.8	Ed=-0.02*TC + 53.2	Ed=-0.02*TC+52.2	Ed=-0.02*TC+52.2
Tp (hr)	Tp=-0.01*TC+23.8	Tp=-0.01*TC+27.7	Tp=-0.02*TC+32.9	Tp=-0.02*TC+29.9
Qpt (mm/hr)	Qpt=-1E-06* TC^{2}+0.002*TC-0.4	Qpt=0.03ln(TC)-0.07	Qpt=-2E-06*TC^{2} +0.003*TC-0.4	Qpt=-2E-06*TC^{2}+0.002*TC-0.5
Qvt (mm)	Qvt=2E-05*TC^{2}-0.04*Tc+21.2	Qvt=-0.01*TC+10	Qvt=0.03*TC+10.6	Qvt=-0.004*TC+6.5
Qpb (mm/hr)	Qpb=-6E-0.5*TC+0.09	Qpb=-9E-05*TC +0.2	Qpb=-0.00001*TC+0.3	Qpb=-7E-05*TC+0.1
Qvb (mm)	Qvb=-0.007*TC+9.5	Qvb=-0.004*TC+4.9	Qvb=0.006*TC+9.2	Qvb=-0.005*TC+6.8
Qp (mm/hr)	Qp=-1E-06*TC^{2}+0.002*TC-0.05	Qp=-1E-04*TC+0.009	Qp=-2E-06*TC^{2}+0.03*TC+0.6	Qp=-1E-06*TC^{2}+0.02*TC-0.6

Qv (mm)	Qv=0.002*TC+2.1	Qv=-5E-06*TC^2+0.01*TC-1.1	Qv=-2E-05*TC^2+0.3*TC-3.2	Qv=0.001*TC+2.4
Rt (hr)	Rt=0.002*TC+3.5	Rt=0.002*TC+1.3	Rt=0.002*TC+2.3	Rt=0.004*TC+1.6

Appendix 16.

Table A.1616.1: Relationship between variables and P, I and API30 for DP groups where data was grouped under growing and non-growing season

Sub-catchmen	Season	Variable	Approach	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)
Inch 1	NGR	P	Pearson	0.9	0.9	0.8	1.0	0.5	0.9	0.8	1.0	0.2
			R2	0.8	0.7	0.6	0.9	0.3	0.9	0.6	0.9	0.0
		I	Pearson	-0.4	-0.2	0.2	-0.2	0.5	-0.2	0.2	-0.2	-0.5
			R2	0.2	0.0	0.1	0.0	0.3	0.0	0.0	0.0	0.2
		API30	Pearson	0.1	-0.4	0.3	0.2	0.5	0.1	0.2	0.2	-0.7
			R2	0.0	0.2	0.1	0.0	0.2	0.0	0.0	0.0	0.5
	GR	P	Pearson	0.4	-0.4	0.7	0.8	0.7	0.8	0.7	0.7	0.9
			R2	0.1	0.1	0.5	0.6	0.6	0.7	0.6	0.5	0.8
		I	Pearson	0.0	0.2	-0.6	-0.6	-0.6	-0.5	-0.6	-0.7	-0.4
			R2	0.0	0.1	0.3	0.3	0.3	0.3	0.4	0.5	0.1
		API30	Pearson	0.0	0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.2
			R2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Inch 2	NGR	P	Pearson	0.8	0.8	0.7	0.9	0.4	1.0	0.8	0.9	0.4
			R2	0.7	0.7	0.5	0.9	0.2	0.9	0.6	0.8	0.2
		I	Pearson	-0.2	-0.2	0.4	0.0	0.3	-0.1	0.4	0.2	-0.6
			R2	0.0	0.0	0.1	0.0	0.1	0.0	0.1	0.0	0.4
		API30	Pearson	-0.4	-0.5	0.3	-0.1	0.6	-0.2	0.2	-0.1	-0.5
			R2	0.1	0.3	0.1	0.0	0.3	0.0	0.0	0.0	0.3
	GR	P	Pearson	0.9	0.9	1.0	1.0	0.5	1.0	1.0	1.0	-0.3
			R2	0.8	0.9	1.0	0.9	0.3	0.9	1.0	0.9	0.1
		I	Pearson	-0.2	-0.3	0.0	-0.1	0.5	-0.1	-0.1	-0.2	-0.7
			R2	0.0	0.1	0.0	0.0	0.3	0.0	0.0	0.0	0.5
		API30	Pearson	0.2	0.3	0.4	0.3	0.4	0.4	0.3	0.3	-0.6
			R2	0.1	0.1	0.2	0.1	0.2	0.1	0.1	0.1	0.4
P2	NGR	P	Pearson	0.8	0.9	0.4	0.9	0.0	0.7	0.6	0.9	0.2
			R2	0.7	0.8	0.2	0.8	0.0	0.5	0.3	0.8	0.0
		I	Pearson	-0.2	-0.6	0.6	0.2	0.4	0.5	0.6	0.1	-0.4
			R2	0.0	0.3	0.4	0.0	0.2	0.3	0.3	0.0	0.2
		API30	Pearson	-0.2	-0.2	0.4	0.0	0.5	0.4	0.1	-0.1	0.6
			R2	0.1	0.1	0.1	0.0	0.3	0.2	0.0	0.0	0.3
	GR	P	Pearson	0.6	0.8	0.7	0.8	0.7	0.8	0.7	0.8	-0.1
			R2	0.3	0.7	0.5	0.6	0.5	0.6	0.5	0.6	0.0
		I	Pearson	-0.4	-0.5	-0.7	-0.6	-0.6	-0.5	-0.7	-0.6	0.8
			R2	0.2	0.2	0.4	0.3	0.3	0.3	0.5	0.3	0.7
		API30	Pearson	0.5	0.1	0.3	0.3	0.2	0.2	0.3	0.3	-0.2
			R2	0.3	0.0	0.1	0.1	0.0	0.0	0.1	0.1	0.1
P3	NGR	P	Pearson	0.8	-0.1	0.0	-0.2	0.2	0.1	-0.2	-0.2	0.1
			R2	0.6	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.0
		I	Pearson	-0.6	0.3	0.2	0.6	-0.2	0.7	0.4	0.5	0.8
			R2	0.4	0.1	0.1	0.3	0.0	0.5	0.1	0.2	0.6
		API30	Pearson	-0.1	-0.3	0.4	0.1	0.8	0.6	0.1	0.0	0.4
			R2	0.0	0.1	0.2	0.0	0.6	0.3	0.0	0.0	0.1
	GR	P	Pearson	0.9	0.8	1.0	1.0	0.1	0.7	1.0	1.0	-0.5
			R2	0.9	0.7	0.9	0.9	0.0	0.4	1.0	0.9	0.3
		I	Pearson	0.0	-0.4	0.1	-0.1	0.4	0.4	0.0	-0.2	-0.4
			R2	0.0	0.1	0.0	0.0	0.2	0.2	0.0	0.0	0.2
		API30	Pearson	0.2	0.2	0.4	0.4	0.2	0.5	0.4	0.3	-0.4
			R2	0.1	0.0	0.1	0.1	0.0	0.2	0.1	0.1	0.2
P4	NGR	P	Pearson	0.6	0.8	0.5	1.0	0.1	0.9	0.6	1.0	-0.1
			R2	0.3	0.7	0.3	0.9	0.0	0.8	0.3	0.9	0.0
		I	Pearson	-0.5	-0.3	0.2	-0.3	0.2	-0.4	0.2	-0.2	-0.7
			R2	0.3	0.1	0.0	0.1	0.0	0.2	0.0	0.0	0.5

		API30	Pearson	0.3	-0.5	0.1	-0.1	0.0	-0.1	0.1	0.0	-0.1
			R2	0.1	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	GR	P	Pearson	0.8	0.8	0.8	0.9	0.3	0.9	0.9	1.0	-0.1
			R2	0.6	0.6	0.7	0.9	0.1	0.7	0.8	0.9	0.0
		I	Pearson	-0.4	-0.5	0.2	-0.2	0.2	-0.4	0.2	-0.2	0.1
			R2	0.2	0.2	0.0	0.1	0.0	0.1	0.0	0.0	0.0
		API30	Pearson	0.4	0.1	-0.2	0.2	-0.7	0.1	-0.1	0.2	-0.4
			R2	0.1	0.0	0.0	0.0	0.5	0.0	0.0	0.1	0.1
P5	NGR	P	Pearson	0.7	0.8	0.7	1.0	0.6	0.9	0.6	0.9	0.5
			R2	0.5	0.6	0.4	1.0	0.4	0.9	0.4	0.8	0.2
		I	Pearson	-0.6	-0.3	0.4	-0.2	0.0	-0.3	0.5	-0.1	-0.5
			R2	0.3	0.1	0.2	0.0	0.0	0.1	0.2	0.0	0.2
		API30	Pearson	0.1	-0.6	0.3	0.1	0.0	-0.3	0.4	0.4	-0.3
			R2	0.0	0.4	0.1	0.0	0.0	0.1	0.1	0.1	0.1
	GR	P	Pearson	0.9	0.9	0.8	0.8	0.7	0.9	0.8	0.8	0.4
			R2	0.7	0.8	0.6	0.7	0.5	0.8	0.6	0.7	0.1
		I	Pearson	-0.1	-0.3	-0.6	-0.5	-0.6	-0.4	-0.6	-0.5	-0.3
			R2	0.0	0.1	0.3	0.2	0.4	0.1	0.3	0.2	0.1
		API30	Pearson	0.2	0.1	0.2	0.2	0.3	0.2	0.2	0.2	0.2
			R2	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
P6	NGR	P	Pearson	0.4	0.7	0.6	0.9	0.5	0.8	0.8	0.9	0.8
			R2	0.2	0.5	0.4	0.8	0.2	0.7	0.6	0.8	0.6
		I	Pearson	-0.6	-0.5	0.1	-0.2	0.1	-0.2	0.1	-0.1	0.1
			R2	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		API30	Pearson	0.3	-0.4	-0.5	-0.4	-0.6	-0.5	-0.5	-0.3	-0.4
			R2	0.1	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	GR	P	Pearson	0.5	0.0	0.8	0.8	-0.2	0.2	0.9	1.0	-0.6
			R2	0.2	0.0	0.6	0.7	0.0	0.1	0.8	0.9	0.3
		I	Pearson	-0.8	-0.9	0.2	-0.4	-0.3	-0.8	0.3	-0.2	-0.5
			R2	0.6	0.7	0.1	0.1	0.1	0.6	0.1	0.0	0.2
		API30	Pearson	0.0	-0.3	-0.3	-0.1	-0.7	-0.5	-0.1	0.1	-0.4
			R2	0.0	0.1	0.1	0.0	0.5	0.2	0.0	0.0	0.1
P7	NGR	P	Pearson	0.6	0.8	0.6	0.9	0.2	0.8	0.7	1.0	0.1
			R2	0.4	0.6	0.4	0.8	0.0	0.7	0.5	0.9	0.0
		I	Pearson	-0.5	-0.4	0.3	-0.3	0.6	-0.4	0.3	-0.3	0.4
			R2	0.3	0.2	0.1	0.1	0.4	0.1	0.1	0.1	0.1
		API30	Pearson	0.2	-0.6	0.2	0.2	0.3	0.3	0.1	0.0	0.6
			R2	0.1	0.4	0.0	0.0	0.1	0.1	0.0	0.0	0.4
	GR	P	Pearson	0.9	0.9	0.8	0.9	0.1	0.9	0.8	0.9	-0.6
			R2	0.8	0.8	0.6	0.8	0.0	0.8	0.7	0.8	0.4
		I	Pearson	0.0	-0.4	-0.6	-0.4	-0.9	-0.3	-0.5	-0.4	-0.1
			R2	0.0	0.2	0.4	0.1	0.8	0.1	0.2	0.2	0.0
		API30	Pearson	0.6	0.2	0.2	0.4	0.0	0.5	0.3	0.3	-0.9
			R2	0.4	0.1	0.0	0.2	0.0	0.3	0.1	0.1	0.8

Table A.1616.2: Relationship between variables and P, I and API30 for WP groups where data was grouped under growing and non-growing season

Sub-catchme	**Season**	**Variable**	**Approach**	Ed (hr)	Tp (hr)	Qpt (mm/hr)	Qvt (mm)	Qpb (mm/hr)	Qvb (mm)	Qp (mm/hr)	Qv (mm)	Rt (hr)
Inch 1	NGR	P	Pearson	0.8	0.8	0.9	1.0	0.3	0.9	0.9	1.0	-0.5
			R2	0.6	0.7	0.8	0.9	0.1	0.7	0.8	0.9	0.2
		I	Pearson	-0.3	-0.1	0.2	0.0	0.2	0.0	0.2	0.1	-0.3
			R2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
		API30	Pearson	-0.2	-0.2	0.3	0.2	0.6	0.4	0.2	0.1	-0.3
			R2	0.0	0.0	0.1	0.1	0.3	0.1	0.0	0.0	0.1
	GR	P	Pearson	0.8	0.1	0.6	0.8	0.1	0.7	0.7	0.8	0.3
			R2	0.7	0.0	0.4	0.7	0.0	0.4	0.5	0.6	0.1
		I	Pearson	0.4	-0.5	0.5	0.5	0.3	0.4	0.5	0.4	-0.1
			R2	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.0
		API30	Pearson	0.3	-0.1	0.9	0.8	0.9	0.8	0.8	0.7	0.6
			R2	0.1	0.0	0.8	0.6	0.8	0.7	0.7	0.5	0.3
Inch 2	NGR	P	Pearson	0.8	0.6	0.9	0.9	0.2	0.8	0.9	0.9	0.6
			R2	0.6	0.3	0.8	0.9	0.0	0.7	0.8	0.8	0.4
		I	Pearson	0.1	0.0	0.3	0.1	0.5	0.2	0.2	0.1	-0.2
			R2	0.0	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.1
		API30	Pearson	-0.2	-0.4	0.4	0.2	1.0	0.6	0.3	0.1	0.0

			R2	0.0	0.2	0.2	0.0	0.9	0.3	0.1	0.0	0.0
	GR	P	Pearson	0.3	0.2	0.9	1.0	0.5	0.8	0.9	0.9	0.0
			R2	0.1	0.1	0.9	0.9	0.3	0.7	0.9	0.9	0.0
		I	Pearson	-0.3	-0.4	0.7	0.6	0.6	0.5	0.7	0.5	0.2
			R2	0.1	0.2	0.5	0.3	0.4	0.2	0.4	0.2	0.0
		API30	Pearson	-0.3	-0.4	0.6	0.5	0.8	0.4	0.6	0.4	0.7
			R2	0.1	0.1	0.4	0.2	0.7	0.2	0.3	0.2	0.5
P2	NGR	P	Pearson	0.0	0.1	0.9	0.6	0.6	0.6	0.8	0.6	-0.1
			R2	0.0	0.0	0.8	0.3	0.4	0.3	0.7	0.3	0.0
		I	Pearson	0.0	-0.1	0.4	0.0	0.7	0.3	0.2	0.0	0.1
			R2	0.0	0.0	0.2	0.0	0.5	0.1	0.1	0.0	0.0
		API30	Pearson	-0.2	-0.4	0.5	0.2	0.8	0.2	0.4	0.2	-0.2
			R2	0.1	0.1	0.2	0.1	0.6	0.1	0.2	0.0	0.0
	GR	P	Pearson	0.4	0.0	0.7	0.8	-0.1	0.2	0.8	0.8	0.3
			R2	0.1	0.0	0.6	0.6	0.0	0.1	0.7	0.6	0.1
		I	Pearson	0.5	-0.1	0.6	0.5	-0.1	0.2	0.6	0.3	0.0
			R2	0.3	0.0	0.4	0.3	0.0	0.0	0.3	0.1	0.0
		API30	Pearson	0.2	0.2	0.9	0.8	0.7	0.9	0.8	0.6	0.4
			R2	0.0	0.0	0.7	0.7	0.5	0.8	0.6	0.4	0.2
P3	NGR	P	Pearson	0.8	0.9	0.9	1.0	0.4	0.9	0.9	0.9	0.0
			R2	0.6	0.8	0.8	1.0	0.1	0.8	0.8	0.9	0.0
		I	Pearson	-0.2	0.1	0.2	0.1	0.4	0.2	0.1	0.0	-0.2
			R2	0.0	0.0	0.1	0.0	0.2	0.1	0.0	0.0	0.0
		API30	Pearson	0.0	0.1	0.4	0.2	0.3	0.2	0.4	0.2	-0.2
			R2	0.0	0.0	0.2	0.1	0.1	0.1	0.1	0.0	0.0
	GR	P	Pearson	0.5	0.2	0.9	0.9	0.4	0.6	1.0	1.0	0.0
			R2	0.2	0.0	0.9	0.9	0.2	0.4	0.9	0.9	0.0
		I	Pearson	0.2	0.1	0.8	0.7	0.7	0.8	0.6	0.6	0.0
			R2	0.0	0.0	0.6	0.6	0.5	0.7	0.4	0.4	0.0
		API30	Pearson	-0.2	-0.5	0.7	0.6	0.8	0.8	0.6	0.5	0.6
			R2	0.1	0.3	0.4	0.4	0.6	0.6	0.3	0.2	0.4
P4	NGR	P	Pearson	0.9	0.9	0.9	0.9	0.7	0.8	1.0	0.9	0.1
			R2	0.8	0.8	0.9	0.8	0.5	0.7	0.9	0.9	0.0
		I	Pearson	-0.1	0.0	0.2	0.0	-0.1	-0.1	0.2	0.1	0.2
			R2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		API30	Pearson	0.0	-0.1	0.4	0.2	0.4	0.2	0.4	0.1	-0.2
			R2	0.0	0.0	0.2	0.0	0.2	0.0	0.2	0.0	0.1
	GR	P	Pearson	-0.4	0.3	0.7	0.7	0.4	0.4	0.7	0.8	0.0
			R2	0.2	0.1	0.5	0.4	0.1	0.1	0.5	0.6	0.0
		I	Pearson	-0.4	0.3	0.6	0.5	0.1	0.2	0.6	0.6	-0.5
			R2	0.2	0.1	0.3	0.3	0.0	0.1	0.4	0.4	0.2
		API30	Pearson	0.3	0.3	0.9	0.9	0.8	0.9	0.9	0.8	0.1
			R2	0.1	0.1	0.7	0.8	0.6	0.9	0.7	0.7	0.0
P5	NGR	P	Pearson	0.7	0.8	1.0	1.0	0.6	0.9	1.0	1.0	0.0
			R2	0.5	0.6	0.9	1.0	0.3	0.7	0.9	1.0	0.0
		I	Pearson	-0.2	-0.1	0.3	0.1	0.0	-0.1	0.3	0.1	0.1
			R2	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0
		API30	Pearson	-0.2	-0.3	0.3	0.1	0.5	0.1	0.4	0.1	-0.1
			R2	0.1	0.1	0.1	0.0	0.3	0.0	0.2	0.0	0.0
	GR	P	Pearson	-0.5	0.8	0.7	0.4	0.3	0.4	0.6	0.5	0.0
			R2	0.2	0.6	0.5	0.2	0.1	0.2	0.4	0.2	0.0
		I	Pearson	-0.2	0.7	0.5	0.4	0.0	0.3	0.5	0.4	-0.5
			R2	0.1	0.5	0.3	0.1	0.0	0.1	0.3	0.1	0.3
		API30	Pearson	0.2	0.2	0.9	0.9	0.7	0.9	0.9	0.9	-0.3
			R2	0.0	0.0	0.8	0.8	0.5	0.8	0.8	0.7	0.1
P6	NGR	P	Pearson	-0.3	1.0	0.9	0.8	0.8	0.8	0.8	0.5	0.0
			R2	0.1	0.9	0.8	0.6	0.6	0.6	0.7	0.3	0.0
		I	Pearson	-0.5	0.1	0.2	0.0	0.1	0.0	0.2	0.1	-0.1
			R2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		API30	Pearson	0.1	0.1	0.4	0.6	0.2	0.4	0.6	0.7	-0.5
			R2	0.0	0.0	0.2	0.3	0.1	0.2	0.4	0.5	0.2
	GR	P	Pearson	0.6	0.4	0.7	0.7	0.4	0.5	0.9	0.9	0.3
			R2	0.4	0.1	0.4	0.4	0.1	0.2	0.8	0.8	0.1
		I	Pearson	0.5	0.3	0.4	0.5	0.1	0.2	0.7	0.8	0.0
			R2	0.3	0.1	0.2	0.2	0.0	0.0	0.5	0.7	0.0
		API30	Pearson	-0.2	-0.3	0.9	0.8	0.9	0.8	0.6	0.5	0.7
			R2	0.0	0.1	0.8	0.7	0.7	0.6	0.4	0.3	0.4
P7	NGR	P	Pearson	0.1	0.8	0.9	1.0	0.9	0.9	0.8	0.8	0.1
			R2	0.0	0.7	0.8	0.9	0.7	0.8	0.6	0.7	0.0
		I	Pearson	-0.7	-0.3	0.2	0.1	0.4	0.1	0.1	0.0	0.2
			R2	0.5	0.1	0.0	0.0	0.2	0.0	0.0	0.0	0.0
		API30	Pearson	0.0	-0.1	0.5	0.3	0.4	0.4	0.5	0.3	-0.3
			R2	0.0	0.0	0.3	0.1	0.1	0.2	0.3	0.1	0.1
		P	Pearson	0.8	0.6	0.6	0.7	0.2	0.6	0.6	0.7	0.2

			R2	0.7	0.4	0.3	0.5	0.1	0.4	0.4	0.5	0.0
		I	Pearson	0.3	0.5	0.5	0.3	0.3	0.2	0.5	0.4	-0.2
			R2	0.1	0.2	0.2	0.1	0.1	0.1	0.2	0.2	0.1
		API30	Pearson	0.1	0.0	0.9	0.8	0.8	0.8	0.9	0.8	0.6
			R2	0.0	0.0	0.8	0.6	0.7	0.6	0.8	0.7	0.4