

# **Exploring the optimal placement of Natural Flood Management (NFM) in different catchment configurations**

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Thesis submitted in fulfilment of the requirements for the degree of:

**Ph.D. in Environmental Geography**

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Nottingham, UK

October 2020

## **Acknowledgments**

I would like to express my pure and genuine thanks to my first supervisor Mathew Johnson for the unconditional support provided during the four years at the University of Nottingham. In part, this research thesis is the result of a joint and guided work that now is consolidated in this document. His great expertise, dedication, confidence and understanding helped me overcome all the obstacles of the doctorate. Huge thanks to Dr Nick Mount, my second supervisor, who challenged me in each supervision meeting getting to push myself to be able to achieve a research with the rigorous and scientific character that it deserves. Also thank to Dr Simon Gosling for being my internal advisor and review the three annual reviews, his expertise in the hydrology field helped me to improve my research.

A special thanks to Fundación las Ceibas, Colombia, who, through the program "Fortalecimiento de capacidades regionales en investigación, desarrollo tecnológico e innovación en el Departamento de Nariño" has funded my doctoral program. I would also like to thank The Digital Research Methods of the University of Nottingham, who provided me with the financial funds to use a virtual platform that allowed me to carry out more than 400 hydraulic and hydrological simulations. Thanks to the University of Nottingham, especially to the staff of the School of Geography since during my four years I did not have a single problem to carry out my research.

Thank to the fellow students who contributed to develop both my professional and personal career. To my office colleagues Chris, Charly and Marzhan with whom we share hours and hours together. A big thank to Luis and Juanda with whom, sitting every week in a Turkish restaurant, we discussed our research and wrote solutions on the restaurant's napkins. Also, thank to Elkin, Juanda and Olmer with whom during the 2020 lockdown we met every week to talk about life and listen good music, this certainly helped me out to breathe and get out of the routine of writing.

To thank my parents, Doña Tere and Luis Álvaro who have given me all the necessary tools to face life, especially my mother who is the engine that makes my life move. To my brothers Andres, Karol, Johanna, as well as to my childhood friends Juan, Yesid and Luisga who have always been there and laugh every day. To my girlfriend Nerea who has been by my side giving me support during the last and hardest stage of the doctorate, she also deserve a prize. Finally, and the most important infinitely thank God for allowing all this to happen.

“Look deep into nature, and then  
you will understand everything better”.

Albert Einstein

## **Abstract**

Fluvial flooding causes significant economic, environmental and social losses, which are predicted to increase in the future due to climate change, land use change and increased urbanisation. To mitigate flooding, focus has moved from hard engineering and structural defences to risk reduction utilising natural processes, particularly tree planting to slow the flow. Whilst Natural Flood Management (NFM) has received a lot of attention, most research has focused on modelling small, upland catchments in the UK, with limited evidence demonstrating where and when NFM interventions are likely to be most effective. Therefore, I aimed to use a coupled hydraulic-hydrological model to explore how the morphology of catchments, intensity of rainfall, and the spatial configuration and coverage of NFM (tree cover), effects peak flows and lag times. The ultimate goal was to ascertain where in a catchment tree cover could be optimally placed to maximise reductions in peak flows.

I achieved this in abstract space, looking at hydrographs generated in 20 abstract catchments of differing size, shape and morphology, with three rainfall intensities (30, 60, 120 mm h<sup>-1</sup>). Results show that establishing 25% NFM in catchments reduced peak flow on average by 23%, whereas covering three-quarters of the catchment led to 57% reductions. However, further coverage beyond 75% of the catchment had negligible additional reductions on peak flow. In contrast, it was found that up to 75% catchment vegetation cover was needed to have a significant impact on lag times. Similar relative patterns were found between catchments and NFM coverages for different rainfall intensities, although absolute values of percent reduction increased with rainfall intensity.

Substantial differences in peak reduction were found between catchments, with catchment slope and drainage density being most significant in controlling hydrograph response to NFM. Situating NFM in areas of flat slopes was found to be effective in reducing peak flows, with coverages as low as 0.7% leading to peak flow reductions equivalent to 17.1%. To optimise NFM placement, a catchment travel time model was employed to focus NFM into areas with similar travel times in an attempt to equalise travel times across the catchment, reducing peak flows. This was found to significantly impact lag times but not to have had as large of an impact on peak flows as hypothesised. The reasons for this are discussed, along with future work needed to assess where and when NFM is likely to be most significant in reducing flood risk.



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## **CHAPTER 1. INTRODUCTION**

### **1.1 Background**

River floods are a serious hazard, causing severe natural disasters globally (Dottori et al., 2018, Alfieri et al., 2017). The hydrological responses causing river floods depend on the type and characteristics of the rainfall event, including its magnitude and frequency (Charlton, 2007, Feldman, 1979, Rao and Hamed, 2000, Ouarda et al., 2001). Changes in the frequency and intensity of flooding can cause serious social, economic and environmental impacts (Quintero et al., 2018, Huizinga et al., 2017). Research has shown that the frequency and intensity of rainfall has increased over the last 3 decades globally and the implications of such changes have been widely discussed (Kundzewicz et al., 2013, Milly et al., 2005, Brakenridge et al., 2004). In particular, changes in rainfall and those projected to occur in the future have the potential to increase the risk of flooding substantially. According to Douben (2006), 65% of river floods worldwide have been caused by intense and prolonged rains, with an additional 15% by short-duration torrential rains and the remaining 15% by other natural hazards. Arnell and Gosling (2016) argue based on future climate modelling, that by 2050 floods with return periods of 100 years could be at least twice as frequent in 40% of the world, increasing global flood risk by 187%.

Flood risk in the UK is relatively high. The Environment Agency of England's (EA) 2009 National Flood Risk Assessment shows that there are 2.4 million properties at risk of flooding and that an additional 2.8 million properties are susceptible to surface water flooding (Environment Agency, 2009). Approaches to dealing with river flooding have traditionally been oriented towards highly engineered structures (Werritty, 2006, Huq and Stubbings, 2015), which serve various functions such as holding, slowing or diverting discharge from streams and lessening potential effects. For many years, hard engineering has been advocated as an effective measure to reduce damage to infrastructure, property, and populations (Werritty, 2006). However, traditional engineering works tend to be robust structures that are expensive, require significant maintenance and monitoring (Hall et al., 2003) and only serve their function locally. In the UK this type of measure has been widely used, however it is increasingly recognized that flood prone areas are too numerous and covering too large of an area for hard engineering alone to be able to protect everywhere (Johnson and Priest, 2008). In response to this, the UK Department for Environment, Food & Rural Affairs (DEFRA) launched its flood management control strategy in 2004 called "Making

Space for Water" looking for alternative strategies, to work alongside grey engineering, to reduce flood risk (Nisbet and Thomas, 2006, DEFRA, 2004).

At a similar time, the European Commission (EC) drafted a Flood Directive (FD) that involved all the member states of the commission, encouraging a new approach to sustainable and holistic water management, which was incorporated and expanded in the Water Framework Directive (WFD) (2007/60/CE) and the Habitat Directive (HD) (European Commission, 2007). The FD encourages the implementation of flood management within the broader context of environmental management, promoting connectivity with floodplains, reducing the degradation of habitats, and considering the operation of the hydrological system as a whole (Holstead et al., 2017). In the UK, the adoption of a more sustainable flood risk management model with a long-term strategic vision, including the potential impacts of climate change, was made through the Flood and Water Management Act (2010) (Flood Water Management Act, 2010). This law was established in response to a sequence of major flood events in the UK, culminating in the summer of July 2007 and due to the fact that it was not feasible to rely solely on bigger defences (Pitt, 2008).

To address the need for holistic flood risk management, the UK concentrated its efforts in Working With Natural Processes (WWNP) to reduce the risk from flooding, which in turn contributes to restore or improve aspects of the natural environment (Lane, 2017). Natural flood management (NFM) was well aligned with the approach to risk management, which takes both non-structural and structural measures and engages stakeholders to identify optimal solutions. The application of NFM today is part of flood policy in the UK (SEPA, 2015, Kay et al., 2019), which has meant a significant government investment. The investment was revealed in the published study on long term investment scenarios (LTIS) (Environment Agency, 2014), which provided an economic assessment of future coastal flood and erosion risk management for 2015-2065. In this sense, NFM was considered as a potential measure to be implemented in the hydrographic catchments in England.

NFM measures have been broadly focusing at catchment scale based on land and rivers as well as their floodplains (Environment Agency, 2017). NFM incorporates a diverse range of measures that aim to store water, improve infiltration and slow down flow velocities (Dadson et al., 2017, Lane, 2017). Measures include the creation of woodland, in-line and off-line water storage areas, leaky dams, sediment management, alteration of channel form, including remeandering, and

the development of runoff attenuation feature (RAF) characteristics to intercept surface flow (Nicholson et al., 2012, Blanc et al., 2012a, Ashley et al., 2015, SEPA, 2015). These measures also provide other, mutual benefits such as the provision of habitats, promoting biodiversity, regulation of water, restoration of riparian vegetation and potential water quality improvements (Janes et al., 2016, Iacob et al., 2014, Short et al., 2019). The growth in interest in NFM is reflected in numerous projects across the UK; for example, there are 65 case studies on the effectiveness of Working With Natural Processes in the Working With Natural Processes Evidence Directory (Environment Agency, 2017a). An emblematic and pioneer project was the 'Slowing the Flow at Pickering' project, which was carried out at Pickering Beck, North Yorkshire, UK (Forestry Commission, 2004). The aim was to demonstrate how the integrated application of a range of land management practices, when carefully incorporated into a wider suite of catchment measures, can help reduce flood risk by decreasing the peak flow and get multiple additional benefits reducing local impacts.

Although there is a growth in interest in NFM (Janes et al., 2016, Barlow et al., 2014), there is uncertainty in three fundamental aspects: the scale, effectiveness, and location of NFM. There is a lack of consistent evidence of their efficacy, and the quantitative prediction of downstream reductions is uncertain, especially for large flood events (Dadson et al., 2017) and there is also still great uncertainty about the implications of NFM in larger hydrological scales ( $> 100 \text{ km}^2$ ) (Dixon et al., 2016, Lavers and Charlesworth, 2017). SEPA (2013) argues that the effects of large-scale NFM are difficult to determine as they are likely the result of the accumulation of many local-scale impacts, which themselves are difficult to quantify. Dixon et al. (2016) argue that without an improvement in a full understanding of the benefits or possible limitations of NFM, progress will remain limited. In addition, Archer et al. (2016) warn that extrapolation of the measurements from one catchment to another must be carefully analysed since the hydrological response is different at different scales.

The location of the NFM continues to be a field of research (Connell, 2008, Hankin et al., 2016). In the UK determining the location of NFM has been limited to conducting an assessment to characterize and report what features can be installed in the particular areas of the watershed (Hankin et al., 2016). This evaluation has been based on producing maps based on the EA's method of identifying watersheds sensitive to changes in land use (Environment Agency, 2009). The EA's method considers four fundamental parameters to reduce the risk of flooding: agricultural runoff, land cover, soil type, slope and standard average

annual precipitation. Overlay analysis of these four factors determines potential areas where NFM is hypothesised to be more effective. The EA's "Working With Natural Processes - Evidence Directory" also encourages the use of hydraulic and hydrological programs to search for alternative methods of determining NFM placement, which contribute to the understanding of NFM in hydrological catchments (Environment Agency, 2017). In addition, a list is made of the areas that are not known and that are future fields of research development. These are listed:

- Effect on large flows and the hydrological response it makes to reducing flood flows.
- How the flood protection measures vary according to:
  - amount and type of woodland
  - its placement in the catchment
  - size of the catchment
- Appropriate parameter ranges to ensure catchment woodland processes are modelled effectively to help predict their flood risk benefits.
- Need to improve the way that hydrology, hydraulic and coupled models represent woodland hydrological processes and to test the upscaling of these to the catchment level.
- Whether they are a greater flood risk benefit if the catchment woodlands are more connected / less fragmented.

## **1.2 Aims and Objectives**

Given these important research gaps, this thesis aims to produce a comprehensive assessment of NFM effectiveness, and how effectiveness is related to catchment morphology. The significance of NFM location in catchments of different configurations will also be explored using a coupled hydraulic-hydrological model.

Specific objectives to achieve these aims are to:

1. Identify key morphometric and physiographic parameters for the characterisation of catchments;
2. Statistically classify catchments into typologies representing predominant morphological characteristics and assess whether hydrological response (peak flow and lag time) differs between categories.
3. Compare the high flow response between catchments of differing morphology under differing rainfall intensities and hyetograph distribution.
4. Calculate hydrographs across multiple catchments, with and without NFM, and statistically compare differences.
5. Quantify how increasing coverage of NFM impacts peak flows and lag times in catchments, and determine how catchment morphology modulates NFM impacts.
6. Determine whether the significance of NFM in catchments is impacted by rainfall intensity.
7. Explore how the location of NFM within catchments may influence the peak flow and lag time
8. Develop a method of optimising NFM placement in a catchment based on identifying morphological drivers of peak flow by investigating flow travel times across catchments.

## **CHAPTER 2. LITERATURE REVIEW**

### **2.1 The science of flooding in rivers.**

Flooding can be associated with rivers and with coasts. Here, the focus is on river flooding, defined by as a high flow event that overwhelms the natural river channel, spilling out of the channel banks onto surrounding land. Douben and Ratnayake (2006) state that worldwide, floods are the most dangerous natural hazard on Earth. Thus, floods have a negative connotation because of the potential damage to infrastructure and loss of life (Gobiet et al., 2014). However, infrastructure is not the unique asset affected by floods, which also impact agriculture, land drainage, ecosystems and human health (Juarez-Lucas et al., 2016). It is reported that between 2008 and 2011 more than 87 million people were displaced by floods (D'Andrea et al., 2011, Yonetani and Holladay, 2012), with most of the displacement occurring in regions with poor socioeconomic conditions (Ghimire and Ferreira, 2016). The overall economic losses caused by floods exceeded US\$630 billion between 1986 to 1995 (Douben and Ratnayake, 2006) and from 2000 and 2012 the global average annual cost of natural disasters was approximately US\$100 billion (Kousky, 2014).

Generally, floods are driven by climatic factors (Guerreiro et al., 2018) but their timing and frequency is dependent on a complex interplay between many physical and hydrological factors (Schumm et al., 1987). Hooijer et al. (2004) describe how floods are generated due to the precipitation rate and distribution over catchments, as well as the manner of how rainfall is transformed into river discharge. They describe five main factors that determine the magnitude of flood peaks: a) characteristics of the rainstorm, b) soil moisture conditions prior to the rainfall event, c) the transfer mechanism of rain to streamflow, d) the size and shape of the channel which determines the propagation of a flood wave, and d) for large catchments, the timing of events in different tributaries (Hooijer et al., 2004). The causes of flooding were also described by Newson (1994) including factors that intensify floods, represented in Figure 2-1.

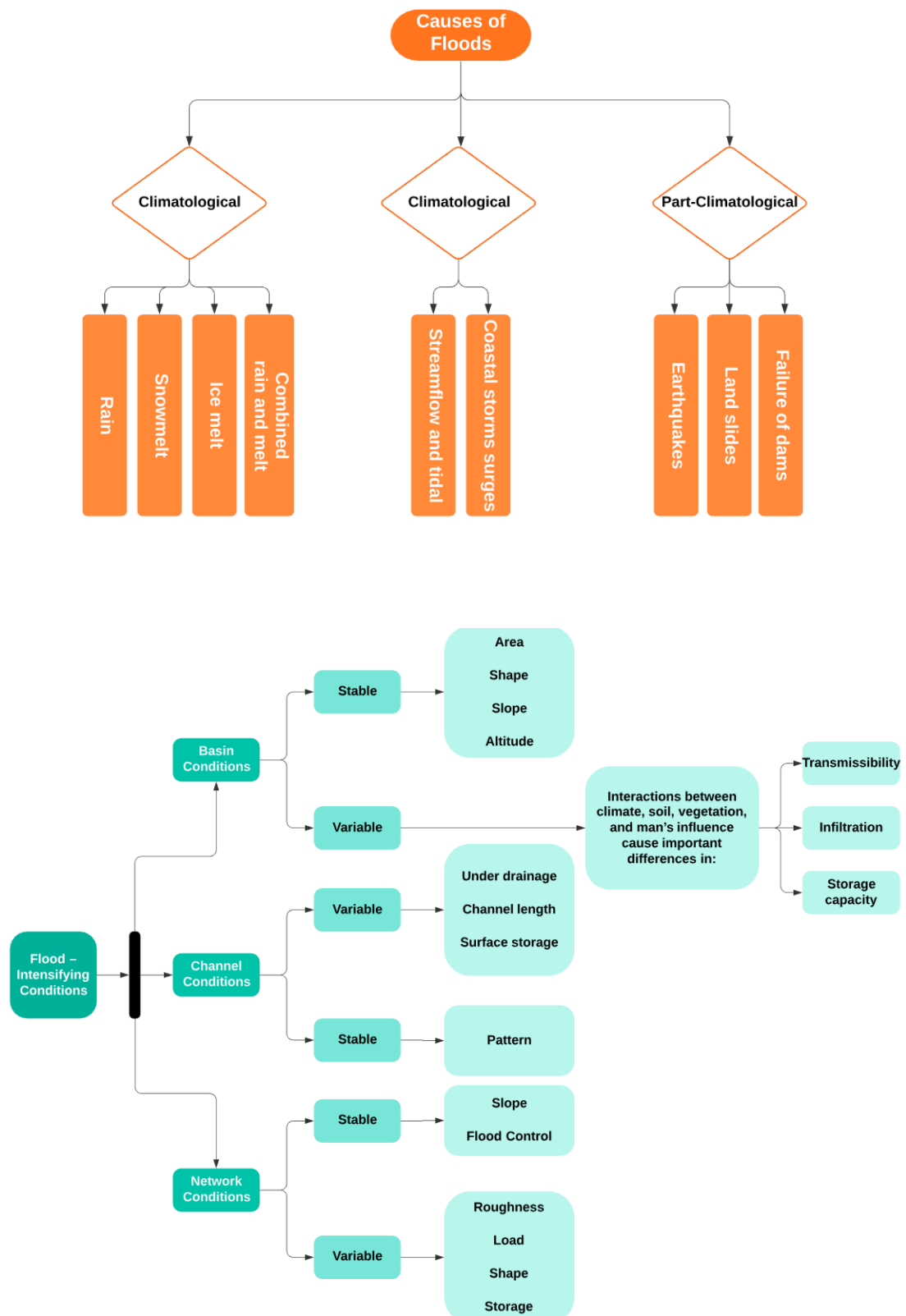


Figure 2-1 The causes of flooding adapted from Newson (1994)



The discharge product of a precipitation event varies in space, usually increasing in a downward direction, and over time in response to discharge from tributaries entering the main channel (Reddy, 2005). Leopold and Maddock (1953) affirm that the discharge is the dominant independent variable in the morphological changes while Beven et al. (1988) suggest that morphology of the catchment is a dominant control on the spatial patterns of hydrological response. Beven et al. (1988) also state that morphology of the catchment and hydrological processes are intimately linked as a result of several geomorphic processes. Discharge is the volume of water that runs through the cross-section of a river in a given period (Chow, 1959) and inputs to the drainage network are produced by many factors, mainly by precipitation across the catchment area (Reddy, 2005). Precipitation reaching the soil can be transformed into runoff or throughflow, moving downslope until it reaches the channelised drainage networks and contributes to the discharge of the river.

Flooding is a natural occurrence and happens because river channels are created and maintained by an average flow rather than maximum flows (Leopold and Maddock, 1953). Whilst large floods have great potential to generate morphological changes, they usually occur too infrequently to be geomorphologically significant to the longer-term morphology or dynamics of the river channel (Chow, 1959). The magnitude and frequency of river discharge are inversely related, with the most geomorphologically effective flows thought to occur every 1 to 5 years and filling the channel to the top of the banks (i.e. bankfull), although great variability exists between rivers (Schumm et al. 1973). The relationship between the magnitude and frequency of river discharge also results in flooding often being quantified with a probability of occurrence or return period, understood as the time interval that on average has to pass to register an event of that magnitude (Reddy, 2005). Using this logic, flood magnitudes can be predicted by extrapolating from known discharge records to specific return periods, often the 100 year flood.

In hydrology, flow hydrographs are used to quantify and characterise the progression of individual flood events (Feldman, 1979). A hydrograph represents the magnitude of the precipitation event and the magnitude of the discharge in the river, through time. The form and magnitude of the hydrograph can produce a great deal of information about catchment hydrological responses (Hannah et al., 2000). The severity of a flood event is often defined, at least partially, by the flood peak value, although other features such as the timing of the flood peak and the duration of the flood can also be highly significant (Grimaldi and Serinaldi,

2006, Yue et al., 1999). Figure 2-2 depicts a hypothetical hydrograph and some key characteristics described by Acreman and Holden (2013), which include:

- The peak flow, which determines the maximum flood level.
- The rise-time, which specifies how rapidly the floodwater rises and how quickly it reaches its peak.
- The lag-time, which indicates how much warning could be given between peak precipitation and the flood peak.
- Duration, indicating how long the flood will last.
- Flood volume, expressing the total amount of water in the flood event and the storage capacity.

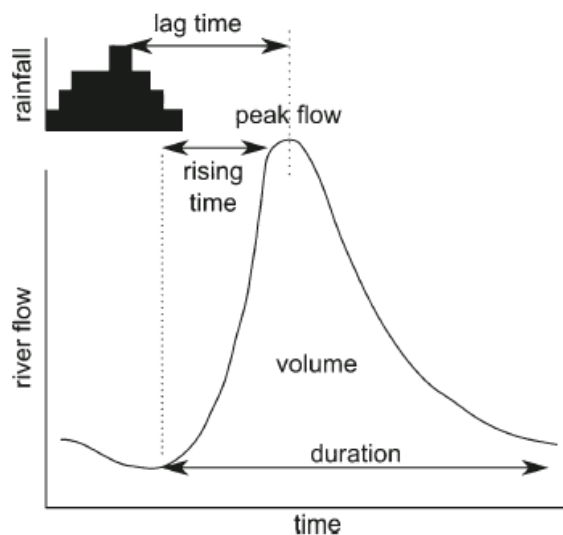


Figure 2-2 Hypothetical river flood hydrograph and hyetograph (Acreman and Holden, 2013).

## 2.2 Flood risk.

People have historically lived near water courses due to the benefits provided, including drinking water, fertile soils and relative ease of trade and transportation of products (Douben, 2006, Re, 1997). However, living near rivers also provides risks, such as floods. Agriculture developed on floodplains where soil fertility is replenished by regular flooding but, as the inconvenience of flooding increased as

populations living near rivers increased, and as farming practices enabled fertility to be replenished in other ways (e.g. manure spreading and fertiliser), flood flows became managed (Johnson and Priest, 2008). With the transition from flooding from being a net positive to a net negative impact, flood mitigation occurred and long-held views of flooding as an overwhelmingly negative natural disaster occurred. The economic damage caused by flooding drives continued management and investment in flood defences. Such work has indeed reduced the vulnerability of people but, economic damage continues to remain high as those most exposed to the dangers of flooding have transitioned from the countryside to the city and, within urban spaces, population density and the value of infrastructure remains high (Hall et al., 2003).

Lane (2017) holds the view that the flood consequences mainly depend on the variation of three major aspects: a) Flood Hazard, b) Exposure, and c) Vulnerability. These aspects may increase or decrease the consequences of flooding for people or infrastructure, and solutions to flood damage should aim to understand flooding through the context of these three aspects. Population growth and increasing population density living alongside rivers, increases human exposure to flooding. There is also evidence that the frequency and magnitude of flooding is increasing, globally, with rainfall expected to further intensify in the 21<sup>st</sup> century further increasing exposure to flood events (Brakenridge et al., 2004) (Parry et al., 2007).

Flood risk and consequences are also dependent on the nature of the precipitation event (Beven and Carling, 1989). The speed with which floods develop are directly linked with the intensity, duration and spatial distribution of the rainfall event determining whether the resulting flood is slow onset or a more rapid onset rain even (Smith and Ward, 1998). For example, prolonged rainfall can lead to slow-onset flooding, with discharge gradually rising over a period of days (Ward and Robinson, 1967). River flooding of this sort is predictable in the short-term, allowing preparation and minimisation of losses, although flood duration tends to be long and flood extents substantial, with implications for infrastructure, transport networks and homeowner possessions (Feldman, 1979). In contrast, short duration, intense rainfall can lead to flash flooding, which is fast onset that strike without warning but short duration and spatially limited; however, such flooding is unpredictable and often highly damaging with significant danger to human life. This type of flood can occur anywhere that heavy rainfall takes place (Archer and Fowler, 2018) but, are especially problematic in steep catchments with narrow valleys (Smith and Ward, 1998, Black, 1995). Shorter events tend to

lead to more significant flooding in small catchments rather than larger catchments because in large catchments flash flooding tends to affect a smaller proportion of the total catchment than in smaller catchments (Smith and Ward, 1998).

Another change that can increase the number and severity of flood hazards are morphological alterations to river channels and catchments (Lane and Kalinske, 1941). The river channel and its catchment should exist in a state of quasi-equilibrium, with alterations to a catchment leading to changes to river channels (Montgomery and Buffington, 1997). Where changes in a catchment are large, such as large-scale deforestation, the morphology and dynamics of a river channel can change dramatically (Shaw, 2005). The underlying geology, soil characteristics, vegetation cover, surface roughness, and the river's transport capacity, determine and configure the characteristics of the channel (Anderson, 2006). For example, sedimentation in a channel can reduce flow conveyance, increasing vulnerability to flooding upstream (Schumm et al., 1987). Additionally, flood magnitude and frequency can be influenced by anthropogenic influences, such as deforestation, urbanisation, river channel straightening and channelisation, and land agricultural land drainage (Brookes and Shields Jr, 1996b, Brookes, 1988). The impact of anthropogenic climate change can also influence flood dynamics (Blöschl et al., 2017, Sayers et al., 2015, Van Aalst, 2006).

### **2.3 Climate change and increasing flood risk.**

Hydrological changes seen during recent decades have increased the uncertainty surrounding the occurrence of flooding, with evidence of increased storm frequency and intensity decreasing the return period of flood events in many parts of the World (Kundzewicz et al., 2013, Milly et al., 2005, Quintero et al., 2018). A study carried out by Brakenridge et al. (2004) shows that globally, flood frequency and magnitude increased between 1985 and 2003, and July and August are the months where floods have occurred most frequently. Additionally, 25 years of data collected from the Dartmouth Flood Observatory since 1985 confirms the increase in flood frequency in the UK (Kundzewicz et al., 2013). Climate modelling by Arnell and Gosling (2016) suggests that by 2050, flooding with a 100-year return period could occur at least twice as often across 40% of the World, estimated to mean 450 million people affected by this increase in flood frequency. Another climate modelling study by Quintero et al. (2018), focused on the Cedar River and Snkunk River in Iowa, USA, indicates that between 2009 and 2099, 100 year return period events might increase by 47% to 52%. Dottori et al. (2018) also suggest that with

a rise in temperature of 1.5 °C, the human losses from flooding may increase by 70 to 83% in a worst case scenario. Direct flood damages are predicted to be 160% to 240% higher than current levels (Dottori et al. 2018).

According to Douben (2006), approximately 65% of river floods globally have been caused by heavy and prolonged rainfall, with a further 15% by brief torrential rainfall and the remaining 10% by other natural hazards. Paprotny et al. (2018) using a database of 37 European countries, which includes records for 1564 flood events from 1870 to 2016, found that 56% were flash floods lasting less than 24 hours; 39% were river floods; while just 4% were coastal flood events. This suggests that attention should be placed on flooding caused by high precipitation rates and intensities, because torrential rain triggers a substantial proportion of floods globally, and in Europe, and flash floods tend to be disproportionately damaging because of the lack of warning. In Europe, especially in the north, precipitation has increased significantly over the last 40 years, increasing the magnitude of river flows and increasing flood frequency (Kundzewicz et al., 2013, Parry et al., 2007).

The impacts of climate change are recognised in international climate legislation that assesses the causes and effects of climate change, globally, and sets guidelines and agreements to prevent its progress and impacts. In 1988, concern about the impacts of climate change gained momentum leading to the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) establishing the Intergovernmental Panel on Climate Change (IPCC). This panel was created to provide comprehensive evaluations of scientific advances, including technical and socio-economic knowledge on climate change, providing countries with tools and strategies to face the causes and potential impacts (Van Aalst, 2006). Additionally, in 1992 the United Nations Framework Convention on Climate Change (UNFCCC) was adopted in New York, in order to establish strong agreements between countries in the field of climate change. As a result of the 1992 agreement, the Kyoto Protocol was adopted in Japan in 1997, where 187 states ratified their participation and agreed to reduce the emissions of greenhouse gasses which likely cause climate change (Rao, 2012). In 2015, as part of the UNFCCC, the annual Conference of Parties (COP 21) was held in Paris, France. At this conference, 195 countries participated in the analysis of the current global climate change situation verifying the agreements to keep global warming below 2 °C, which was initially the aim of the Kyoto Protocol (Gross, 2019). More recently in 2019, the UN Climate Change Conference COP25 took place in Chile with logistical support from the Government of Spain. However, despite this work

and agreements as to the impacts and drivers of climate change, flood frequency and magnitudes are still expected to increase over the next century and flood risk to increase substantially because of the additional impacts of continued urbanisation in areas of flood risk.

## **2.4 Historical approaches to managing flooding and the paradigm of hard engineering.**

Prior to the 1990s, flood risk management predominantly focused on enhancing land drainage with hard engineered flood defences situated to protect valuable, at risk areas (Johnson and Priest, 2008), particularly focused at protecting farm profitability and urban infrastructure. With the development of new materials (e.g. concrete) and technological improvements, hard engineering solutions have improved and do reduce flood risk of many people living in high-risk areas (Oliver et al., 2018).

The approach of hard engineering has traditionally focused on the design of very robust, large structures situated in key locations to protect extensive areas from flood water (Smith et al., 2019). These structures are regularly in contact with river flows and, as such, require solid and deep foundations to provide a stable structure over long time-periods. For instance, the most frequently constructed structures are longitudinal flood walls and embankments, flood alleviation channels, river channelisation, and storage and retention dams. These structures are usually built in, or very close to the river channel, with the aim of confining high flows to the area of the channel, by increasing channel size, speeding up the flow, and storing water in marginal structures (Brookes, 1988). The design of these structures is usually associated with hydraulic modelling of a “design discharge”, which is the discharge associated with the critical flood magnitude responsible for causing danger to life, possessions, and infrastructure (Bao et al., 1987). Often the hydraulic discharge is related to storms that have the probability of occurrence of 1% every year, which correspond to the return period of 100 years (Quintero et al., 2018).

Although hard engineered schemes can work well in protecting specific areas (Smith et al., 2019), it is clear that, more broadly, flood risk has increased over the last century and will continue to, and that hard engineering alone will not be able to prevent significant damage and loss of life in the future (Pitt, 2008, Johnson et al., 2020). In addition, the increased frequency of flood events due to the

manifestation of climate change means that hard engineering schemes will be more regularly overtopped in the future, not providing the level of protection they do today (Rubinato et al., 2019)

Hard engineered schemes often increase flood risk downstream due to the reduction of roughness and associated increase in flow velocity, and lack of upstream storage (Knighton, 2014, Arnaud-Fassetta et al., 2005). Structures such as flood walls and dams also interrupting the natural longitudinal and transverse connectivity between the channel and riparian areas, resulting in significant geomorphological detriment to fluvial and riparian ecological communities (Brouwer and Van Ek, 2004), sometimes leading to a negative feedback where flood risk can be increased in areas of hard engineering unless there is continued intervention. For example, dredging to increase channel size, leads to sedimentation, which decreases flow conveyance capacity, increasing flood risk unless the channel is regularly re-dredged (Bhowmik and Stall, 1979).

Hard engineering schemes are typically also expensive and so their cost-benefit can be problematic, especially when ongoing maintenance costs are included, making it unsustainable and unaffordable in many cases (Hall et al., 2003). Additionally, hard engineering flood defence costs are prohibitive to many poorer countries, with wealthier countries more likely to invest in flood management (Jonkman et al., 2008). Governments are generally committed to protecting large cities, where benefits of preventing flooding are likely to be high relative to costs. For example, two of the most important cities in the Netherlands (Amsterdam and Rotterdam) are at high risk of flooding, but are protected through substantial investment justified by favourable cost-benefit analysis (Brouwer and Van Ek, 2004). This results in some of the most vulnerable areas to flooding being in areas with poorer economic conditions or considered to be of lower monetary value. Some efforts are made to deal with the bias towards wealthy, urban areas in cost-benefit analyses, such as in the UK where, since 2005, additional criteria are used in an attempt to equalise regional discrepancies in costs-benefits (DEFRA, 2004).

The cost of flood defences, and the scale of necessary consideration, means flood walls and other grey infrastructure are usually associated with central governments, who are also typically responsible for flood risk assessment. In the UK, central government estimates flood losses and commissions flood defences, and any infrastructure that may alter flood risk has to be permitted by government agencies (Environment Agency, 2010). For example, in the UK flood management seeks a cost-benefit ratio of around one to five, which is very ambitious and the

ratio is generally lower. However, the objective has been to find a balance between the economic aspects and the social benefits that make the investment more justifiable. It is clear that this approach prevents expensive structures with low impact or benefit being built, which has also driven a focus towards more novel approaches.

Another significant aspect of flood management using hard engineering is that it is increasingly recognized that flood-prone areas are too many, covering too large an area, for hard engineering to protect everywhere (Johnson and Priest, 2008). In response to this, in 2004, the UK DEFRA launched their strategy for flood management control called "*making space for the water*" looking for alternatives to work alongside hard engineering that are efficient through time and do not require exorbitant investment (Nisbet and Thomas, 2006, Werritty, 2006). These include land use planning and controlling runoff at a catchment scale, in addition to building new hard engineered infrastructure and maintaining existing defences (Hall et al., 2003). Likewise, the UK governments has been willing to invest more money to face flooding; for example, the UK public spending was amplified from £600 million in 2007-2008 to £800 million in 2010-2011 after a series of major flood events since 1998 (Environment Agency, 2009). These novel approaches, often called sustainable approaches to flood management, aim to reduce the efficiency of drainage, lowering peak flows by slowing down runoff in the catchment, temporarily storing it in soils and upland retention areas, such as bogs, moors, ponds and upstream of 'leaky dams'. Therefore, it is increasingly apparent that hard engineering alone is not sufficient to successfully manage rivers in the future, particularly in the context of climate change, and as such, novel approaches need to be developed and implemented to more holistically manage flood risk (Rubinato et al., 2019, Rehman et al., 2019).

## **2.5 Sustainable methods, approach to Flood Management**

The term "sustainable development" (SD) was initially introduced by Brundtland et al. (1987) in the report of the World Commission on Environment and Development (WCED), later quoted in Agenda 21 of the Earth Summit in Rio in 1992 (United Nations, 1997, Sitarz, 1993):

*"Sustainable Development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: the concept of*



*"needs", in particular the essential needs of the world's poor, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organisation on the environment's ability to meet present and future needs."*

This term has been widely accepted and criticised at the same time, and more definitions and complementary meanings have been given. For example, IUCN (1991) presented its definition of sustainable development:

*"Sustainable development means improving the quality of life while living within the carrying capacity of supporting ecosystems"*

In this sense, sustainable development involves human and environmental aspects, which have been the focal point in developing a complementary and accurate definition. In 1999 the UK strategy for sustainable development "Better Quality of Life" suggested that SD may guarantee a better human condition in time if four objectives are achieved: 1) social development, 2) protection of environment, 3) adequate use of natural resources, and 4) maintenance the economic stability of the country (DETR, 1999).

These definitions have been extrapolated to different fields to contribute to more specific debates. For instance, the term Sustainable Flood Management (SFM) is now widely used and defined in the context of Integrated Water Resource Management by DEFRA (DEFRA, 2004) as:

*"The concept of sustainable development will be firmly rooted in all flood risk management and coastal erosion decisions and operations. Full account will be taken of the social, environmental and economic pillars of sustainable development, and our arrangements will be transparent enough to allow our customers and stakeholders to perceive that this is the case. Account will also continue to be taken of long-term drivers such as climate change. Decisions will reflect the uncertainty surrounding a number of key drivers and will where appropriate take a precautionary approach. Decisions will be based on the best available evidence and science."*

At the same time, The Scottish National Technical Advisory Group (NTAG) had proposed a succinct vision of what sustainable flood management entails (Scottish Executive, 2005).:

*"Sustainable flood management provides the maximum possible social and economic resilience against flooding, by protecting and working with the*

*environment, in a way which is fair and affordable both now and in the future.”*

This definition includes the word ‘resilience’, which means to be able to recover quickly and effectively. Gouldby and Samuels (2005) in the “Language of Risk” attempted to define SFM, describing four essential aspects: a) reduce the flood risk damage and improve quality of life by being prepared for floods; b) mitigate the environmental impact using strategies implemented to reduce the flood risk; c) the reasonable use of natural resources and maintenance of flood defences structures, and; d) keep the productivity and economic stability of the land.

In 2006, the European Commission produced a Flood Directive (FD) that involved all member states, representing a new approach focused on holistic catchment management (European Commission, 2007). The concept of sustainable and holistic management was further incorporated in, and expanded on, in the Water Framework Directive (WFD) (2007/60/EC) and Habitat Directive (HD), as a tool to achieve the objectives of these directives. Member states are encouraged to implement flood management within the broader context of environmental management, not unnecessarily degrading habitats, promoting connectivity longitudinally and with floodplains, and considering the whole catchment and stakeholders and publics, with funding schemes to develop pilots projects (Holstead et al., 2017). For example in Scotland, the adaptation of the FD led to the introduction of a holistic framework of flood management (Flood Risk Management (Scotland) Act, 2009) establishing a new approach to the assessment and sustainable management of flood risks (Spray et al., 2009). Evers and Nyberg (2013) summarised the interplay of three main considerations when attempting to ensure the effective and coherent mitigation of flooding (Figure 2-3).

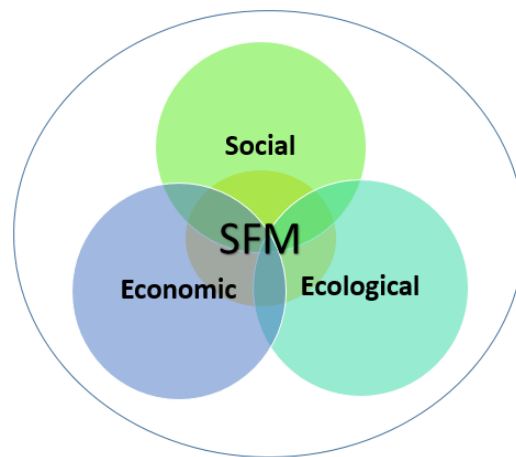


Figure 2-3. Aspects of sustainable flood management. Adapted from Evers and Nyberg (2013).

Wheater and Evans (2009) argued that the main factors increasing flood risk are urban development, floodplain development and land use changes, all because of increased impermeable surfaces, increasing runoff and therefore flood peaks. Deforestation, poor field drainage and agricultural intensification are also key factors that can increase flood risk. For example, in the Plynlimon catchment in mid-Wales, the role of vegetation was assessed, concluding that increases in streamflow are not associated by increases in rainfall but, by changes in vegetation cover affecting the water balance (Hudson and Gilman, 1993). In this sense, recognising the causes of flooding and what may trigger or intensify a flood, is important in finding a sustainable solution.

Nature-Based Solutions (NBS) represents a subset of SFM, defined by Cohen-Shacham et al. (2016) as the manner of enhancing and using biodiversity by society in a sustainable way while incorporating social factors such as socio-economic growth and governance. This concept has been introduced by the European Commission (2015) as a solution that uses nature as a source of inspiration and support, while providing social and economic benefits, helping to build resilience in a cost-effective manner. Short et al. (2019) state that NBS are commonly used to define an approach for increasing resilience to the impact of climate change. In the UK, NBS are framed in an initiative called “Working with Natural Processes” (WWNP) which aims to protect, defend, restore and emulate the natural functions of catchments, floodplains, and rivers. WWNP is the approach of a project commissioned by the Environment Agency’s Flood and Coastal Erosion

Risk (FCRM) board. The legislative policy drivers for WWNP begin with the statements made by (Pitt, 2008) in his review of drivers of flood risk in the UK, arguing that flood risk cannot be simply managed by building ever bigger grey infrastructure. In 2009, strategic plans were promoted to identify potential opportunities for WWNP (DEFRA, 2009) through the appraisal of flood and coastal erosion risk management, which underlined the importance of understanding natural processes across the whole country. In 2011, the Environment Agency advised local authorities that they should use a WWNP approach where possible in aiming to reduce flood risk whilst enhancing and restoring the environment (DEFRA and Environmental Agency, 2011).

The WWNP project document summarises research and practical work on natural processes in the UK. The project allows flood risk managers to access up-to-date material and evidence on natural process and to be able to understand the potential benefits of a WWNP approach . WWNP takes many diverse forms and can be applied in urban and rural areas, and on rivers, estuaries and coasts (Figure 2-4). This project was carried out considering three key factors, all evidence based: evidence directory; mapping the potential for WWNP, and; identifying knowledge gaps. The evidence directory compiles 65 case studies of the effectiveness of WWNP measures from the FCRM authority perspective and the benefits that can be provided to ecosystems. The mapping the potential for WWNP shows the types of measure that could be implemented and work effectively in catchments in the UK. Also, the use of the right combination of measures in the right places can help to slow flood peaks and reduce the depth and duration of flooding meanwhile achieving more benefits. The knowledge gaps section identifies key priorities for future research, importantly including an urgent need for information on the placement of natural flood infrastructure in catchments for optimising impacts.

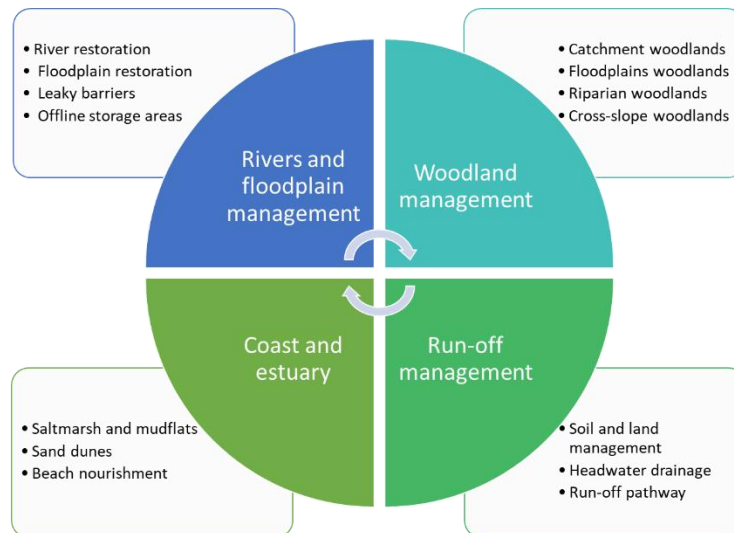


Figure 2-4 WWNP takes many different forms and can be applied in urban and rural areas, and on rivers, estuaries and coasts.

## 2.6 Natural Flood Management (NFM).

In the UK, WWNP has become the dominant paradigm in river management, driven largely by the implementation of the EU WFD, and leading to flood risk reduction being considered largely in the context of Natural Flood Management (NFM). A definition of NFM provided by Janes et al. (2016) is to improve the natural functioning of catchments and to attenuate the flood peak downstream by a range of measures such as storing and slowing the flow, physical restoration of channels and floodplains. Dadson et al. (2017) defined NFM as techniques used to manage flood risk by altering or enhancing, natural processes in a catchment as well as land use management, rivers and reservoirs. Moreover, NFM has been broadened to include multiple benefits, for example, delivering further ecosystem services (e.g. provisioning of natural habitats, promoting biodiversity, and regulation of water), river restoration and the promotion of natural sediment dynamics, restoration of riparian vegetation, reduced the runoff, reducing the long term cost in relation to building river infrastructure (Janes et al., 2016, Iacob et al., 2014, Short et al., 2019). NFM also involves flood water storage that can be supplemented or associated with improved biodiversity, water quality, carbon storage, animal habitat conservation, and in some cases human benefits (SEPA, 2015, Environment Agency, 2017). In addition to this, NFM might comprise altering multiple elements of a catchment such as the water balance, infiltration,

and groundwater storage, evapotranspiration, and increasing flow resistance (Jacob et al., 2014, Forbes et al., 2015).

The aims of NFM were assessed by Nisbet et al. (2011) at a small, upland catchment near Pickering, where landscape restoration was taking place. In 2006, a study by Nisbet and Thomas (2006) highlighted the importance of more sustainable solutions to flooding, looking at the role of vegetation in the enhancement of the catchment. The authors affirmed that woodland in a catchment played an important role in the mitigation of downstream flooding, as well as in the enrichment of the ecological system (Nisbet et al. 2011). A study carried out by Janes et al. (2016) at Johnson Creek – a tributary of the Willamette River, Oregon, USA - evaluated the impacts of the implementation of NFM approaches into channel restoration by re-meandering channelised reaches of river, reconnecting floodplains, the addition of riparian vegetation, and provision of in-channel large wood. The study found that more natural reaches had greater potential for pollutant removal, providing multiple benefits associated with NFM and river restoration.

In 2013, the Scottish Environmental Agency (SEPA) defined three NFM approaches: run-off reduction, floodplain storage, and sediment management (SEPA, 2013). All three of these approaches involve the management of floodplains and the strategic reconnection of floodplains to store water and sediment in areas upstream of infrastructure, reducing flood peaks.

NFM has gained importance in the UK (Howgate and Kenyon, 2009, Janes et al., 2016) and in 2011, the Parliamentary Office of Science and Technology (POST) described the strategies to classify NFM depending on its location in catchments (Figure 2-5). The figure suggests that different measures complement each other and more spatially diffuse strategies are beneficial in upstream reaches. Although there are numerous NFM measures, the main objective of NFM is still focused on reducing the peak flow and delaying the flood arrival time. Thus, objectives are achieved by restricting the free flow of water through a catchment, with four proposed mechanisms of effect: 1. Storing water 2. Increasing soil infiltration, 3. Slowing water 4. Flow connectivity (POST, 2011). The strategy suggests that NFM implementation depends on several factors such as soil type, geology, topography, climate and river channel distribution in the catchment. It is also suggested that the size of the catchment is also relevant for the NFM effectiveness (POST, 2011). The report indicates that the drainage network is the main parameter that determines flooding in larger hydrographic catchments. However, a major problem

to be considered is land governance and the cooperation of landowners for NFM implementation (POST, 2011).

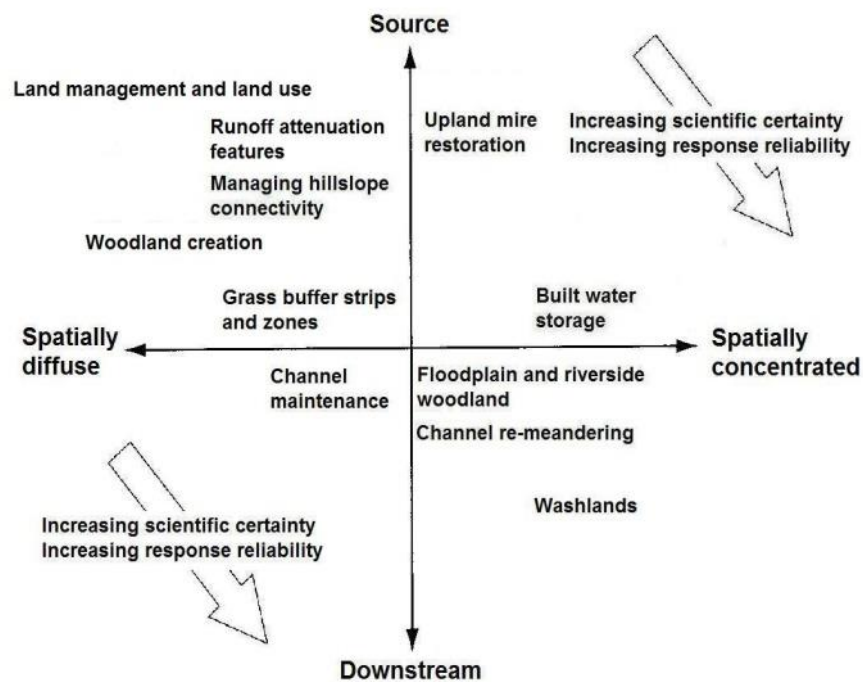


Figure 2-5. Classification of NFM strategies (POST, 2011).

More recently in the UK, NFM has been framed within WWNP, together with other terms that have been used such as Nature-Based Solutions, Engineering with Nature and Catchment Based Flood Management (Figure 2-6). However, NFM is the most commonly used term associated with WWNP in UK policy (Environment Agency, 2017). A wide range of techniques has been attributed to NFM which can be used to reduce the peak flow and achieving more benefits. The techniques are listed as follow:

- Restoring functioning floodplains
- Restoring rivers and removing redundant in-channel structures
- Installing or retaining large woody material in river channels
- Restoring peat moorlands
- Remeandering rivers
- Targeted woodland planting
- Improving floodplain connectivity

- Land and soil management measures
- Restoring moorland and woodland in the headwaters
- Creating rural and urban sustainable drainage schemes
- Restoration and management of sand dunes, saltmarshes and mudflats
- Managed realignment
- Beach nourishment

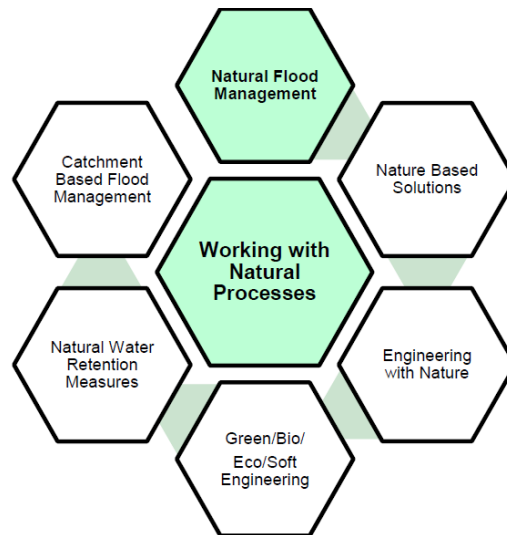


Figure 2-6 Alternative terms used to mean WWNP (Source: Environment Agency (2017)).

In the UK over the past decade, there has been a significant increase in the number of publications about NFM and SFM and, in some cases, the results are impressive although others suggest more research is needed improve our understanding of this emerging field. Table 2.1 shows a list of recent publications about NFM in Europe and the UK, with a brief description of their findings. Work on NFM outside of the UK is relatively rare (Connelly et al. 2020), although more natural, holistic approaches to flood management are being considered globally. Of the papers in Table 2.1, 22% are modelling studies, with only 3 studies able to assess effectiveness of NFM with field measurements, and two are in catchments smaller than 6 km<sup>2</sup> and one of 65km<sup>2</sup>, supporting the conclusions of Lane (2017) that our understanding of NFM effectiveness is limited because of the predominant focus on numerical modelling of small UK, upland catchments.



Table 2.1 Summary of NFM publication carried out in the UK and Europe.

| Author and date          | Type                | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   | Catchment size (km <sup>2</sup> ) |
|--------------------------|---------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------|
| (Nicholson et al., 2020) | Field and modelling | Field measurements alongside modelling of runoff attenuation features and offline storage in the upper Belford Burn catchment (5.7 km <sup>2</sup> ), Northumberland, UK. Success assessed using the peak flow reduction. The study found that by storing 20,000 m <sup>3</sup> in offline storage, the peak flow was reduced by more than 30% downstream. The study included a monitory program looking at individual storage areas, which were demonstrated to reduce peak flow locally for low magnitude rainfall events.                                                                                                                                                                                                                                                                                                                                                  | 5.7                               |
| (Connelly et al., 2020)  | Review              | Examines NFM as a measure to protect, improve, emulate or restore the natural functioning of rivers in the European space. It is argued that most of the literature and evidence of the effectiveness of NFM comes from the United Kingdom. The document also highlights that the literature does not make a special focus on climate change as a determining factor to measure the effectiveness of NFM in the future. The article explores the evidence from cases in Europe and how the effectiveness of NFM is evaluated in the face of climate change.                                                                                                                                                                                                                                                                                                                   | N/A                               |
| (Short et al., 2019)     | Modelling           | Explores NFM in the River Frome watershed (250 km <sup>2</sup> ), southern Cotswolds, UK. The project analysed the effect of NFM on reducing peak flows but also the cost-benefit of implementation. The project occurred because of the commitment of 12 private landowners and 4 NGOs, with the implementation of over 400 individual NFM measures, including 170 large wood dams, 1 drystone wall deflector, 3 spring-fed and 3 solar cattle drinking troughs, 5 large earth bunds, 10 small earth bunds/check dams, 6 gully systems stuffed with wood, 1.7 km streamside fencing, 1 large dry pond, 400 trees planted, and other interventions. Over 20% of the catchment (52.5 km <sup>2</sup> ) now flows through NFM interventions and water height decreased dramatically from 1.8 to 0.4 m when the new NFM is compared using hydraulic modelling to floods in 2007. | 250                               |
| (Wilkinson et al., 2019) | Modelling           | The potential of NFM to manage runoff in a rural landscape is analysed in two examples from UK: Belford Burn and Tarland Burn catchments. The orientation of flow paths and the use of floodplains and riparian areas were considered. The cumulative impact of small-scale, dispersed storage in small catchments (<10 km <sup>2</sup> ) was found to mitigate flood runoff. The article also argues that there is a lack of evidence about the effectiveness of NFM in larger catchments, and with extreme flood events.                                                                                                                                                                                                                                                                                                                                                    | 6                                 |

|                                 |              |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |     |
|---------------------------------|--------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| (Norbury et al., 2018)          | Modelling    | Exploration of the challenges in implementing NFM using a case study in Blackbrook catchment (21 km <sup>2</sup> ) in North West England. Demonstrates the need to combine traditional, grey engineering approaches with NFM. It is argued that the design of structures could facilitate the approval of necessary permits for implementation. The combination hard and soft engineering could provide better opportunities to obtain more efficient flood management than either alone.                                                                                                                                                                                                                                                                                                                            | 21  |
| (Waylen et al., 2018)           | Review       | Explores the factors that limit the implementation of NFM using qualitative analysis of interviews with those who influence and enable flood risk management in Scotland. The study case is a includes a summary of barriers to enable and implement NFM, mainly stakeholders having difficulties in securing the resources to implement NFM and the limited evidence and uncertainties associated with NFM. The study concludes that better linkages between research, policy and practitioners are critical.                                                                                                                                                                                                                                                                                                       | N/A |
| (Lavers and Charlesworth, 2018) | GIS analysis | Examines a methodology used to identify areas that could be used to install NFM measures to mitigate storm surges and provide ecosystem services. The research was carried out in the Warwickshire-Avon catchment using a GIS database of geomorphological characteristics and interactions with landowners. The chosen areas were located in high surface connectivity areas or areas where the river and floodplain interact to increase peak delay times with previous use of the adjacent floodplain. The study concludes that the drive to adopt NFM reflects considerable interest from landowners; however, better links between research, policy and professionals are needed.                                                                                                                               | 187 |
| (Dadson et al., 2017)           | Review       | Reviews the scientific evidence of the impacts of NFM strategies in the UK. The study focuses on analysing the processes that affect flooding and the increase in its risk potential, especially concerning the frequency of rainfall, but also in the speed and depth of water. The study concludes that the risk of flooding in small catchments and associated with small floods events can be significantly reduced by NFM. However, the evidence suggests that NFM would have less impact on larger floods, or floods in larger-scale catchments. Additionally, it is suggested that the effectiveness of NFM is directly linked to the intensity of rain or the severity of the event; for example, NFM can be more effective in short duration rainfall events rather than in intense or long duration rains. | N/A |
| (Lane, 2017)                    | Review       | Presents a concept of NFM and the types of interventions that are recommended, as well as a critical evaluation of the effectiveness of NFM. Questions the extent to which                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | N/A |

|                           |                             |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |      |
|---------------------------|-----------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
|                           |                             | NFM may be more effective than traditional engineering. In addition, an analysis of the benefits of NFM is made, where the application is not only based on flood risk management but also an enhancement of the environment. The study also raises critical issues, such as questions about the effectiveness of NFM at different spatial scales.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |      |
| (Janes et al., 2016)      | Field                       | Field study in Johnson Creek, Oregon, USA aiming to assess the impacts of implementation of NFM measures as part of channel restoration approaches, including re-meandering, floodplain reconnection, the addition of riparian vegetation, and in-channel large wood. The study has a particular focus on water quality and sediment contamination.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             | 140  |
| (Dixon et al., 2016)      | Modelling                   | Modelling work on the Lymington catchments, UK (98 Km <sup>2</sup> ) examining the effects of land use and channel network changes as a result of river restoration upon peak flows. The study considered individual segments of the river network, as well as the combination of sub-catchments to cover the entire catchment area. The study found that floodplain restoration at the sub-catchment scale with 20% to 35% catchment tree planting, could lead a reduction in the peak flow up to 20%.                                                                                                                                                                                                                                                                                                                                                                         | 98   |
| (Huq and Stubbings, 2015) | Review                      | Focused on Cumbria, UK and how local level flood policies promote NFM as a method of flood risk reduction. An overview of European and UK flood management law is provided, which suggests that the number of NFM actions in local flood management policies are limited compared to NFM potential. Additionally, they identify that non-structural measures such as NFM are gaining importance in comparison with hard engineering options. A range of 51 opportunities for incorporating NFM into Cumbria management was made, divided into five groups: 1. woodland creation and management; 2. habitat management including wetlands; 3. river and floodplain management ; 4. soil and agricultural land management (e.g. Improve and create flood storage within floodplain particularly by wet pastures, water meadows and reed-beds), and; 5. infrastructure management. | 6768 |
| (SEPA, 2013)              | Review, field and modelling | The study aims to identify opportunities for NFM in Scotland to accomplish the following aims: 1. runoff reduction, 2. floodplain storage, 3. sediment management, 4. estuarine surge attenuation, and 5. wave energy dissipation. Techniques considered were: woodland planting, creation/restoration of non-floodplain wetlands, upland drain blocking, land and soil management practices, reach and floodplain restoration, instream structures (e.g. large woody debris and boulders, remeandering), offline                                                                                                                                                                                                                                                                                                                                                               | N/A  |

|                             |                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |     |
|-----------------------------|---------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
|                             |                     | storage areas and washlands, sediment traps, bank restoration (e.g. riparian planting, green bank restoration).                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |     |
| (Nisbet and Thomas, 2008)   | Modelling           | A pilot project on the River Laver / Skell in North Yorkshire aimed to establish 40 hectares of woodland in the floodplain at four different sites in the catchment. The study found that for a 100 year flood, there was a 55 minute delay in flood peak; however, the flood peak was only reduced by 1% to 2% as a result of the desynchronization of its tributaries. Additionally, the author describes that the implementation of one hectare of forest is equivalent to 1.4 minutes in the delay of the flood.                                                                                                                                                                                                                                | 0.4 |
| (Acreman and Holden, 2013). | Review              | This study focuses on the importance of conserving and managing wetlands, especially for the management of flood risk. The study makes a classification of two types of wetlands; upland rain-fed wetlands and floodplain wetlands, to demonstrate the difference in the effectiveness of these against floods. Upland wetlands generally tend to be flood-generating areas whereas the wetlands of the floodplain have more potential to reduce flood peaks. However, wetlands of the same type will not behave the same way and so the location of the wetlands and landscape configuration, as well as the characteristics of the soil, and the topography, determine the effectiveness of wetlands as a method for the reduction of flood risk. | N/A |
| (Blanc et al., 2012a)       | Review              | A report providing a brief overview of relevant studies of NFM and a synthesis of the state of the art of this field. It focuses on establishing the effectiveness of NFM features at a catchment scale, particularly in relation to desynchronisation of flood peaks and alleviation the flood risk. Some topics addressed to evaluate the effectiveness of NFM are: flood risk reduction at the local scale, farming practice and antecedent soil conditions, soil characteristics, and location and spatio-temporal rainfall/runoff characteristics. Finally, the study concludes that there is a lack of evidence and uncertainties that could result in NFM measures not making a significant contribution towards flood risk reduction.       | N/A |
| (Nicholson et al., 2012)    | Field and modelling | Field work at the Belford Burn catchment (5.7 km <sup>2</sup> ), Northumberland in North-East England. The paper provides a review and assessment of sustainable solutions or Runoff Attenuation Features (RAFs) to manage flood risk. The approach taken involves different alternatives, such as storage ponds, barriers, bunds, planting vegetation, and woody debris in the riparian zone. Permeable timber barriers were capable of storing approximately 800 m <sup>3</sup> of floodwater, which during high magnitude storm events could                                                                                                                                                                                                     | 5.7 |

|                                |                          |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |       |
|--------------------------------|--------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|
|                                |                          | be 30% of the water volume. Pond could be filled over 8–10 hours and subsequently drained over 5–6 hours, of benefit to downstream communities.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |       |
| (Wahren et al., 2012)          | Modelling                | This study was carried out at the Schlettenbach catchment (size 6.8 km <sup>2</sup> ) in Saxony, Germany. The effect of the forest on the reduction of flood peaks was evaluated through the use of hydraulic modelling. The study indicated that peak flow reduction can vary between 3% to 70% according to the nature of the precipitation and the characteristics of the soil and vegetal cover.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | 6.8   |
| (Thomas and Nisbet, 2012)      | Modelling                | The study was carried out in the Fenni River catchment, specifically in Great Triley Wood in South Wales. The main objective of the study was to corroborate the hypothesis that large wood can increase the storage of flood flows, thus decreasing the flood peak. The study was carried out through the use of a 1-D hydrodynamic numerical model. The large wood structures were adjusted in the model so that they blocked the river channel by 70%. Manning n-values of 0.05 and 0.15 were adopted for the channel and floodplain respectively. The study considered different precipitation events related to different return periods, which varied between 0.5 years and 50 years. The results of the study show that a single isolated large wood structure increased the water level by 1.5 m, with a minimum difference in the peak of 2 - 3 minutes for each dam. However, the study suggested that the large wood could be more effective on a larger scale if an extensive series of dams was constructed along the upper and middle reaches of the catchments. | 9.2   |
| (POST, 2011)                   |                          | The document describes different steps in the establishment of NFM in UK law and emphasises that NFM is a strategy to meet the requirements made by the EU Water Framework (2000/60/EC) Directive, The EU Floods (2007/60/EC) Directive, and the Environment Agency's (EA) Catchment Flood Management Plans (CFMPs) to achieve "good ecological status" of the water bodies. The document also makes a brief definition of NFM, as well as a classification of the NFM strategies by their likely location and distribution in a catchment. Additionally, the document summarized evidence of the application of NFM and its effectiveness as an alternative for the reduction of flood risk.                                                                                                                                                                                                                                                                                                                                                                                  | N/A   |
| (Broadmeadow and Nisbet, 2010) | GIS analysis and Mapping | The study was carried out in the Yorkshire and Humber region. The study aimed to generate maps for the identification of potential areas to expand the floodplain and riparian forests to reduce the risk of flooding downstream. The study excluded 20% of the floodplain because of urban infrastructure and other land identified by the                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 15000 |

|                            |           |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |      |
|----------------------------|-----------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|
|                            |           | Environment Agency for washlands, and another 32% because of buffer areas created downstream of the built environment and roads. An additional 21% was excluded because the width of the lower floodplain exceeding 1 km as priority areas for targeting the restoration of floodplain. It was found that the remaining 27% had potential for forest plantation, which had potential to reduce the flood peaks.                                                                                                                                                                                                                 |      |
| (Howgate and Kenyon, 2009) | Review    | Survey work in Borthwick Water Valley, Hawick in the Scottish Borders. The objective was to evaluate the problems faced by the implementation of NFM, and the incidence of these in the communities involved. The results show that the willingness to cooperate is affected by a lack of information and common concern about new techniques. In addition, a lack of knowledge about the possible benefits of NFM was noted. It affirms that the success of the application of NFM must follow established principles of public participation.                                                                                 | N/A  |
| (Wheater and Evans, 2009)  | Review    | The study revises the historical problems of land use management and water resources, making a comparison with the current state. The paper emphasises the main factors that can cause the deterioration of rural and urban catchments. Additionally, new sustainable approaches applied to land management and natural resources are mentioned.                                                                                                                                                                                                                                                                                | N/A  |
| (Nisbet and Thomas, 2008)  | Modelling | Facilitated the establishment of floodplain woodland in the River Laver catchment, North Yorkshire, UK, to demonstrate benefits for flood alleviation. Objectives were to: 1. evaluate the impact of planting floodplain woodland; 2. investigate the influence of woodland design and management factors on flood flows; 3. facilitate an application for a Woodland Creation Grant under the English Woodland Grant Scheme; 4. assess the impact of planting floodplain woodland on flood depth, velocity, storage and timing, and; 5. demonstrate and communicate the benefits of floodplain woodland for flood alleviation. | 0.4  |
| (Calder et al., 2008)      | Review    | Reviews the national and international literature on the impacts of trees and woodland in temperate systems, considering the implications for water resources at a catchment scale, regionally and nationally in the UK. The study focuses on both water quality (e.g turbidity and riverbank stability) and water quantity (e.g. streamflow, groundwater recharge, soil infiltration, peak flows, and flood frequency etc). Additionally, the project assessed the impacts of climate change.                                                                                                                                  | N/A  |
| (Thomas and Nisbet, 2007)  | Modelling | 1-D and 2-D numerical modelling to understand the potential role of NFM in flood alleviation in the Parrett catchment, Southwest England. Evaluated an event                                                                                                                                                                                                                                                                                                                                                                                                                                                                    | 1690 |

|                                                                      |        |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |        |
|----------------------------------------------------------------------|--------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------|
|                                                                      |        | corresponding to a 100 year flood with scenarios including: 1) current conditions, floodplain covered by pasture (Manning's $n = 0.035$ ); 2) floodplain fully covered by thick broadleaved woodland ( $n = 0.15$ ), and; 3) 500 metres in the middle of the floodplain planted with 50 ha of woodland. The results indicated that in Scenario 2 there was 71% more water storage compared to 15% of scenario 1. Implementation of measures had a large impact on flow velocities, which decreased by 60%-70%. The peak was attenuated, increasing the flood-time by 30 minutes for scenario 2 and by 140 minutes for scenario 3. The overall conclusion is that NFM can alleviate downstream flow efficiently. |        |
| (Werritty, 2006)                                                     | Review | This paper examines the hard engineering paradigm of flood risk management in the UK and contrasts it with sustainable equivalents. Hard engineering is described as being highly successful when large structures are used and it is questioned whether sustainable approaches can ever be truly sustainable given future uncertainty. Additionally, the paper contrasts the Scottish introduction of a strong view of the sustainable approach of flood management and the weaker version emerging in England and Wales.                                                                                                                                                                                      | N/A    |
| (Nisbet and Thomas, 2006)                                            | Review | This paper examines the importance of forests in flood mitigation through the increased use of water by trees. A literature review supports that the greater hydraulic roughness associated with riparian forests can help reduce flood peaks considerably. In addition, environmental and ecological benefits are obtained through forested areas.                                                                                                                                                                                                                                                                                                                                                             | N/A    |
| (Klijn et al., 2004, van Stokkom et al., 2005, Hooijer et al., 2004) | Review | Description of IRMA-SPONGE project in the Rhine and Meuse river catchments. The project aims to develop methods and tools to assess the impacts of flood risk reduction measures and land-use and climate change scenarios, to support the spatial planning process for the Rhine and Meuse River catchment. The project involved six countries (Belgium, France, Germany, Switzerland, Austria and the Netherlands), and was divided into 13 sub research projects, more than 30 organizations were involved.                                                                                                                                                                                                  | 191000 |
| (Nijland, 2005)                                                      | Review | Addresses the sustainable development of floodplains carried out in the catchment area of the River Rhine. The project aimed to ensure sustainable multifunctional development of the Rhine floodplains to reduce high-water floods. The project goals were: improved river engineering and navigation, improve nature and environment development, enhanced social action and communication. 54 floodplain measures were designed of which 12 were considered 'sustainable'. Some of the measures were                                                                                                                                                                                                         | N/A    |

|                             |                              |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |     |
|-----------------------------|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
|                             |                              | dyke relocation, creation of retention polders, construction of inlet works, creation of side channels, removal of hydraulic obstruction, and lowering of floodplain area.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |     |
| (Forestry Commission, 2004) | Field, modelling and mapping | 'Slowing the Flow at Pickering' was carried out at Pickering Beck, North Yorkshire, UK. The aim was to demonstrate how the integrated application of a range of land management practices can help reduce flood risk and get multiple additional benefits. Work included planting 50 ha of riparian woodland in Pickering and 30 ha in an adjacent catchment to delay and reduce flood flows and the construction of 150 large wood debris dams across both catchments.                                                                                                                                                                                                                                                                              | 69  |
| (Hall et al., 2003)         | Review                       | This paper describes an integrated framework for flood risk management in England and Wales. The changes and transitions to integrated flood risk management are explained, as well as the measures that must be carried out to achieve the objectives in integrated management. The paper concludes that flood events in England and Wales generated a real concern for flood risk management and that significant changes in risk management can only be achieved through a more systematic approach, including tools for the control of floodplain runoff, the construction and maintenance of flood defences, the management of urban drainage systems; early warning and alarm systems, and the preparation for emergencies in cases of floods. | N/A |



## 2.7 How to locate NFM for maximum benefit

In 2013 the Scottish Environmental Protection Agency (SEPA) published “*identifying different opportunities for Natural Flood Management*”, this refers to an assessment that was made by the agency within its territory to find strategic areas where the NFM would be more effective to be implemented. The publication was carried out and supported by the Forestry Commission Scotland, and other organizations such as Scottish Advisory and implementation forum for flooding (SAIFF) and Centre of Expertise for Water (CREW) and five maps were produced which classified the 5 main aspects. 1. Runoff reduction, 2. Floodplain storage, 3. Sediment management, 4. Estuarine surge attenuation, and 5. Wave dissipation. The main techniques designed to achieve these aspects are shown in Table 2.2.

Table 2.2 NFM techniques relevant to each map (SEPA, 2013).

| NFM Map Technique                  | Map Technique                                                                                      |
|------------------------------------|----------------------------------------------------------------------------------------------------|
| <b>Runoff reduction</b>            | Woodland planting (including upland, floodplain, riparian, gully or cross slope woodlands)         |
|                                    | Creation/restoration of non-floodplain wetlands                                                    |
|                                    | Agricultural and upland drainage modifications (e.g. upland drain blocking)                        |
|                                    | Land and soil management practices (e.g. ploughing along the contour of the land or soil aeration) |
| <b>Floodplain storage</b>          | Reach and floodplain restoration                                                                   |
|                                    | Floodplain and riparian woodlands                                                                  |
|                                    | Instream structures (e.g. large woody debris and boulders)                                         |
|                                    | Reach restoration (e.g. meandering)                                                                |
|                                    | Offline storage areas and washlands                                                                |
| <b>Sediment management</b>         | Reach restoration (e.g. meandering)                                                                |
|                                    | Sediment traps                                                                                     |
|                                    | Bank restoration (e.g. riparian planting, green bank restoration)                                  |
| <b>Estuarine surge attenuation</b> | Restoration of intertidal habitats including managed realignment                                   |
| <b>Wave energy dissipation</b>     | Beach management (e.g. beach recharge)                                                             |
|                                    | Sand dune restoration                                                                              |
|                                    | Restoration of intertidal habitats including managed realignment                                   |

SEPA suggests that the amount of runoff that reaches the river channel is influenced by many factors, of which the average slope of the catchment is key (SEPA, 2013). The slope determines the degree to which soils allow water infiltration and, therefore, soils with higher slopes generate a greater amount of runoff. Tree planting as NFM reduces runoff because it acts as an interceptor for rainfall and also contributes to increased soil water storage by increasing soil permeability and decreasing runoff. To identify potential areas to establish NFM and reduce runoff, SEPA produced a set of maps that identify areas that contribute most to the generation of flow. These maps are based on the method of identifying catchments sensitive to change in land use established by the Environment Agency (DEFRA, 2008). This method determines that the generation of runoff from slopes in rural catchments is determined by physical and management factors, which are listed below:

- Soils (e.g. standard percentage runoff, infiltration, soil storage potential, bypass flow).
- Climate (e.g. rainfall intensity and duration, evaporation/evapotranspiration, hydrologically effective rainfall).
- Topography (e.g. slope, shape).
- Land cover (e.g. vegetation type, roughness).
- Land management (e.g. soil and crop management activities).
- Drainage network (e.g. drainage density, hydrological connectivity).

Using this method, maps have been generated for the UK for each factor, with a spatial resolution of 250 x 250 m. Factor maps were assigned a score depending on the degree of influence on runoff generation, then the values of each map were averaged to determine the final map showing areas of medium and high potential for runoff reduction. Figure 2-7 shows the Ripon catchment in North Yorkshire where the methodology was tested indicating the five factor maps generated.

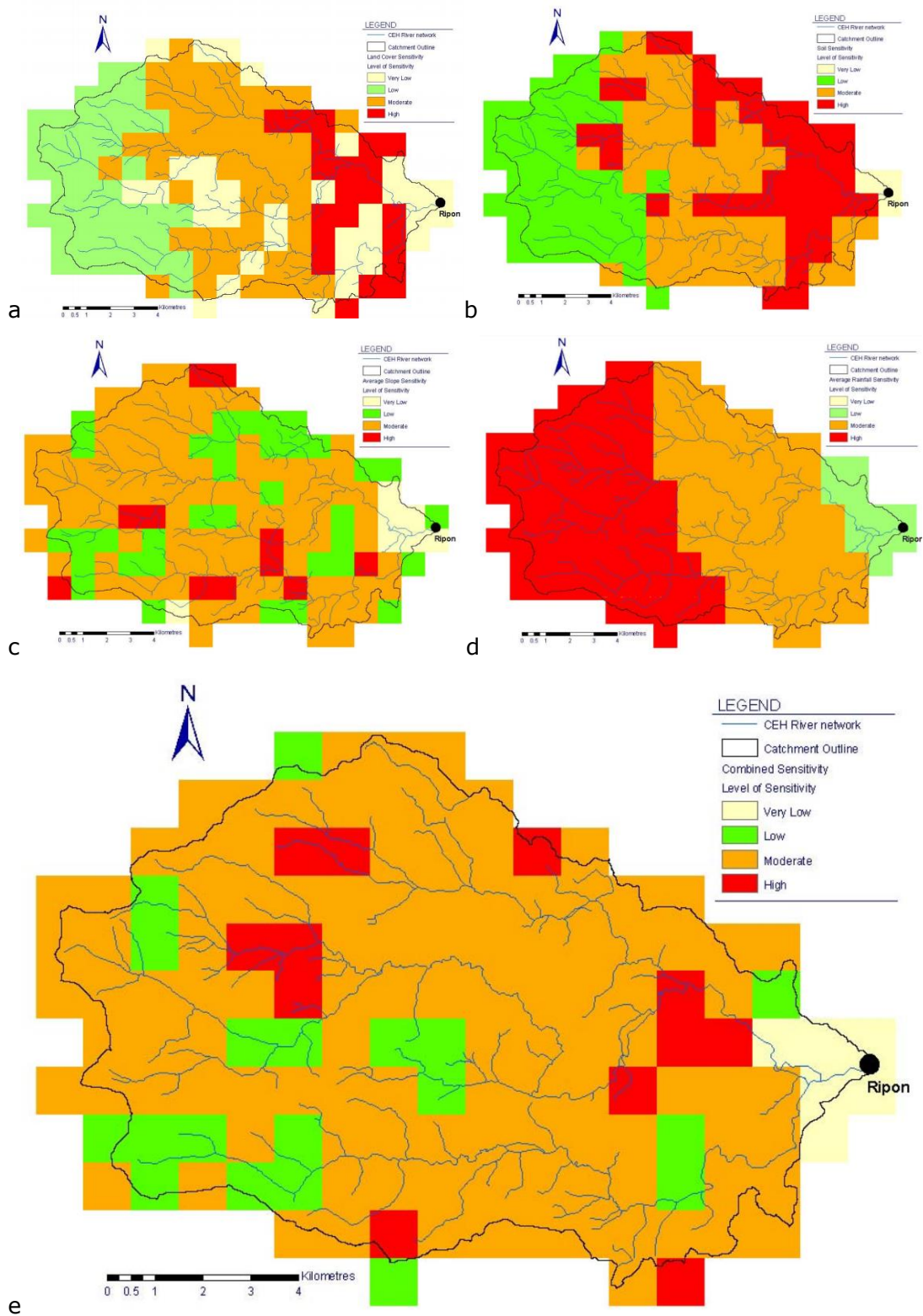


Figure 2-7 Ripon catchment in North Yorkshire where the SEPA methodology for the identification of catchments sensitive to land was tested. The potential for runoff reduction is assessed based on the following maps: a) land cover, b) soils, c) slope, d) rainfall, e) combined.

In 2015, SEPA published the "*Natural Flood Management Handbook*" in collaboration with the Forestry Commission Scotland, Forest Research, Risk and Policy Analysts Ltd., River Restoration Centre, Scottish Advisory and Implementation Forum for Flooding, Scottish Government, Scottish Natural Heritage, Tweed Forum, the University of Dundee, and West Sands Partnership. The focus of this guide was mainly designed to provide a support tool for the proper implementation of natural measures for flood control. The guide emphasizes the different variables within the catchments are fundamental for the implementation of the natural measures. It also describes a series of studies carried out by SEPA in which a range of natural measures of protection against flooding was applied. In 2016, the Environment Agency delivered a suite of interactive maps called the National Strategic NFM Opportunity Maps to help understand the extent of the potential for NFM areas across England. The maps were included in the flood and coastal erosion risk management (FCERM) schemes.

## **2.8 Effect of Natural Flood Management in Flood peak reduction**

Table 2.1 demonstrates that a range of NFM objectives exist but, most NFM studies focus on reducing surface runoff and slowing down water from reaching the channelised drainage network (POST, 2011, Hooijer et al., 2004, Nisbet and Thomas, 2006, Nisbet and Thomas, 2008, SEPA, 2013, Wheeler et al., 2010). Attenuating flows can be achieved through river channel restoration, floodplain reconnection and recovery, retention ponds, drainage network improvements and changes, afforestation and riparian woodland planting, and in-channel woody debris to slow down in-channel flows. The function of such measures is to increase channel, floodplain and catchment roughness to slow the flow, in addition to increasing the capacity of catchment soils to temporarily store water (Nisbet and Thomas, 2006, Wheeler et al., 2008). Alongside studies on the impacts of NFM on peak flow reduction, several papers also define the importance of stakeholders, landowners and community perspectives given the large areas required for implementation of schemes, which are often remote from areas of high flood risk (Holstead et al., 2017, Lavers and Charlesworth, 2018, Waylen et al., 2018, Smith et al., 2019, Nicholson et al., 2020, Wingfield et al., 2019, Environment Agency, 2017).

The effectiveness of NFM has predominantly been quantified with consideration of the peak flow reduction in modelling studies (see Table 2.1). For example, Nicholson et al. (2020) found that by storing 20,000 m<sup>3</sup> in offline storage, the

peak flow was reduced by more than 30% downstream. A similar magnitude of peak flow reduction (20%) was identified by Dixon et al. (2016) in the Lymington catchments, UK (98 Km<sup>2</sup>) when 20% to 35% of the catchment is afforested. In many cases, smaller changes are observed, on the order of 10 – 15% reductions in peak flow, such as in Pickering (Thomas and Nisbet, 2012) and on the R. Cherwell, UK (Bullock and Acreman, 2003). On the River Cherwell, the relatively small reduction in peak flow of 10% when river channels and floodplains were reconnected and rehabilitated is counterbalanced by modelling that showed the placement of an embankment, disconnecting the floodplain from the channel would increase peak flows by 150%. Larger impacts on peak flows have been predicted where greater catchment coverages of NFM are predicted; for example, Wheeler et al. (2008) in the Pontbren catchment, Wales, identify complete woodland coverage could reduce peak flows between 9% and 69% compared to baseline conditions. Therefore, there is an urgent need to assess the potential of NFM in larger catchments, with a range of characteristics and to assess the potential reasons for differing % reductions.

## **2.9 Types of Natural Flood Management**

### **2.9.1 Catchment Woodland**

One of the first attempts to use natural processes to manage flood water was carried out in the UK in 2006 by Nisbet and Thomas (2006) who analysed the benefits of sustainable measures or soft engineering, now termed NFM. The researchers analysed the importance of woodland in a catchment and how it can attenuate and decrease the flood peak downstream. Nisbet and Thomas (2006) highlighted that reductions in flood peak can be achieved by: a) the use of water by trees with evapotranspiration and interception process; b) the "*Sponge Effect*"; c) increased hydraulic roughness, which is a feature of riparian vegetation and floodplain woodland. The type of trees has been analysed finding that the percentage of annual rainfall interception by conifer stands is 10-25% in comparison with 25-45% of broad leaves (Calder and Aylward, 2006, Nisbet, 2002). In addition, the season of the year also influences the plants' ability to intercept rainfall, for example, during winter when there is a higher probability of rainfall in the UK, there are also few leaves on trees to intercept water (Calder et al., 2008). In this sense, the vegetation cover may be an essential factor to be considered under the flood management framework but their impact will be complex and variable. For instance, catchments with poor or low density

vegetation might have flashier hydrographs than equivalent catchments with dense, healthy vegetation (Hooijer et al., 2004).

Several studies have looked at the impact of floodplain woodland on peak flows. A modelling study by Connell (2008) in the River Maddach (164.5 km<sup>2</sup>) in central Wales, assessed planting floodplain woodland at 3 sites by changing the Manning value in a hydrological model. The study found that the floodplain water depth increased by between 0.5 m to 1.2 m, and delayed peak flows by more than 30 minutes. A study by (Zell et al., 2015) in an urban floodplain reach of the Hinkson Creek catchment (231 km<sup>2</sup>) in central Missouri, USA, found that hardwood forest had 16% greater evapotranspiration and 28% more water storage compared to agricultural fields. A smaller peak flow reduction was observed by Johnson (2006) in the River Enrick catchment (264 km<sup>2</sup>) in northern Scotland, UK, from a large-scale planting along the floodplain which showed just 0.8% in peak flow reduction and, similarly, Ghavasieh et al. (2006) found woodland strips along a 20 km river reach could reduce peak discharge by 3.8%.

The fundamental role of forest coverage in catchment drainage has been demonstrated in the water balance and water cycle (Bullock and Acreman, 2003, Newson, 1994). The increased infiltration capacity of forested areas could also help mitigate flood peaks, and therefore reduce potential flood risk (Wahren et al., 2012, Calder and Aylward, 2006). In a South African catchment, a runoff decrease was reported by Scott and Lesch (1997) where after 9 years of planting *Eucalyptus Grandis* the catchment runoff was net zero. In contrast, a *Pinus patula* plantation of the whole catchment had a slower response, with zero runoff reached in the twelfth year. Farley et al. (2005) described afforestation in 26 catchments, with planting 20% to 40% of the catchment with *Pinus* and *Eucalyptus* potentially leading to peak flow reduction by 40% to 75%.

Whilst forestry has been demonstrated to be an effective way to reduce peak flows, the location of the trees in the catchment is fundamental (Connell, 2008). The Environment Agency states that the effectiveness of floodplain woodland will be greatest along meandering channels within the lower to middle catchment; and will have little effect in reducing the flood peak when located within flood storage areas, or in areas behind already installed flood defences. The Environment Agency also states that floodplain woodland is a long-term measure, with mutual benefits lasting in perpetuity with appropriate management (Figure 2-8).

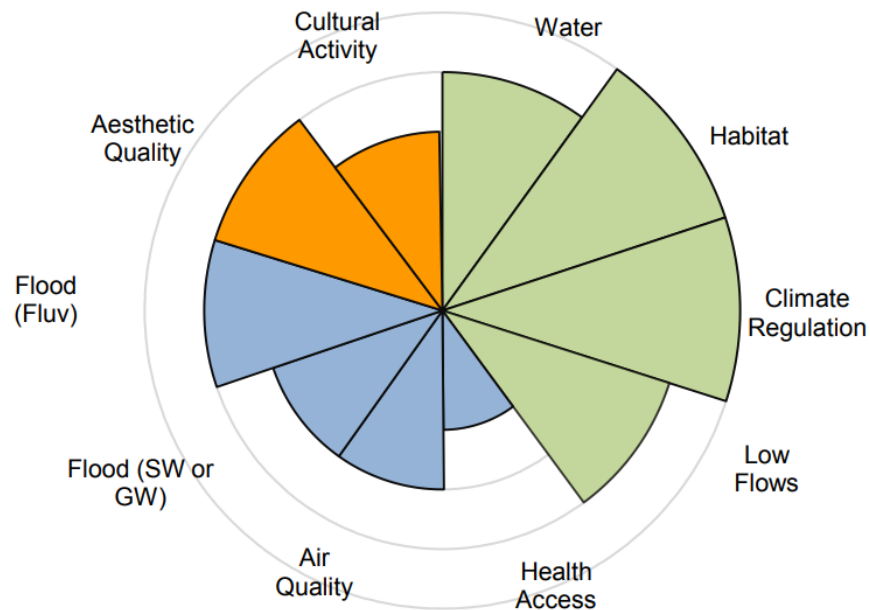


Figure 2-8 Multiple benefits of floodplain and riparian woodland (Environment Agency, 2017).

### 2.9.2 Large Woody Debris "Leaky Dams"

Large Woody Debris (LWD), now more frequently referred to as 'large wood' is sometimes used to construct 'leaky dams', consisting of fragments of deadwood of different sizes and combined with native vegetation creates a natural barrier for the flow (Linstead and Gurnell, 1999). LWD in many cases is the result of natural processes (Lisle, 1986) but can be promoted as an NFM intervention. Linstead (2001) argues that LWD in the headwaters can have a significant impact on water depth and flow velocity, and improves physical habitat. Many benefits are attributed to LWD including increased sediment storage, reduced erosion and improved water quality (Thomas and Nisbet, 2012). An assessment of the multiple benefits of the LWD suggests that water quality, habitat and climate regulation are greater than the benefits for flood mitigation .

Hygelund and Manga (2003) found that the natural accumulation of woody debris in rivers increases hydraulic roughness, decreasing flow velocities. A study carried out by Odoni and Lane (2010) in the Pickering Beck catchment, UK, used a modelling tool to optimise LWD location in headwaters to maximise reductions in peak flow reduction. The model suggested that the optimal installation was for the placement of 100 leaky dams reducing peak flow from  $29.5 \text{ m}^3 \text{ s}^{-1}$  to  $27.3 \text{ m}^3 \text{ s}^{-1}$



(7.5% peak reduction). Research undertaken by Thomas and Nisbet (2012) in the River Fenni catchment in the north of Abergavenny in South Wales used a hydraulic modelling approach to simulate LWD dams. The model reveals that LWD could lead a reduction in the flow velocities as much by  $2.1 \text{ m s}^{-1}$  delaying peak flows by 15 minutes for a 100-year flood event. Figure 2-9 show an example of the existing LWD in the main watercourse at Great Triley Wood in South Wales, UK.



Figure 2-9 Pre-existed LWD in the main watercourse at Great Triley Wood in South Wales, UK. (source: Thomas and Nisbet (2012))

### **2.9.3 River channel restoration**

Restoration is increasingly becoming an integral part of flood management, intended to enhance water quality, flow dynamics, sedimentation, aquatic ecosystems and flood control (Palmer et al., 2014). This approach is a response to the perceived detrimental impacts and lack of resilience caused by humans through historic river management (Brookes and Shields Jr, 1996a, Johnson et al., 2020). Traditional, grey engineering work have caused serious long-term detriment to major rivers around the World, including the Mississippi, Missouri, Rhine, Yellow, Yangtze and Vistula Rivers (Gore and Shields, 1995). Extensive areas have been modified; for example, in the United States in the 16<sup>th</sup> and 17<sup>th</sup> centuries, between 85 and 90 per cent of the territory of Illinois was covered by



wetlands, which were drained, largely with canals, after European colonisation for increased agricultural production (Dahl, 1990).

A monitoring study in the Lymington River (24 km<sup>2</sup>), in Hampshire, UK, 10 km of river were restored to a sinuous course, with large wood areas in channels, reconnecting floodplains and old meanders, as well as restoring wetlands and riparian forest (Sear et al., 2006). The project found that river restoration reduced the peak flow by 21% and increased lag times by 33% for small events. Figure 2-10 shows a section of the River Lymington where the re-meandering process was carried out.



Figure 2-10 Section of the River Lymington in the New Forest catchment, Hampshire, UK. (Source: Environment Agency)

#### **2.9.4 Retention ponds**

The main advantage attributed to retention ponds is that they contribute to reduced peak flow and sediment removal (Verstraeten and Poesen, 1999, Guo, 2001, Yousef et al., 1994). A modelling study carried out by (Ghimire et al., 2014) in the Tarland catchment, UK (25 km<sup>2</sup>) argues that stakeholders prefer small scale ponds instead of a single large storage area. The modelling found that a single pond that stores 27,000 m<sup>3</sup> mitigated the flood peak by 9% for a 1 and 2-year return period event. However, by installing several ponds from 4,000 to 6,000 m<sup>3</sup>

with total capacity of 48,000 m<sup>3</sup>, could reduce peak flows by 12%. Because retention ponds accumulate sediment, their capacity to store water is reduced through time and so, require frequent maintenance (Yousef et al. (1994)). A pond network model using a hypothetical river reach was used by Quinn et al. (2013) to determine the mitigating effect of increasing the number of offline storage ponds located in the Belford catchment. Figure 2-11 shows the hypothetical reach of the pond model and offline ponds in the Belford catchment. The study found that the maximum flow reduction for a theoretical network of 35 storage areas was 15% to 30%, depending on the rainfall event.

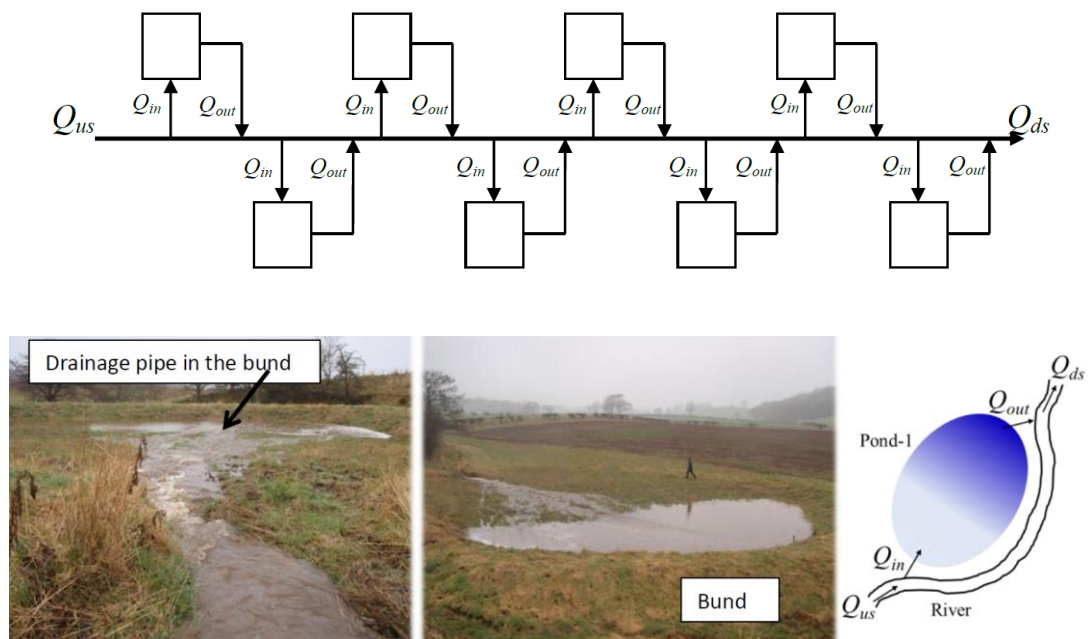


Figure 2-11 The hypothetical reach of the pond model and offline pond in the Belford catchment (source: Quinn et al. (2013)).

The term offline store is normally linked with run-off attenuation features at smaller scales (e.g. ponds) while the term washlands are mostly used for larger scale features (e.g. reservoirs). For example, a flood alleviation scheme carried out in the Chapel Beck catchment (8.32 km<sup>2</sup>) in Guisborough, North Yorkshire, UK, used a range of offline storage areas as well as large wood, wetlands, and drain blocking to reduce the peak flow in a very modified catchment. The project found that by installing 15,000 m<sup>3</sup> of water storage, the peak flow for the 100-year event could be reduced up to 10.9%. The Holnicote project is another example of offline storage measures, covering two catchments, Horner Water (22

km<sup>2</sup>) and the Aller (18 km<sup>2</sup>) in Porlock Bay, UK. Figure 2-12 shows an example of the flood storage area at Holnicote project. Here, five floodplain offline storage ponds (25,000 m<sup>3</sup>) were installed, with a 10% attenuation of peak flows determined using a 1D–2D hydraulic model (National Trust, 2015). It is also argued that the peak flow reduction may be up to 25% for floods with a smaller return period than that modelled, which occurred in December 2013.



Figure 2-12 Flood storage area at Holnicote project (source: (National Trust, 2015))

Ponds have been also shown to contribute effectively by improving water quality and decreasing the concentration of pollutants. A study described by Winston et al. (2013) describes the installation of two wet retention ponds in Durham, North Carolina, USA, designed to reduce the impacts of maximum flows with return periods ( $T_r$ ) of 1, 2, and 10 years and improve water quality. During the monitoring period, 79 and 74 rainfall events occurred with ponds reducing the total concentrations of total nutrients and suspended solids by 36% and 92%, respectively. Verstraeten and Poesen (1999) state that spatial scale plays a very important role in the effectiveness of retention ponds, stating that they are useful



on a small scale but would have minimal impact on flooding unless many ponds were used.

Although the acceptance of offline storage areas as a flood alleviation scheme seems to be growing, further research is needed to assess the effectiveness in larger catchments as well as the potential in the peak flow synchronisation (Dixon et al., 2016, Dadson et al., 2017). A review by the Environment Agency (2017) describe the multiple benefits that the offline storage areas can lead Figure 2-13.

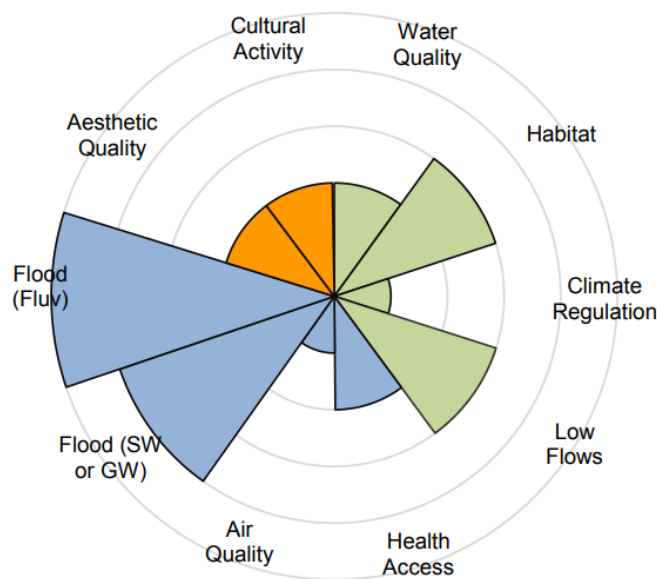


Figure 2-13 Multiple benefits of offline storage areas (Environment Agency, 2017).

### 2.9.5 Drainage

The UK is recognized as one of the most drained countries in Europe, because its lands have to be adapted to increase productivity (Wheater and Evans, 2009). The drainage revolution occurred between the 1940s and the 1980s, due to post-war subsidies provided by the government to enhance production (Robinson and Armstrong, 1988). Likewise, during the 1970s there was a major expansion in rural fields, with 10% (1 million Ha) of the land drained. According to Blanc et al. (2012), agricultural productivity was achieved by reducing the water table through land drainage, thus expanding the agricultural frontier and obtaining more grazing areas to feed livestock. However, this approach did not suitable consider catchment functioning and the longer-term implications of land drainage,

particularly to flood risk. O'Connell et al. (2007) affirm that many of the drains implemented at that time are now blocked.

Field drainage causes an alteration in runoff, increasing the speed with which water reaches the highly efficient channel network, decreasing storage in soils (Wheater and Evans, 2009). Early studies of the impact of forest drainage made by Newson and Robinson (1983) in Tylwch, UK, found a reduction of the peak flow due to the agricultural drainage system. In contrast, research carried out by Robinson and Newson (1986) in the northwest of the UK at Coalburn, showed an increase of peak flow with similar agricultural drainage but different soil types. This suggests that the peak flow variation could vary significantly depending on catchments characteristics but, in general in the UK now, the consensus is storing water in upland areas by reducing the efficiency of land drainage, decreases flood risk downstream.

#### ***2.9.6 Infiltration and the 'sponge effect'***

A considerable amount of literature has been published on the "sponge effect", which is the faculty of soil to soak up and store water after rainfall and gradually releasing it to the river network (Calder and Aylward, 2006). Soil features such as macropores aid the movement of water through the soil structure, reducing the probability of saturation and the enhancement of runoff (Nisbet and Thomas, 2006, Nisbet and Thomas, 2008). This concept had also been explored almost one century before in the USA by Bates and Henry (1928) who analysed the influence of forest cover and climate on runoff. This study was carried out in adjacent valleys in the catchment of the Rio Grande in Colorado (United States), demonstrating that the underlying concepts of NFM have a much longer history than the use of the terminology.

Healthy soils infiltrate and store more water than degraded soils (Zell et al., 2015, Birkeland, 1984). This is because soil structure plays an important role in the infiltration process, for example, less compacted soils allow more infiltration and, therefore, reduce runoff compared to compacted soils (SEPA, 2015). Moreover, unprotected soils with poor structural conditions, for example caused by deforestation, require long time periods, often in excess of decades, to recover their hydrological ability to store water effectively (Hooijer et al., 2004). In urban areas, principles of soil infiltration and storage are replicated to some degree by Sustainable Urban Drainage System (SUDS), which use blue and green

infrastructure in an attempt to mitigate flood risk (Charlesworth and Warwick, 2011). SUDS also help achieve WFD objectives of reducing flood risk whilst protecting and improving aquatic environments (Boogaard and Stockel (2012). Many SUDS have been designed according to future population projections and specific weather conditions; however, in many cases these have not been sufficient to prevent flooding.

The impacts of poor infiltration and soil water storage are demonstrated by the impacts of urbanisation, where large areas are replaced with non-permeable areas. As a result of the rapid run-off, into piped drainage systems efficiently taking water to the channel network, peak flows are increased and lag times decreased relative to rural areas (Charlesworth et al., 2003). These impacts were described early by Leopold (1968) by using a hypothetical hydrograph, which depicts the increase in the peak flow and reduction in the time lag Figure 2-14.

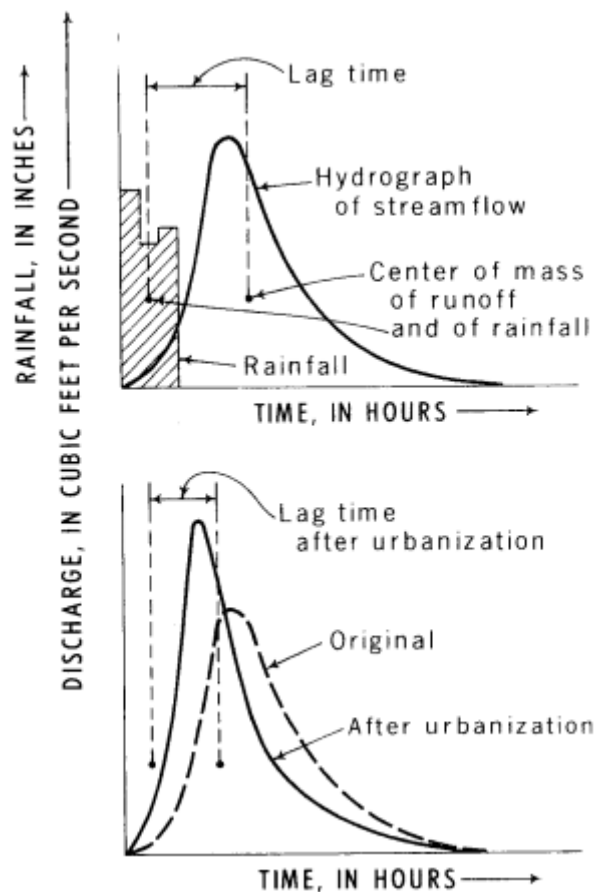


Figure 2-14. Hypothetical unit hydrographs relating runoff to rainfall, differences in shape after urbanization. Adapted from (Leopold, 1968).

## **2.10 Limitations with current Natural Flood Management knowledge**

The potential benefits attributed to NFM are many and Pitt (2008) argues that NFM options can play a key role in comprehensive flood protection schemes. However, there is public concern about moving away from grey infrastructure and Blanc et al. (2012a) argue that to be more secure in the implementation of NFM, it is necessary to have very strong evidence of its effectiveness. Currently, this is not the case. As discussed above, a large proportion of publications on NFM are based on hydraulic modelling in small, upland catchments in the UK. Whilst several of these studies have found significant results in flood peak reduction (Nisbet and Thomas, 2006, Environment Agency, 2009, Dixon et al., 2016, Environment Agency, 2017) magnitudes of impact differ markedly and great uncertainties still exist. A major uncertainty is understanding whether and how the effects observed and expected from NFM in small catchments, are scalable to larger catchments (Dadson et al., 2017). The importance of scale to catchment hydrology was recognized in the 1990s and, in the UK, the Catchment Hydrology and Sustainable Management (CHASM) project explored how to integrate multiscale effects in sustainable freshwater management. According to Hooijer et al. (2004), the hydrological systems in large catchments have to be carefully analysed, especially emphasising the timing of events in different tributaries.

Also, past work suggests the benefits of NFM are greatest for smaller events and are more limited in winter periods, which is also when flooding is more likely (Beschta et al., 2000). Evidence suggests that NFM and, in particular afforestation, is more effective in reducing the flood peaks for small rainfall events (return periods < 10 years) than for extreme events (Salazar Galán et al., 2012, Lane et al., 2005, Francés et al., 2008, Environment Agency, 2017).

Another key barrier to NFM implementation is the public perception (Dadson et al., 2017). A shift towards more forested land implies changes to existing agricultural land practices and uses, which may need to occur over large areas (Iacob et al., 2014). In practice, such changes generally entail environmental compensation and incentives (Collentine and Futter, 2018) and, ideally, require an assessment of where to prioritise changes for maximum positive impact, minimising unnecessary changes and potential conflict. However, very limited information exists on where to situate NFM in catchments. Technical reports suggest buffers on floodplains, near channels in the lower and middle reaches of rivers will be the most effective locations (e.g. (Environment Agency, 2017) but, this is not well evidenced). Other studies identify locations where NFM could be

situated but without consideration of where the optimal locations for effectiveness are (e.g. (Broadmeadow and Nisbet, 2010)). Therefore, there is an urgent need for work, at a range of scales and catchment types, to consider the importance of NFM location in determining its effectiveness, and attempting to inform where NFM should be situated for maximum benefit.



## **CHAPTER 3. EXPERIMENTAL METHODS**

### **3.1 Overview of the methodological approach**

This section will outline the methodological framework and approach used to investigate the effectiveness of the NFM and is of relevance to all subsequent chapters. Methodological details specific to the content of an individual chapter will be outlined in that chapter. The research has adopted a modelling approach, which allows the evaluation of five NFM levels (5 catchment coverages of broadleaved forest) in a set of twenty catchments with a range of morphological conditions, and in response to a set of different rainfall scenarios (Three magnitudes, four distribution types). A hydraulic and hydrological model was used, enabling a large range of catchment morphologies and NFM scenarios to be modelled. In order to identify how catchment morphology may impact NFM effectiveness, synthetic catchments were used with no attempt made to replicate real-world catchments. Abstracted catchments were used so as to keep focus on morphometric conditions and offer the opportunity to standardise other potentially significant geospatial and hydrological conditions. The modelling aimed to inform under which subset of circumstances NFM has the greatest potential to be significant. Additionally, the model was performed on a sub-set of catchments to test the effectiveness of NFM depending on its scale and placement within the catchment. A visual summary of the methodology is shown in Figure 3-1 and Figure 3-2.

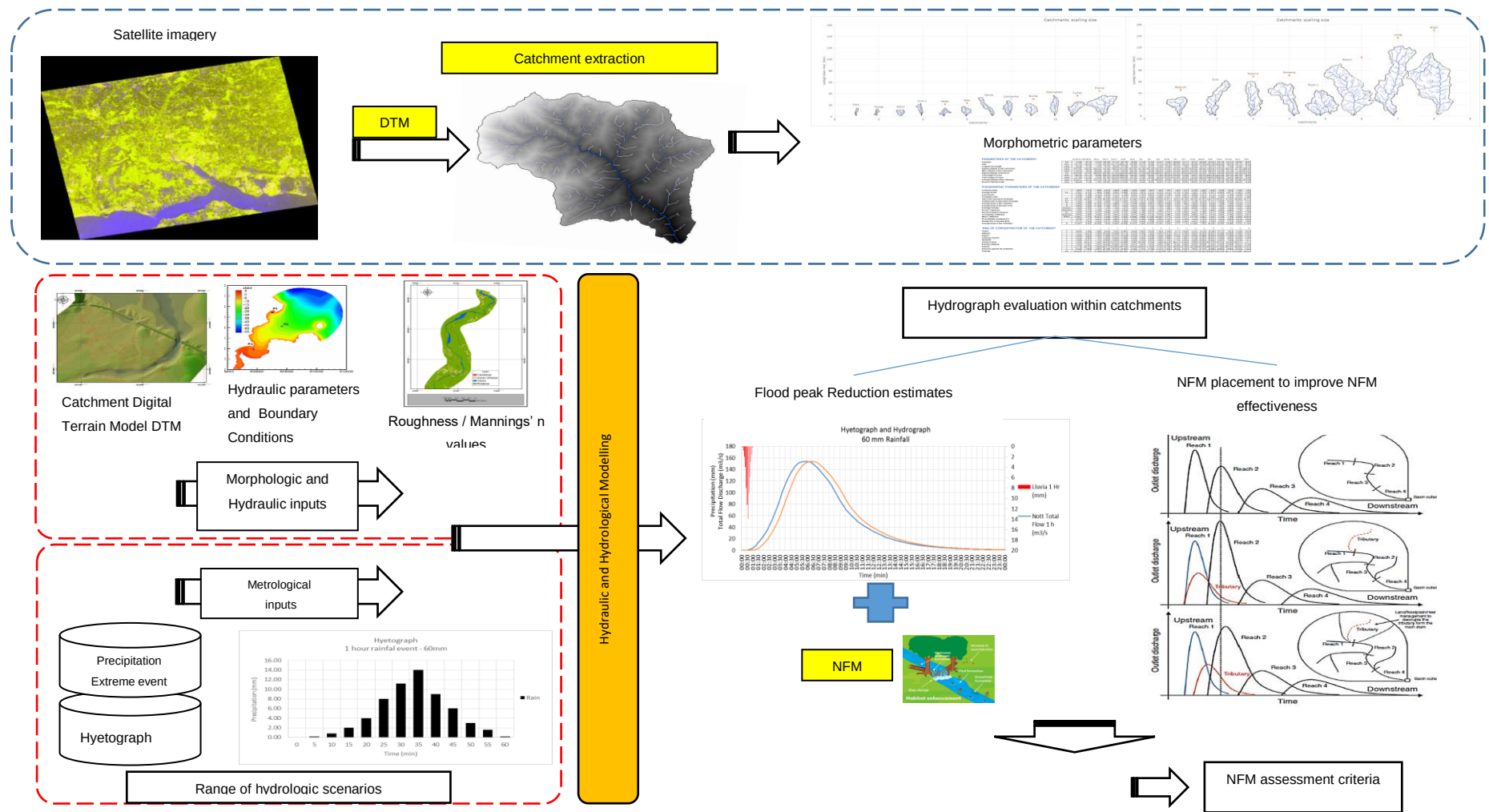


Figure 3-1 Methodological scheme. Catchment delimitation, hydraulic and hydrological inputs, generating hydrographs based on catchments representing a range of morphometric conditions. Modelling will be done to determine the potential benefit of NFM. Peak flow and lag time will be analysed to assess how they change with NFM placement and extent.

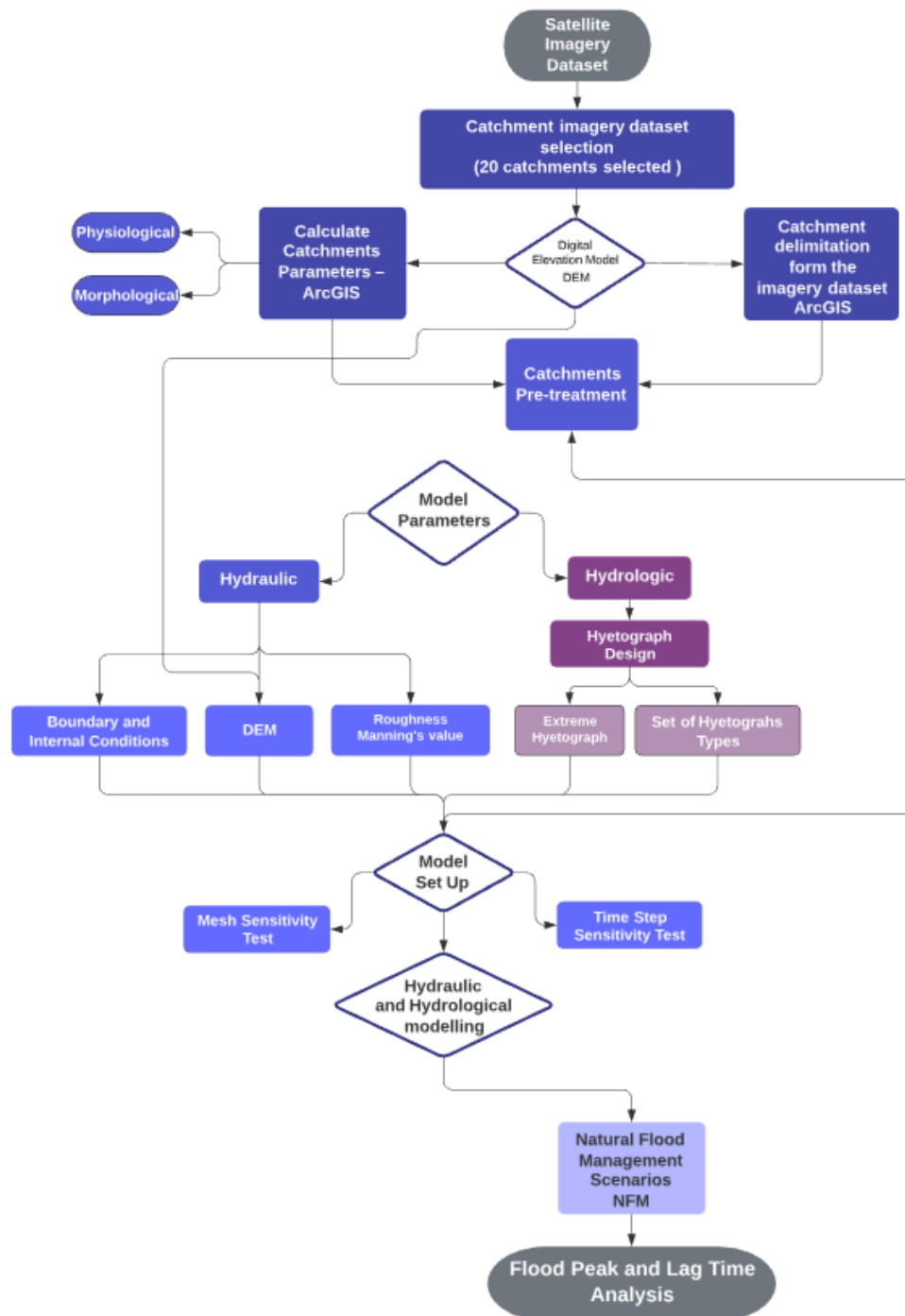


Figure 3-2 Methodology flowchart. Hydraulic and hydrological inputs and spatial information are inputted into a mathematical model, generating hydrographs based on catchments representing a range of morphometric conditions. Modelling will be done to determine the potential benefit of NFM. Flood peak and lag time will be analysed to assess changes on NFM placement and extent.

## **3.2 Construction of abstracted catchments**

### **3.2.1 Image acquisition and processing / Base data - ALOS PALSAR**

To construct the abstracted catchments an imagery data-set was taken from the Alaska Satellite Facility (ASF) website, which makes remote-sensed data accessible. The data is high-resolution terrain data with a spatial resolution of 10 metres. The "DAICHI" or ALOS satellite was used to obtain the data set. "DAICHI" or ALOS is the abbreviation for Advanced Land Observing Satellite, which was a part of a project by the Japan Aerospace Exploration Agency (JAXA).

ALOS has three sensors: 1) PRISM, 2) AVNIR-2, and PALSAR. In this case, ALOS PALSAR was considered as a main source of information. The satellite was launched on 24th January 2006 from the Tanegashima Space Centre and recorded data until May 4th, 2011 (Suzuki et al., 2006). Between these dates, ALOS PALSAR collected data from multiple observation modes with variable polarization, resolution, swath width, and off-nadir angle. PALSAR also has three modes: Fine resolution (FBS and FBD), ScanSAR (WB1, WB2) and Polarimetric (PLR). The fine single polarization (FBS) resolution beam mode was used to acquire images due to its spatial resolution of 10 metres (pixel = 10 m x 10 m). ScanSAR and Polarimetric were not used because of their relatively low resolution.

### **3.2.2 Catchment selection**

Although catchments were considered abstract in all subsequent analysis, the topographic basis of real-World catchments was used to generate the series of synthetic 20 catchments, each with different shape, size and morphology. The 20 catchments were selected based on a random search procedure, following a series of nested decisions. The first was data availability since the ALOS PALSAR satellite does not cover all areas of the Earth surface. Most of the observations made by ALOS PALSAR were based on particular sites of interest (EORC, 2008). The availability of data was also limited because not all observed areas used the FBS beam mode with the finest resolution. There were also some large regions such as Greenland and the South Pole without any data available whereby these areas were excluded of this study.

To select the 20 catchments, three hundred points were randomly created across the globe using ArcGIS. These points were then contrasted with the ALOS PALSAR dataset to identify which points had available data. 15 points with FBS resolution

were then selected, partly based on their catchment morphology. The catchment area upstream of these points was downloaded, described in more detail in section 3.2.3. Five additional points (catchments) were selected in targeted regions of Colombia and the UK in order to provide morphologies that were deemed lacking from the selection process of the other 15 catchments. Because of the lack of FBS data across most of the world, catchments were restricted to certain areas, mostly in Europe (Table 3.1, Figure 3-3). However, given catchments are subsequently treated in an abstracted manor, and are only represented by their morphology (e.g. shape, slope), and the aim is to provide results and rules that can be generically applied to catchments based on their morphology, the lack of catchments in some regions, particularly Africa, was not deemed problematic.

Table 3.1 Location coordinates and coordinate reference system of 20 catchments selected.

| Country        | Region          | River               | Coordinate reference system | Coordinates |           |
|----------------|-----------------|---------------------|-----------------------------|-------------|-----------|
|                |                 |                     |                             | Latitude    | Longitude |
| Colombia       | Putumayo        | Mulato              | WGS_1984_UTM_zone_18N       | 1.143495    | -76.6425  |
| United Kingdom | South West      | Cary                | WGS_1984_UTM_zone_30N       | 51.04887    | -2.63323  |
| Serbia         | Barajevo        | Berajevska          | WGS_1984_UTM_zone_34N       | 44.60349    | 20.45241  |
| Italy          | Messina         | Mazzarrà            | WGS_1984_UTM_zone_33N       | 37.91275    | 15.01107  |
| Colombia       | Nariño          | Pasto               | WGS_1984_UTM_zone_18N       | 0.915971    | -77.2769  |
| Hungary        | Miskolc         | Hór-patak           | WGS_1984_UTM_zone_34N       | 48.05273    | 20.54177  |
| Ireland        | County Kilkenny | Dinin               | WGS_1984_UTM_zone_29N       | 52.77427    | -7.20662  |
| China          | Xizang          | Yazu                | WGS_1984_UTM_zone_47N       | 28.66128    | 97.46692  |
| Turkey         | Mersin          | Kurtcukuru          | WGS_1984_UTM_zone_36N       | 37.15908    | 34.75578  |
| Australia      | Queensland      | Yandaran Creek      | WGS_1984_UTM_zone_56S       | -24.7078    | 152.1714  |
| Colombia       | Cauca           | Caqueta             | WGS_1984_UTM_zone_18N       | 1.514763    | -76.5883  |
| Colombia       | Tolima          | Combeima            | WGS_1984_UTM_zone_18N       | 4.400306    | -75.2915  |
| Spain          | Lleida          | Noguera Ribargozana | WGS_1984_UTM_zone_31N       | 41.68785    | -0.703    |
| United Kingdom | East Midlands   | Trent               | WGS_1984_UTM_zone_30N       | 52.90093    | -1.24997  |
| Angola         | Bengo           | Metome              | WGS_1984_UTM_zone_33S       | -8.80146    | 13.65114  |
| Belgium        | Hainaut         | Sambre              | WGS_1984_UTM_zone_31N       | 50.39762    | -4.39773  |
| France         | Bretagne        | L'Aulne             | WGS_1984_UTM_zone_30N       | 48.22057    | -3.70738  |
| Russia         | Krasnodar Kray  | Mayala Laba         | WGS_1984_UTM_zone_37N       | 43.606      | 40.2617   |
| United Kingdom | Yorkshire       | Swale               | WGS_1984_UTM_zone_30N       | 54.32385    | -1.51612  |
| Romania        | Suceava         | Bistrita            | WGS_1984_UTM_zone_35N       | 47.35175    | 25.36093  |

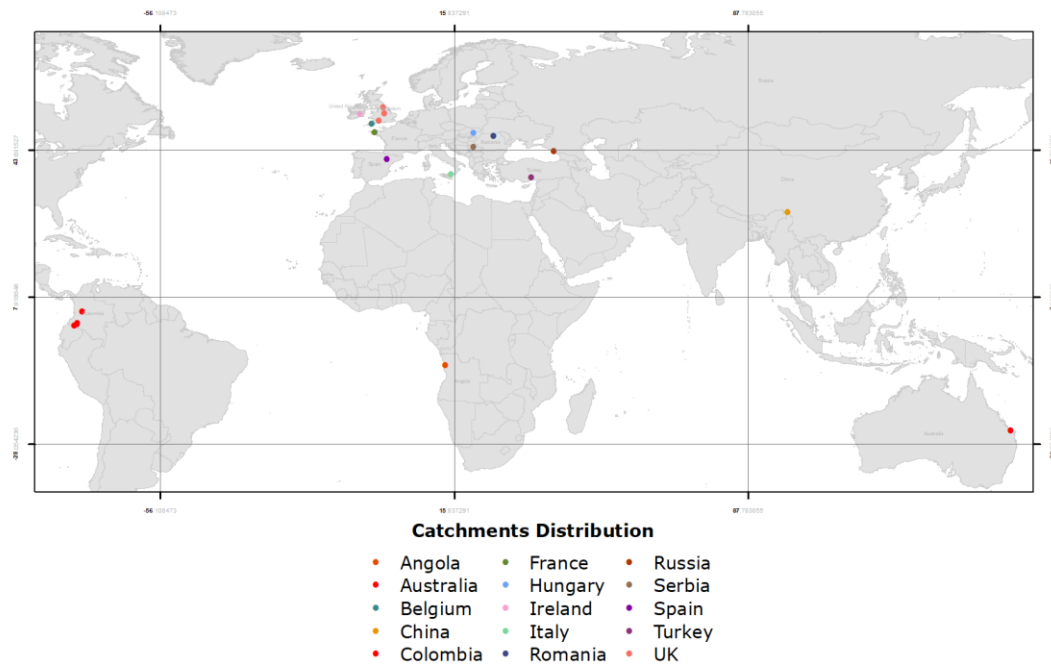


Figure 3-3 Geographical distribution of 20 catchments points selected in different locations around the world.

### 3.2.3 Catchments delimitation

Different techniques have been developed to delimitate and parameterise catchments and their characteristics (Sekulin et al., 1992), and different approaches and estimations have been also considered (Morris and Heerdegen, 1988, Skop and Loaiciga, 1998). To delimit the catchments here, the high terrain resolution imagery (HTRC) obtained from the ALOS PALSAR satellite was used. The HTRC is a Digital Elevation Model (DEM) and delimitation of catchments was achieved according to the procedure described by Smith and Brilly (1992) and summarized in Figure 3-4. Catchments were independently treated and delimited due to the differences in the coordinate reference system. The software ArcGIS was used to delimitate catchments using the ArcHydro extension. Figure 3-5 shows an example of river Caquetá catchment in Colombia and its delimitation from the DEM.

The delimitation procedure included the calculation of the drainage network. Delineating drainage networks in a system is a fundamental parameter but it turned out to be not a straightforward task. No methodology was found to determine the drainage systems for a diverse group of catchments. However, the

most common method is deterministic 8 (D8) described by O'Callaghan and Mark (1984) based on the flow direction, which can be used to analyse catchments independently. This method uses the eight possible directions to determine the flow direction and is based on the steepest slope of each cell and the steepest slope of its neighbour. This limit is modified by making a visual contrast with the real drainage network, although this can introduce subjectivity and error because it is not possible to validate manually all the drainage network, especially in large catchments (Rosim et al., 2017). Different problems have been attributed to the calculation of the drainage network, such as having parallel and orthogonal networks when the threshold values are very small (Kiss, 2004). Due to the complexity of the drainage networks of the 20 chosen catchments and to avoid errors due to visual verification, I used a single threshold of 2000 in all catchments ensuring that there were no problems with parallel and orthogonal drainages. The calculation of this parameter does not affect the hydraulic and hydrological modelling since the drainage network in the model will be determined by the DEM. This value of the drainage network of each catchment is instead used subsequently to explore the potential significance of drainage density in controlling peak flow and lag times.

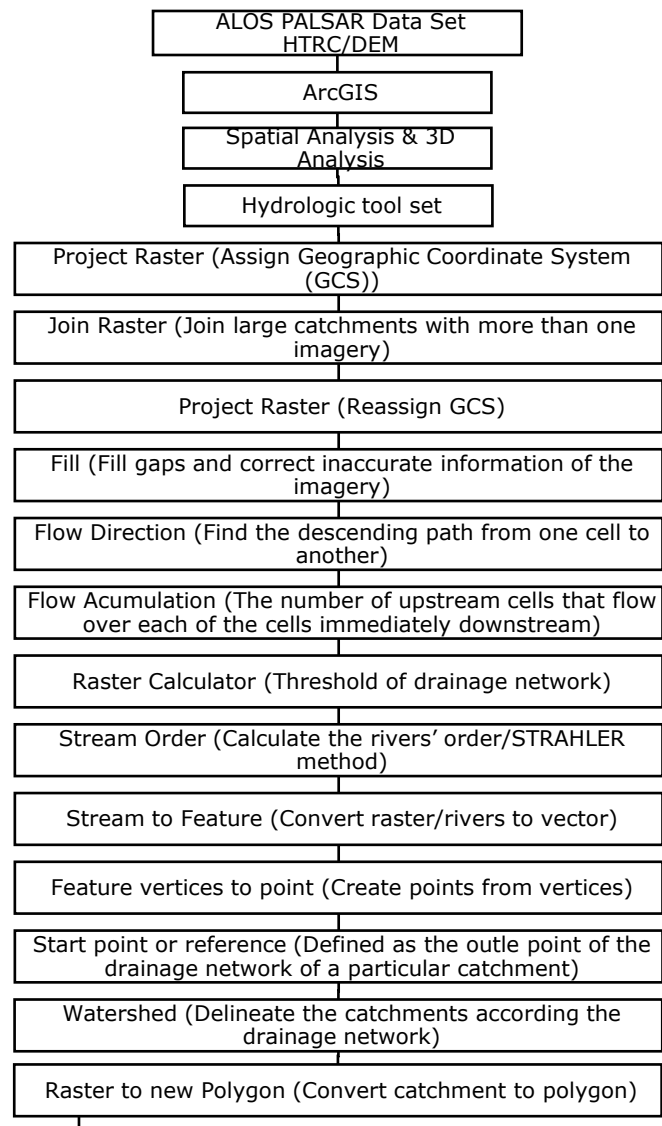
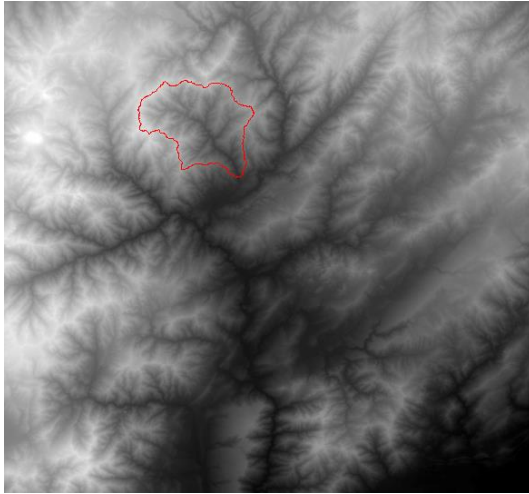
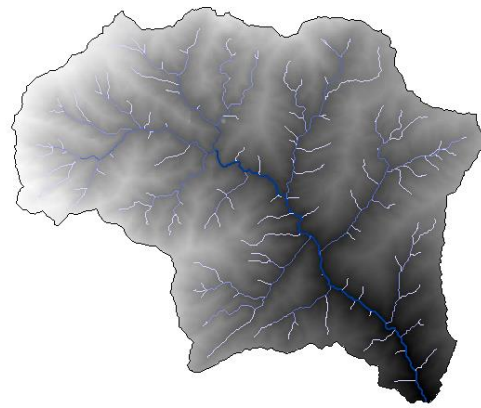


Figure 3-4 Description of the procedure to delineate catchments from DEM and the range of ArcGIS tools used for it.





Scale 1:500.000



Scale 1:125.000

Figure 3-5 DTM of a catchment before and after the delimitation process.

Twenty catchments were extracted using the procedure described above. The choice of catchments represents a diverse range of catchment configurations such as shapes, sizes, drainage systems, slopes and morphologies, quantified and presented below. Although the catchments exist, they were only used as a representation of a range of catchment configurations in an abstracted space, with their spatial location being insignificant to the study aims. Therefore, there is no intention of reproducing real-world hydrological conditions, instead focusing on comparisons between catchment morphology for given artificial hydrological events.

### **3.3 Morphometric and physiographic parameters**

#### ***3.3.1 Introduction to catchment parameterisation***

Catchment morphology is directly linked to hydrological processes and is a fundamental variable when studying hydrodynamic processes within catchments (Beven et al., 1988). From the delimited catchments, a set of parameters were calculated and are detailed in the following sections (section 3.3.2 and 3.3.3). These parameters, also called indices, are widely and commonly used to represent and describe the physical characteristics of a single catchment (Horton, 1932, Strahler, 1957, Chow, 1988). These parameters were classified into two groups

according to Porqueras (1985): i) morphological/independent or direct variables that are calculated directly on the topographic map (DEM) without mathematical operations, and ii) physiographic/dependent variables, which require mathematical operations (Figure 3-6). Although a limited number of variables have been selected to describe catchments, not all variables are considered in future analyses. In Chapter 4, a correlation of all the parameters is carried out to determine which parameters are different or "orthogonal" to each other. This procedure is important to limit the number of parameters and to not unnecessarily include parameters that do not contribute to these analyses.

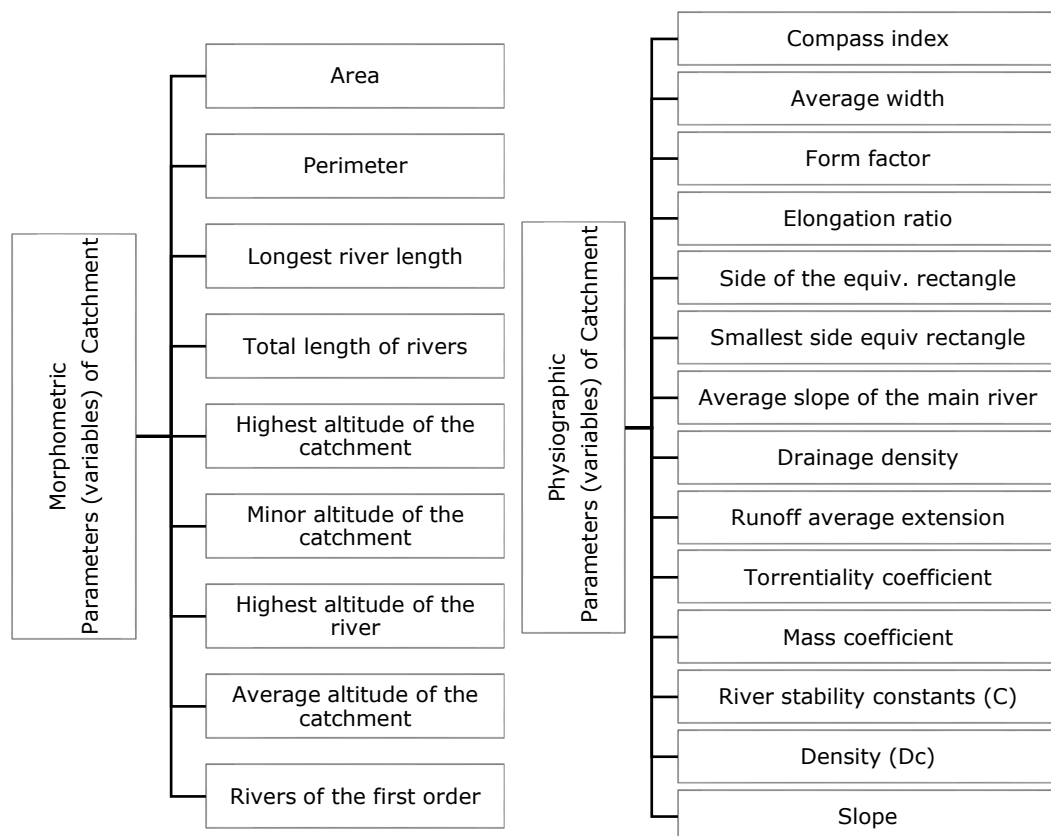


Figure 3-6 Morphometric and physiographic parameters chosen to describe catchments.

Both morphologic and physiographic parameters were calculated for the full set of 20 catchments. ArcGIS was used to extract the direct variables from the DEM's data set. The calculation of the indirect variables was made through the equations described below.

### **3.3.2 Morphometric parameters**

The morphological variables are mainly used to quantify the size of a particular catchment (Horton, 1932), but also consider factors that affect the drainage network and density (Reddy, 2005). Area and perimeter are the principal variables that indicate the size of the catchment based on direct measures. The area is related to the total area of the surface (catchment) while the perimeter length provides an idea of the area but conditioned to the shape of the catchment (i Porqueras, 1985). The area of a catchment is a key variable when calculating other parameters and also allows the establishment of a classification between different catchments according to their size. The maximum and minimum altitude of the catchment area is also a key variable to provide a preliminary geospatial sense of location, as well as overall slope magnitudes.

### **3.3.3 Physiographic variables**

Physiographical variables are commonly used in hydrology, not just to classify catchments into groups according to their features but, also to distinguish between catchments of similar morphological or physiological variables. Some of these features are the result of long term impacts of climate and geology, whereas others vary on shorter timescales (Reddy, 2005). Physiological variables have impacts on the flow regime, for example, in catchments with high drainage density, water has a shorter path to the channelized drainage network, leading to a more rapid flow response and higher peak flow. Likewise, elongated catchments tend to have a rapid response in comparison to more rounded catchments, but with a more gentle peak (Charlton, 2007). Eleven variables were chosen for this study as to have a better understanding of their role in the hydrological response, detailed in Table 3.2.

Table 3.2 Physiographic parameters used in this study and calculated for the full set of catchments.

| Variable / Index | Description | Equation |
|------------------|-------------|----------|
|------------------|-------------|----------|

|                                           |                                                                                                                                                                                                                                                             |                                                              |
|-------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------|
| Gavelius index or Compass index ( $I_c$ ) | Wisler and Brater (1959) defined the Graveluis compass index ( $I_c$ ) as the dimensionless quotient between the perimeter of the catchment ( $P$ ) and the perimeter of a circle ( $P_c$ ) with an area equal to the size ( $A_c$ ) of the catchment in Km | $I_c = \frac{P}{P_c} = \frac{0.282 P}{\sqrt{A_c}}$           |
| Average width ( $W$ )                     | This is the relationship between the area of the catchment ( $A$ ) and the length of the main river ( $L_r$ )                                                                                                                                               | $W = \frac{A}{L_r}$                                          |
| Horton index or Form Factor ( $F$ )       | Horton (1932) defined the form factor ( $F$ ) as an index of the width to the length of the catchment.                                                                                                                                                      | $F = \frac{A_c}{L_r}$                                        |
| Elongation ratio ( $Re$ )                 | This is defined as the dimensionless quotient between the diameter ( $D$ ) of a circle of the same area of the catchment ( $A_c$ ) and the same length of the main river ( $L_r$ ).                                                                         | $Re = \frac{D}{L_r} = \frac{1.1284}{\sqrt{\frac{A_c}{L_r}}}$ |
| Drainage density ( $D_d$ )                | It is defined as the total length of the channels ( $L_t$ ) within the catchment, divided by the total drainage area ( $A_c$ ).                                                                                                                             | $D_d = \frac{L_t}{A_c}$                                      |
| Torrentiality coefficient ( $C_t$ )       | The torrentiality coefficient reflects the drainage density of order 1 indicates the dynamic of the surface flows during the transfer phases (Menani and Bennedjai, 2006).                                                                                  | $C_t = \frac{Ro1}{A_c}$                                      |
| Mass coefficient ( $K_m$ )                | This index relates the mean height of the catchment ( $H_m$ ) to the total area ( $A_c$ ). Therefore, High values of $K_m$ coefficient correspond to mountainous catchments and low values to flat catchments.                                              | $K_m = \frac{H_m}{A_c}$                                      |
| Density ( $D_c$ )                         | It is defined by the ratio of the total number of rivers/streams ( $Nu$ ), regardless of the order number of the river ( $u$ ), between the areas of the catchment ( $A_c$ ).                                                                               | $D_c = \frac{Nu}{A_c}$                                       |

In addition, the hypsometric curve plays an important role as a physiographic variable, incorporating both catchment form and process (Schumm, 1956). The hypsometric curve is the distribution of the areas in partial zones of the catchments according to a range of elevations (Figure 3-7). The curve represents the relation between the values of the relative height in the ordinates with the relative area in the abscissas (Strahler, 1952b). This curve has additionally been used by Strahler (1952a) to classify catchments and their erosive potential, as well as to determine whether a catchment is young or mature. Hypsometric curves were calculated using ArcGIS using the DEM's data set for all catchments.

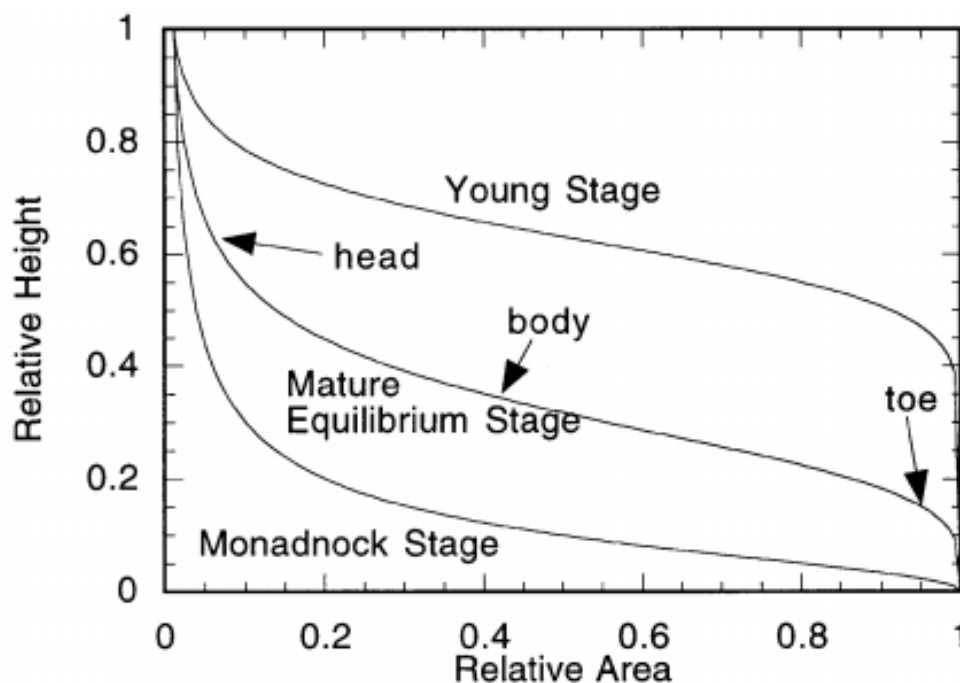


Figure 3-7 Hypsometric curve classification adapted from (Strahler, 1952b).

### 3.4 Catchment classification (by Area and Slope)

Catchments were preliminarily classified by their area and slope. The slope classification considered was proposed by Curtis et al. (1965). This classification is defined based on the frequency of occurrence of particular slopes angles and, for this reason, the classification is likely to be consistent with natural conditions. The methodology was developed in several countries covering a wide range of morphologies. It has also been used in 17 other classifications, including the classification of the U.S. Soil Survey that is widely used. The classification ranges

are described as follow: < 2% Flat, 2% - 8% Gently Sloping, 8% - 15% Moderately Sloping, 15% - 30% Strongly Sloping, 30% - 40% Moderately Steep, 40% - 60% Steep, >60% Very Steep (Table 3.3). Additionally, the histogram of the frequency of each catchment was plotted, which represents the percentage of the area between two determined heights.

Table 3.3 Catchments classification in terms of the slope.

| Country        | Region          | River              | Slope % | Slope Classification |
|----------------|-----------------|--------------------|---------|----------------------|
| United Kingdom | South West      | Cary               | 4.5     | Gently Sloping       |
| United Kingdom | East Midlands   | Trent              | 6.4     | Gently Sloping       |
| Angola         | Bengo           | Metome             | 6.4     | Gently Sloping       |
| Ireland        | County Kilkenny | Dinin              | 7.2     | Gently Sloping       |
| Belgium        | Hainaut         | Sambre             | 7.3     | Gently Sloping       |
| United Kingdom | Yorkshire       | Swale              | 7.9     | Gently Sloping       |
| France         | Bretagne        | L'Aulne            | 8.7     | Moderate Sloping     |
| Australia      | Queensland      | Yandaran Creek     | 9.0     | Moderate Sloping     |
| Serbia         | Barajevo        | Berajevska         | 14.5    | Moderate Sloping     |
| Colombia       | Nariño          | Pasto              | 21.7    | Strongly Sloping     |
| Hungary        | Miskolc         | Hór-patak          | 25.3    | Strongly Sloping     |
| Spain          | Lleida          | Noguera Ribarozana | 27.9    | Strongly Sloping     |
| Italy          | Messina         | Mazzarrà           | 33.5    | Moderately Steep     |
| Romania        | Suceava         | Bistrita           | 34.3    | Moderately Steep     |
| Colombia       | Tolima          | Combeima           | 47.1    | Steep                |
| Turkey         | Mersin          | Kurtcukuru         | 47.5    | Steep                |
| Colombia       | Putumayo        | Mulato             | 50.8    | Steep                |
| Russia         | Krasnodar Kray  | Mayala Laba        | 60.4    | Very Steep           |
| Colombia       | Cauca           | Caqueta            | 62.0    | Very Steep           |
| China          | Xizang          | Yazu               | 70.7    | Very Steep           |

Catchments were also classified for further analysis according to the area. Hydrology does not yet have a general consensus on an area classification. However, considering that the 20 catchments of this research are located spatially in different areas of the world, there are relevant classifications, such as the that described by the Inter-American Centre for Integral Development of Waters and Soils, which has been widely used in hydraulic and hydrological studies (CIDIAT-MARNR, 1984). The classification range is described as follows: a) Hydrographic system (> 300,000 ha) b) Catchment (60,000 - 300,000 ha) c) Sub Catchment (10,000 - 60,000 ha) d) Micro Catchment (<10,000 ha) Table 3.4.

Table 3.4 Catchments classification in terms of area, adjusted from (CIDIAT-MARNR, 1984).

| Country        | Region             | River                  | Area (Km <sup>2</sup> ) | Area Classification |
|----------------|--------------------|------------------------|-------------------------|---------------------|
| Colombia       | Putumayo           | Mulato                 | 17.5                    | Micro-Catchment     |
| United Kingdom | South West         | Cary                   | 22.8                    | Micro-Catchment     |
| Serbia         | Barajevo           | Berajevska             | 44.6                    | Micro-Catchment     |
| Italy          | Messina            | Mazzarrà               | 52.7                    | Micro-Catchment     |
| Colombia       | Nariño             | Pasto                  | 56.3                    | Micro-Catchment     |
| Hungary        | Miskolc            | Hór-patak              | 75.2                    | Micro-Catchment     |
| Ireland        | County<br>Kilkenny | Dinin                  | 85.6                    | Micro-Catchment     |
| China          | Xizang             | Yazu                   | 101.5                   | Sub-Catchment       |
| Turkey         | Mersin             | Kurtcukuru             | 120.7                   | Sub-Catchment       |
| Australia      | Queensland         | Yandaran<br>Creek      | 139.8                   | Sub-Catchment       |
| Colombia       | Cauca              | Caqueta                | 151.0                   | Sub-Catchment       |
| Colombia       | Tolima             | Combeima               | 161.7                   | Sub-Catchment       |
| Spain          | Lleida             | Noguera<br>Ribargozana | 179.9                   | Sub-Catchment       |
| United Kingdom | East<br>Midlands   | Trent                  | 192.5                   | Sub-Catchment       |
| Angola         | Bengo              | Metome                 | 291.9                   | Sub-Catchment       |
| Belgium        | Hainaut            | Sambre                 | 337.6                   | Sub-Catchment       |
| France         | Bretagne           | L'Aulne                | 519.1                   | Sub-Catchment       |
| Russia         | Krasnodar<br>Kray  | Mayala<br>Laba         | 522.7                   | Sub-Catchment       |
| United Kingdom | Yorkshire          | Swale                  | 527.0                   | Large-Catchment     |
| Romania        | Suceava            | Bistrita               | 759.7                   | Large-Catchment     |

### 3.5 Hydraulic and hydrological modelling

#### 3.5.1 Hydraulic and hydrological overview

To analyse the dynamics of the river in a catchment, hydrodynamic numerical models are widely used (Bladé et al., 2014, Howes et al., 2006, Hunter et al., 2008, Nguyen et al., 2016). Those models have also been used to obtain evidence of the effect of particular interventions on catchments (Nicholson et al., 2020). There is an extensive range of models with variable capabilities (Hunter et al., 2008), which solve complex equations and work under complex topographies; however, there is not a unique model that fits all study cases. A diverse number of considerations exist such as the hydraulic and hydrological equations used (i.e. process representation), the computational time, the minimum inputs requirements, and the number of dimensions.

Table 3.5 shows a range of models for the analysis of high flows, which work under different mathematical formulations and calculation methods. They are mostly based on dimensionality or how two different dimensional approaches are combined. The most common models are 1D and 2D models that are robust enough to cover many of the hydraulic modelling applications and provide tools for flood risk management strategies (Néelz, 2009). The 3D methods are derived from the Navier-Stokes equations, averaged in 3D by Reynolds but that, nevertheless, still have practical challenges to overcome due to their complex mathematical formulation and the diversity of potential scenarios.

Hydrodynamic models based on 2D shallow water equations are the most widely used today and often use 2D St-Venant equations (Hervouet, 2007, Demeritt and Nobert, 2014). Mathematical solutions are made through numerical methods such as finite differences, finite elements or finite volumes. An advantage of these models is that they use different numerical grids or meshes from which structured or unstructured meshes can be highlighted. These meshes are frequently used depending on the scenario to be modelled; for example, unstructured meshes are suited to more complex morphologies (Cea and Bladé, 2015) while structured meshes can be used when there are no abrupt changes or in the case of channels. 1D models based on a form of the 1D St-Venant or shallow water equations (Saint-Venant, 1871) have not been considered in this investigation because their use is limited to where the direction of the water movement is aligned with the centre line of the river channel.

Another relevant consideration in hydraulic modelling is their interaction with hydrological conditions; however, hydrological and hydraulic models are often used independently. The hydrological model applies a mathematical model of rainfall-runoff, to later convert precipitation into runoff, which will later be an input parameter to the two-dimensional hydraulic model. Currently, there are a limited number of models that have been adapted with dual functionality, which allows consideration of a wider analysis series. The advantage of these models is the direct simulation of a rainfall event on the calculation mesh where the catchment morphology is immersed in the calculation of runoff. Due to the nature of this study and the available data, a coupled model which integrates hydraulic and hydrological components was selected.



Table 3.5 Available methods for hydraulic modelling (adapted from Pender (2006)).

| Method | Software                              | Model description                                                                                                                                               | Application                                                                                                                                                                                      |
|--------|---------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1D     | Infoworks RS (ISIS), Mike 11, HEC-RAS | Solution of the 1D St Venant equations.                                                                                                                         | Design scale modelling which can be of the order of 10 s to 100 s of km depending on catchment size                                                                                              |
| 1D+    | Infoworks RS (ISIS), Mike 11, HEC-RAS | Solution of the 1D St Venant equations with a flood storage cell approach to the simulation of floodplain flow.                                                 | Design scale modelling which can be of the order of 10 s to 100 s of km depending on catchment size, also has the potential for broad-scale application if used with sparse cross-sectional data |
| 2D-    | LISFLOOD-FP                           | 2D minus the law of conservation of momentum for the floodplain flow                                                                                            | Extensive scale modelling or urban inundation depending on cell dimensions. It is proficient of simulating grids up to $10^6$ cells for dynamic flood events.                                    |
| 2D     | TUFLOW, Mike 21, TELEMAC, DIVAST      | Solution of the 2D shallow wave equations                                                                                                                       | Design-scale modelling of the order of 10 s km. May have the potential for use in broad-scale modelling if applied with very course grids                                                        |
| 2D     | IBER                                  | Solves the two-dimensional depth-averaged Shallow Water Equations (SWE), also known as the 2D Saint Venant equations.                                           | Simulation of free surface flow, morphodynamics, transport processes and habitat in rivers and estuaries. The hydrological module of IBER enables the transformation of rainfall into runoff.    |
| 2D+    | TELEMAC 3D                            | 2D plus a solution for vertical velocities using continuity only. Finite volume style numerical techniques                                                      | Predominantly coastal modelling applications where 3D velocity profiles are important. Can be applied to reach-scale river modelling.                                                            |
| 2D/3D  | TUFLOW FV                             | 1D, 2D (vertically averaged) and 3D. Finite volume numerical model. Parallelised that capitalise on the computing power of multiple processor/thread computers. | Simulates hydrodynamic, sediment transport and water quality processes in coastal waters, estuaries, oceans, rivers and floodplains.                                                             |
| 3D     | Delft 3D                              | Multi-dimensional (2D or 3D) hydrodynamic and transport simulation programme which calculates non-steady flow and sediment transport.                           | Suitable to investigate hydrodynamics, sediment transport and morphology and water quality for fluvial, estuarine and coastal environments.                                                      |
| 3D     | CFX, FLUENT, PHEONIX                  | Solution of the three-dimensional Reynolds averaged Navier–Stokes equations                                                                                     | Local predictions of 3D velocity fields in main channels and floodplains.                                                                                                                        |

The selected model was the IBER river modelling simulation tool package. This model was designed for the simulation of hydrodynamic and morphological river flows (Corestein et al., 2010, Cea and Bladé, 2015). It solves the two-dimensional

(depth-averaged) shallow water equations (2D-SWE) also known as 2D St. Venant equations, applying the Finite Volume Method (FVM) based on the scheme described by (Roe, 1986). IBER works either in stationary or non-stationary flow and has the potential to be used for simulation of free-flow, assessment of flooding zones, flood risk, calculations of dam rupture, channelling, and processes of erosion and sedimentation (Bladé et al., 2014). IBER was chosen because it meets the criteria above (i.e. 2D, coupled hydraulic-hydrological) and because the pre-processing interface features allow the generation of unstructured meshes, which are of particular importance in this research due to the wide range of morphologies used. The regular mesh is generated directly from a DEM of the catchment through either the generation of an ASCII file from ArcGIS or other format, which makes the model adaptable to different geoprocessing software (Cea Gómez, 2019). The DEM resolution also defines the resolution of the mesh, which can be modified or adjusted depending on the study requirements. The mesh design is typically one of the processes that require the most time and effort when developing a numerical simulation (Bladé et al., 2014). The meshing methods based on the chordal error (i.e. the maximum difference between the original field and the mesh) are very sensitive to reduce the number of elements with smooth transitions.

IBER also allows the evaluation of the effect of vegetation roughness on the hydrodynamic calculation mesh, by being automatically imported from georeferenced land use data (Bladé et al., 2014). This type of utility becomes an advantage when considering the flexibility to evaluate different scenarios by using particular land use layers. IBER has got a distributed hydrological model based on 2D shallow water equations which are an advantage over the other models described above in Table 3.5. The module allows the calculation of the transformation of rain to runoff and, therefore, to be incorporated into the hydraulic module. In this sense, it is possible to define the rain fields either from hyetographs or georeferenced raster files. The module also allows the definition of other hydrological inputs such as water losses through infiltration using models including the Green-Ampt, Horton and constant infiltration approaches. The hydrological model also allows simulation of the effect of the wind and how particular rainfall moves across the catchment. However, in this study precipitation is the only hydrological variable used and other hydrological variables, such as evaporation and interception, were kept constant. This avoids variability between catchments that is not attributable to catchment morphology. The implications of the absence of these variables are discussed later. As such, we refer to IBER as a coupled hydraulic-hydrological model but it should be noted that the hydrological

component is only used to transform rainfall to runoff. The model has been widely used in different countries and for a suite of different flood issues (Martins et al., 2018).

IBER solves the following set of mass and momentum conservation equations for the hydraulic model:

$$\frac{\partial h}{\partial t} + \frac{\partial h U_x}{\partial x} + \frac{\partial h U_y}{\partial y} = 0$$

$$\frac{\partial}{\partial t}(h U_x) + \frac{\partial}{\partial x}\left(h U_x^2 + g \frac{h^2}{2}\right) + \frac{\partial}{\partial y}(h U_x U_y) = -gh \frac{\partial Z_b}{\partial x} + \frac{\tau_{s,x}}{\rho} - \frac{\tau_{b,x}}{\rho} + \frac{\partial}{\partial x}\left(v_t h \frac{\partial U_x}{\partial x}\right) + \frac{\partial}{\partial y}\left(v_t h \frac{\partial U_x}{\partial y}\right)$$

$$\frac{\partial}{\partial t}(h U_y) + \frac{\partial}{\partial x}(h U_x U_y) + \frac{\partial}{\partial y}\left(h U_y^2 + g \frac{h^2}{2}\right) = -gh \frac{\partial Z_b}{\partial y} + \frac{\tau_{s,y}}{\rho} - \frac{\tau_{b,y}}{\rho} + \frac{\partial}{\partial x}\left(v_t h \frac{\partial U_y}{\partial x}\right) + \frac{\partial}{\partial y}\left(v_t h \frac{\partial U_y}{\partial y}\right)$$

(1)

Where  $h$  is the water depth,  $U_x$ ,  $U_y$  is the horizontal velocities averaged in depth,  $g$  is the acceleration of gravity,  $\rho$  is the density of the water,  $Z_b$  bed channel level,  $\zeta_s$  is the friction of the free surface due to the friction produced by the wind,  $\zeta_b$  is the friction due to the roughness of the bed channel, and  $V_t$  is the turbulent viscosity.  $\zeta_b$  as the friction due to the roughness of the bed channel could be also calculated as:

$$\tau_{b,x} = \rho g h \frac{n^2 U_x |U|^2}{h^{4/3}} \quad \tau_{b,y} = \rho g h \frac{n^2 U_y |U|^2}{h^{4/3}}$$

(2)

And the turbulent viscosity  $V_t$  is calculated as:

$$V_t = 0.068 \sqrt{gn} |U| h^{5/6}$$

(3)

The hydrological model of IBER also works based on the same shallow water equations, which were improved by including the precipitation and losses processes as new source terms ( $R$ , and  $f$ ) on the mass conservation equation (Cea and Bladé, 2015).

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = R - f$$

$$\frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q_x^2}{h} \right) + \frac{\partial}{\partial y} \left( \frac{q_x q_y}{h} \right) = -gh \frac{\partial s}{\partial x} - gh \frac{\partial Z_s}{\partial x} - gh \frac{n^2 |q|}{h^{10/3}} q_x$$

$$\frac{\partial q_y}{\partial t} + \frac{\partial}{\partial y} \left( \frac{q_y^2}{h} \right) + \frac{\partial}{\partial x} \left( \frac{q_x q_y}{h} \right) = -gh \frac{\partial s}{\partial y} - gh \frac{\partial Z_s}{\partial y} - gh \frac{n^2 |q|}{h^{10/3}} q_y$$

(4)

Where  $R$  is the rainfall intensity,  $f$  is the rainfall losses (infiltration, evapotranspiration, interception and surface retention),  $Z_s$  is the free surface elevation,  $h$  is the water depth,  $(q_x, q_y)$  are the two components of the unit discharge ( $X$  and  $Y$  components),  $|q|$  is the unit discharge,  $g$  is the gravity acceleration,  $n$  is the Manning coefficient.

### **3.5.2 Required model inputs and parameters**

Another factor in the selection of IBER is that it requires a relatively small number of hydraulic and hydrological parameters and inputs to be able to run (Cea Gómez, 2019). These parameters are: geometry/morphology (DEM), boundary and initial conditions, roughness values, rainfall (hyetograph), infiltration, mesh type, mesh size and general calculation options such as calculation time, time step, and output parameters. Hence, those parameters were set up as follow:

### **3.5.2.1 Geometry**

The geometry in IBER represents the morphology of a given catchment through a DEM. To represent the geometry of every single catchment, the DEM's data set was imported individually into IBER using the DXF method (Cea Gómez, 2019). The geometry was used to assign the hydrodynamic conditions in IBER.

### **3.5.2.2 Hydrodynamic conditions**

IBER has two main hydrodynamic conditions to be set up, the initial conditions and the boundary conditions.

#### *Initial condition*

Initial conditions are defined in IBER to determine whether the catchment has water in the system or whether the catchment starts dry or without water. Given the abstracted nature of the catchments and the need for consistency between catchments, the initial condition was set to have a water depth of zero and, thus, all territory in all catchments was considered without water at the beginning of the simulation. In addition, no infiltration was also considered to avoid losing water volume due to the infiltration process (see hydrological process below). The initial dry surface is also used to avoid numerical instabilities (Esteves et al., 2000).

#### *Inlet boundary conditions*

In a two-dimensional model, it is necessary to distinguish between inlet and outlet boundary conditions to make sure that the two-dimensional shallow water equations are well posed from a mathematical point of view. IBER has three possibilities of assigning the inlet boundary conditions (e.g. total discharge, specific discharge, water level). This refers to the inflow discharge hydrograph to be modelled as an input parameter. It is normally the result of the rain-runoff transformation but it can also be obtained through gauging station records, spot water elevation or flux measurements and tidal curves. This input is normally used to analyse the downstream effect of a particular discharge in a catchment. However, when distributed rainfall is modelled in the hydrological module of IBER, no internal conditions need to be set up because the inlet boundary conditions are generated directly by the rainfall input (Bladé et al., 2014). The hyetograph design is described in section 3.7.1.

### *Outlet boundary conditions*

The outlet boundary conditions define the area where the flow leaves the catchment and it depends on the catchment data availability and the study approach. Normally in rivers, the flow runs slowly in the contours of the section modelling. In this case, the most common approach is to impose the depth of the water or the level of the free surface on the downstream contour. In contrast, if the flow regime is critical or supercritical at the outlet, there is no need to assign any boundary condition and the flow will leave the catchment without restrictions. This does not imply that the flow is supercritical when leaving the catchment or the flow regimen will be affected by the outlet boundary condition. What is implied is that the flow will flow freely without any restriction. Supercritical flow condition is recommended when there is not enough data in the outlet of the catchment to define a depth or level of the free surface (Bladé et al., 2014, Cea Gómez, 2019). Additionally, subcritical flow conditions are used when there is a need to calibrate the model based on a known, measured depth of the water in the system being modelled. In this case, the catchments are being treated as synthetic, with no attempt made to recreate measured hydrographs and, as such, a supercritical outflow was chosen and no traditional validation against measured data was performed.

### *Internal conditions*

Internal conditions can be assigned to the elements of the catchments such as weirs, bridges, gates or local loses. This research did not consider any structures within any catchments so no internal condition was set up.

### *Soil roughness*

Soil roughness coefficients are used to characterise the resistance to flood flows in water systems and flood plains (Arcement and Schneider, 1989). Roughness is normally defined by assigning the Manning's  $n$  roughness coefficient, which is tabulated depending on the factor that affects it. IBER has a list of default options with common Manning roughness coefficient values assigned to each land use; however, the model allows adding or removing land uses. The model also allows the setting up of Manning values through an automatic mapping with georeferenced data that generally comes from a layer of land use data. The most common format is ASCII from ArcInfo that contains the distribution of georeferenced roughness coefficients of a particular catchment studied. A second CSV format file must be generated containing a list of the classes/land uses used.

Both files must have the same name and be located in the same directory (e.g. Dinin\_Cathment.txt, Dinin\_Cathment.csv). Once the files are created, they are loaded and the program reads the information and automatically assigns the corresponding Manning coefficient to the elements of the mesh (Cea Gómez, 2019). In this investigation, various roughness scenarios will be used that will be consistent in all the catchments, the roughness values and the spatial location will be assigned according to the methodology established in section 3.5. Figure 3-8 shows an example of the automatic assignation of Manning “n” roughness coefficient.

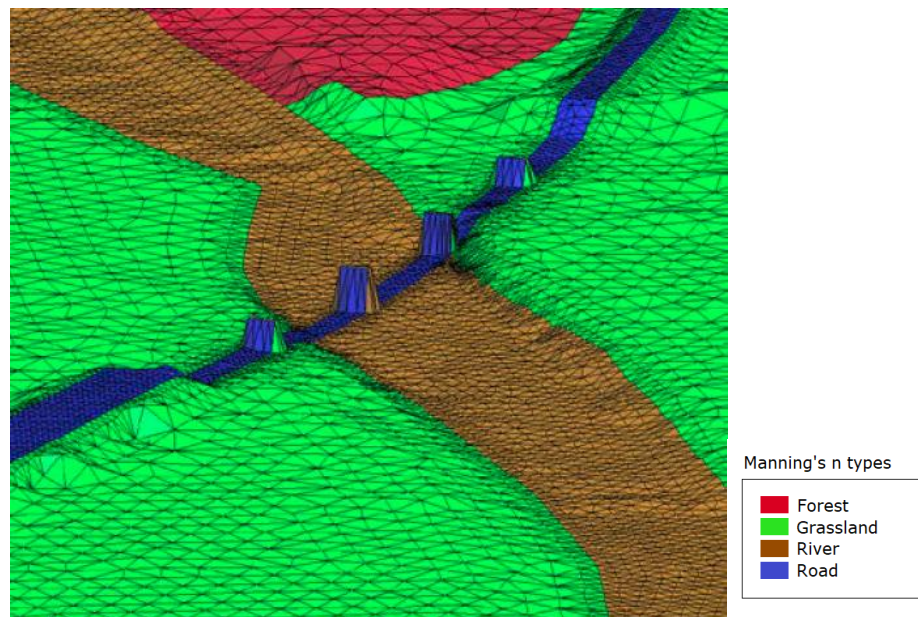


Figure 3-8 Automatic assignation of Manning “n” roughness coefficient. Image describing four types of land used (e.g. River, bushlands, infrastructure, fields).

### *Mesh*

The numerical mesh structure and size are fundamental to the model results (Cea and Bladé, 2015, Nguyen et al., 2016, Cook and Merwade, 2009). The mesh is used in IBER to calculate the model equations in all its elements. Therefore, a refined mesh implies high computational time whereas a mesh with bigger element sizes requires less computational time but, poorer process representation. IBER has two types of mesh (e.g. structured and non-structured) (Figure 3-9). Unstructured meshes are normally used when there are no abrupt changes in soil morphology, such as well-defined channels and urban flood analyses. The non-structured mesh is known to adapt better to complex morphology (Cea and Bladé,

2015). Part of this research is to determine the hydrological response of particular rainfall events, so the accurate representation of catchment morphologies is fundamental. As such, the non-structural mesh was selected because they have better adaptability to complex morphologies. To choose the element size, several sensitivity tests were performed to define the value or values. A full description of the sensitivity testing is described in Chapter 4, section 4.3.

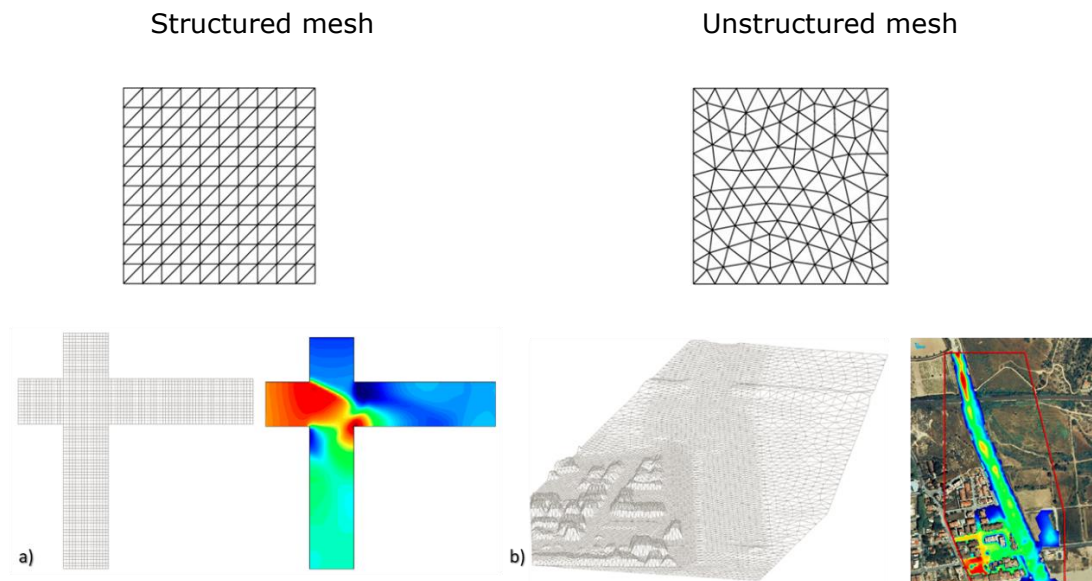


Figure 3-9 Types of mesh. a) Structured mesh. Normally used where there are not many changes in the cross-section or in the channels profile (e.g. study of road conduction). b) Unstructured mesh. It is normally used when the morphology requires more detail, this mesh adapts better to complex morphology (e.g. river inundation simulation). (Source: IBER applications basic guide. Accessible from <https://www.iberaula.es/54/iber-model/downloads>).



### **3.5.2.3 Hydrological Processes**

As mentioned above, the only hydrological variable considered in this study is precipitation. Other variables such as infiltration, interception or the effect of the wind have not been considered since these are outside the scope of this investigation. However, the implications of these omissions will be discussed later.

#### *Infiltration*

Modelling infiltration of surface water into the ground is important in simulating the transformation of rainfall to runoff. Saturated terrain has low infiltration rates while unsaturated terrain has higher saturated rates. Infiltration is considered in the model by a negative source term in the equation of conservation of mass (see equation 4). Unlike the initial condition where the mesh was considered without water or dry, this condition instead refers to the percentage of water that can be infiltrated into the soil. The initial condition is an onset state that changes temporarily with the water inflow into the catchment, while the infiltration condition is a permanent condition throughout the modelling. The start condition here was considered with no infiltration into the subsurface, in other words, the soil was impermeable. To meet this condition in IBER, the soil has to be completely saturated preventing water from infiltrated. This was because the objective of the modelling is to explore how NFM affects surface water and also to ensure consistency between the 20 catchments and hydrological scenarios; for example, James and Roulet (2009) found that there is a strong nonlinear change when analysing pre-saturated soil conditions and dry conditions under different rainfall scenarios and catchments sizes. The implications of having a saturated soil is the potential for higher peak flow values compared to unsaturated soils. The infiltration in the catchment is a very sensitive variable since it depends on many catchment parameters, such as the slope, soil type, and the vegetation cover, which can also vary over short distances, increasing the uncertainty in abstracted catchments.

#### *Sediment Transport and Wind.*

No sediment transport or wind conditions were considered in the model as it was out of the scope of the research. Wind conditions are unlikely to have a significant hydrological impact at the scale of the modelling performed in this thesis. Sediment transport and resultant geomorphic changes to channels have the potential to be highly significant but, given the difficulties of accurately modelling sediment transport (Nicholas and Walling, 1997), coupled with the abstracted

nature of catchments, NFM and meteorological scenarios, the lack of sediment transport in the model is unlikely to significantly affect the interpretation of the results to achieve the aims of this thesis. In addition, the ultimate aim of this thesis is to provide generic and generalised rules in simplified scenarios and so, the impact of sediment transport is unlikely to alter the trends between catchments and scenarios observed herein.

#### **3.5.2.4 Other input parameters**

The second dataset of input parameters was set up as follow:

##### *Initial time*

The initial time is used to dictate the start time when the model begins computing and reading model outputs. A value of zero (0) was set up in the model. A spin-up time of one hour was also set up in the model to allow the model to find an equilibrium before the model began computing model outputs. In hydrological and hydrological modelling, this is a common practice i.e. to specify an initial state of the model, as well as to run the model for a chosen period of time (spin-up) until the model reaches equilibrium (Seck et al., 2015, Ajami et al., 2014). The spin-up also provides information about the model response and the interdependencies between variables, as well as the relative contribution of parameters to model stability (Seck et al., 2015). The spin-up time is not considered in the presentation of hydrographs in this thesis but, its effect is discussed.

##### *Maximum simulation time*

The maximum simulation time is used to describe the total time that the model is set up to run a particular scenario. In this case, the total simulation time had to extend from the initial moment of rainfall to when all the rainfall had washed through the catchment outlet. Therefore, this value depends mainly on catchment and mesh size but, it is also related to the slope of the catchment and the roughness. Initially, it was not possible to know the maximum simulation time for each catchment without actually running the model. To determine the total time for each catchment, preliminary models were run in the largest catchments. It was found that the total time ranges between 50,000 sec (14 hours) for micro-catchments to 200,000 sec (55 hours) for catchments over 500 km<sup>2</sup>. The time for each catchment was taken at the moment when the water had left the catchments

completely. Then, these ranges were used to set up the total time for each catchment individually.

The implication of very small values in the maximum simulation time is that the model simulation would stop and the output hydrographs would be incomplete. In contrast, large simulation time can fully represent the hydrograph but computational time can be very long. The computational time of the model depends directly on the size of the catchment and the resolution of the mesh. As such, computational time was reduced by altering mesh size (detailed in Chapter 4) and through setting-up IBER to not read dry cells. In this way, the model determines or considers only the cells where there is a constant flow, significantly reducing computational time.

#### *Results time interval*

The result interval time is used to define how often the data is output by the model. It also has a major impact on the total size of files once the model has finished running. To set up the results time interval, a sensitivity test was performed to determine the optimum step time that does not lead to significant loss information and not excessive computational time. This test was performed using four-step time values (e.g. 5, 10, 15 and 20 minute) with 5-minutes being the finest input and representing a baseline to which other time steps were compared. A detail description of this sensitivity analysis and the results are presented in Chapter 4, Section 4.4.4.

### **3.5.3 Model outputs**

Despite the wide range of output results that the IBER model offers, here only the water depth, flow velocity and specific discharge were outputted. These variables were generated for each catchment at the maximum simulation time (model end) and for each results interval time. Output results files were saved and stored onto a hard drive. The specific discharge was used to calculate hydrographs in the outlet of every catchment. Description of hydrograph generation and its particular use in this research can be found in section 3.8.

### **3.6 Natural Flood Management (NFM) scenarios**

Although NFM includes a range of potential measures (see Section 2.9), tree planting has been selected for this research as the main technique to be evaluated. The scope of this research has been designed to evaluate 20 catchments with a number of woodland configurations as well as set of hydrological scenarios, leaving insufficient time to also evaluate other NFM measures, although I acknowledge their potential significance. The tree planting has been chosen because is a widely used technique internationally and within different landscape configurations, so it can be applicable to the range of catchments used in this study. In contrast, other NFM techniques such as leaky dams or ponds are more likely to provide smaller intervention coverages compared to planting trees, and their efficacy is more likely to be affected by small-scale variations in landscape, such as channel dimensions and connectivity, not easily considered at the spatial scale of the catchments selected in this study. Additionally, the literature available for woodland creation is larger than other NFM techniques, which aids our interpretation of the findings and enables comparison to other studies.

The NFM was set up in the model by changing the land use and assigning a higher manning n value, representing the increased roughness of woodland. This was through the automatic assignment of roughness described in section 3.5.2. Five NFM scenarios were adopted by covering 0%, 25%, 50%, 75% and 100% of the catchment area with thick broadleaved woodland. The remaining areas were not covered by NFM and were instead, covered by pasture with high grass. The NFM coverages were designed from upstream to downstream dividing the area according to the percentages, mentioned above. This was decided as it allowed consistency between the 20 catchments. Chapter 6 explores the effect of NFM on peak flow and lag time while Chapter 7 explores the alternative placement of NFM. The NFM manning n values were set according to the study carried out by Thomas and Nisbet (2007). The model set up and the Manning n-values used are explained in detail in Chapter 6.

### **3.7 Hydrological scenarios**

As mentioned in section 3.5.2 an input condition to the model is used to determine the type of rainfall. In this study, a distributed rainfall event throughout the catchment area was used. In this sense, a set of synthetic rainfall events with different characteristics were generated and then used to perform the modelling.

These rainfall events were used to determine the hydrological response of the study catchments, as well as to evaluate the effect of different types of rainfall in a set of NFM configurations.

### **3.7.1 Design of a rainfall event (Hyetograph)**

#### **3.7.1.1 Magnitude and duration**

Hydrological modelling is one of the key tools used to assess the impact of a rainfall event on a catchment and the design of integrated water management (Arnold et al., 1998). Within IBER, the hydrological input has to be set up as a rainfall event through a hyetograph (Bladé et al., 2014, Cea and Bladé, 2015). The hyetograph represents the duration of the rainfall event and either accumulative rainfall or rainfall intensity. To set up the hydrological input in IBER an abstracted hyetograph was created following two predominant conditions. The first is that the rainfall event was not related to a return period ( $T_r$ ) of any particular area on Earth, in keeping with the abstracted nature of the modelling space and because the objectives of the study do not require or benefit from, modelling of real-World events or scenarios. It has also been suggested that rainfall events of 60 minutes or less should be considered independent of a return period (Borga et al., 2005). The second condition is that the rainfall event has to be considered as a heavy or extreme event. Therefore, the rain type classification used by the Meteorology Statal Agency (AEMET) and described in the manual of use of meteorological data was used (AEMET, 2015). This rainfall classification has been classified according to the rainfall intensity in Table 3.6.

Table 3.6 Classification of rain according to the rainfall intensity (AEMET, 2015).

| <b>Class</b> | <b>Average intensity in an hour</b>                |
|--------------|----------------------------------------------------|
| Shower       | $\leq 2 \text{ mm h}^{-1}$                         |
| Strong       | $> 2 \text{ mm h}^{-1} \leq 30 \text{ mm h}^{-1}$  |
| Very strong  | $> 30 \text{ mm h}^{-1} \leq 60 \text{ mm h}^{-1}$ |
| Torrential   | $> 60 \text{ mm h}^{-1}$                           |

For comparison, the thresholds for rainfall intensity used by the United Kingdom Meteorological Office (UKMO) considers a similar range as follow: Light  $< 2.5 \text{ mm}^{-1}$ , Moderate  $2.5 \text{ mm}^{-1} - 10 \text{ mm}^{-1}$ , Heavy  $10 \text{ mm}^{-1} - 50 \text{ mm}^{-1}$ , Torrential  $> 50 \text{ mm}^{-1}$  (King et al., 2017). Therefore, a rainfall event of 60 mm/h was selected for this study. This magnitude of event is considered by many authors as a heavy rainfall event that would trigger a flash flood (Hooijer et al., 2004, Environment Agency, 2009, Ramsbottom et al., 2012), which are the result of short, high-intensity rainfall, mainly due to confined convective rainfall (Borga et al., 2014, Gaume et al., 2009).

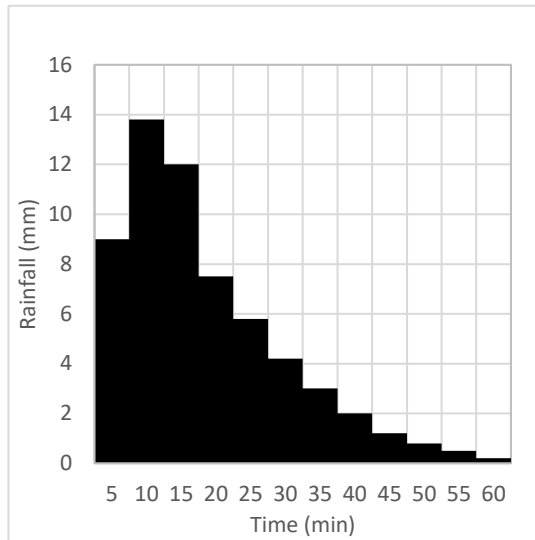
### **3.7.1.2 Hyetograph distribution type**

Once the magnitude and duration of the rainfall event had been defined, the distribution of the hyetograph had to be defined (Haan et al., 1994). The key criteria for the hyetograph are replicability between the 20 catchments and also between event magnitudes. Therefore, four out of the six hyetograph distribution types categorized by Coutinho et al. (2014) were considered for the design of the rainstorm event. These hyetographs are also considered as the four typical intensity distributions (USDA, 1986).

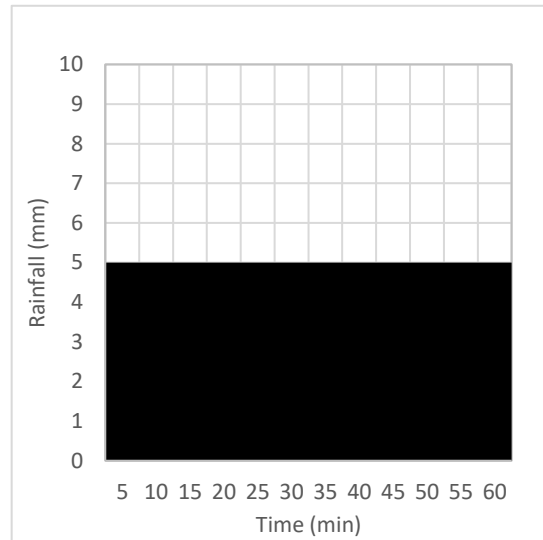
1. unimodal hyetograph with a left-skewed peak
2. unimodal right-skewed peak
3. unimodal with a centred peak
4. rectangular hyetograph or uniformly distributed

Figure 3-10 shows an example of these scenarios. The spatial distribution of rainfall events within catchments is spatially homogenous so the whole area of every catchment experienced the same hyetograph. The hydrological differences between these hyetographs are explored in Chapter 5 but, the unimodal left-skewed hyetograph was chosen as a baseline for research. This is based on the research question to analyse the effect of different types of rainfall distributions on the hydrological response of catchments, because differing rainfall patterns could lead to significantly different peak flow and travel times. The left-skewed hyetograph was chosen as the baseline because this is the predominant distribution of extreme storms, which are generally the cause of severe hydrological responses (Barbosa et al., 2018, Wartalska et al., 2020).

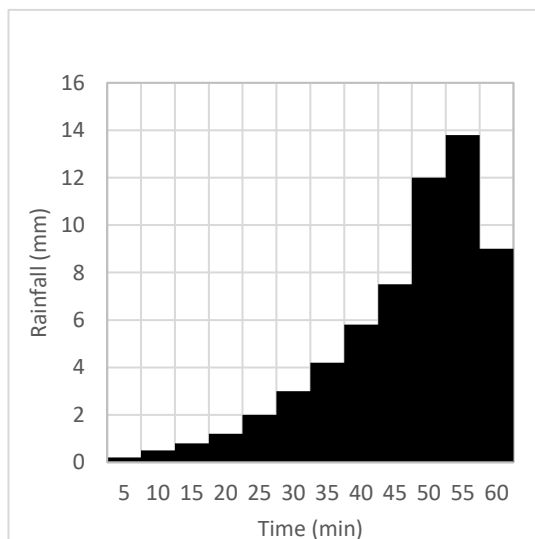
a) Unimodal left-skewed peak



b) Rectangular



c) Unimodal right-skewed peak



d) Unimodal with centred peak

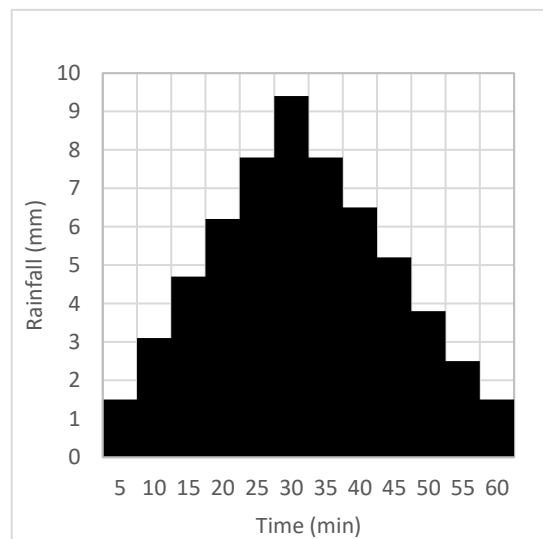


Figure 3-10 Types of hyetograph: a) Unimodal hyetograph with a left-skewed peak, b) Rectangular hyetograph or uniformly distributed, c) Unimodal right-skewed peak, d) Unimodal with centred peak.

Once defined the type of the hyetograph and the duration and intensity of the rainfall event, the hyetograph distribution values had to be calculated. The hyetograph distribution indicates how the total amount of water (cumulative rainfall of 60 mm) is distributed along with the duration of the rainfall (Yen and Chow, 1980). The rainfall distribution was divided into periods of 5 min for 1 hour.

As for the rectangular hyetograph the distribution was calculated by dividing the 60 mm of the accumulated rain between the 12 intervals in one hour. In the case of the unimodal hydrographs with centred peak, the values were adjusted to a triangular distribution where the peak appeared at 30 minutes. A different design process was used for the unimodal left-skewed peak and the unimodal right-skewed. The methodology described by Huff (1967) was used, which allows determination of the distribution and the peak of any rainfall event based on the skewness of the hyetograph, as well as the total accumulated rain and the duration period.

### 3.7.2 Hyetograph intensity ranges.

To assess the effect of intensity on the flood peak on catchments a set of two additional hyetographs were created with an increased and decreased intensity (e.g. 30 mm/h and 120 mm/h). Hyetographs were created for the unimodal left-skewed distribution type for all three magnitudes and are used in Chapter 6. Figure 3-11 shows the array of hyetographs used for this research.

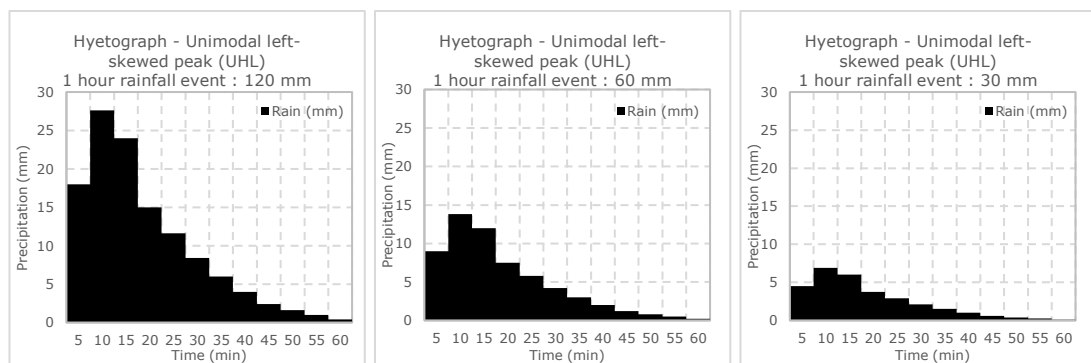


Figure 3-11 Hyetographs for the unimodal left-skewed distribution. Accumulated rain of 120mm, 60 mm and 30 mm in 1-hour period.

## 3.8 Hydrograph generation

To record the high flow behaviour caused by the set of designed rainfall events, as well as the peak flow and time lag, hydrographs were calculated in the outlet of each catchment. The specific discharge obtained by IBER was used to calculate the hydrographs. In IBER hydrographs ( $\text{m}^3 \text{s}^{-1}$ ) are the result of the integration of



the specific discharge ( $\text{m}^3 \text{s}^{-1} \text{m}^{-1}$ ) over time through a cross-section (Cea Gómez, 2019). The peak flow and the lag time are the two main features of the outlet hydrographs used for this research. The peak flow determines the maximum flood level at a given time by a rainfall event (Figure 2-2). Flood control studies use the flood peak as a measure to classify flood magnitude and also to quantify damages (Feldman, 1979). The time lag describes the time from the centre of mass (centroid) of rainfall excess to the centroid of the corresponding runoff hydrograph. Lag time is widely used as a factor for quantifying the time response of runoff in a given catchment (Watt and Chow, 1985), therefore this factor is normally used in the hydraulic and hydrological design and modelling (Granato, 2012).

## **CHAPTER 4. CATCHMENTS PRE-TREATMENT AND MODEL SET-UP**

### **4.1 Introduction**

This chapter will describe the pre-treatment conditions, which must be selected and determined in order to parameterise the model inputs and outputs, and define the initial model set-up.

It is widely known that morphometric and physiographic parameters can be used to describe and parameterise catchments (Reddy, 2005). The most commonly used parameter is the area, which provides a sense of the scale of the catchment (Davies et al., 2007). In this research catchments are classified as having small areas from about 17 km<sup>2</sup> to very large areas over 600 km<sup>2</sup> (see Table 3.6). There are many other parameters that have been used to describe catchments based on other key characteristics (Reddy, 2005, Ward and Robinson, 1967, Birkeland, 1984), but the most relevant for this study are those that have hydrological or geomorphological significance, where similarity in the parameter indicates a similarity in the hydrological response to precipitation events. These parameters also tend to be numerical, offering the ability for quantitative comparison and avoiding challenges associated with the use of more subjective parameters such as 'big', 'steep' or 'narrow' (Leopold et al., 1995).

Catchments are all singular in terms of their morphology and physiography and, as mentioned above, a large range of parameters can be used to parameterise them. The identification of similar hydrological responses between catchments is a fundamental issue to hydraulic and hydrological research as specific knowledge could be transferred from one catchment to another (Toth, 2013). Similarities in catchments can be measured by the hydrological responses of a given rainfall event that can provide an idea of the flow behaviour across the catchment (Oudin et al., 2010). Of particular management significance, is the peak flow given its significance for flooding, channel dynamics and erosive potential (Feldman, 1979). Consequently, the effect of catchment parameters on the peak flow is an important research question that will be examined in this thesis (research in Chapter 5 and 6).

Nowadays, many environmental issues are approached by computer modelling, as it is an efficient way to save time and effort to find a solution for a given issue, especially for temporal and spatial scale issues that are not easily assessed using other methods. However, the use of particular software or models lies not just in their capabilities and limitations but also in the adequate set up of the inputs.

However, despite the fact that there are a large number of models as shown in Table 3.5, all of these in some way need to be adjusted or calibrated in order to optimise their performance. The model selected for this research (IBER) requires a number of inputs to be set up (Chapter 3 section 3.5) and decisions to be made regarding the mesh structure and the results time interval (time step). The mesh is part of the model and is composed of elements that define the vertices of a particular surface. In IBER, the mesh element size is defined by the DEM and can be as fine resolution as the DEM allows. Very fine meshes tend to require large computational efforts and time (Cook and Merwade, 2009, Bladé et al., 2014). Therefore, to get the best efficiency in terms of computational time and quality of the result, an adequate mesh that captures the hydraulic and hydrologic response from a given event needs to be determined.

Therefore, the objectives of this chapter are to:

1. Identify how morphometric and physiographic parameters of the selected catchments relate to each other, to determine patterns between parameters and remove redundant variables that are highly correlated to others
2. To determine how the 20 catchments relate to each other, and to statistically determine whether there are clusters of similar catchments that could be used to sub-sample the total number in future analysis.
3. To analyse the effect of the input mesh element size on model outputs and computational time to optimise its selection.
4. To analyse the effect of the model time step on the model outputs and computational time to optimise its selection.

The outcomes of these four objectives will define how the IBER model is set-up for future modelling work, presented in Chapters 5 and 6.

## **4.2 Catchment morphological and physiographic descriptor selection**

### **4.2.1 Methodology**

Twenty-three parameters commonly used to describe catchments were statistically analysed using a matrix correlation method to investigate and establish relationships between variables (Table 4.1). This method is also known as the Pearson product-moment correlation coefficient, or Pearson's  $r$  correlation

coefficient (Manly, 2008). The method is obtained by dividing the covariance of two variables by the product of their standard deviations. The Pearson's method is particularly useful when the data set contains different units as the method is dimensionless so it is not influenced by changes in scale. The analysis was performed in R (Team, 2013). The correlation matrix analysis was used to identify which parameters to use in this research because if two or more variables are highly correlated, they do not provide any extra information. In this case, one or more parameters are redundant and could be removed from analysis with little impact on model performance.

Table 4.1 Full set of physiographical and morphological parameter calculated for all catchments.

| MORPHOMETRIC PARAMETERS               |          | Combeima          | Trent  | Mulato | Swale          | Berajevsk<br>a | Noguera<br>Ribargozana | Caqueta         | Cary     | Hór-patak | Mazzarrà |
|---------------------------------------|----------|-------------------|--------|--------|----------------|----------------|------------------------|-----------------|----------|-----------|----------|
| Perimeter                             | Km       | 77.1              | 94.7   | 27.9   | 174.1          | 36.2           | 70.8                   | 59.8            | 31.2     | 56.0      | 51.8     |
| Area                                  | Km2      | 161.7             | 192.5  | 17.5   | 613.1          | 44.6           | 179.9                  | 151.0           | 22.8     | 75.2      | 54.8     |
| Longest river length                  | msnm     | 30.0              | 31.3   | 12.0   | 69.4           | 11.9           | 28.5                   | 24.0            | 11.7     | 19.9      | 23.7     |
| Highest Altitude of the Catchment     | msnm     | 3707.0            | 248.0  | 2362.0 | 766.0          | 392.0          | 3274.0                 | 3554.0          | 201.0    | 987.0     | 1381.0   |
| Minor altitude of the Catchment       | msnm     | 1178.0            | 78.0   | 582.0  | 77.0           | 157.0          | 971.0                  | 954.0           | 69.0     | 255.0     | 45.0     |
| Highest Altitude of the River         | Km       | 3578.0            | 197.0  | 1928.0 | 512.0          | 308.0          | 2535.0                 | 2879.0          | 137.0    | 637.0     | 1023.0   |
| Total length of rivers                | Rios     | 165.7             | 151.1  | 20.6   | 708.5          | 51.0           | 191.8                  | 165.6           | 29.7     | 92.1      | 63.1     |
| Average altitude of the Cathment      | msnm     | 2536.0            | 149.8  | 1370.2 | 345.6          | 274.8          | 1965.6                 | 2213.9          | 92.7     | 582.5     | 751.4    |
| Rivers of the first order             | Rios     | 106.0             | 71.0   | 15.0   | 505.0          | 29.0           | 160.0                  | 123.0           | 22.0     | 70.0      | 40.0     |
| PHYSIOGRAPHIC PARAMETERS              |          |                   |        |        |                |                |                        |                 |          |           |          |
| Compass index                         |          | 1.7               | 1.9    | 1.9    | 2.0            | 1.5            | 1.5                    | 1.4             | 1.8      | 1.8       | 2.0      |
| Average Width                         | Km       | 5.4               | 6.1    | 1.5    | 8.8            | 3.7            | 6.3                    | 6.3             | 2.0      | 3.8       | 2.3      |
| Form Factor                           |          | 0.2               | 0.2    | 0.1    | 0.1            | 0.3            | 0.2                    | 0.3             | 0.2      | 0.2       | 0.1      |
| Elongation ratio                      |          | 0.5               | 0.5    | 0.4    | 0.4            | 0.6            | 0.5                    | 0.6             | 0.5      | 0.5       | 0.4      |
| Side of the equivalent rectangle      | Km       | 33.7              | 42.9   | 12.6   | 79.3           | 15.2           | 29.3                   | 23.5            | 14.0     | 25.0      | 23.6     |
| Smallest side of equivalent rectangle | Km       | 4.8               | 4.5    | 1.4    | 7.7            | 2.9            | 6.1                    | 6.4             | 1.6      | 3.0       | 2.3      |
| Average slope of the main river       | %        | 8.0               | 0.4    | 11.3   | 0.6            | 1.3            | 5.5                    | 8.0             | 0.6      | 1.9       | 4.1      |
| Drainage Density                      | Km/km2   | 1.0               | 0.8    | 1.2    | 1.2            | 1.1            | 1.1                    | 1.1             | 1.3      | 1.2       | 1.2      |
| Runoff Average Extension              | Km       | 0.2               | 0.3    | 0.2    | 0.2            | 0.2            | 0.2                    | 0.2             | 0.2      | 0.2       | 0.2      |
| Torrentiality coefficient             | Rios/km2 | 0.7               | 0.4    | 0.9    | 0.8            | 0.7            | 0.9                    | 0.8             | 1.0      | 0.9       | 0.7      |
| Mass Coefficient                      | M/km2    | 15.7              | 0.8    | 78.2   | 0.6            | 6.2            | 10.9                   | 14.7            | 4.1      | 7.7       | 13.7     |
| River stability constants (C)         |          | 1.0               | 1.3    | 0.9    | 0.9            | 0.9            | 0.9                    | 0.9             | 0.8      | 0.8       | 0.9      |
| Density (Dc)                          |          | 0.7               | 0.5    | 0.8    | 0.8            | 0.8            | 0.7                    | 0.8             | 0.9      | 0.8       | 0.8      |
| Slope                                 | %        | 25.2              | 3.7    | 26.9   | 4.5            | 8.3            | 15.6                   | 31.8            | 2.6      | 14.2      | 18.5     |
| MORPHOMETRIC PARAMETERS               |          | Yandaran<br>Creek | Zayu   | Dinin  | Kurtcukur<br>u | Sambre         | Metome                 | Mayala-<br>Laba | Bistrita | L'Aulne   | Pasto    |
| Perimeter                             | Km       | 75.9              | 44.5   | 52.1   | 83.4           | 120.1          | 96.0                   | 132.7           | 181.5    | 139.0     | 47.0     |
| Area                                  | Km2      | 139.8             | 95.7   | 85.6   | 120.7          | 337.6          | 291.9                  | 522.7           | 759.7    | 519.1     | 56.3     |
| Longest river length                  | msnm     | 31.0              | 18.0   | 17.9   | 36.6           | 45.8           | 32.1                   | 42.5            | 71.6     | 44.9      | 21.7     |
| Highest Altitude of the Catchment     | msnm     | 374.0             | 5877.0 | 394.0  | 3552.0         | 368.0          | 254.0                  | 3319.0          | 2284.0   | 431.0     | 4065.0   |
| Minor altitude of the Catchment       | msnm     | 53.0              | 3397.0 | 158.0  | 534.0          | 151.0          | 47.0                   | 936.0           | 831.0    | 111.0     | 2574.0   |
| Highest Altitude of the River         | Km       | 166.0             | 5055.0 | 359.0  | 3073.0         | 327.0          | 225.0                  | 2623.0          | 1438.0   | 302.0     | 3723.0   |
| Total length of rivers                | Rios     | 193.5             | 110.1  | 88.0   | 144.2          | 407.2          | 382.6                  | 547.1           | 801.4    | 635.8     | 89.0     |
| Average altitude of the Cathment      | msnm     | 99.8              | 4627.8 | 300.7  | 1662.9         | 278.4          | 132.4                  | 2161.0          | 1298.0   | 238.9     | 3076.1   |
| Rivers of the first order             | Rios     | 121.0             | 102.0  | 69.0   | 108.0          | 321.0          | 252.0                  | 433.0           | 597.0    | 468.0     | 53.0     |
| PHYSIOGRAPHIC PARAMETERS              |          |                   |        |        |                |                |                        |                 |          |           |          |
| Compass index                         |          | 1.8               | 1.3    | 1.6    | 2.1            | 1.8            | 1.6                    | 1.6             | 1.8      | 1.7       | 1.8      |
| Average Width                         | Km       | 4.5               | 5.3    | 4.8    | 3.3            | 7.4            | 9.1                    | 12.3            | 10.6     | 11.6      | 2.6      |
| Form Factor                           |          | 0.1               | 0.3    | 0.3    | 0.1            | 0.2            | 0.3                    | 0.3             | 0.1      | 0.3       | 0.1      |
| Elongation ratio                      |          | 0.4               | 0.6    | 0.6    | 0.3            | 0.5            | 0.6                    | 0.6             | 0.4      | 0.6       | 0.4      |
| Side of the equivalent rectangle      | Km       | 33.8              | 16.4   | 22.2   | 38.6           | 53.8           | 40.8                   | 57.2            | 81.4     | 61.0      | 20.8     |
| Smallest side of equivalent rectangle | Km       | 4.1               | 5.8    | 3.9    | 3.1            | 6.3            | 7.1                    | 9.1             | 9.3      | 8.5       | 2.7      |
| Average slope of the main river       | %        | 0.4               | 9.2    | 1.1    | 6.9            | 0.4            | 0.6                    | 4.0             | 0.8      | 0.4       | 5.3      |
| Drainage Density                      | Km/km2   | 1.4               | 1.2    | 1.0    | 1.2            | 1.2            | 1.3                    | 1.0             | 1.1      | 1.2       | 1.6      |
| Runoff Average Extension              | Km       | 0.2               | 0.2    | 0.2    | 0.2            | 0.2            | 0.2                    | 0.2             | 0.2      | 0.2       | 0.2      |
| Torrentiality coefficient             | Rios/km2 | 0.9               | 1.1    | 0.8    | 0.9            | 1.0            | 0.9                    | 0.8             | 0.8      | 0.9       | 0.9      |
| Mass Coefficient                      | M/km2    | 0.7               | 48.4   | 3.5    | 13.8           | 0.8            | 0.5                    | 4.1             | 1.7      | 0.5       | 54.6     |
| River stability constants (C)         |          | 0.7               | 0.9    | 1.0    | 0.8            | 0.8            | 0.8                    | 1.0             | 0.9      | 0.8       | 0.6      |
| Density (Dc)                          |          | 1.0               | 0.8    | 0.7    | 0.8            | 0.8            | 0.9                    | 0.7             | 0.7      | 0.8       | 1.1      |
| Slope                                 | %        | 5.1               | 35.3   | 4.1    | 25.4           | 4.2            | 3.7                    | 31.1            | 18.9     | 5.0       | 12.2     |

#### 4.2.2 Correlation matrix of the catchment parameters

Figure 4-1 shows the matrix correlation analysis for the full set of parameters of the catchments. The bar scale to the right-hand side represents the r-value from -1 to 1, and the size of the coloured dots represents how strongly the parameters are correlated. The graph indicates that 15 out of 23 parameters are highly positively or negatively correlated ( $r > 0.8$  and  $r < -0.8$ ) with at least three other parameters. The high number of parameters that are highly correlated indicates the dominant influence of some key variables such as the area, perimeter and river length on the empirical equations used to calculate some of the parameters. The matrix correlation also shows six parameters (i.e. slope, average width, compass index, form factor and elongation ratio) that are correlated with one or two other parameters. The other two parameters - Torrentiality Coefficient and Mass Coefficient - are not highly correlated ( $r < 0.8$ ) with any other parameter.

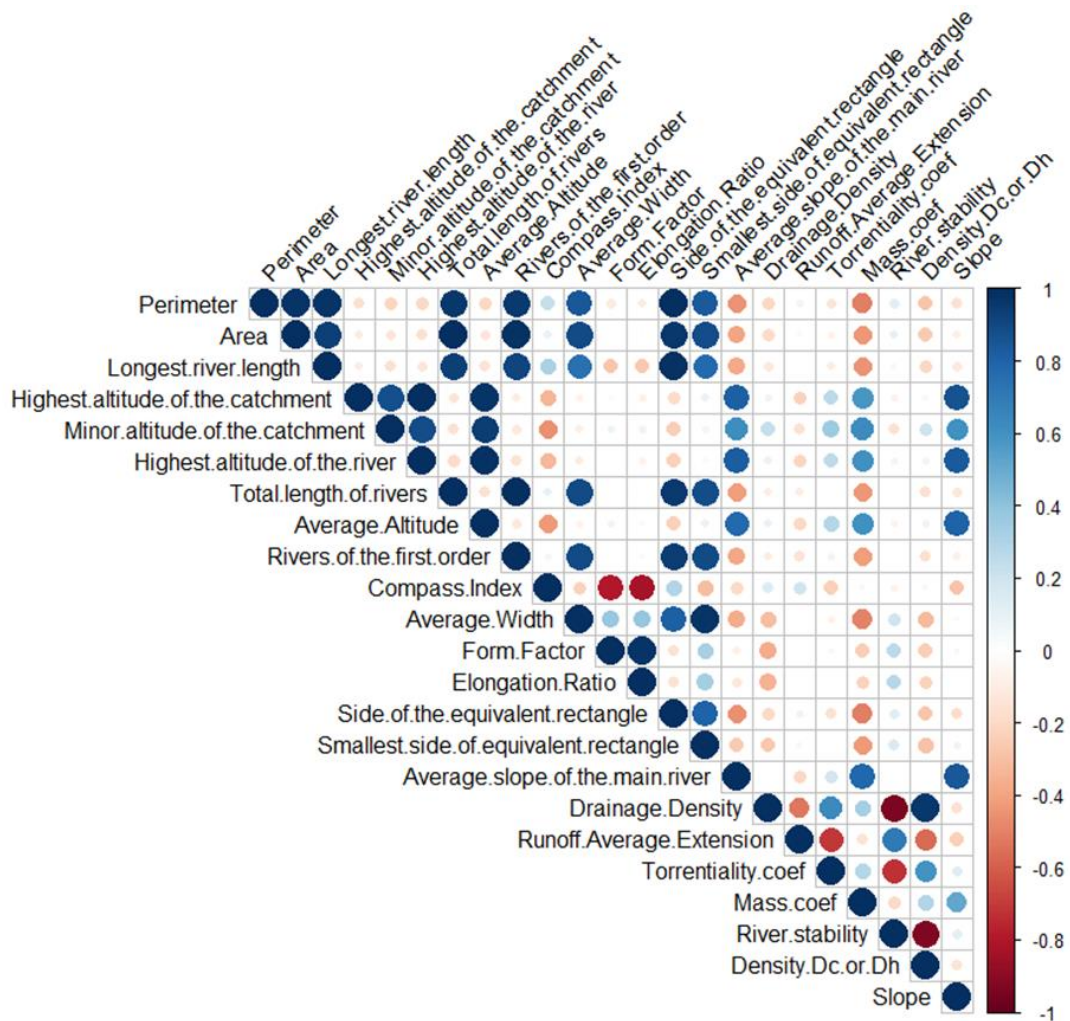


Figure 4-1 Pearson's correlation matrix of the full set of parameters of the catchments.

The correlation matrix analysis allowed the definition of a set of variables that are relevant for this study and that are not highly correlated with each other. Table 4.2 shows the eight variables that were selected based on this analysis, which are not highly correlated to each other ( $r < 0.8$ ). Figure 4-2 shows the Pearson's correlation matrix of selected catchment parameters. There are two exceptions, the compass index and the form factor are highly correlated ( $r = -0.82$ ), as are the area and average width ( $r = 0.89$ ) but, in these cases it was decided to retain both variables because they were not highly correlated to any of the other eight variables, and all four variables were felt to offer potentially important insight into the hydrological responses of catchments.

Table 4.2 Selected parameters from Pearson's correlation analysis.

| <b>No</b> | <b>Selected<br/>Parameters</b> |
|-----------|--------------------------------|
| 1         | Area                           |
| 2         | Compass Index                  |
| 3         | Average Width                  |
| 4         | Form Factor                    |
| 5         | Drainage Density               |
| 6         | Torrentiality<br>Coefficient   |
| 7         | Mass Coefficient               |
| 8         | Slope                          |

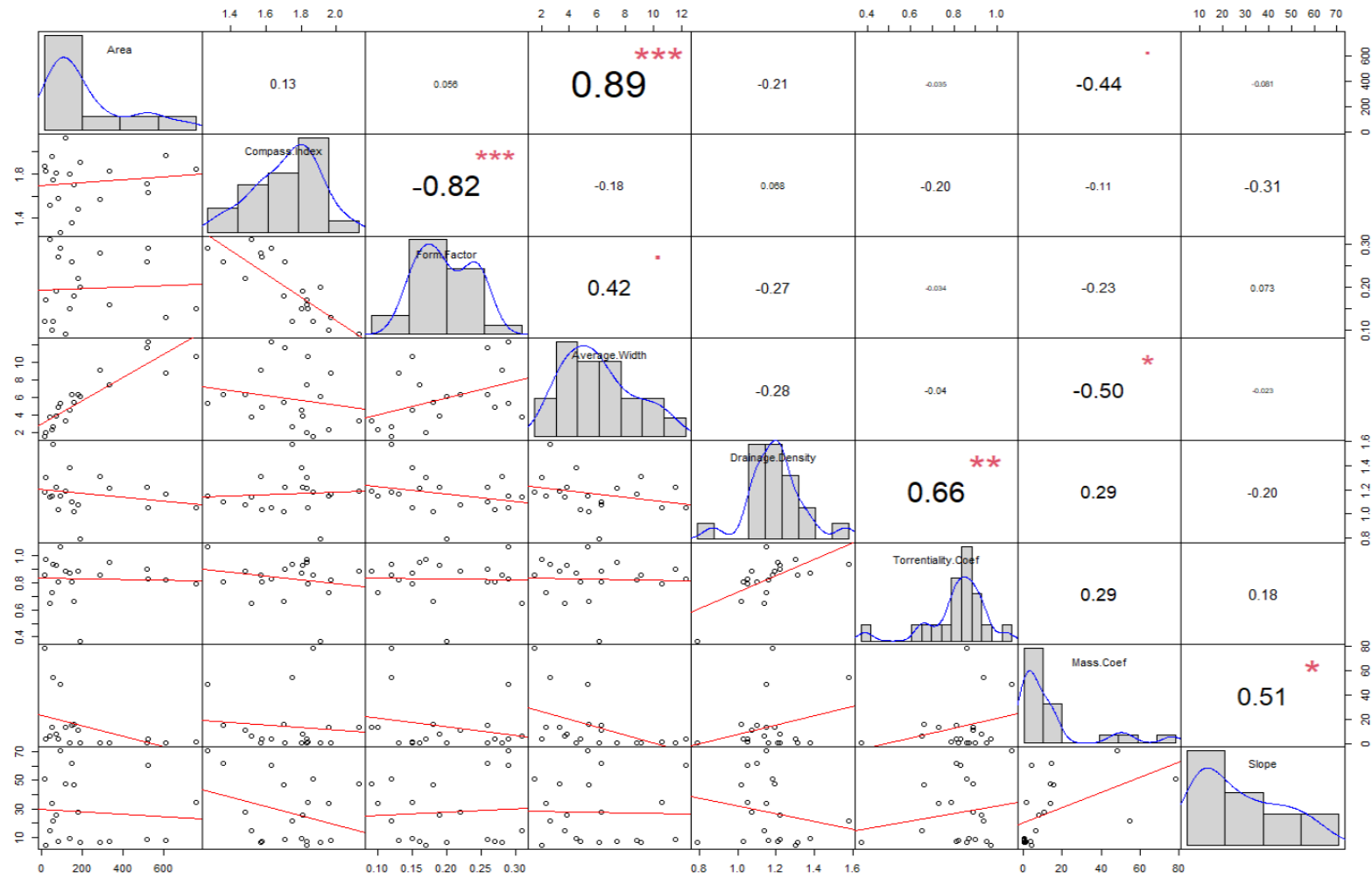


Figure 4-2 Pearson's correlation matrix of selected catchment parameters. The upper panel shows R values for all relationships and the lower panel scatter plot between variables including a linear regression. The diagonal represents the histogram of every single variable, which represents the frequency of the data as well as the Pearson distribution of this data.



### **4.3 Catchments pre-treatment**

#### **4.3.1 Methodology**

A cluster analysis was performed to classify the 20 catchments on the basis of a set of measured variables (e.g. morphometric and physiographic parameters). This is a multivariate analysis that can either merge (agglomerative) smaller clusters into large clusters or split (divisive) larger clusters into small clusters (Rao and Srinivas, 2006, Lin and Chen, 2006). The result is a clustering of the catchments into different groupings, such that similar catchments are placed in the same group. The analysis was performed for the sub-set of selected parameters as a result of the matrix correlation analysis, described above. Two cluster methods were used to perform the analysis, the hierarchal method and the non-hierarchal method, also known as k-means clustering. The Euclidean distance has been used to measure the distance between variables. The catchment parameters were standardized (converted to z-scores) avoiding variables with large magnitudes dominating the analysis. The Ward's agglomerative algorithm was used to calculate the distance between clusters and how much the sum of its squares increased when clusters merged (Szekely and Rizzo, 2005, Shalizi, 2009). In regards to the non-hierarchal method, the number of clusters had to set in advance (Rao and Srinivas, 2006, Peterson, 2002), so this number was specified depending on the results from the hierarchal method. The analysis was performed in SPSS, version 25.0.0.1 (Ibm, 2017). The cluster analysis was used to perform model sensitivity tests later in this chapter (section 4.4).

A principal component analysis (PCA) was also undertaken to analyse the interrelationships among all parameters and catchments. The PCA reduces the dimensionality of the data while gathering most of the information about the variables (Ringnér, 2008). Thus, the analysis was made to explain these variables in terms of a smaller number of variables that are normally called principal components with the minimum loss of information.

#### **4.3.2 Classification of catchments by physiographic and morphometric variables (Cluster analysis)**

Figure 4-3 shows the hierarchal analysis performed for the selected group of eight variables for each catchment. The graph in the left-hand side is the cluster analysis performed with no standardization and the graph on the right-hand side is the

analysis with standardized variables. The cluster analysis clearly shows that standardization has a substantial influence on the cluster analysis results. Peña (2013) and Castellarin et al. (2001) point out that the lack of standardization might cause inconsistencies in the cluster solutions. The non-standardized parameters have two groups; one of these contains 11 catchments grouped with the same weight, which might indicate that the analysis is influenced by a factor such as the scale of parameters. This result was expected, as it is well known that in this type of analysis, variables with higher units tend to dominate over the others (Milligan and Cooper, 1988). For instance, the range of values of the catchment area extends from 17 to 970 km<sup>2</sup>, whereas the Form Factor values only ranges from 0.5 to 1. Therefore, such differences in the values scale influence the results when the analysis is performed.

In regards to the hierarchal cluster analysis with standardized values, there are three main clusters, with 8, 5 and 7 catchments in each. This indicates that these groups have similar characteristics in terms of their hydrological features. However, the analysis is subjective in the respect that those three groups could be subdivided into smaller groups. It is reported that there is not an unique solution for particular problems, as it might vary depending on the agglomerative method used (Gallardo, 2011). Although clustering algorithms are effective identifying patterns in both large and small datasets (Rao and Srinivas, 2006), it is suggested that hierarchal clustering provides good responses when the data set is less extensive (Lin and Chen, 2006). The dendrogram plot is showing not only which data (catchments) were joined at each point but, also the distance between clusters when they merged together (X-axis). The number of clusters could be subjective as mentioned above but, alternatively clusters can be chosen based on a threshold dissimilarity.

In regards to the non-hierarchal cluster analysis, this was set up in advance with three clusters based on the results of the hierarchal analysis. Table 4.3 shows the results of this analysis performed by the K-means method. The most evident fact is that the groups are not equally distributed in terms of the number of catchments. For instance, three catchments are isolated from the others (e.g. Berajevska, Dinin and, Trent), which also belong to the same cluster in the hierarchal analysis. With respect to the other clusters, there is one large cluster containing ten catchments and another with seven catchments. If the three isolated catchments mentioned above are chosen as an independent cluster in both analyses (hierarchal and non-hierarchal), the remainder clusters totally match indicating that these catchments are more distinct from the other 17

catchments, than the differences within these 17 catchments. It is reported that the biggest issue with K-means algorithm is that results depends on how many clusters have been set (Gülagiz and Sahin, 2017), three in this case. Thus, the non-hierarchical analysis was also performed using four clusters to assess the sensibility of the method but results showed a completely different set of catchments with no relation with the hierarchical analysis.

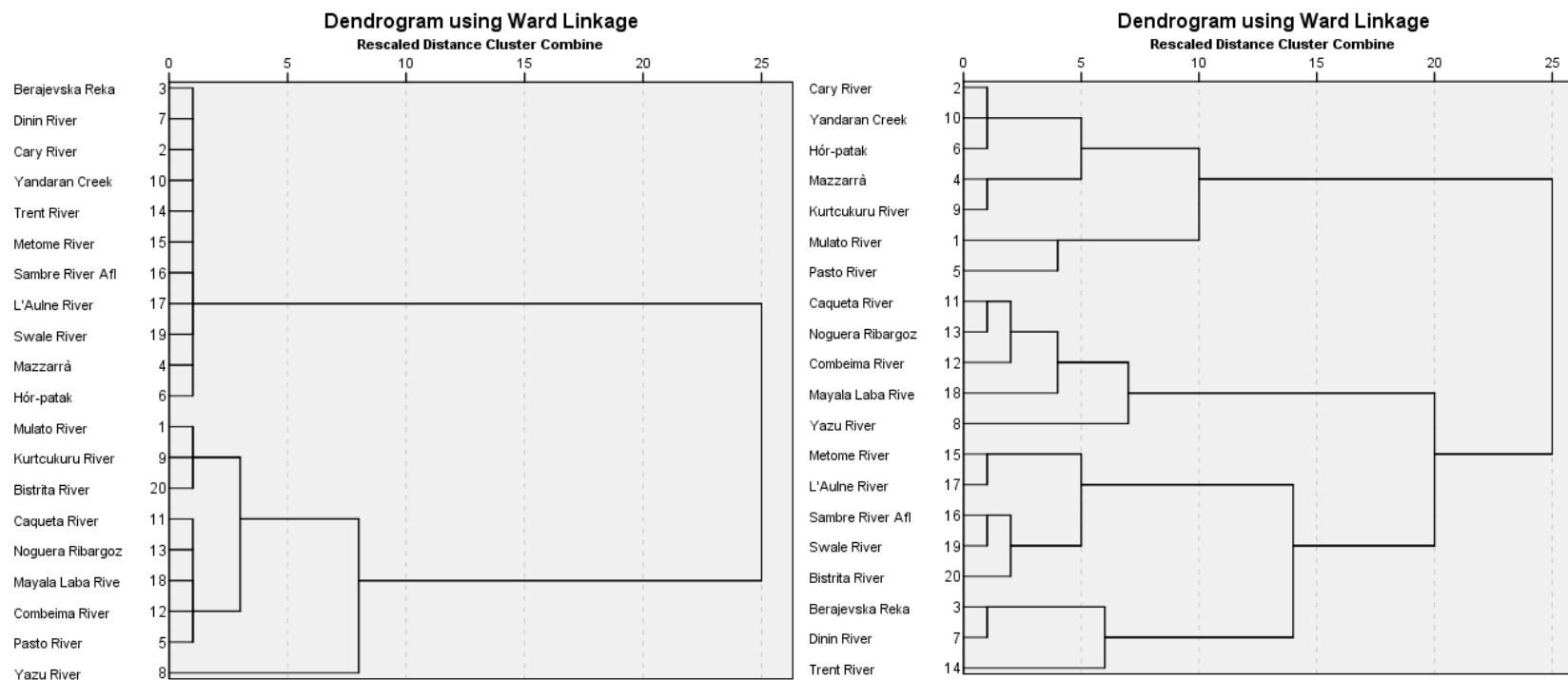


Figure 4-3 Hierarchal analysis using the full range of catchment parameter. To the left side, the analysis with non-standardization and to the right parameter values standardized.

Table 4.3 Non-hierarchical cluster analysis K-means for selected variables.

| <b>Cluster Membership</b> |                           |                |
|---------------------------|---------------------------|----------------|
| <b>Case Number</b>        | <b>Catchment</b>          | <b>Cluster</b> |
| 1                         | Mulato River              | A              |
| 2                         | Cary River                | A              |
| 3                         | Berajevska Reka           | B              |
| 4                         | Mazzarrà                  | A              |
| 5                         | Pasto River               | A              |
| 6                         | Hór-patak                 | A              |
| 7                         | Dinin River               | B              |
| 8                         | Yazu River                | C              |
| 9                         | Kurtcukuru River          | A              |
| 10                        | Yandaran Creek            | A              |
| 11                        | Caqueta River             | C              |
| 12                        | Combeima River            | C              |
| 13                        | Noguera Ribargozana River | C              |
| 14                        | Trent River               | B              |
| 15                        | Metome River              | C              |
| 16                        | Sambre River Afluent      | C              |
| 17                        | L'Aulne River             | C              |
| 18                        | Mayala Laba River         | C              |
| 19                        | Swale River               | C              |
| 20                        | Bistrita River            | C              |

In defining the clusters of catchments, different input hydrological parameters may have a difference weighting i.e. a different significance in controlling the resultant clusters. This can be explored with topology maps (Toth, 2013). Figure 4-4 is a topology map created using the K-means analysis, which indicates the variability in the weight of the variables used to explain the clusters. For example, the average width and form factor have the greatest weighting in cluster A whereas the torrentiality coefficient and drainage density are most important in cluster B. As for the cluster C the average width and area seem to be the most relevant variables. These results suggest that there are consistent hydrological signatures that determine these groups of catchments and it is worthwhile to analyse these separately for each cluster.

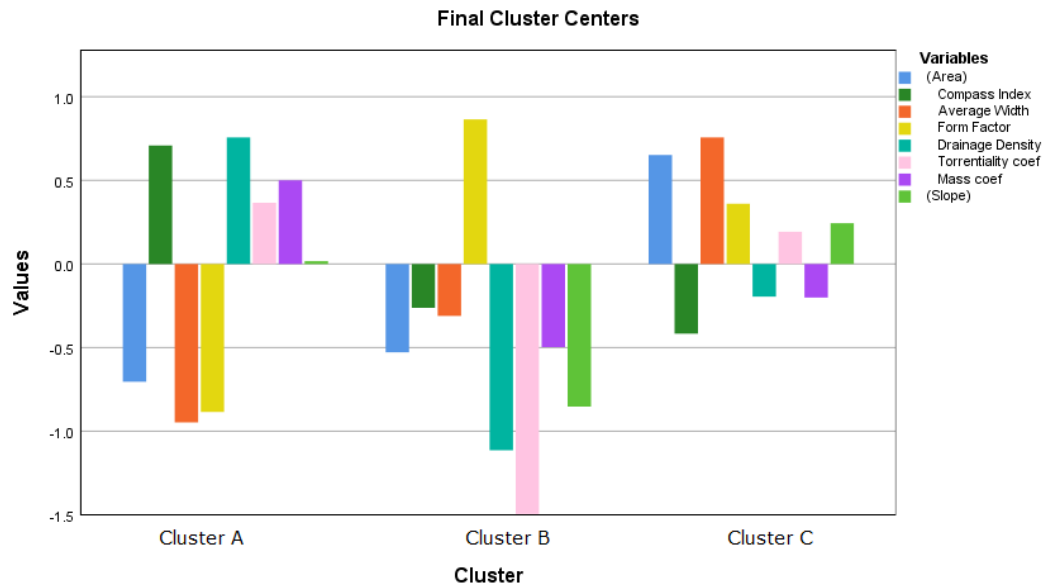


Figure 4-4 Topology map of the weight of the variables used in the k-means cluster analysis.

Besides the topology map, the results shown in the Figure 4-1 also indicate particular patterns of the catchments, for example, cluster A is driven by area and average width with the highest correlation,  $r = 0.9$ . This particular group has smaller sized, more elongated catchments than the rest. Form factor is another important variable in Cluster B and C, with smaller values indicating more elongated catchments with small peak flows of longer duration (Horton, 1932). Likewise, the form factor in cluster A has larger values, meaning catchments in this group are more rounded with larger peaks of shorter duration. Mass coefficient provides a sense of the slope with low values representing flat catchments, such as in cluster B, whereas high values are more related to steeper catchments, as in cluster A. The torrentiality coefficient is the main driver in cluster B where catchments have small values, leading to low peak flows. Finally, in cluster C average width is the main driver and, interestingly, is opposite to cluster A, indicating catchments that are less rounded with shorter peak flows. The torrentiality coefficient is an indicator of linear erodability and discharge capacity of catchment, thus high values indicate high susceptibility to erosion, shorter time to peak and high torrentiality (Busnelli and Horta, 2014).

Taking confidence from the results in these analyses using both hierarchal and non-hierarchal methods, three main clusters can be defined, as shown in Figure

4-5. Even though catchments can be grouped by using either hierarchal or non-hierarchal the final clustering is a hybridization of both methods. A study conducted by Rao and Srinivas (2006) investigating regionalization of catchments in Indiana USA, found that from a range of hybrid-clustering methods, Ward's and K-means algorithms provides good estimates of groups of catchments. These final three groups capture the differences between catchments based on their morphological and physiographic parameters. Therefore, these groups or clusters will be also used in Chapter 5, 6 and 7 analysing the effect of cluster classification on peak flow for a range of NFM configurations and set of intensities. This analysis will allow an understanding of the effect of particular morphometric and physiographic features of the catchments in hydrological responses. Clusters will also be used to perform the sensitivity analysis in the next section (model set up).

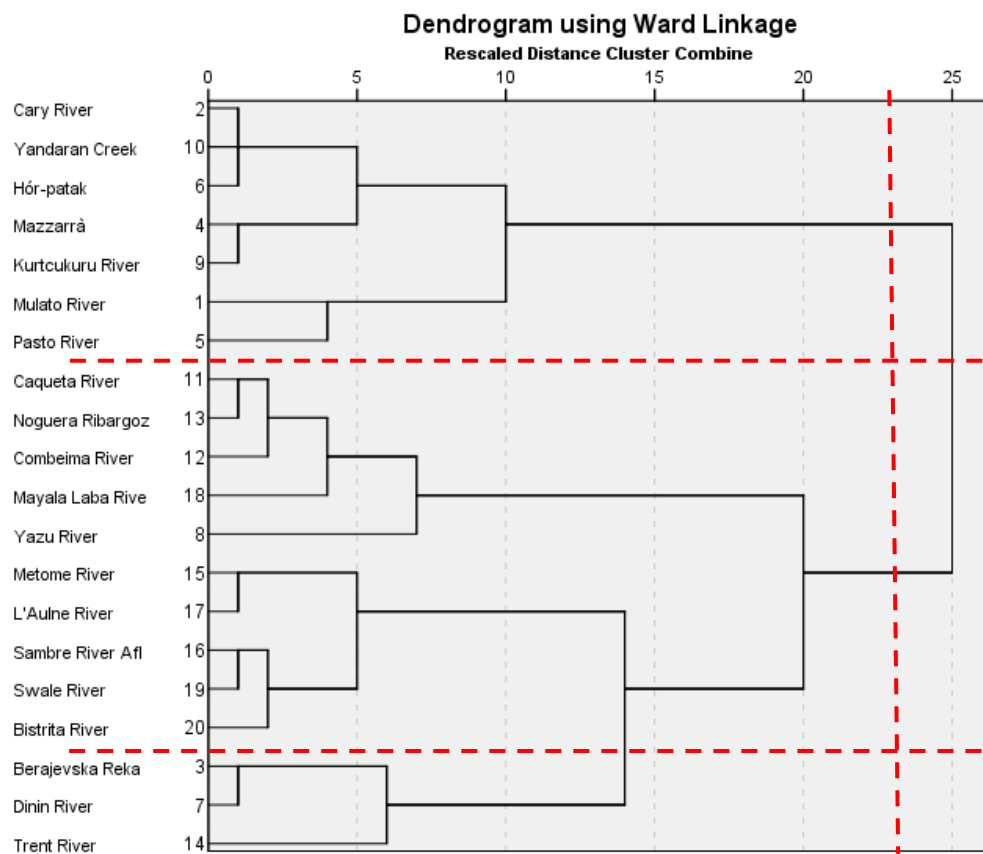


Figure 4-5 Hierarchal analysis with the final cluster of the catchments.

### 4.3.3 Principal component analysis (PCA)

The component analysis helps to interpret differences and similarities between catchments, with variation in the dataset registered by the principal components through linear combinations of the variables (Toth, 2013). The PCA analysis indicates that the four principal components explain 90.9% of the total variance in the dataset analysed (the selected parameters) (Table 4.4). It is expected that a minimum number of components gather the maximum variability (Ringnér, 2008). The first component captures 32.7% of the variability of the data, which also represent the component with the greatest variance. The second component captures 26.8% of the variability of the data, having a cumulative percentage of 59.5% of all information in both components.

Table 4.4 Summary of principal component analysis.

| <b>Axes</b>                            | <b>1</b> | <b>2</b> | <b>3</b> | <b>4</b> | <b>Total Variance</b> |
|----------------------------------------|----------|----------|----------|----------|-----------------------|
| Eigenvalues                            | 0.327    | 0.268    | 0.167    | 0.148    | 1.000                 |
| Cumulative percentage variance of data | 32.7     | 59.5     | 76.1     | 90.9     |                       |

Figure 4-6 shows the PCA for the 20 catchments and selected parameters. The x-axis is the first principal component and the y-axis is the second principal component. The red vectors on the graph are the selected parameters and their angle and magnitude indicates how strong the relationship is between the variables/parameters. The first component indicates that there is a group of catchments that are more related to each other and are positively associated with the slope, and negatively with the average width and the area. This supports the topology map (Figure 4-4) where the weight of the variables is shown for the creation of the clusters. Despite being in opposite quadrants, the form factor and the compass index are highly correlated, suggesting that when the form factor increases the compact index decreases, also shown in the topology plot as well.

Perhaps most interesting in the PCA analysis is the group of catchments (L'Aulne, Bistrita, Dinin, Berajevska, and Metome) that are highly related to the average width and area; therefore, most of the variance is explained by these two variables in the first component. This supports the matrix correlation analysis performed above, where average width and area have a high correlation of ( $r < 0.8$ ) (Figure 4-2).



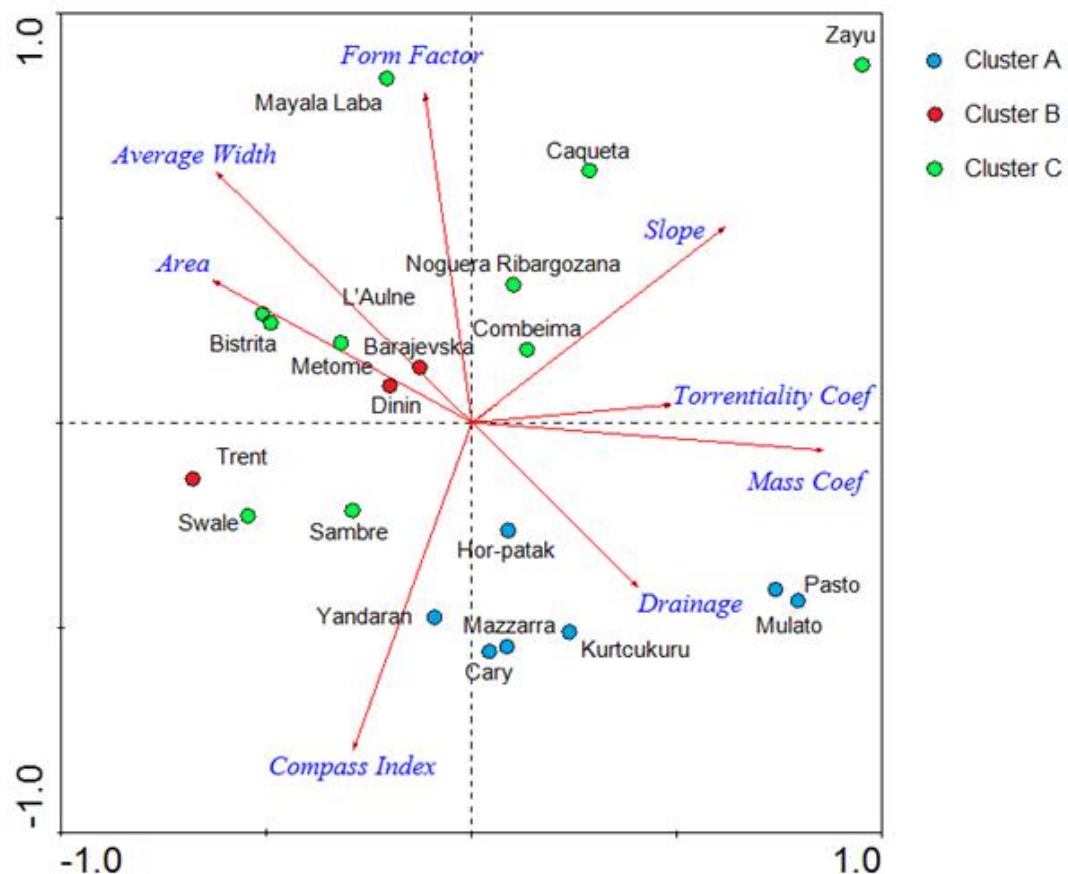


Figure 4-6 Principal component analysis PCA for the set of 20 catchments and the selected parameters. Catchments have been coloured according to final cluster classification (see Figure 4-5).

#### 4.4 Model sensitivity analysis

##### 4.4.1 Overview of the sensitivity analysis

This section addresses how the IBER model was configured and the determination of the format of input data necessary for model set up. This analysis aimed to maximise the efficiency of the model, in terms of computational time, whilst not significantly degrading the accuracy.

In IBER, the computational time mostly depends on the area of the study case (e.g. catchment area) and the DEM resolution. To achieve an optimum computational time without losing information, two different sensitivity tests were undertaken. The first test looked at the effect of the element size of the DEM mesh on the computational time and the output hydrographs, specifically the peak flow and lag time values. The second test looked at the effect of changing the time

interval (step time) on total computational time, as well as the peak flow and lag time outputs. An additional test was made to assess the effect of a refined mesh along the main river drainage network on hydrographs. The sensitivity analysis was undertaken using a subset of the catchments as a result of the cluster analysis made in section 4.3.2, listed in Table 4.5.

Table 4.5 Catchments selected for the sensitivity analysis.

| Catchment   | Sensitivity test |           |
|-------------|------------------|-----------|
|             | Mesh Size        | Step time |
| Italy       | X                |           |
| Pasto       | X                | X         |
| Kurtcukuru  |                  | X         |
| Mayala Laba | X                | X         |
| Metome      |                  | X         |
| Berajevska  |                  | X         |
| Dinin       | X                | X         |

The hydraulic and hydrological parameters mentioned in section 3.5 were set-up in the model with a unimodal, left-skewed hyetograph with an intensity of 60 mm\hr (Figure 4-7). The Manning's n value used across the entirety of all catchments was 0.035, representing pasture with high grass. The river network had a manning's n value of 0.04, representing a gravel-bedded, meandering stream. Boundary conditions were set up as described in section 3.5.2 and were kept consistent across all catchments and scenarios.

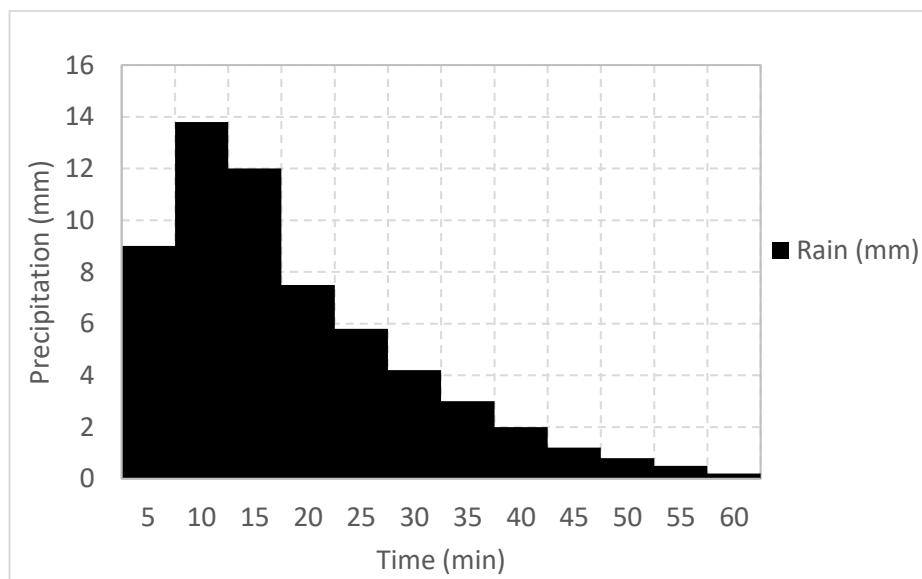


Figure 4-7 Hyetograph for the unimodal left-skewed distribution (UHL). Accumulated rain of 60 mm in 1hr.

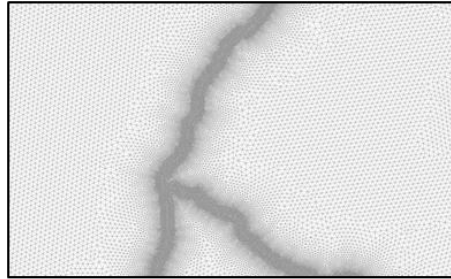
#### **4.4.2 Mesh-size sensitivity analysis methods**

Two mesh sensitivity tests were conducted to understand the effect of the element size on the computational time, flood peak and lag time of the hydrograph. This analysis allowed a determination of which element size best suits the modelling aims of this research. As mentioned above, this research used a DEM with a minimum pixel resolution of 10 m x 10 m, which in particular cases might not provide enough detail to represent relevant morphology clearly. In contrast, a 10 m resolution might be unfavourable, particularly for large catchments, due to the large number of elements that could increase computational time significantly.

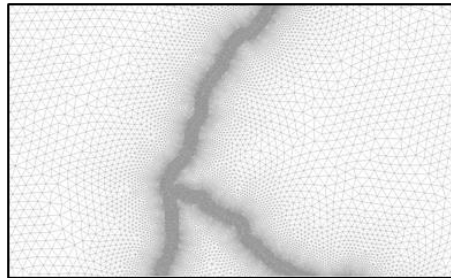
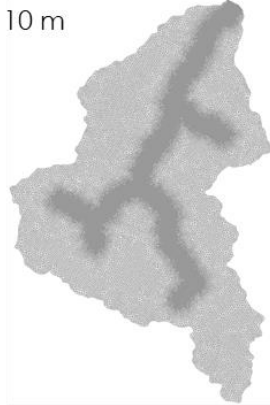
The first test was performed by setting up three scenarios with different mesh element sizes in the selected catchments. A buffer of 200 m was created in each catchment along the main river drainage system to define a minimum element size resolution of 10 m. The mesh element size outside the buffer varied between 100, 200, and 300 m, respectively (Figure 4-8). Pasto, Mayala Laba and Dinin catchments were used to run this test (Table 4.6). To analyse the effect of the element size on the computational time, the final time that IBER took to perform the scenarios were used and compared between scenarios. The output hydrographs were calculated and compared to assess the effect of such element sizes on the flood peak and lag time. All scenarios were designed with an unstructured mesh in IBER.

**Element size**

- Main river network (buffer 200m): 10 m
- Catchment: 100 m
- Elements: 430138

**Element size**

- Main river network (buffer 200m): 10 m
- Catchment: 200 m
- Elements: 364510

**Element size**

- Main river network (buffer 200m): 10 m
- Catchment: 300 m
- Elements: 355668

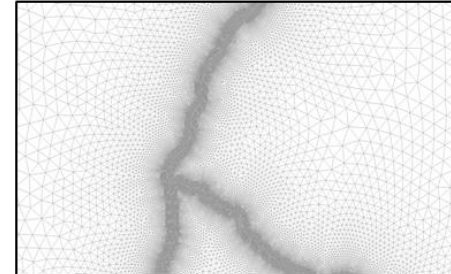
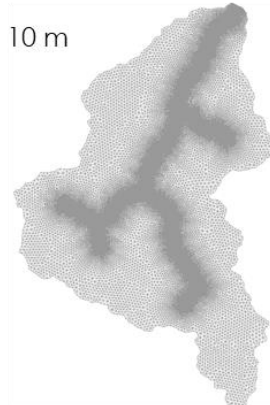


Figure 4-8 Modelling test by using different element sizes. Dinin catchment, area 527 km<sup>2</sup>.

Table 4.6 Area and size classification of the catchments used to perform the mesh size test.

| Catchment   | Area  | Size Classification |
|-------------|-------|---------------------|
| Pasto       | 56.3  | Micro-Catchment     |
| Dinin       | 85.6  | Micro-Catchment     |
| Mayala Laba | 522.7 | Small-Catchment     |

The second analysis specifically assessed the effect of the inclusion of a river channel on flood hydrographs and analysis time. When the minimum pixel size is 10 m, a channel cannot be discerned in the 20 catchments used here. To understand the potential significance of this, a channel was created with a 2 m resolution mesh for the Mazzarrà catchment (Figure 4-9). The hypothetical channel was created according to hydraulic geometry relationships, which relate the area of the upstream catchment to the depth and width of the channel with power laws (Thornton et al., 2007). Only the channel of the main river in the catchment was constructed, determined using maps of the river and flow accumulation layers. The software AutoCAD was used to design the channel and then exported and added into IBER. A buffer along this river channel was created to keep the resolution of the DEM at its finest (10 m). Outside this buffer area, the element size of 100 meters was used. This scenario was then compared to the same scenario without a channel.

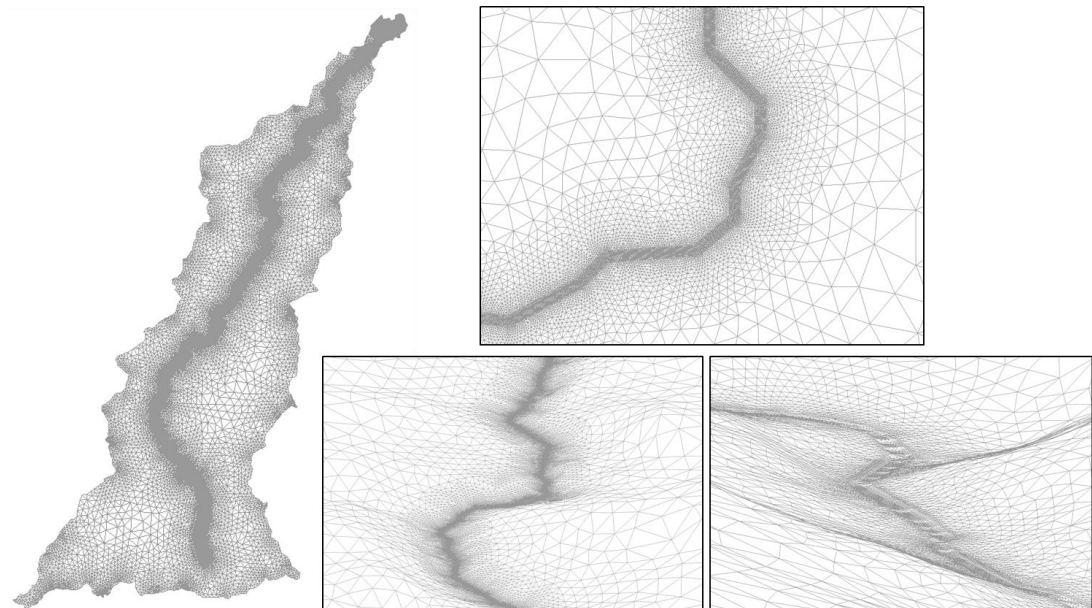


Figure 4-9 Hypothetical channel test. Catchment area and top and 3D views of the Mazzarrà catchment (54.8 km<sup>2</sup>) showing the refined mesh of a hypothetical channel along with the main drainage system of 2-meter element size resolution. A buffer of 200m along the main river with a resolution of 10 meters and 100 m element size in the area outside the buffer (catchment domain).

#### **4.4.3 Mesh size sensitivity modelling results and discussion**

The hydrographs obtained from the first mesh size modelling test with different mesh element sizes are shown in Figure 4-10. It is clear that visually, the three hydrographs representing mesh sizes of 100, 200 and 300 m are similar, with similar peak flow and lag time data for all three catchments. The Mayala Laba catchment shows the biggest differences between hydrographs for the three mesh sizes, with a noticeable increase in peak flow as mesh size decreases (i.e. resolution increases). These results are likely to be related to the scale of the catchments because Mayala Laba is almost 10 times larger than Pasto and 8 times larger than Dinin (Table 4.6). Hooijer et al. (2004) state that hydrological responses in large catchments have to be carefully analysed, as there could be some negative effects due to the scale. However, these effects might be more relevant when the resolution of the mesh is coarse due to catchment scale. In this case, some attenuation of peaks flows in areas not well represented by the mesh could be misrepresented in large catchments (Gupta and Dawdy, 1995).

Differences between the 100, 200 and 300 m scenarios are small - less than 1% for Pasto and Dinin but, is 3.5% between the 100 m and 200 m element sizes in Mayala Laba, and 8.2% between 100 m and 300 m. Such differences could be important considering the significance of the discharge peak to understanding the hydrological regime, and as a focus for NFM.

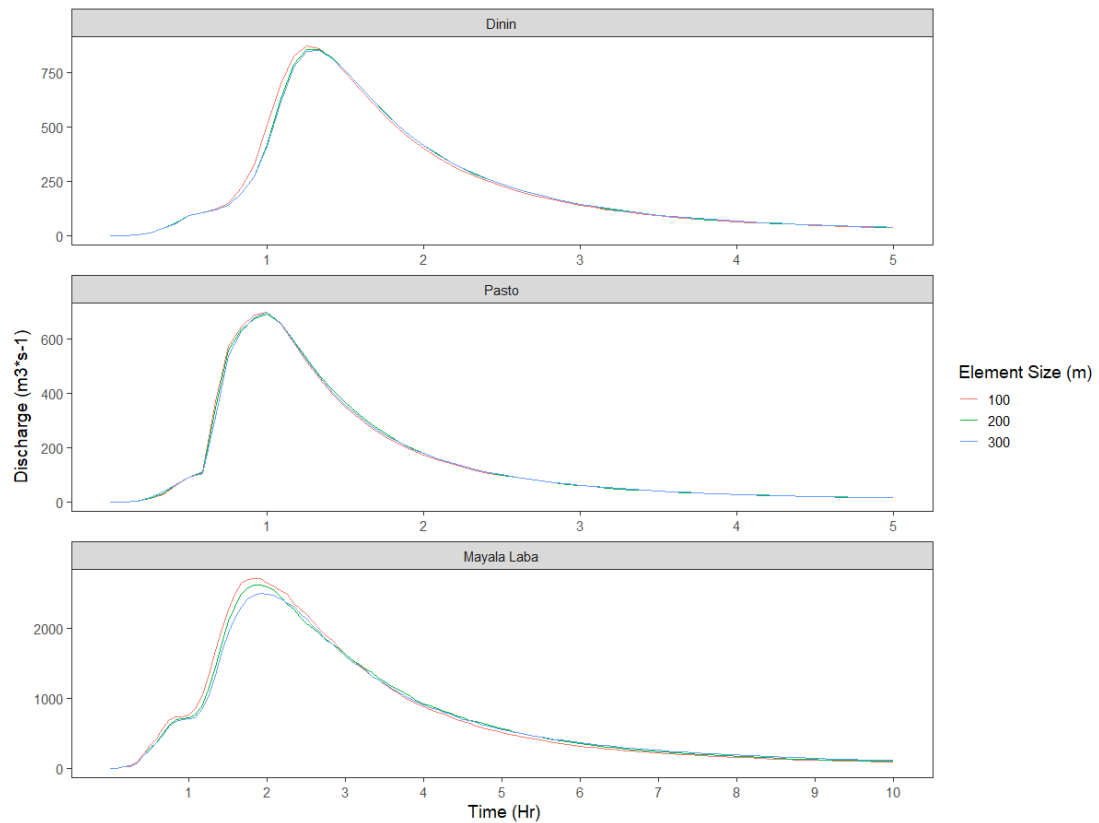


Figure 4-10 Output hydrographs from the size test with different mesh element size under a 60 mm/h rainfall event. a) Pasto catchment b) Dinin catchment c) Mayala Laba catchment.

Overall, these results indicate that there could be an underestimation of the peak discharge when there is an increase of the mesh element size, which is more evident in bigger catchments than smaller ones. To better understand this issue, the element size test was repeated for the Swale catchment, which has a similar catchment area to Mayala Laba. It can be seen from the hydrographs in Figure 4-11 that all three scenarios have the same shape, but differences between peak flows are approximately 3% between 100 and 300m element sizes. These are not as high as for the Mayala Laba catchment but, still elevated over the smaller catchments. This elements size scenario also identifies some instabilities at the beginning of the hydrograph which might be caused by the relatively short spin-up period of 1 hour, which may not have been sufficient in the largest catchments for the model to fully stabilise (Figure 4-11). However, the instabilities do not affect the performance of the model or the rising and falling limbs of the hydrographs.

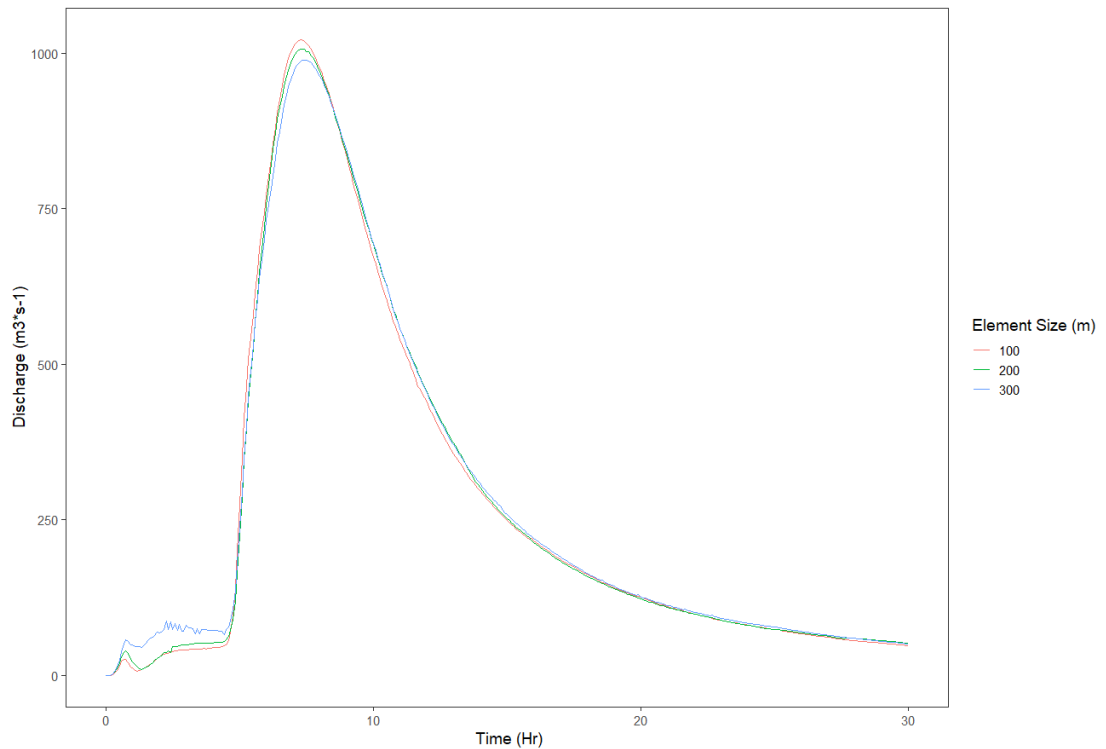


Figure 4-11 Output hydrographs from the size test with different mesh element size under a 60 mm/h rainfall event (e.g. Swale catchment).

The computational time for different mesh sizes are presented in Figure 4-12. For example, the Pasto catchment performs 16% faster using 200 m element size compared to 100 m, and a 36% faster with 300 m resolution. In contrast, the computational time saved for Mayala Laba is proportionately less compared to the other catchments. The largest element size performs 14% faster than the finest, and 9% faster than the intermediate. However, the larger catchment has a higher total computational time saved, and it is this that is more significant to the logistics of the modelling approach. This suggests that mesh element size for micro-catchments could be set with the finest element size (100 m) as the differences in computational time are not significant; however, the finest mesh size would be disadvantageous for large catchments due to the computational time.



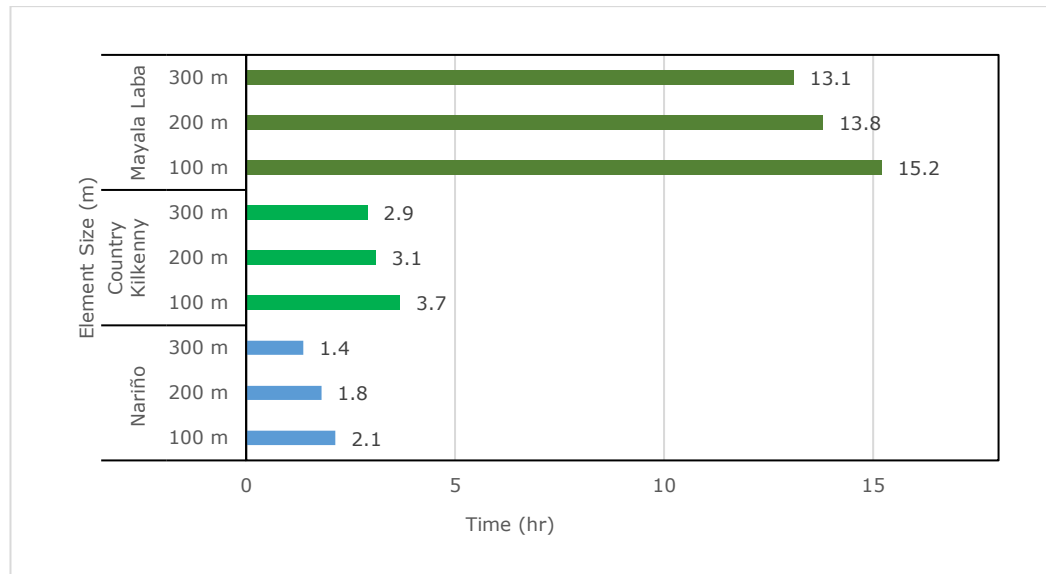


Figure 4-12 computational time for the mesh size test.

The sensitivity test that included a hypothetical channel showed slight differences in the peak flow between scenarios. Figure 4-13 shows the output hydrographs obtained from IBER for both scenarios. The shape of both hydrographs is similar but the peak flow with a channel is  $40 \text{ m}^3 \text{ s}^{-1}$  greater than with no channel ( $< 5\%$  different). The lag times are almost identical with a 5 minute time step. A bigger difference between these options is the computational time. Using the refined mesh with a hypothetical channel increases the computational time from 1 hour and 24 minutes (scenario without channel) to 59 hours and 19 minutes. This is because the number of elements in the model, and therefore number of equations the model must solve, is significantly larger than without a channel. All models were run on an Intel® Xenon® CPU ES-1620 v4 @ 3GHz desktop computer with 32.0 GB installed memory RAM and a 64-bit operation system. The graphical board used is the NVIDIA NVS 310.

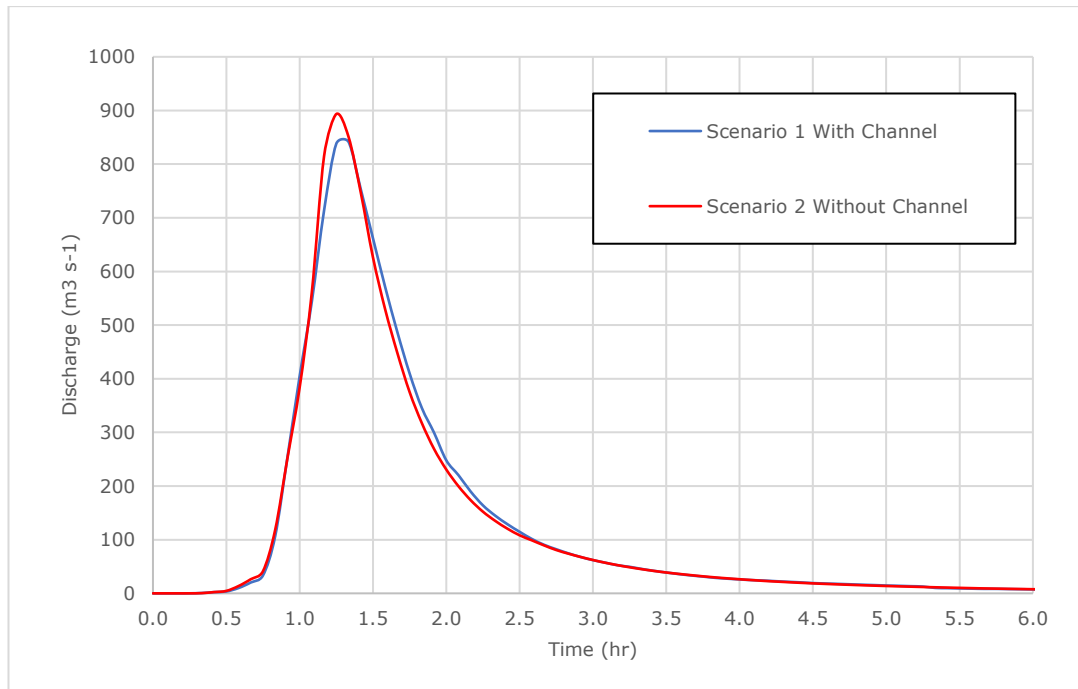
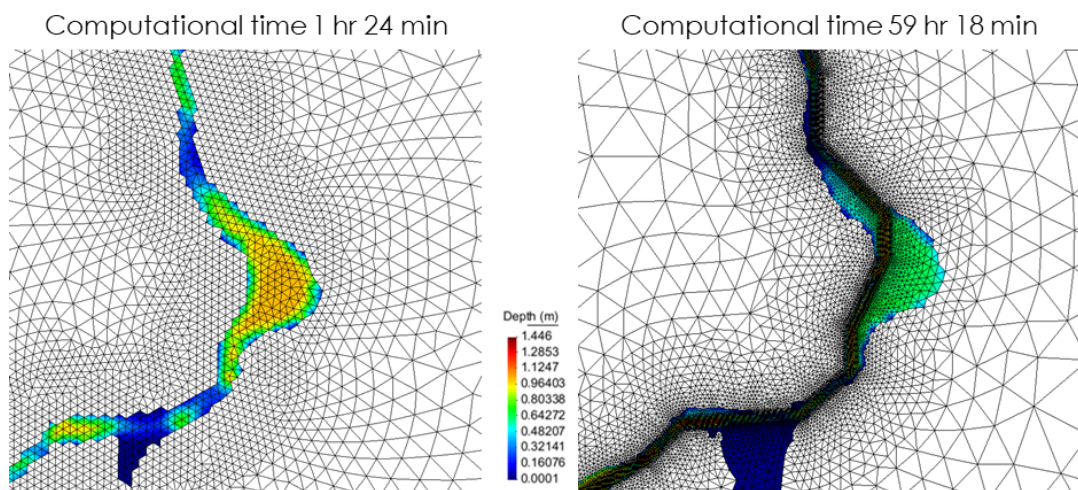


Figure 4-13 Output hydrographs obtained from the hydraulic and hydrological modelling within two different mesh resolutions (mesh with a hypothetical channel and minimum resolution of 2m (Right), and mesh with a minimum resolution of 12 m (Left) and under a rainfall scenario of 60 mm/h.

Together these results provide important insights into determining the best mesh element size for all catchments, which optimise the trade-off between time efficiency and data quality. It was not logistically feasible to run the models with a defined channel given the significant increase in computational time; however, this was not seen as a major limitation given the relatively small difference between modelling outputs with and without a channel. Similarly, element mesh

size within the catchment was not substantially different between 100 m and 200 m in any case tested (max. 3.5%). Therefore, all catchments had a 10 m element size along the main drainage system and micro-catchments had a 100 m element size for the remaining area of the catchment, whereas small-catchments and large-catchments both had a 200 m resolution in the rest of the catchment.

#### ***4.4.4 Time-step sensitivity analysis methodology***

The time step sensitivity analysis was undertaken to evaluate the performance of the model. The time step is the time interval used by the model to generate outputs, expressed in minutes. This test aims to understand how the time step influences the computational time and also the output hydrographs. This test was performed using 5, 10, 15 and 20 minute time step values. All hydraulic and hydrological variables, including the depth, velocity and rain depth were saved for each time step. The 5 minute scenario was the finest input and was, therefore, used as the baseline to which other time steps were compared. This test was performed with the same left-skewed hyetograph of 60mm in a period of an hour as used in section 4.4.1. Two catchments from each of the clusters identified in section 4.3.2 were selected to perform the test (Table 4.5). The results from this test (and those above focusing on mesh size) were used to set up the final model for all catchments. IBER was run for the full set of catchments and the computational time related to the area of each catchment.

#### ***4.4.5 Time step sensitivity analysis results***

Figure 4-14 shows the time step test performed in the six test catchments. As expected, the results show that smaller time steps result in a more detailed output hydrograph. This is particularly evident at the beginning of ascending limb, the peak flow and end of the descending limb, where hydrographs are visibly more rounded when the time step is shorter. This occurs because the longer time steps cannot accurately represent changes in gradient that are short in duration relative to the time step. These differences are more evident in smaller catchments, such as Pasto, Kurtcukuru, Dinin and Berajevska since the duration of events is shorter than larger catchments.

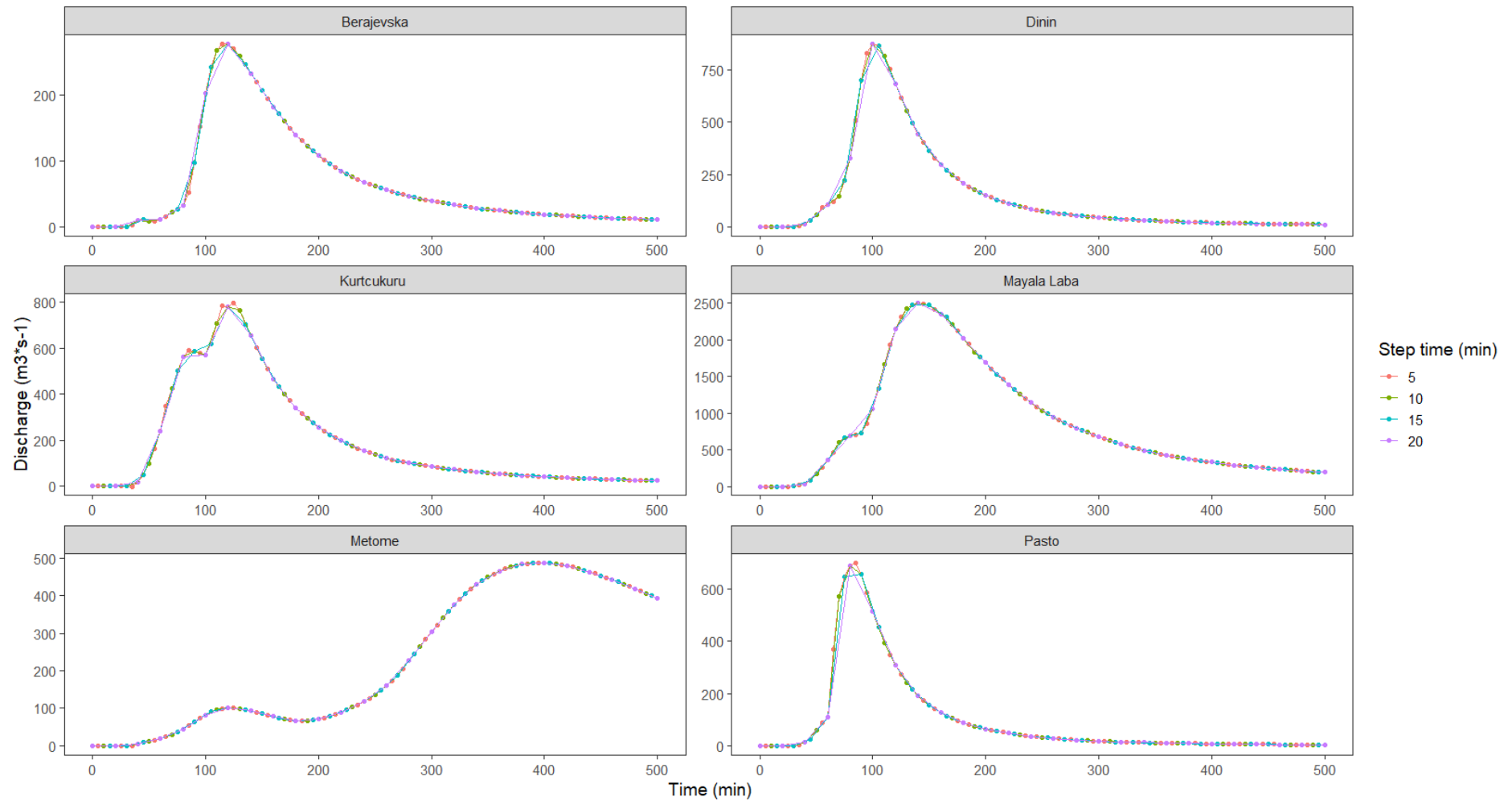


Figure 4-14 Time step test performed in six catchments. Time step values are 5 min, 10min and, 15min.

Although the resolution of the curve is affected by the time step, the difference in peak flow and lag time is minimal. Differences are more noticeable for smaller catchments but, do not exceed a 5% difference to the finest time step in any case. However, the trend shows that the differences do become larger as the time step value increases, particularly above 15 minutes. Increases in the time step value also have repercussions for the total volume of water produced by a rainfall event, since this is calculated hydrologically as the area under the hydrograph curve (Ward and Robinson, 1967, Shaw, 2005).

Increasing the time step did decrease the computational time for large catchments but made little difference for smaller catchments (Figure 4-15). For example, the increase in the computational time by choosing a smaller step time value (from 20 min to 5 min) is about 4% in Pasto Kurtcukuru but is 16% for Mayala Laba.

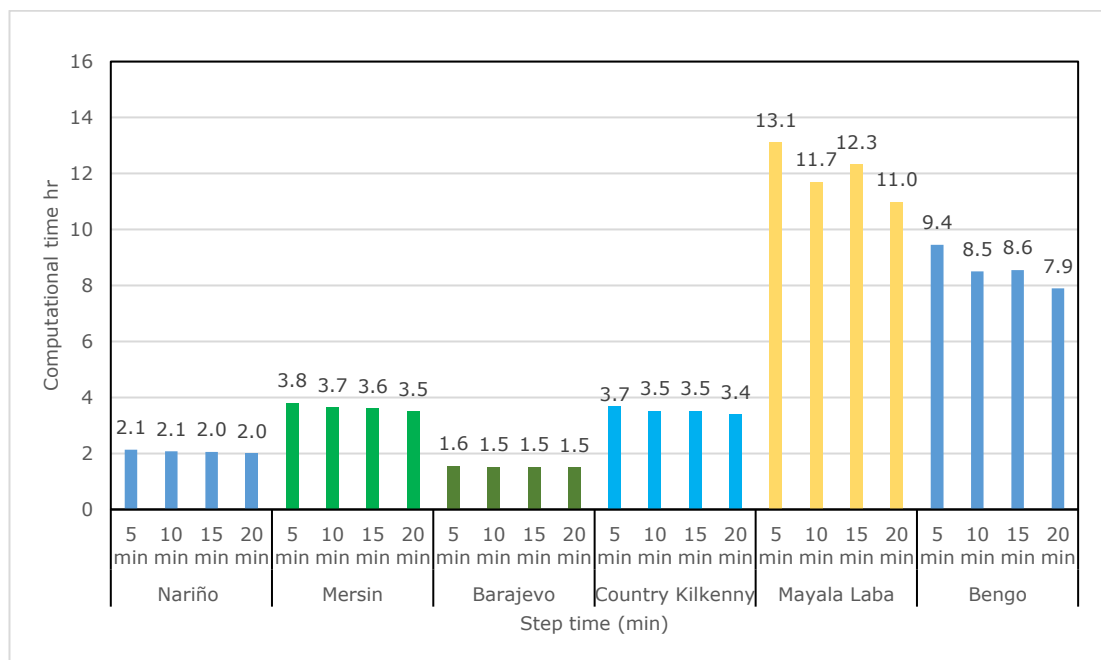


Figure 4-15 Computational time from the computational modelling of different step time values.

Given that hydrographs of larger catchments were relatively unaffected by changing time steps up to 20 minutes, but that computational time can be significantly reduced, it makes sense to use a longer time step. In contrast, in small catchments the time step makes little difference to the computational time but, a longer time step does notably degrade the resolution of the hydrograph. Therefore, in these cases it makes sense to use a shorter time step. As such, micro-catchments and small-catchments will use a time step values of 5 minutes and large catchments will use a time step of 20 minutes.

#### 4.4.6 Computational time for all catchments

The effect of mesh size and time step values on hydrographs and computational time has been assessed and used to optimise the final selection of input data for modelling. This final section of the chapter applies the IBER model, using this selection, for all 20 catchments and correlates the computational time spent modelling to the number of elements in the mesh covering the catchment. The results of the correlation analysis is shown in

Figure 4-16 and indicates, as would be expected, a strong positive correlation between computational times and number of elements in the mesh. A linear trend line has been adjusted to the data set to determine the correlation between both variables, showing a high correlation of  $R^2 = 0.8528$ . A single run took < 30 hours for the largest catchments using the time step and mesh sizes described above, which was deemed logistically feasible for the required modelling tasks.

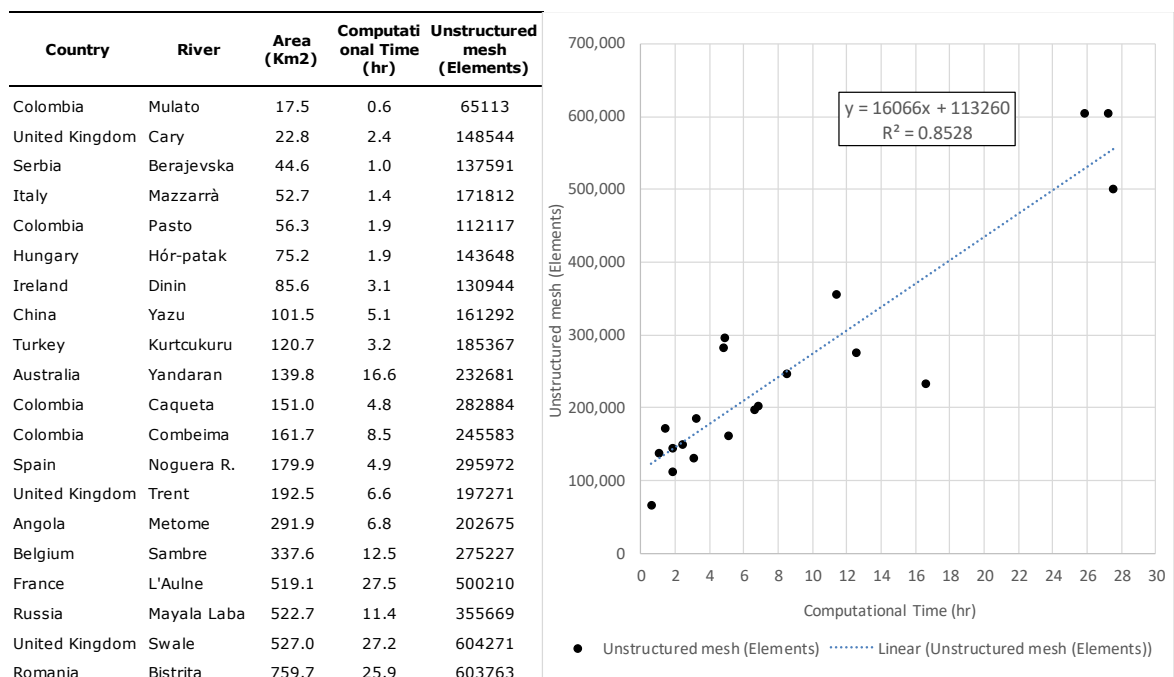


Figure 4-16 Non-structural mesh and computational time from the 2D computational modelling across all catchments. To the right, the scatter plot between no-structural mesh versus computational time.

## CHAPTER 5. EFFECT OF CATCHMENTS ON PEAK FLOW AND LAG TIME

### 5.1 Introduction

Floods are hydrological responses to hydrometeorological circumstances such as extreme rainfall, cyclones or thunderstorms (Villarini and Smith, 2010). Hydrological response depends on the rainfall event type and characteristics, such as the magnitude and the frequency of rainfall (Charlton, 2007, Ouarda et al., 2001, Feldman, 1979, Rao and Hamed, 2000). One of the principal indicators of hydrological responses is the hydrograph (Chow, 1988), which provides information about the volume and duration of a rainstorm and hydrological response, as well as the lag time between peak rainfall and peak flow (Smith and Ward, 1998, Feldman, 1979).

In this research, floods due to extreme rainfall are the particular focus because the frequency and intensity of such events globally are thought to be increasing (Kundzewicz et al., 2013, Milly et al., 2005, Brakenridge et al., 2004) and because floods caused by long-lasting rain or brief torrential rain (i.e. flash floods) are the most destructive natural phenomenon in the World (Douben and Ratnayake, 2006, Douben, 2006).

Hydrological responses to rainfall are also related to the morphological and physiographic features of catchments. For example, flash floods tend to be most severe in areas with steep slopes and narrow valleys because water more rapidly flows into, and through, the drainage system (Smith and Ward, 1998). Catchment features can, therefore, increase the severity of flood events; for instance, catchments with steep slopes tend to have higher peak flows and shorter lag times (Ward and Robinson, 1967). (Sivapalan, 2006, p.3) highlights "*the catchment is a self-organizing system, whose form, drainage network, ground, and channel slopes, channel hydraulic geometries, soils, and vegetation, are all a result of adaptive ecological, geomorphic, and land-forming processes*". Hence, it is important that when undertaking extensive hydrological studies on multiple catchments, to clearly understand how catchments with diverse morphological and physiographic features behave hydrologically. Although catchments develop their own system and can behave independently of each other, there are similarities between catchments that might be transferrable from one to another, indicating similar hydrological patterns and relationships to morphometric features (Toth, 2013). There are many studies that utilise the physical similarity approach with the aim of estimating hydrological parameters in ungauged catchments from

similar gauged catchments (Wagener et al., 2007, Burn and Boorman, 1993, Oudin et al., 2010).

## **5.2 Aims Chapter 5**

Before the efficacy of NFM can be ascertained in catchments, it is necessary to understand the similarities and differences in their hydrological response to simulated rainfall events. Therefore, this chapter aims to quantify how morphological and physiographic differences between catchments generate differing hydrographs for the same rainfall event. This will be achieved by addressing the following objectives:

1. Use a coupled hydraulic and hydrologic model (IBER) to estimate the flood response across 20 catchments, under a particular hydrological scenario (e.g.  $60\text{mm hr}^{-1}$ ).
2. Quantify the differences in hydrographs between modelled catchments.
3. Determine whether there is a relationship between peak flow and lag time and catchment morphological conditions.
4. Quantify how peak flow and lag time in the modelled catchments varies under a subset of hyetograph distributions (e.g. unimodal left-skewed, unimodal right-skewed, unimodal with centred peak and rectangular).

## **5.3 Methodology**

### ***5.3.1 Methodological Overview***

The effect of a single rainfall event on catchments is discussed. The hydrograph peak flow and lag time will be the only two factors that are addressed to evaluate the impact of different landscape configurations. The coupled hydraulic and hydrological model IBER (described in Section 3.5) was used to calculate a hydrograph at the outlet of each of the 20 catchments described in Section 4.3. Additionally, maps of spatial extent were produced with a five minute interval (see Section 4.4). The rainfall event used to perform this scenario is a left-skewed rainfall event of  $60\text{ mm hr}^{-1}$  distributed uniformly across all catchments area (rainfall event described in Section 3.7). The Manning n roughness values used to



perform IBER were 0.035 (e.g. pasture with high grass) for the total area of catchments except for the main river network, where 0.04 was used, describing a clean and winding channel with some pools and shoals .

General patterns of the hydrographs from the full set of 20 catchments were first visually examined. The skewness of the hydrographs was also assessed by using the function 'skewness' in R. The relationship of the hydrograph peak flow, lag time and the morphological parameters of the catchments are also examined. A subset of eight catchment parameters (detailed in Table 4.2) selected from the full set of morphological and physiographical parameters were then used to statistically quantify relationships between hydrographs (e.g. peak flow and lag time) and catchment characteristics. The effect of hyetograph distribution (Section 3.7; Figure 3-10) on catchment response, were then examined by evaluating the hydrograph peak flow and lag time for each rainfall event type.

Peak flow was statistically examined using a Shapiro-Wilk test to determine whether the data follows a normal distribution (Villasenor Alva and Estrada, 2009). Results of the test suggested that peak flow did not have a normal distribution ( $W = 0.870$ ,  $p\text{-value} = 8.3e^{-07}$ ) and, therefore, non-parametric analysis was performed in all statistical analysis in this research (Sprinthall and Fisk, 1990, Siegel, 1957). A flowchart of the statistical approach is presented in Figure 5-1.

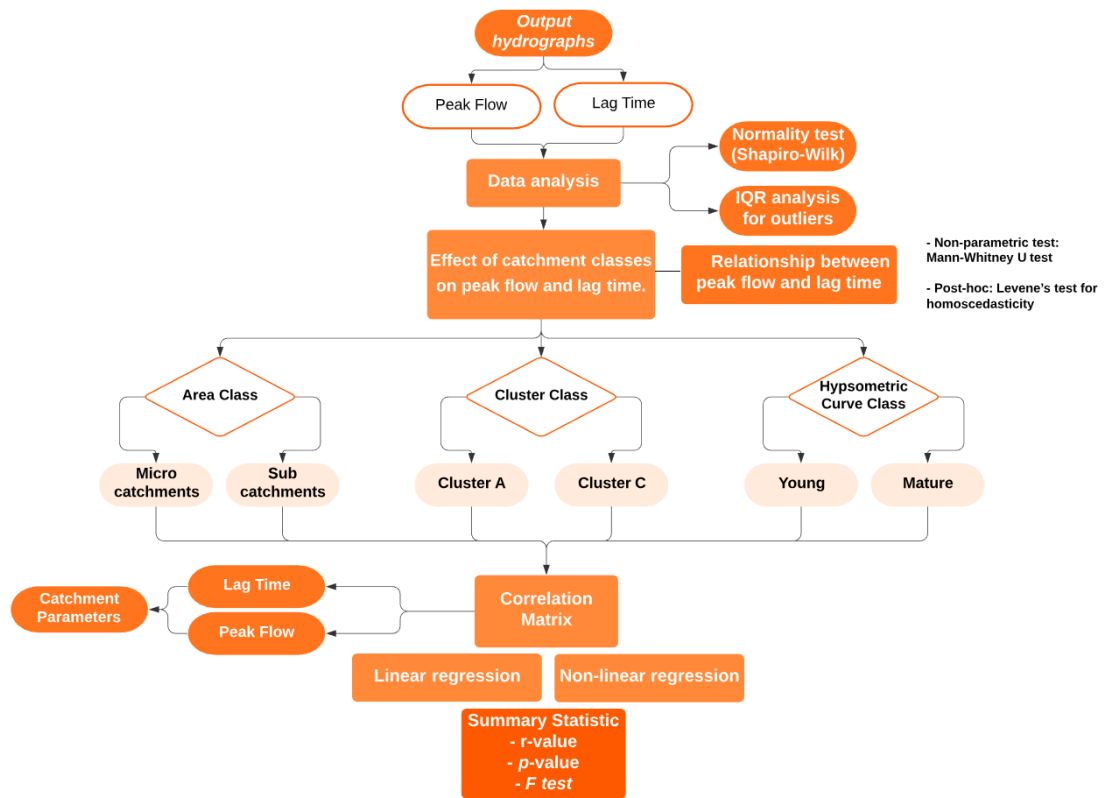


Figure 5-1 Effect of catchments on peak flow and lag time methodology flowchart. Peak flow and lag time are assessed to determine relationship between peak flow and lag time and catchment morphological conditions. Non-parametrical test were used to determine similarities between peak flow and lag time within a sub set of catchments classes.

### 5.3.2 Correlation between catchment parameters and peak flow and lag time

To evaluate the effect of a rainfall event on peak flow and lag time across catchments, the hydrographs at the catchment outlet were individually plotted to quantify the magnitude of the hydrological response. Peak flow and lag time values were calculated from hydrographs for each modelled catchment (see Section 3.8). Peak flow and lag time were first examined using the interquartile range (IQR) described by (Tukey, 1977), aiming to find potential outliers. Boxplots were used to display the IQR method where the boxes represent the first and the third quartile of the data calculated from the median of each variable. Then the boxplot's whiskers from each quartile determined the minimum or maximum values to be considered between the boundary range. The values outside of the maximum and minimum range were considered outliers and statistical analysis was performed

twice, once including and once excluded these values that were inconsistent with other data (Jeong et al., 2017). The IQR analysis was also performed for the catchment parameters individually to determine the potential influence of abnormal values. Therefore, observed outliers are presented throughout but were not considered at any analysis of this study.

The outliers do not represent erroneous values but; instead, indicate that these catchments have hydrological responses that are distinct from the rest of the catchments. These catchments are therefore potentially important, which is why correlation analysis between the peak flow and catchment parameters was performed both with and without the outliers (Appendix A).

The peak flow and lag time versus parameters of the catchments were correlated. Two regression models were fitted for peak flow and lag time magnitudes and the selected catchment parameters (i.e. linear and polynomial). The equation, significance and  $r$  values of each regression were calculated and displayed to identify which regression fitted better to the data. Both regression models were statistically compared, performing a partial F test in R. The test is used to identify whether a non-linear model has a significantly better fit than a linear model (Crossley, 2000); thus, no significant differences between models imply that the regression statistically fits better to a linear model, whereas significant differences imply that the regressions model is non-linear.

### ***5.3.3 Effect of catchment size on peak flow and lag time.***

To further analyse the effect of catchment size on peak flow and lag time, the size classification range proposed by (CIDIAT-MARNR, 1984) and described in Section 3.4 was used. A Mann-Whitney U test was performed to examine whether the median of the peak flows and lag times in each size class were statistically different. This test is normally used to examine whether two independent samples (e.g. micro and sub-catchments) were selected from data sets having the same distribution (Mann and Whitney, 1947). Thus, the null hypothesis of the Mann-Whitney U test is that the median of the peak flow of micro-catchments is equal to the median of the peak flow of sub-catchments. The large catchment class was not included in this analysis because there are only two catchments within this class, and therefore not enough to perform the test. A post-hoc Levene's test was performed to assess the homogeneity of variance or homoscedasticity in both classes. The Levene's test is assessed by the p-value considering a value less than

the significance level ( $p < 0.05$ ) as samples with equal variance (Derrick et al., 2018).

A correlation matrix analysis was performed separately for catchments within each area size class. As above, two regression models were fitted for peak flow and time lag and the equation, significance and  $r$  values of each regression were calculated to identify the strength of relationships between each catchment parameter and the peak flow and lag time. The partial F test was also performed to determine which regression have better statistical fit. The outliers found for each variable (e.g. peak flow and lag time) were also not considered for the analysis. Considering that the normality test for peak flow suggested that the data set is not normally distributed a non-parametric statistical test is performed. All analysis and plots were performed using the R software.

#### **5.3.4 Effect of cluster classification on peak flow**

Peak flow was also examined within each of the clusters of catchments identified and described in section 4.3.2, which are based on the cumulative impact of morphometric parameters. The non-parametric Mann-Whitney test for independent samples was performed between peak flow in each cluster. Cluster B was not included because the number of catchments within this cluster was not sufficient to perform the statistical test. This analysis aimed to determine whether patterns between hydrograph variables and catchment parameters were stronger within individual subsets of catchments than when comparing all the catchments together. The null hypothesis of the Mann-Whitney U test is that the median of the peak flow of catchments within Cluster A is equal to the median of the peak flow of catchments within Cluster C. The post-hoc Levene's test was also performed to assess the homogeneity of variance in both classes.

As in the previous analysis, a correlation matrix was also performed within each cluster grouping using a linear and polynomial regression. The equation, significance and  $r$  values of each regression were calculated to identify the strength of relationships between each catchment parameter and the peak flow and lag time and or each cluster class. The partial F test was also performed to determine which regression have better statistical fit.

### **5.3.5 Effect of hypsometric curve classification on peak flow**

The hypsometric curve was also used to investigate patterns between peak flow and catchment characteristics. Hypsometric curves were calculated as described in Section 3.2 as old, mature and young. No firm threshold exists in the literature to determine which of these three categories a curve fits within and, therefore, a threshold was established by the author. The thresholds were delineated using the shape of the hypsometric curves, following the theoretical work of Strahler (1952). Concave hypsometric curves indicate catchments that have undergone substantial erosion (old catchments) whereas convex curves characterize 'young' catchments, that are less eroded. S-shaped hypsometric curves characterise mature catchments, i.e. those that are moderately eroded and intermediate between young (convex) and old (concave). The threshold was determined by taking the area between the curves and dividing it into three equal parts whilst maintaining the characteristics that define each curve and using the inflexion points proposed by (Strahler, 1952b). Hypsometric curves were calculated for each catchment and all those curves that were totally contained within the threshold limits were classified into either the young, mature and old categories. The catchments whose curves crossed the boundaries were independently observed and if more than 50% of the curve was contained in one of the categories, it was classified within that class.

This classification was then used to perform a non-parametric Mann-Whitney U test for independent samples to analyse whether the median of the peak flow in each class of catchment was significantly different. The post-hoc Levene's test was then performed to assess the homogeneity of variance in both young and mature classes. The correlation analysis was also performed for the peak flow and catchment parameters and for the hypsometric classes. Two models were fitted (e.g. linear and polynomial) and the partial F test was executed to determine which model statistically fit better to each catchments parameter within hypsometric classes. All analysis was performed using R software.

### **5.3.6 Effect of hyetograph distribution on peak flow and lag time**

The effect of different skewed patterns of rainfall (e.g. unimodal left-skewed peak, unimodal right-skewed peak, unimodal with a centred peak, and rectangular hyetograph distributions) on resultant hydrographs were assessed. All hyetographs were designed and adjusted to a 60 mm hr<sup>-1</sup> rainfall event, described

in Section 3.7. The entire set of catchments was modelled using the four hyetograph distributions in IBER. The peak flow and lag time were calculated for all 80 resultant hydrographs (i.e. twenty catchments and four hyetographs distributions). To be able to analyse statistically the effect of a set of different rainfall event on peak flow and lag time on catchments, the non-parametric Friedman test for repeated measures was selected. The Friedman test is the non-parametric alternative to the one-way ANOVA with repeated measures when data is not normally distributed (Dytham, 2011). The test is used for dependent analysis, in this case, the use of different treatments (i.e. rainfall events) across the same set of catchments. The non-parametric Friedman test for repeated measures was performed to assess the effect of hyetograph distribution on peak flow and lag time. The test ranks hyetographs for each catchment and then compares across the 20 catchments. The Wilcox Signed Rank post-hoc test was performed to explore more deeply how hydrograph distributions relate to each other and which hyetographs are more similar or different from the others. All analysis and plots were performed using the R software.

## 5.4 Results

### ***5.4.1 Effect of a rainfall event on peak flow and lag time in catchments.***

Figure 5-2 depicts the output hydrographs for all 20 catchments and Table 5.1 depicts the area, slope, peak flow and lag time values for each catchment. Hydrographs have been plotted using their own scale and are coloured by their area classification. Peak flow values range from  $22 \text{ m}^3 \text{ s}^{-1}$  (Cary) to  $2887 \text{ m}^3 \text{ s}^{-1}$  (Combeima) catchments. There are two other catchments that also have a peak flow over  $2000 \text{ m}^3 \text{ s}^{-1}$ ; Caqueta and Mayala Laba ( $2399.99$  and  $2498.1 \text{ m}^3 \text{ s}^{-1}$ , respectively). These two catchments do not have the largest areas but do have some of the highest slopes (Table 5.1). Of particular interest is that the smallest catchment - Mulato (area  $17 \text{ km}^2$ ) - has a relatively high peak flow of  $442.0 \text{ m}^3 \text{ s}^{-1}$ , which is nearly twice the peak flow of Berajevska Reka, despite it having a catchment twice as large. Likewise, Mulato has similar peak flow to Hor-patak ( $503.3 \text{ m}^3$ ) which is nearly three times bigger. This small catchment also has a similar peak to Metome, which has a catchment area nearly seventeen times larger than Mulato. Other catchments such as Mazzarrà, Dinin, Pasto and Kurtcukuru have similar peak flows, ranging between  $698.0 \text{ m}^3 \text{ s}^{-1}$  to  $874.6 \text{ m}^3 \text{ s}^{-1}$ . These particular catchments also have a narrow area range from  $54.81 \text{ km}^2$  to  $120.69$

km<sup>2</sup>. The smallest peaks were for Cary and Yandaran, which had 22 and 48.2 m<sup>3</sup> s<sup>-1</sup> respectively.

In terms of the peak flow and slope, the data reveals some catchments that have some similarities such as Metome and L'Aulne, which have a slope of 6.4 and 8.7% respectively and the peak flow is around 500 m<sup>3</sup> s<sup>-1</sup> for both catchments. Likewise, Swale and Dinin catchment had similar slope values (7.2 and 7.9%) and the peak flow is 874.6 and 988.1 m<sup>3</sup> s<sup>-1</sup>. A similar trend is seen for Mayala Laba and Caquetá catchments. The flattest catchment – Cary (slope 4.5%) - has a relatively small peak flow of 22.0 m<sup>3</sup> s<sup>-1</sup> while the steepest catchment, Yazu, (slope 70.70%) has nearly 65 times the peak flow of Dinin. Surprisingly Yazu despite having the steepest topography does not have the highest peak flow. Although some similarities can be seen, a qualitative analysis of these relationships will be assessed in the next section.

Table 5.1 Area, slope, peak flow and time lag for the full range of catchments

| <b>Catchment</b> | <b>Area<br/>(Km<sup>2</sup>)</b> | <b>Slope<br/>(%)</b> | <b>Peak Flow<br/>(m<sup>3</sup> s<sup>-1</sup>)</b> | <b>Lag time<br/>(Hr)</b> |
|------------------|----------------------------------|----------------------|-----------------------------------------------------|--------------------------|
| Mulato           | 17.52                            | 50.80                | 442.8                                               | 0.4                      |
| Cary             | 22.77                            | 4.50                 | 22.0                                                | 7.8                      |
| Berajevska Reka  | 44.59                            | 14.50                | 279.1                                               | 1.4                      |
| Mazzarrà         | 54.81                            | 33.50                | 806.5                                               | 0.8                      |
| Pasto            | 56.30                            | 21.70                | 698.0                                               | 0.8                      |
| Hór-patak        | 75.24                            | 25.30                | 503.3                                               | 1.6                      |
| Dinin            | 85.63                            | 7.20                 | 874.6                                               | 1.1                      |
| Yazu             | 95.70                            | 70.70                | 1473.1                                              | 0.7                      |
| Kurtcukuru       | 120.69                           | 47.50                | 795.5                                               | 1.5                      |
| Yandaran         | 139.79                           | 9.00                 | 48.2                                                | 20.2                     |
| Caqueta          | 150.95                           | 62.00                | 2399.8                                              | 0.8                      |
| Combeima         | 161.73                           | 47.10                | 2887.1                                              | 0.7                      |
| Noguera R.       | 179.88                           | 27.90                | 1288.0                                              | 1.4                      |
| Trent            | 192.50                           | 6.40                 | 272.9                                               | 5.5                      |
| Metome           | 291.90                           | 6.40                 | 488.1                                               | 6.0                      |
| Sambre           | 337.62                           | 7.30                 | 353.8                                               | 8.7                      |
| L'Aulne          | 519.11                           | 8.70                 | 534.4                                               | 7.6                      |
| Mayala Laba      | 522.73                           | 60.40                | 2498.1                                              | 1.8                      |
| Swale            | 613.13                           | 7.90                 | 988.1                                               | 7.1                      |
| Bistrita         | 759.70                           | 34.30                | 1325.7                                              | 6.2                      |

Lag times were similarly variable between catchments with the Yandaran and Mulato having the longest (20.22 hours) and shortest (0.4 hours) lag time, respectively. These values are in proportion to the total time duration for the entire rainfall event to drain through the outlet of the catchment, which was 4 hours to over 100 hours (about 4 days) in Yandaran. There is a set of catchments such as Berajevska Mazzarrà, Mulato, Caquetá, Noguera R. Kurtcukuru, and Dinin which area range goes from 17 to 200 km<sup>2</sup> where the lag time is between 0.4 and 1.8 hours while the remainder catchments had a relatively larger area range. The lag time values for these catchments goes from 5 to 10 hours except Yandaran which, as mentioned above, had the longest lag time (Table 5.1). This catchment has a particularly high value which is not in the range of the other catchments, indicating that a particular feature of the catchment is driving different flow behaviour to other catchments. Regarding the peak flow and slope, the data show a group of catchments (e.g. Metome, Carry, Sambre, L'Aulne and Swale) with slope ranges between 4.5 to 14.5, having similar lag time values from 5.5 to 8.7 hours. Catchments with larger slopes (> 15%) do not have lag times greater than 1.8 hours except Bistrita catchment.

The hydrograph rising limb is very steep for Mulato indicating a very quick flood onset, whereas the rising and descending limb for Cary are smoother, leading to a relatively longer duration high flow event. Interestingly, there are catchments such as Metome, Noguera R., Mersin, Cary, Yandaran, and Bistrita that have a shoulder on the rising limb. This peculiarity will be explored in the next section, where the relationship between the peak flow and catchment parameters will be discussed. In terms of the shape of the hydrograph, the skewness analysis determined that all catchments had positive skew indicating that the receding limb on the right-hand side of the distribution is longer than the rising limb. Therefore, the receding limb had lower slope than the rising limb. However, the specific values of limb length and slope vary substantially between catchments.



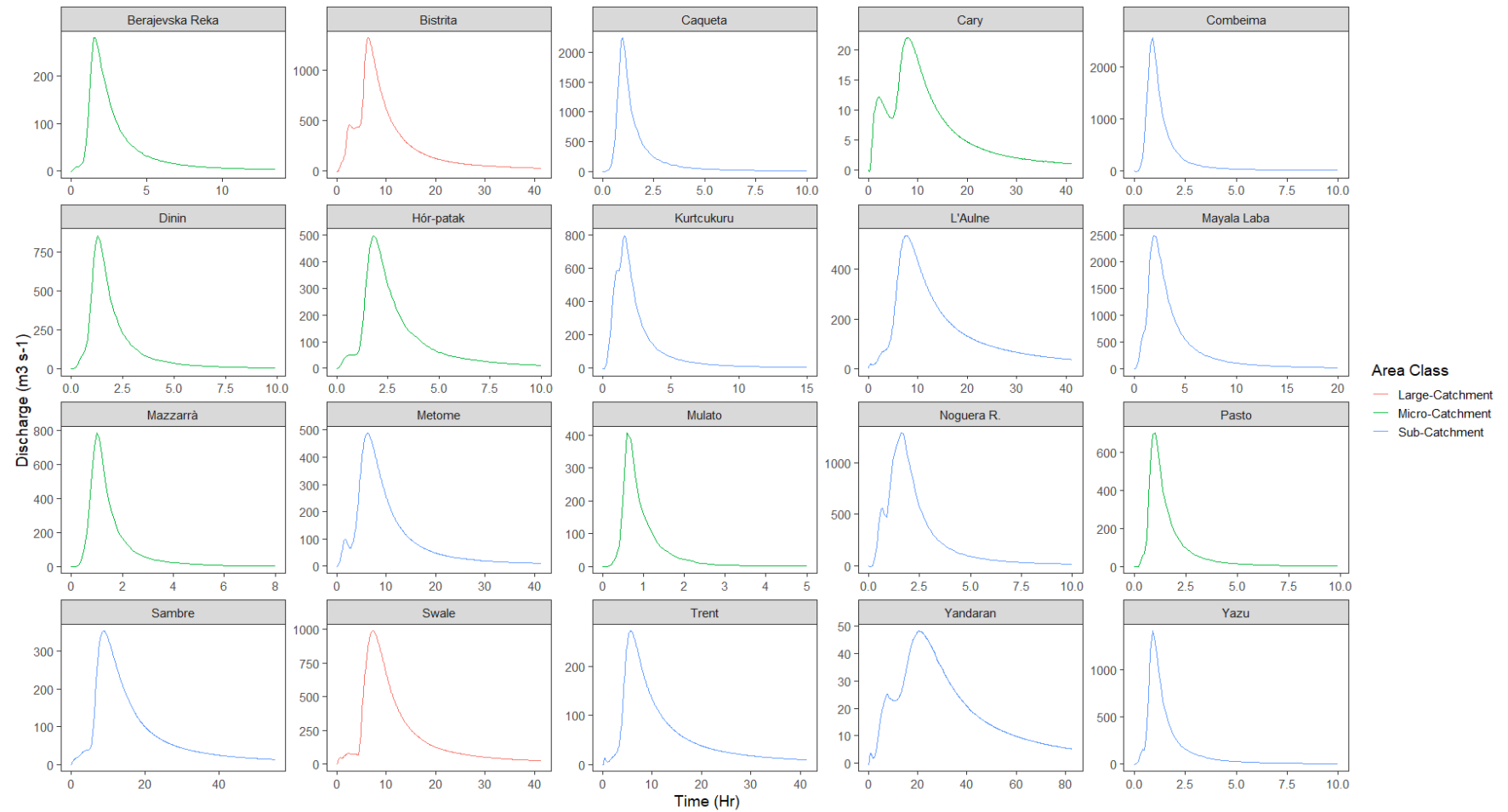


Figure 5-2. Hydrographs of the full set of catchments under a rainfall event of 60 mm hr<sup>-1</sup> unimodal left-skewed. The Manning n roughness values used to perform IBER were 0.035 for all area of catchments equivalent to pasture with high grass, and 0.04 for the main river network describing a clean and winding channel with some pools and shoals. Coloured lines indicating the area categories where each catchment has been classified.

#### 5.4.2 Relationship between peak flow and lag time to catchment parameters.

Peak flow and lag time were initially analysed to identify potential outliers. Figure 5-3 shows the boxplot with the IQR method used to identify outliers. The analysis shows that Combeima catchment was identified as an outlier for the peak flow. As mentioned above, this catchment has the largest peak flow of  $2887.1 \text{ m}^3 \text{ s}^{-1}$  and is also one of the steepest catchments (47.1%). As for the lag time, the Yandaran catchment was identified as an outlier having a lag time value of 20.2 hr, which is outside of the maximum IQR range. This catchment also has one of the smallest peak flows ( $48.2 \text{ m}^3 \text{ s}^{-1}$ ) and a low slope value (9.0%). The box plot for the time lag also shows that the first interquartile (i.e. below the median) is narrower compared to the third interquartile (i.e. above the median) this might indicate that there is a set of catchments with similar lag time responses.

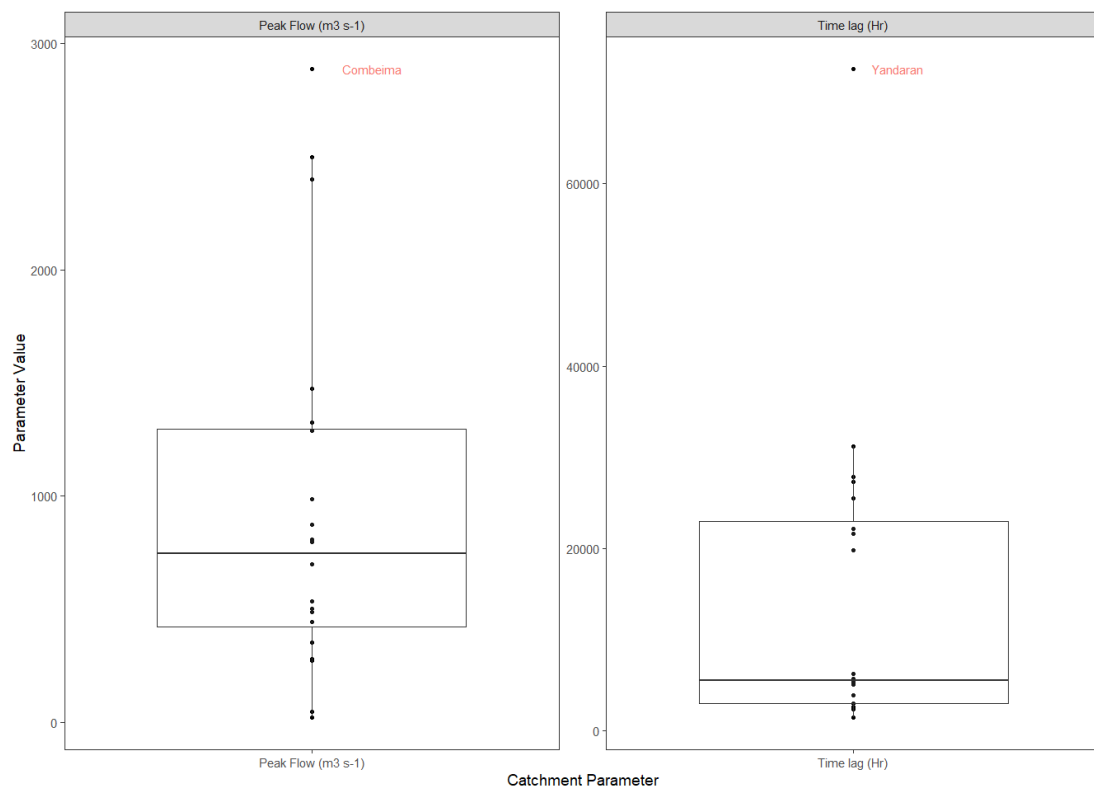


Figure 5-3 Box-plots showing the distribution of the peak flow and lag time for the whole range of catchments. The black horizontal line is the median in each variable. The boxes indicating the first quartile to the third quartile. The whiskers indicate the minimum and maximum interquartile range (IQR) and points outside the IQR range are the outliers.

The peak flow and selected parameters of the catchments were initially evaluated qualitatively to determine potential correlations. The full set of catchments and its corresponding morphologic and physiologic parameters, including the area, cluster and hypsometric curve classifications are shown in Table 5.2. Figure 5-4a shows the scatter plots of peak flow versus the catchment parameters and indicates scatter in all relationships. It also indicates some anomalous data points, which complicate the predominant relationships between variables (Figure 5-4a). For example, drainage density has two values that are clearly distanced from the line tendency. The mass coefficient also shows that three points are isolated from the main group of data. As for the torrentiality coefficient, two values at each side of the line of tendency can be seen. The outlier analysis was performed and identifies these points as being anomalous (Figure 5-4b). A commonality between outlier catchments is that they all have a relatively high slope and areas above 100 km<sup>2</sup>, except for Trent catchment which is has a low slope value with an area greater than 100 Km<sup>2</sup>.

Table 5.2 Full set of catchments and its corresponding morphologic and physiologic parameters, including the area, cluster and hypsometric curve classifications.

| Catchment              | Peak Flow<br>(m <sup>3</sup> s <sup>-1</sup> ) | Time Lag<br>(Hr) | Area<br>(Km <sup>2</sup> ) | Compactness Index<br>(Km/Km <sup>2</sup> ) | Form Factor<br>(Km <sup>2</sup> /Km <sup>2</sup> ) | Average Width<br>(Km) | Drainage Density<br>(Km/Km <sup>2</sup> ) | Torrentiality Coeff<br>(Km <sup>2</sup> /Km) | Mass Coeff<br>(m/Km <sup>2</sup> ) | Slope (%) | Size Class      | Cluster Class | Hypsometric Curve Class |
|------------------------|------------------------------------------------|------------------|----------------------------|--------------------------------------------|----------------------------------------------------|-----------------------|-------------------------------------------|----------------------------------------------|------------------------------------|-----------|-----------------|---------------|-------------------------|
| <b>Mulato</b>          | 442.8                                          | 0.42             | 17.52                      | 1.87                                       | 0.12                                               | 1.47                  | 1.18                                      | 0.86                                         | 78.20                              | 50.80     | Micro-Catchment | Cluster A     | Mature                  |
| <b>Cary</b>            | 22.0                                           | 7.75             | 22.77                      | 1.83                                       | 0.17                                               | 1.95                  | 1.30                                      | 0.97                                         | 4.07                               | 4.50      | Micro-Catchment | Cluster A     | Old                     |
| <b>Berajevska Reka</b> | 279.1                                          | 1.42             | 44.59                      | 1.52                                       | 0.31                                               | 3.73                  | 1.14                                      | 0.65                                         | 6.16                               | 14.50     | Micro-Catchment | Cluster B     | Young                   |
| <b>Mazzarrà</b>        | 806.5                                          | 0.83             | 54.81                      | 1.96                                       | 0.10                                               | 2.31                  | 1.15                                      | 0.73                                         | 13.71                              | 33.50     | Micro-Catchment | Cluster A     | Young                   |
| <b>Pasto</b>           | 698.0                                          | 0.83             | 56.30                      | 1.75                                       | 0.12                                               | 2.59                  | 1.58                                      | 0.94                                         | 54.64                              | 21.70     | Micro-Catchment | Cluster A     | Mature                  |
| <b>Hór-patak</b>       | 503.3                                          | 1.58             | 75.24                      | 1.81                                       | 0.19                                               | 3.79                  | 1.22                                      | 0.93                                         | 7.74                               | 25.30     | Micro-Catchment | Cluster A     | Mature                  |
| <b>Dinin</b>           | 874.6                                          | 1.08             | 85.63                      | 1.58                                       | 0.27                                               | 4.78                  | 1.03                                      | 0.81                                         | 3.51                               | 7.20      | Micro-Catchment | Cluster B     | Young                   |
| <b>Yazu</b>            | 1473.1                                         | 0.67             | 95.70                      | 1.27                                       | 0.29                                               | 5.31                  | 1.15                                      | 1.07                                         | 48.36                              | 70.70     | Micro-Catchment | Cluster C     | Mature                  |
| <b>Kurtcukuru</b>      | 795.5                                          | 1.50             | 120.69                     | 2.13                                       | 0.09                                               | 3.30                  | 1.19                                      | 0.89                                         | 13.78                              | 47.50     | Sub-Catchment   | Cluster A     | Mature                  |
| <b>Yandaran</b>        | 48.2                                           | 20.17            | 139.79                     | 1.80                                       | 0.15                                               | 4.51                  | 1.38                                      | 0.87                                         | 0.71                               | 9.00      | Sub-Catchment   | Cluster A     | Old                     |
| <b>Caqueta</b>         | 2399.8                                         | 0.75             | 150.95                     | 1.36                                       | 0.26                                               | 6.28                  | 1.10                                      | 0.81                                         | 14.67                              | 62.00     | Sub-Catchment   | Cluster C     | Mature                  |
| <b>Combeima</b>        | 2887.1                                         | 0.67             | 161.73                     | 1.70                                       | 0.18                                               | 5.39                  | 1.02                                      | 0.66                                         | 15.68                              | 47.10     | Sub-Catchment   | Cluster C     | Young                   |
| <b>Noguera R.</b>      | 1288.0                                         | 1.42             | 179.88                     | 1.48                                       | 0.22                                               | 6.32                  | 1.07                                      | 0.89                                         | 10.93                              | 27.90     | Sub-Catchment   | Cluster C     | Mature                  |
| <b>Trent</b>           | 272.9                                          | 5.50             | 192.50                     | 1.91                                       | 0.20                                               | 6.14                  | 0.79                                      | 0.37                                         | 0.78                               | 6.40      | Sub-Catchment   | Cluster B     | Mature                  |
| <b>Metome</b>          | 488.1                                          | 6.00             | 291.90                     | 1.57                                       | 0.28                                               | 9.10                  | 1.31                                      | 0.86                                         | 0.45                               | 6.40      | Sub-Catchment   | Cluster C     | Mature                  |
| <b>Sambre</b>          | 353.8                                          | 8.67             | 337.62                     | 1.83                                       | 0.16                                               | 7.38                  | 1.21                                      | 0.95                                         | 0.82                               | 7.30      | Sub-Catchment   | Cluster C     | Young                   |
| <b>L'Aulne</b>         | 534.4                                          | 7.58             | 519.11                     | 1.71                                       | 0.26                                               | 11.56                 | 1.22                                      | 0.90                                         | 0.46                               | 8.70      | Sub-Catchment   | Cluster C     | Mature                  |
| <b>Mayala Laba</b>     | 2498.1                                         | 1.75             | 522.73                     | 1.63                                       | 0.29                                               | 12.30                 | 1.05                                      | 0.83                                         | 4.13                               | 60.40     | Sub-Catchment   | Cluster C     | Young                   |
| <b>Swale</b>           | 988.1                                          | 7.08             | 613.13                     | 1.97                                       | 0.13                                               | 8.83                  | 1.16                                      | 0.82                                         | 0.56                               | 7.90      | Catchment       | Cluster C     | Mature                  |
| <b>Bistrita</b>        | 1325.7                                         | 6.17             | 759.70                     | 1.84                                       | 0.15                                               | 10.62                 | 1.05                                      | 0.79                                         | 1.71                               | 34.30     | Catchment       | Cluster C     | Mature                  |

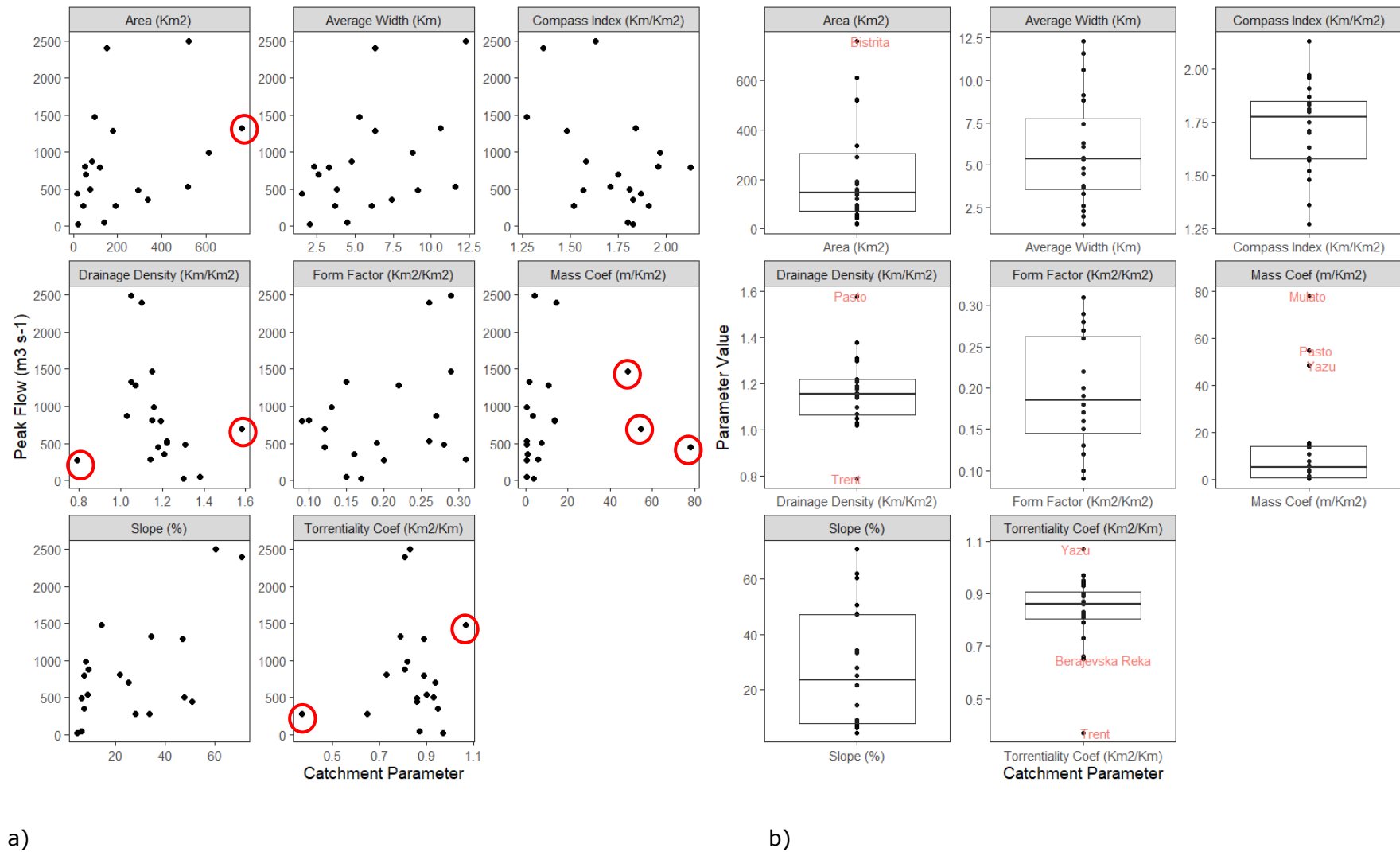


Figure 5-4 Scatter plot between peak flow and catchment parameters. Boxplot of catchment parameters identifying outliers.

Two regression models, linear and polynomial were fitted to the data to assess the correlation between peak flow and catchment parameters excluding peak flow outliers (Figure 5-5). The  $r$  and  $p$ -value, and equation of each regression were calculated to estimate the strength of each model (Table 5.3). The figure below indicates that parameters such as area, average width, drainage density and mass coefficient tend to have a linear correlation whereas compass index, slope and torrentiality follow a polynomial regression. The strength of the correlation varies between parameters of the catchments, being positive for area, average width, form factor, slope and mass coefficient, indicating an increase of the peak flow as these values increase. Linear regression was firstly assessed to determine potential correlations. It was found that drainage density was highly correlated ( $r = -0.7, p < 0.05$ ) followed by the Slope ( $r = 0.62, p = 0.001$ ). The weakest relationship, which was insignificant, was with the area ( $r = 0.30, p = 0.226$ ) which was expected to be strongly related to peak flow.

The analysis of the polynomial regressions indicated that the drainage density and slope were highly correlated ( $r = -0.71, p < 0.01$ ;  $r = 0.75, p < 0.05$ , respectively). Although there is a high correlation between peak flow and these two variables, the polynomial correlation is unlikely to represent the physical behaviour of these variables; for example, it would be expected that an increase in the slope would lead to an increase in the peak flow. However, the partial F test allowed the determination of whether the polynomial model was statistically significant when compared to the linear model (Table 5.3). Results of the analysis show that  $p$  values were all higher than  $p > 0.05$  indicating that the polynomial regression does not provide a statistically significant better fit than the linear model. Therefore, only drainage density and slope were highly correlated to peak flow, both by a linear model.

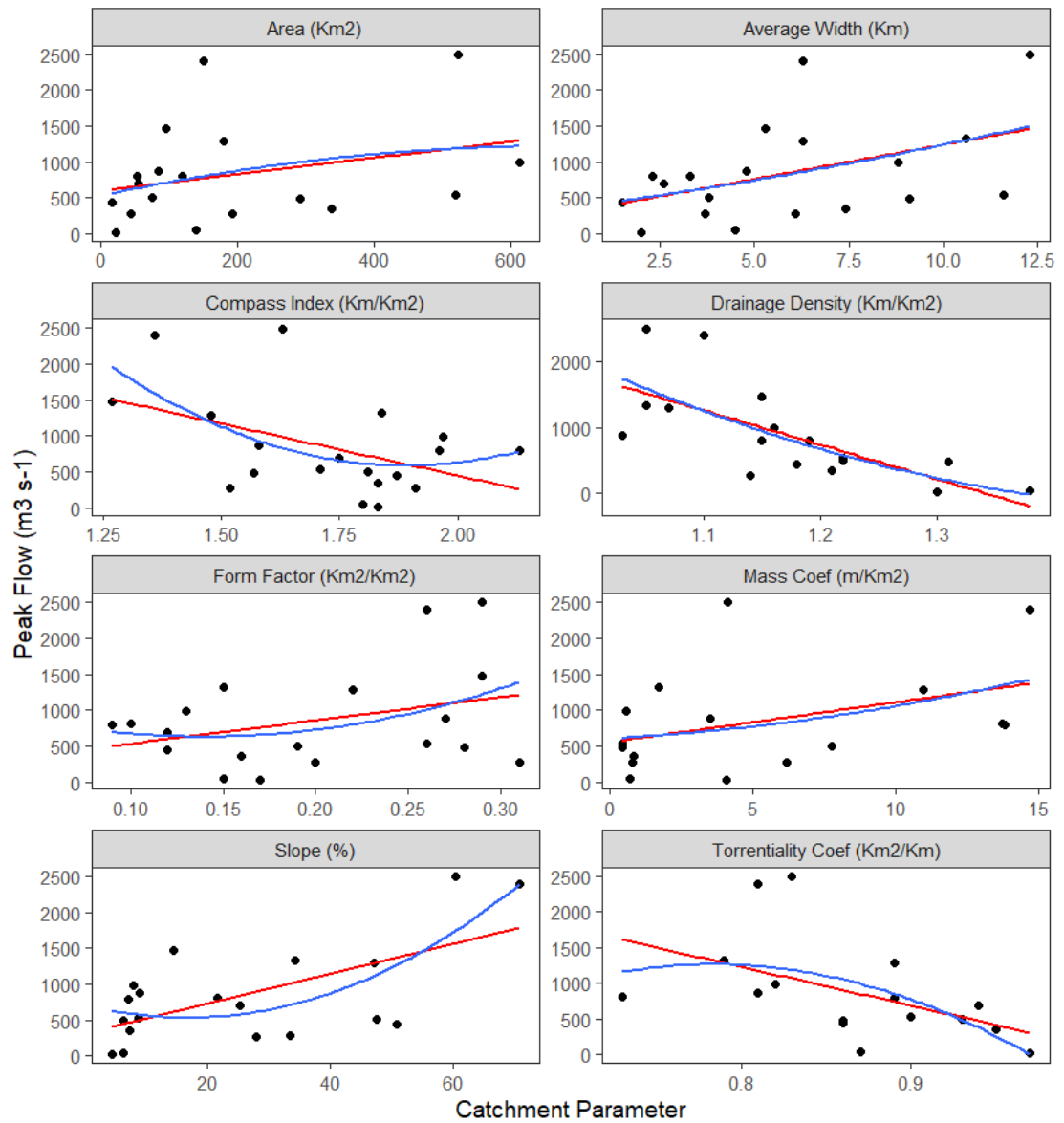


Figure 5-5 Scatter plot of the peak flow and parameters of the catchment for the full set of catchments excluding peak flow outliers. Linear (red) and polynomial (blue) regression adjusted to the data.

Table 5.3 R, p values, and equation from the linear and polynomial models between peak flow and parameters of the catchment. The last column indicates the p-value from the differences between models.

| Peak Flow                 |              |         |                |                  |         |                           |                           |
|---------------------------|--------------|---------|----------------|------------------|---------|---------------------------|---------------------------|
| Catchment Parameter       | Linear model |         |                | Polynomial model |         |                           | F test Model difference s |
|                           | r            | p-value | Equation       | r                | p-value | Equation                  | p-value                   |
| <b>Area</b>               | 0.30         | 0.226   | $y=600+1.1x$   | 0.31             | 0.479   | $y=530+2x-0.0015x^2$      | 0.817                     |
| <b>Average Width</b>      | 0.45         | 0.077   | $y=280+96x$    | 0.43             | 0.218   | $y=350+69x+2x^2$          | 0.905                     |
| <b>Compactness Index</b>  | -0.46        | 0.037   | $y=3400-1500x$ | 0.59             | 0.042   | $y=13000-13000x+3600x^2$  | 0.150                     |
| <b>Drainage Density</b>   | -0.70        | 0.003   | $y=7000-5200x$ | 0.71             | 0.011   | $y=17000-21000x+6800x^2$  | 0.524                     |
| <b>Form Factor</b>        | 0.34         | 0.126   | $y=200+3200x$  | 0.42             | 0.238   | $y=1100-7400x+26000x^2$   | 0.444                     |
| <b>Mass Coef</b>          | 0.40         | 0.097   | $y=550+56x$    | 0.45             | 0.260   | $y=600+22x+2.4x^2$        | 0.819                     |
| <b>Slope</b>              | 0.62         | 0.001   | $y=310+21x$    | 0.75             | 0.002   | $y=710-22x+0.64x^2$       | 0.446                     |
| <b>Torrentiality Coef</b> | -0.49        | 0.076   | $y=5600-5400x$ | 0.53             | 0.133   | $y=21000+57000x-37000x^2$ | 0.325                     |

The same analysis was performed for the lag time. Two regression models, linear and polynomial were fitted to the data to assess the correlation between lag time and catchment parameters (Figure 5-6). The r and p-value, and equation of each regression were also calculated to estimate the strength of each model (Table 5.4). Overall results show that catchment parameters such area, average width and torrentially coefficient tend to have a linear trend since both linear and polynomial fitted models show the same pattern, however, the strength of the correlations are not high in any case. The results from the linear model indicate that the strength of correlations was slightly higher as for the peak flow. The higher significant correlation was with the mass coefficient ( $r = -0.79$ ,  $p < 0.05$ ) followed by the slope ( $r = -0.66$ ,  $p = 0.002$ ). Surprisingly, the correlation between the catchment area and lag time increased compared to the peak flow ( $r = 0.58$ ,  $p = 0.01$ ). As for the polynomial model, significant correlations were found between lag time and mass coefficient ( $r = 0.85$ ,  $p < 0.05$ ) and slope ( $r = 0.72$ ,  $p = 0.003$ ). Similar to the previous analysis of the peak flow, the polynomial correlation does not represent the physical processes of the variables and is, instead, indicative more broadly of non-linear behaviour. For example, there is no physical meaning to support that the correlation of the slope changes from a negative correlation to a positive correlation after a slope of 50%.

The partial F test determined that the polynomial model was not statistically significant for any of the catchment parameters except for the mass coefficient ( $p$



= 0.048) (Table 5.4). In this particular case, the mass coefficient was highly correlated for both linear and non-linear models but, statistically the polynomial model has a better fit to the data indicating a decrease of the lag time with an increase of the mass coefficient value. Normally, the mass coefficient is an indicator of the steepness of the catchment suggesting low values for flat catchments and high values for relatively steep catchments.

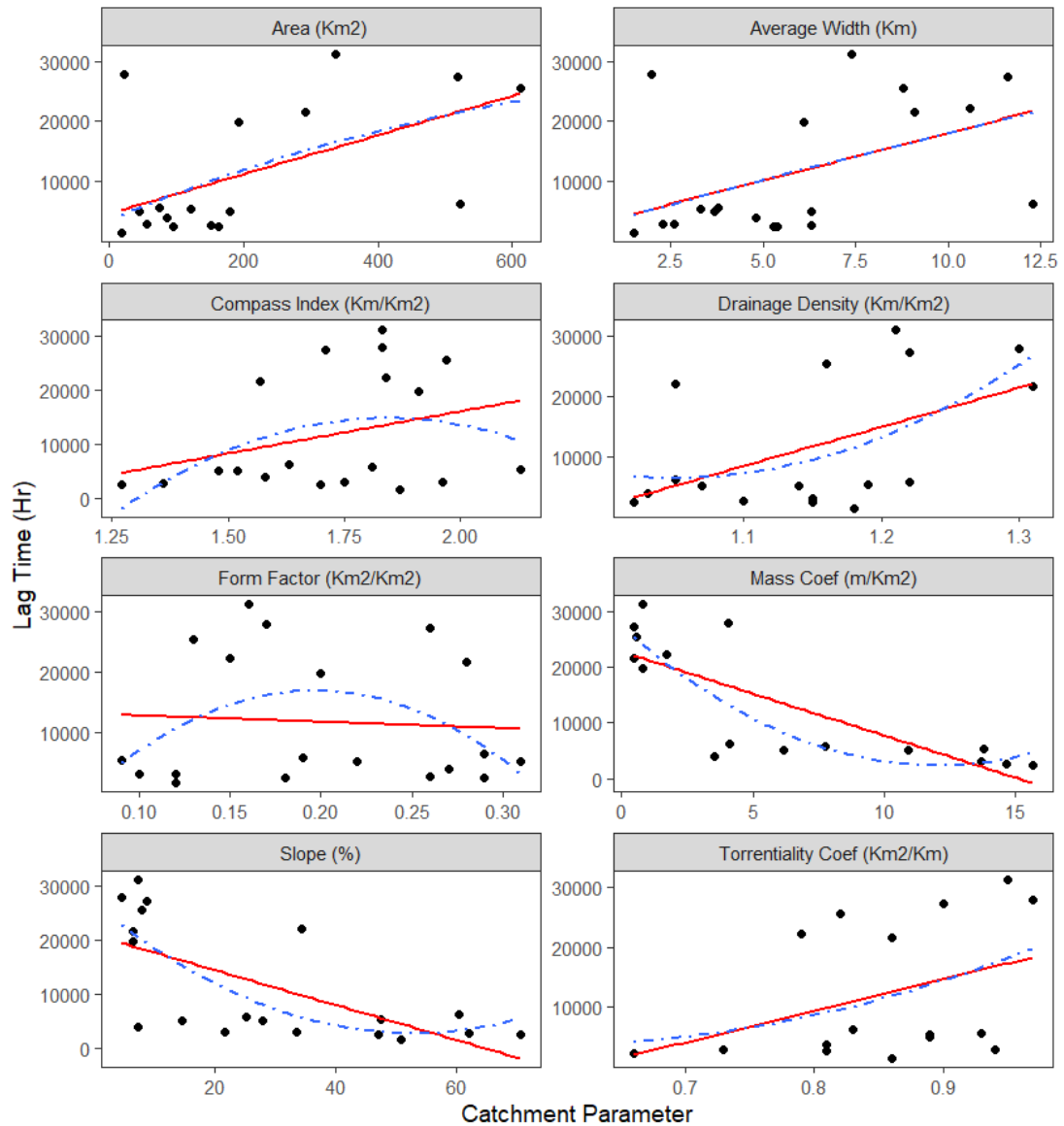


Figure 5-6 Scatter plot of the lag time and parameters of the catchment for the full set of catchments excluding lag time outliers. Linear (red) and polynomial (blue) regression adjusted to the data.

Table 5.4 R, p values, and equation from the linear and polynomial models between lag time and parameters of the catchment. The last column indicates the p-value from the differences between models.

| Catchment Parameter       | Time Lag     |         |                   |                  |         |                                |                          |
|---------------------------|--------------|---------|-------------------|------------------|---------|--------------------------------|--------------------------|
|                           | Linear model |         |                   | Polynomial model |         |                                | F test Model differences |
|                           | r            | P-value | Equation          | r                | P-value | Equation                       | p-value                  |
| <b>Area</b>               | 0.58         | 0.010   | $y=4700+33x$      | 0.59             | 0.032   | $y=3700+45x-0.022x^2$          | 0.530                    |
| <b>Average Width</b>      | 0.48         | 0.039   | $y=2300+1600x$    | 0.48             | 0.128   | $y=1900+1700x-12x^2$           | 0.961                    |
| <b>Compactness Index</b>  | 0.32         | 0.186   | $y=15000+16000x$  | 0.41             | 0.225   | $y=-160000+190000x-50000x^2$   | 0.264                    |
| <b>Drainage Density</b>   | 0.52         | 0.033   | $y=-63000+65000x$ | 0.56             | 0.071   | $y=340000-630000x+3x10^5x^2$   | 0.346                    |
| <b>Form Factor</b>        | 0.07         | 0.777   | $y=14000-11000x$  | 0.39             | 0.260   | $y=-24000+420000x-10100000x^2$ | 0.111                    |
| <b>Mass Coef</b>          | -0.79        | 0.000   | $y=23000-1500x$   | 0.85             | 0.000   | $y=27000-4100x+170x^2$         | 0.048                    |
| <b>Slope</b>              | -0.66        | 0.002   | $y=210000-320x$   | 0.72             | 0.003   | $y=27000-9000x+8.6x^2$         | 0.106                    |
| <b>Torrentiality Coef</b> | 0.39         | 0.140   | $y=330000+52000x$ | 0.39             | 0.335   | $y=4000-120000x+110000x^2$     | 0.761                    |

#### 5.4.3 Effect of catchment size classification on peak flow and lag time

Catchment area was shown above to not be correlated to peak flow or lag time ( $r = 0.30$ ,  $p = 0.226$ ;  $r = 0.58$ ,  $p = 0.01$ ; Table 5.3 and Table 5.4). However, this analysis aims to explore if catchment size classification has an impact on the strength of correlations with other variables. Catchments were classified according to their size (see Table 3.4 and Table 5.2) into micro-catchments, sub-catchments and large-catchments. From this array, only micro- and sub-catchments were used to execute the analysis because it was deemed that there were not enough large catchments to perform statistical analysis. Outliers previously identified were also removed to not influence the statistical analysis. The results of the Mann-Whitney U test analysis are shown in Figure 5-7 and confirm that micro-catchments and sub-catchments are not significantly different ( $W = 33$ ,  $p = 0.572$ ). Although the variance is larger for sub-catchments, the results of a Levene's test indicate that the variance of both classes is not significantly different either ( $f = 2.758$ ,  $p = 0.116$ ). The box plot also indicates that the peak flow for the sub-catchments is not always larger compared to micro-catchments indicating that, for these catchments, larger areas do not produce larger peak flows. This also suggests that the area is not the only driver of peak flows within this particular set up of the model (i.e. particular rainfall event). The same analysis was also performed for the lag time. Results indicate the lag time between size classes are significantly different ( $W = 26$ ,  $p\text{-value} = 0.046$ ).

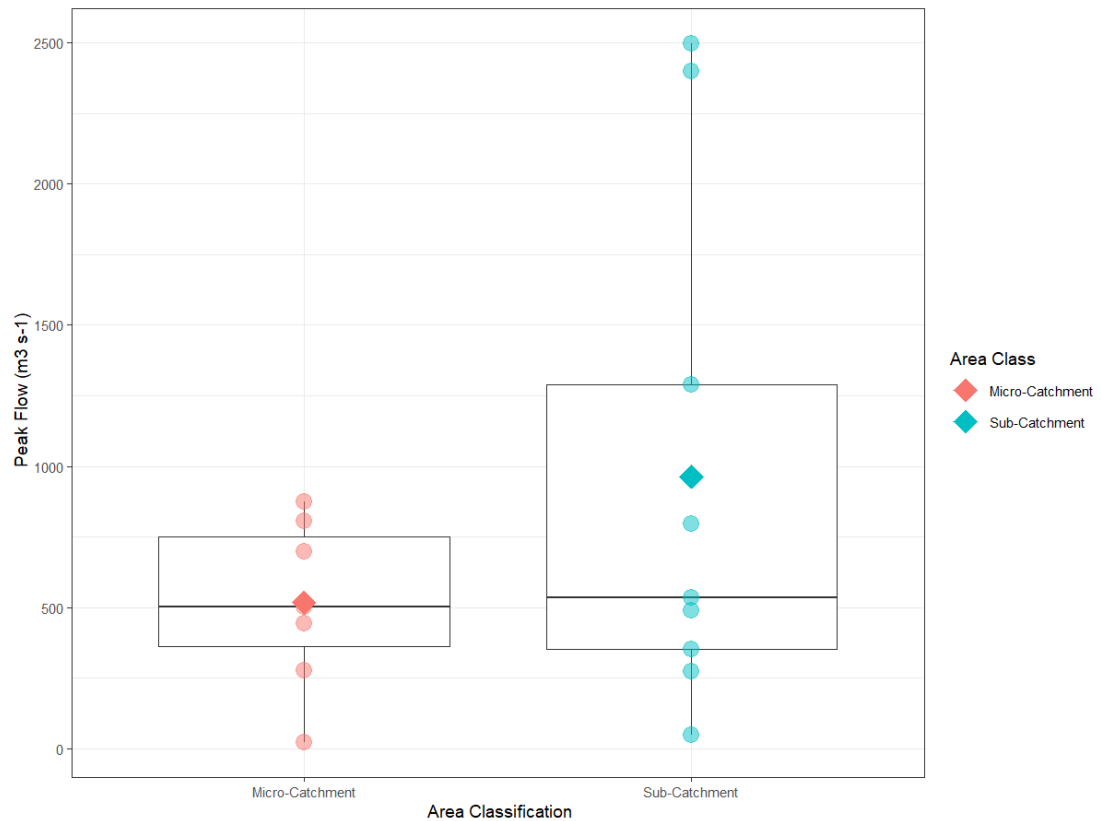


Figure 5-7 Box-plots showing the median of peak flow in each area class (black horizontal line), mean peak flow in each area class (diamond), with boxes indicating the interquartile range (IQR) and coloured points indicating the peak flow of all individual catchments.

Although the IQR range is clearly larger for sub and micro-catchments no statistical differences were found between classes and there is no correlation between catchment size and peak flow across all catchments, or within the sub-catchment class. However, a strong relationship was found between the catchment area and peak flow within the group micro-catchments ( $r = 0.80$ ,  $p = 0.016$ ). Peak flow and the torrentiality coefficient also had high  $r$ -values but were not significant ( $r = -0.70$ ,  $p = 0.121$ ). In contrast, area is insignificant for sub-catchments and torrentiality coefficient becomes significant ( $r = 0.72$ ,  $p = 0.043$ ). Slope is also significant in sub-catchments ( $r = 0.90$ ,  $p = 0.001$ ) but not in micro-catchments (Table 5.5). For sub-catchments, the drainage density is significantly correlated to peak flow ( $r = 0.84$ ,  $p = 0.008$ ) whereas it is insignificant for micro-catchments. Some correlations, such as the peak flow with drainage density and mass coefficient in the micro-catchment class, have no clear trends which might be attributed to the lack of data in each group due to the removal of outliers (Figure 5.8).

The polynomial regression analysis indicates that peak flow is highly correlated to area in micro-catchments ( $r = 0.84$ ,  $p = 0.047$ ). Other parameters such as average width, compass index, slope and torrential coefficient in micro catchments had a high  $r$ -value but its  $p$ -value indicates these were not statistically significant. As for the sub-catchments just drainage density and slope were significantly correlated to peak flow ( $r = 0.89$ ,  $p = 0.022$ ;  $r = 0.92$ ,  $p = 0.004$ ). Although some catchment parameters have stronger correlations when using the polynomial regression, the partial F test indicates that none were a significantly better fit than the linear equivalent. Thus, only the highly correlated parameters from linear models were considered.

Table 5.5. R and  $p$  values from the matrix correlation between parameters of the catchment and Peak flow classified by Catchment Area.

| Peak Flow              |                    |             |            |                  |                 |                            |                                    |         |
|------------------------|--------------------|-------------|------------|------------------|-----------------|----------------------------|------------------------------------|---------|
| Catchment<br>Parameter | Linear model       |             |            | Polynomial model |                 |                            | F test<br>Model<br>difference<br>s |         |
|                        | Micro-Catchment    |             |            |                  |                 |                            |                                    |         |
|                        | r                  | P-<br>value | Equation   | r                | P-<br>valu<br>e | Equation                   |                                    | p-value |
| Area                   | 0.80               | 0.016       | y=-72+13x  | 0.84             | 0.047           | y=300-59x+0.17x^2          | 0.356                              |         |
| Average Width          | 0.66               | 0.077       | y=-48+210x | 0.77             | 0.108           | y=1200-640x+120x^2         | 0.224                              |         |
| Compactness Index      | -0.58              | 0.132       | 2500-1100x | 0.77             | 0.104           | y=15000-17000x+48000x^2    | 0.134                              |         |
| Drainage Density       | -0.28              | 0.647       | 5400-4100x | 0.32             | 0.901           | y=140000+240000x-1x10^5x^2 | 0.852                              |         |
| Form Factor            | 0.26               | 0.539       | 370+1400x  | 0.36             | 0.706           | y=1400-10000x+28000x^2     | 0.571                              |         |
| Mass Coef              | -0.11              | 0.885       | 530-21x    | 0.65             | 0.757           | y=3800-1300x+120x^2        | 0.102                              |         |
| Slope                  | 0.67               | 0.070       | 270+13x    | 0.70             | 0.180           | y=450-3.1x+0.22x^2         | 0.515                              |         |
| Torrentiality Coef     | -0.70              | 0.121       | 2600-2400x | 0.75             | 0.289           | y=-7200+21000-14000x^2     | 0.533                              |         |
|                        | Sub-Catchment      |             |            |                  |                 |                            |                                    |         |
|                        | Area               | 0.20        | 0.611      | y=650+1.1x       | 0.41            | 0.575                      | y=2400-12x+0.021x^2                | 0.371   |
|                        | Average Width      | 0.33        | 0.393      | y=240+98x        | 0.36            | 0.661                      | y=1200-180x+17x^2                  | 0.706   |
|                        | Compactness Index  | -0.58       | 0.099      | y=4800-2300x     | 0.71            | 0.121                      | y=23000-24000x+6200x^2             | 0.207   |
|                        | Drainage Density   | -0.84       | 0.008      | y=9200-6800x     | 0.89            | 0.022                      | y=40000-58000x+21000x^2            | 0.258   |
|                        | Form Factor        | 0.52        | 0.155      | y=-500+6900x     | 0.62            | 0.230                      | y=2300-25000x+81000x^2             | 0.317   |
|                        | Mass Coef          | 0.59        | 0.093      | y=510+88x        | 0.69            | 0.139                      | y=200+400x-22x^2                   | 0.263   |
|                        | Slope              | 0.90        | 0.001      | y=71+34x         | 0.92            | 0.004                      | y=370-3.8x+0.57x^2                 | 0.335   |
|                        | Torrentiality Coef | -0.72       | 0.043      | y=15000-16000x   | 0.82            | 0.063                      | y=140000-210000x+170000x^2         | 0.193   |

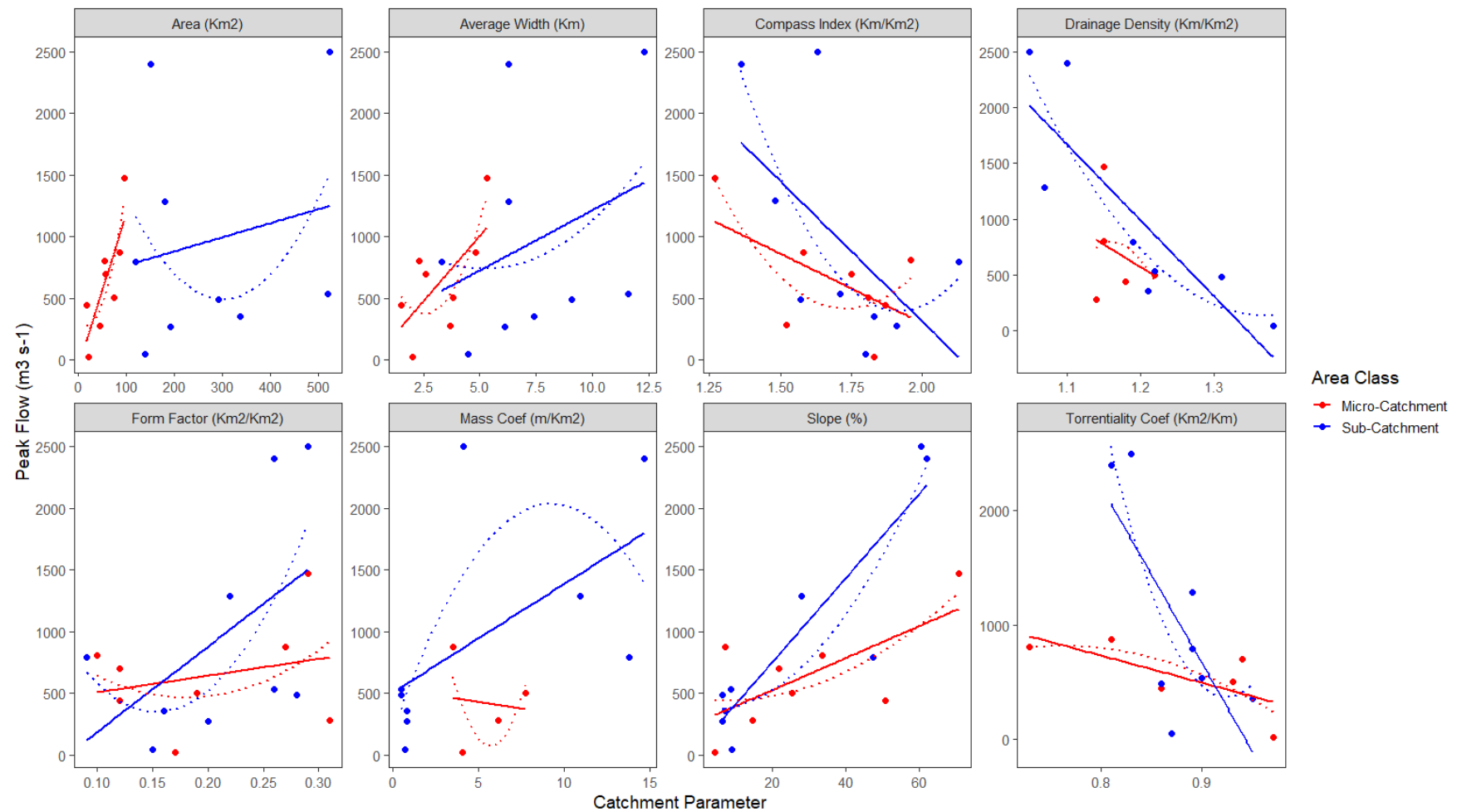


Figure 5-8 Scatter plot between peak flow and catchment parameters. Coloured points indicating the distribution of the data according to each size class. Linear and polynomial regression adjusted to the data for each area class. Excluding outliers.

The same analysis for lag time and catchment parameters was performed within each of the two size categories. Results are presented in Table 5.6 and Figure 5.9 and indicate that none of the parameters of the catchments are significantly correlated in micro-catchments when fitting the data to a linear regression except mass coefficient ( $r = 1.00$ ,  $p = 0.028$ ). However, this particularly high correlation is likely associated with the lack of data, as a result of removing clear outliers within this parameter. As for sub-catchments, mass coefficient and slope are negatively correlated to lag time ( $r = 0.86$ ,  $p = 0.007$ ;  $r = 0.87$ ,  $p = 0.005$ ). In contrast, it was found that only the mass coefficient was significantly correlated in sub-catchments using the polynomial model. There were no correlations found in micro-catchments using this regression. In terms of the partial F test, the result indicates that the drainage density in the micro-catchments and compactness index in the sub-catchments had better fit than the linear regression ( $p = 0.031$ ,  $p = 0.047$ ). Although the statistical test suggests that the polynomial model fitted better the data, the p values indicated no significant correlation for none of these variables.

Table 5.6 R and p values from the matrix correlation between parameters/variables of the catchment Vs lag time classified by Micro and Sub-catchments.

| Time Lag               |                   |             |               |                  |             |                           |                          |       |
|------------------------|-------------------|-------------|---------------|------------------|-------------|---------------------------|--------------------------|-------|
| Catchment<br>Parameter | Linear model      |             |               | Polynomial model |             |                           | F test<br>Model<br>diff  |       |
|                        | Micro-Catchment   |             |               |                  |             |                           |                          |       |
|                        | r                 | P-<br>value | Equation      | r                | P-<br>value | Equation                  | p-value                  |       |
| Area                   | 0.29              | 0.525       | y=0.7+0.0045X | 0.66             | 0.312       | y=-0.28+0.046x-0.00036x^2 | 0.185                    |       |
| Average Width          | 0.37              | 0.408       | y=0.59+0.11X  | 0.52             | 0.240       | y=-1.7+1.7x-0.23x^2       | 0.013                    |       |
| Compactness Index      | 0.05              | 0.909       | y=1.1-0.093X  | 0.53             | 0.512       | y=-10+14x-4.4x^2          | 0.2784                   |       |
| Drainage Density       | 0.32              | 0.603       | y=-4.7+4.8x   | 0.99             | 0.055       | y=960-1600x+700x^2        | 0.031                    |       |
| Form Factor            | 0.42              | 0.351       | y=0.59+1.9x   | 0.54             | 0.498       | y=-0.72+17x-38x^2         | 0.456                    |       |
| Mass Coef              | 1.00              | 0.028       | y=0.67+0.12x  | 0.98             | 0.850       | y=0.54+0.17x-0.0048x^2    | 0.862                    |       |
| Slope                  | -0.65             | 0.112       | y=1.4-0.012x  | 0.66             | 0.325       | y=1.4-0.018x+7.2x10^-5x^2 | 0.859                    |       |
| Torrentiality Coef     | 0.53              | 0.634       | y=-0.27+1.4x  | 0.40             | 0.837       | y=15-36x+22x^2            | 0.708                    |       |
|                        | Sub-Catchment     |             |               |                  |             |                           |                          |       |
|                        | Area              | 0.44        | 0.279         | y=1+0.01x        | 0.77        | 0.102                     | y=-9.7+0.094x-0.00013x^2 | 0.074 |
|                        | Average Width     | 0.33        | 0.432         | y=0.6+0.42x      | 0.51        | 0.468                     | y=-7.8+2.8x-0.14x^2      | 0.351 |
|                        | Compactness Index | 0.27        | 0.526         | y=-2+3.4x        | 0.78        | 0.095                     | y=-88+100x-29x^2         | 0.047 |
|                        | Drainage Density  | 0.71        | 0.071         | y=-25+25x        | 0.73        | 0.219                     | y=-75+110x-38x^2         | 0.690 |
|                        |                   |             |               |                  |             |                           |                          |       |

|                           |       |       |               |      |       |                        |       |
|---------------------------|-------|-------|---------------|------|-------|------------------------|-------|
| <b>Form Factor</b>        | 0.01  | 0.989 | $y=3+3.4x$    | 0.37 | 0.688 | $y=-2+61x-150x^2$      | 0.410 |
| <b>Mass Coef</b>          | -0.86 | 0.007 | $y=6.6-0.41x$ | 0.92 | 0.009 | $y=7.5-1.2x+0.052x^2$  | 0.110 |
| <b>Slope</b>              | -0.87 | 0.005 | $y=7.2-0.11x$ | 0.36 | 0.009 | $y=9.1-0.34x+0.035x^2$ | 0.129 |
| <b>Torrentiality Coef</b> | 0.69  | 0.088 | $y=-16+23x$   | 0.70 | 0.254 | $y=87-240x+170x^2$     | 0.682 |

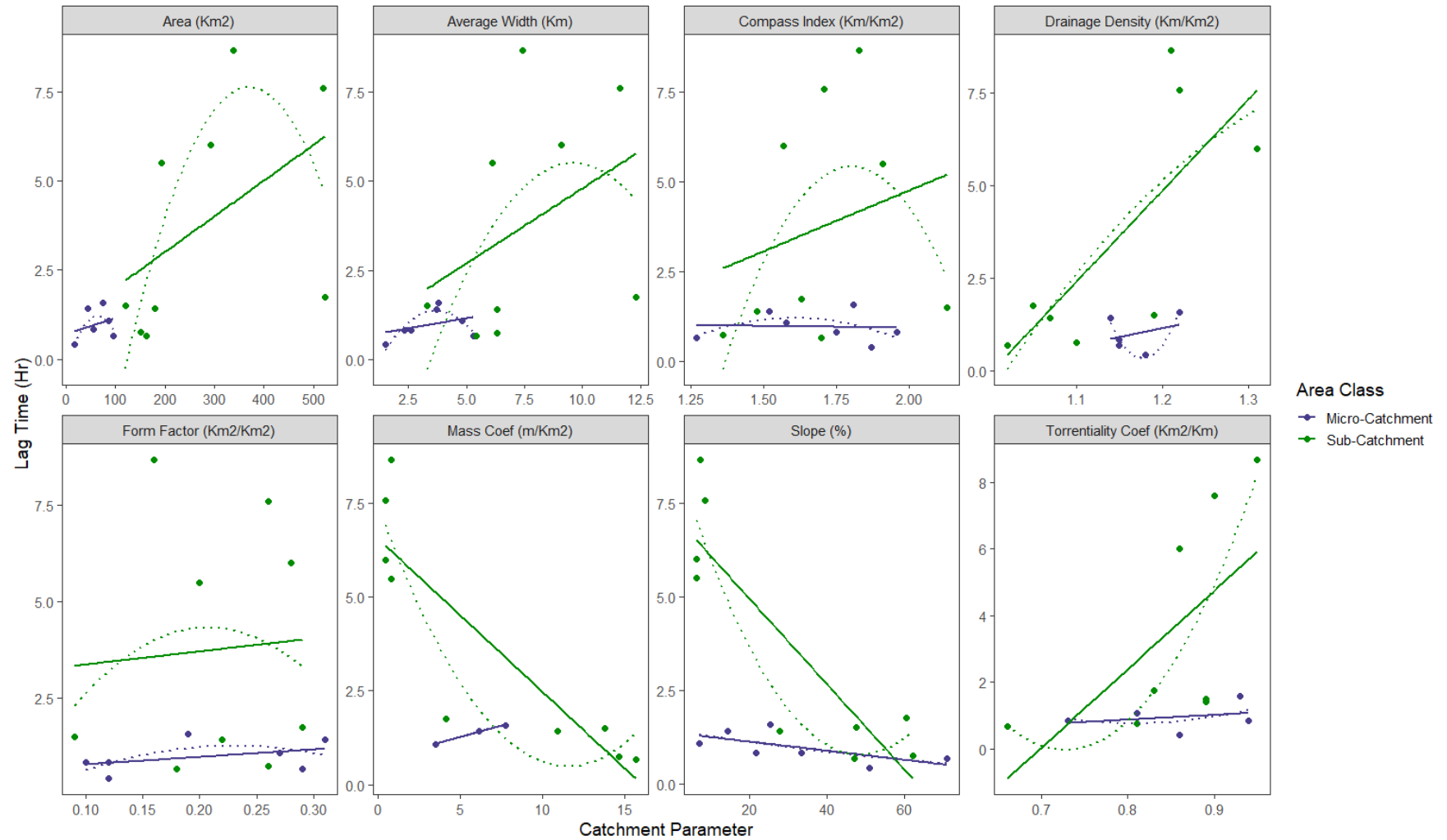


Figure 5-9 Scatter plot between lag time and catchment parameters. Coloured points indicating the distribution of the data according to each size class. Linear and polynomial regression adjusted to the data for each area class. Excluding outliers.



#### 5.4.4 Relationship between peak flow and morphometric clusters

Peak flow was also examined within the catchment clusters determined in Section 4.3.2. A Mann-Whitney U test was performed between the peak flows for each cluster. The null hypothesis was that the median of the peak flows is the same for both clusters. 'Cluster B', which was the small sized and rounded catchments, has been removed from the analysis as it only contained 3 catchments (see Table 5.2). The results of the Mann-Whitney U test are presented in Figure 5-10 and significant differences were found between Cluster A (small catchments [less than 100 km<sup>2</sup>] with elongated shapes) and Cluster C (relatively large in size [more than 100 km<sup>2</sup>] with rounded shapes) ( $W = 12$ ,  $p = 0.024$ ). The variance differs substantially between Cluster A and C but a Levene's test suggests that this difference was not significant ( $f = 4.209$ ,  $p = 0.06$ ).

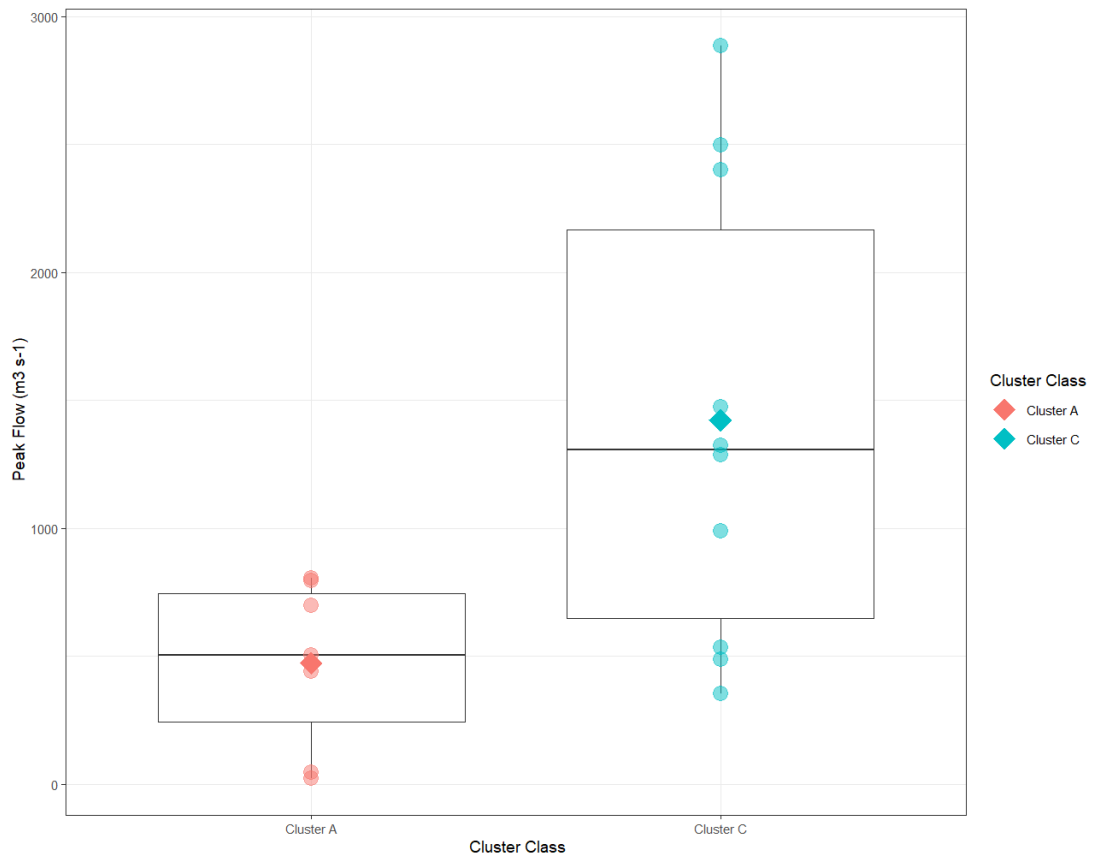


Figure 5-10 Box-plots showing the median peak flow in each cluster (black horizontal line), the mean peak flow (diamond), interquartile range (IQR) of peak flows (boxes) and the complete data set (coloured points).

Linear and non-linear correlations between peak flow and catchment parameters and for the cluster groups are shown in Figure 5-11. The figure shows that the distribution of each cluster within the whole data set except cluster B. It can be seen in cluster A that catchments tend to have lower values for area, average width and form factor whereas cluster C catchments have higher values for these parameters. In contrast, cluster A have a narrower range, tending to higher values for the compass index, drainage density and torrentiality coefficient compared to cluster C, where catchments have a wider range. As for the slope, catchments in cluster A have a narrower range tending to lower values compared to catchments in cluster C. In terms of the linear and non-linear regressions, some of them have abnormal tendencies, such as the polynomial model for area, average width and mass coefficient in cluster C and compass index and torrentiality coefficient in cluster A.

The matrix correlation analysis between peak flow and catchment parameters within each of the two clusters and for both regressions was executed (Table 5.7). Results indicate that the strongest correlation for the linear model was between peak flow and drainage density in both clusters (Cluster A  $r = -0.89$ ,  $p = 0.042$ ; Cluster C  $r = -0.76$ ,  $p = 0.018$ ). Area was reasonably correlated to peak flow ( $r = 0.65$ ,  $p = 0.016$ ) in cluster A but not in cluster C. Mass coefficient was also highly correlated with peak flow in cluster A ( $r = 0.97$ ,  $p = 0.030$ ) but this high correlation might be due to the lack of data within this group because after removing the outliers, the group had just three catchments within it. Slope also had a high correlation with peak flow in cluster C ( $r = 0.86$ ,  $p = 0.003$ ) but was insignificant in cluster A. In contrast, the polynomic regressions in cluster A were not significantly correlated for any variable. However, in cluster C mass coefficient and slope were highly correlated to the peak flow with polynomial trends ( $r = 0.94$ ,  $p = 0.035$ ;  $r = 0.90$ ,  $p = 0.008$ ). The overall lack of correlation for the polynomial model in cluster A could be attributed to the limited data points.

The partial F test performed to evaluate which model fits better have suggested that none of the catchment parameters is statistically significant in cluster A except for mass coefficient. However, mass coefficient was not considered due to the lack of data within the group as mentioned above. As for the polynomial model in cluster C, none of the catchments parameters provides a statistically better fit compared to the linear model ( $p > 0.05$ ).

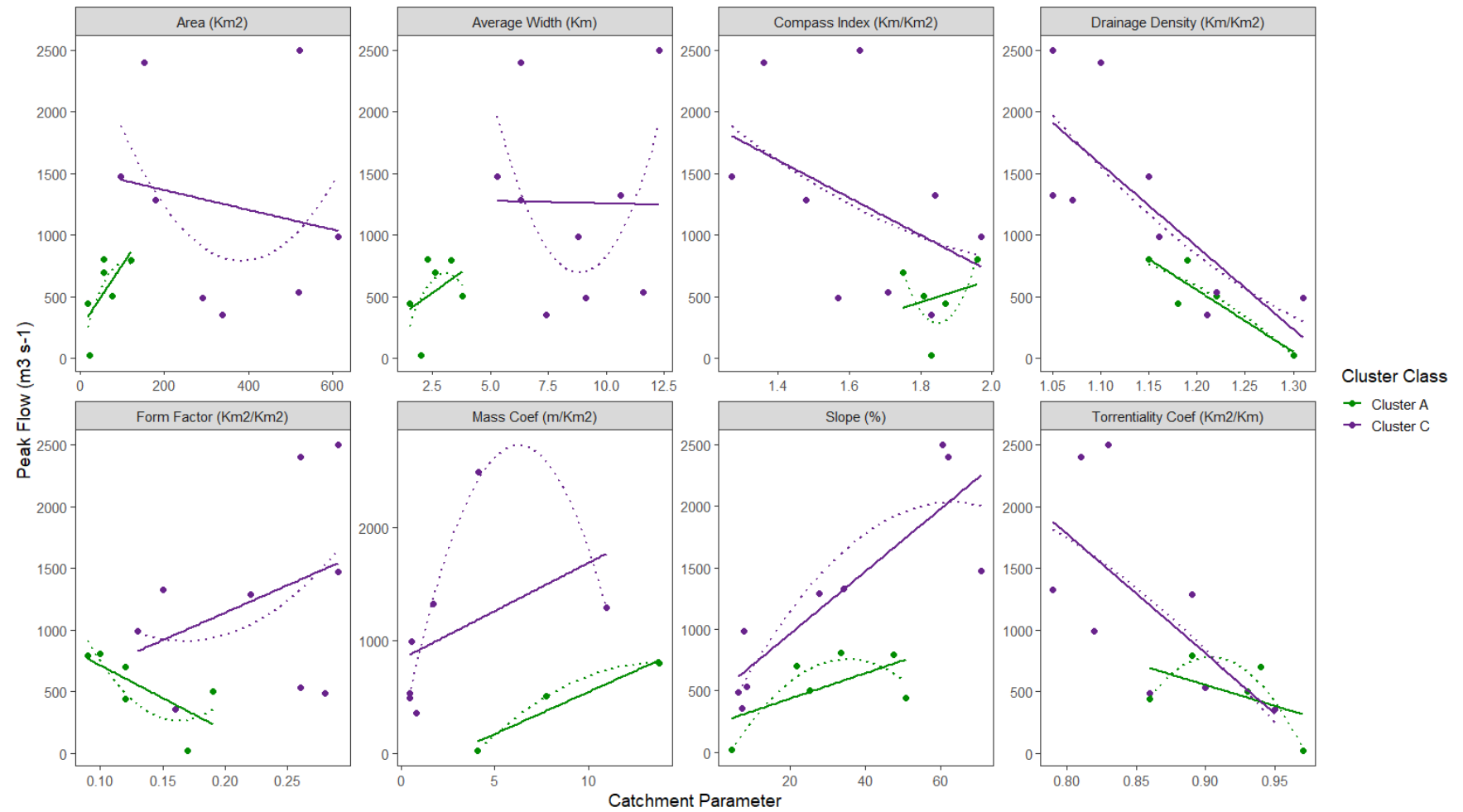


Figure 5-11 Scatter plot between peak flow and catchment parameters. Coloured points indicating the distribution of the data according to each cluster class. Linear and polynomial regression adjusted to the data for each cluster class. Excluding outliers.

Table 5.7. R and *p* values from the matrix correlation between parameters of the catchment and Cluster A and C.

| Peak Flow              |                    |             |               |                  |             |                             |                         |       |
|------------------------|--------------------|-------------|---------------|------------------|-------------|-----------------------------|-------------------------|-------|
| Catchment<br>Parameter | Linear model       |             |               | Polynomial model |             |                             | Model<br>differences    |       |
|                        | Cluster A          |             |               |                  |             |                             |                         |       |
|                        | r                  | p-<br>value | Equation      | r                | p-<br>value | Equation                    | p-value                 |       |
| Area                   | 0.65               | 0.016       | y=250+5.1x    | 0.71             | 0.343       | y=-150+23x-0.14x^2          | 0.520                   |       |
| Average Width          | 0.38               | 0.462       | y=200+130x    | 0.51             | 0.635       | y=-1300+1400x-240x^2        | 0.535                   |       |
| Compactness Index      | 0.23               | 0.705       | y=-1200+910x  | 0.82             | 0.329       | y=160000-170000x+46000x^2   | 0.193                   |       |
| Drainage Density       | -0.89              | 0.042       | y=66000-5000x | 0.90             | 0.194       | y=27000-38000x+14000x^2     | 0.758                   |       |
| Form Factor            | -0.71              | 0.114       | y=1200-5300x  | 0.82             | 0.193       | y=1300-52000x+170000x^2     | 0.314                   |       |
| Mass Coef              | 0.97               | 0.030       | y=-200+75x    | 1.00             | 0.012       | y=-43+48x+x^2               | 0.032                   |       |
| Slope                  | 0.63               | 0.254       | y=230+10x     | 0.89             | 0.214       | y=310+59x-.82x^2            | 0.197                   |       |
| Torrentiality Coef     | -0.59              | 0.222       | y=3600-3400x  | 0.68             | 0.396       | y=-160000+340000x-190000x^2 | 0.477                   |       |
| Catchment<br>Parameter | Cluster C          |             |               |                  |             |                             |                         |       |
|                        | Area               | -0.19       | 0.660         | 1500-0.8x        | 0.44        | 0.590                       | y=2700-10x+0.013x^2     | 0.415 |
|                        | Average Width      | -0.01       | 0.973         | 1300-4.1x        | 0.61        | 0.254                       | y=8600-1800x+100x^2     | 0.112 |
|                        | Compactness Index  | -0.45       | 0.221         | 3700-1500x       | 0.46        | 0.495                       | y=6500-5000x+1100x^2    | 0.861 |
|                        | Drainage Density   | -0.76       | 0.018         | 8900-6700x       | 0.76        | 0.072                       | y=23000-21000x+10000x^2 | 0.731 |
|                        | Form Factor        | 0.36        | 0.335         | 250+4500x        | 0.39        | 0.609                       | y=2300-17000x+50000x^2  | 0.721 |
|                        | Mass Coef          | 0.47        | 0.346         | 830+86x          | 0.94        | 0.035                       | y=140+830x-66x^2        | 0.382 |
|                        | Slope              | 0.86        | 0.003         | 450+26x          | 0.90        | 0.008                       | y=12+61x-0.48x^2        | 0.240 |
|                        | Torrentiality Coef | -0.63       | 0.094         | 9600-9700x       | 0.63        | 0.278                       | y=-4200+22000x-18000x^2 | 0.879 |

#### 5.4.5 Relationship between peak flow and hypsometric curves

The hypsometric curve is an important physiographic parameter of catchments that represent either the relative area below or above a given altitude (Strahler, 1952b). The uses of the hypsometric curves are many; from differentiating between tectonically active and inactive areas (Keller and Pinter, 1996) to deducing the development of river drainage networks (Sarp et al., 2011). They have also been widely used to classify catchments between young, mature equilibrium, and monadnock stage (Strahler, 1952b) (see Figure 3-7), which describes the erosion potentiality of a catchment. Figure 5-12 and Figure 5-13 shows the hypsometric curves calculated for the catchments considered in this study. In Figure 5-13, the continuous black lines are the threshold conditions that define the three hypsometric curve categories. From the full set of catchments, twelve have been classified as a mature stage, six as young stage, and two as old stage.

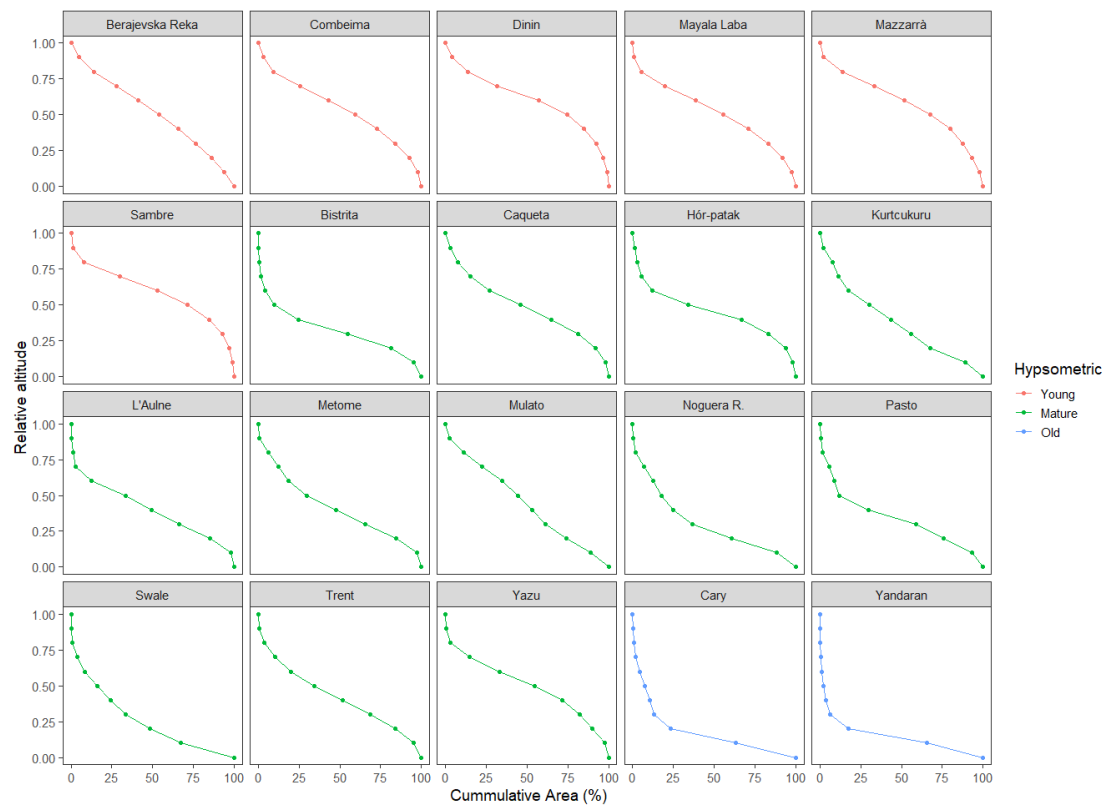


Figure 5-12 Hypsometric curves of the full set of catchments, coloured according to whether they fit within the young, mature or old categories.

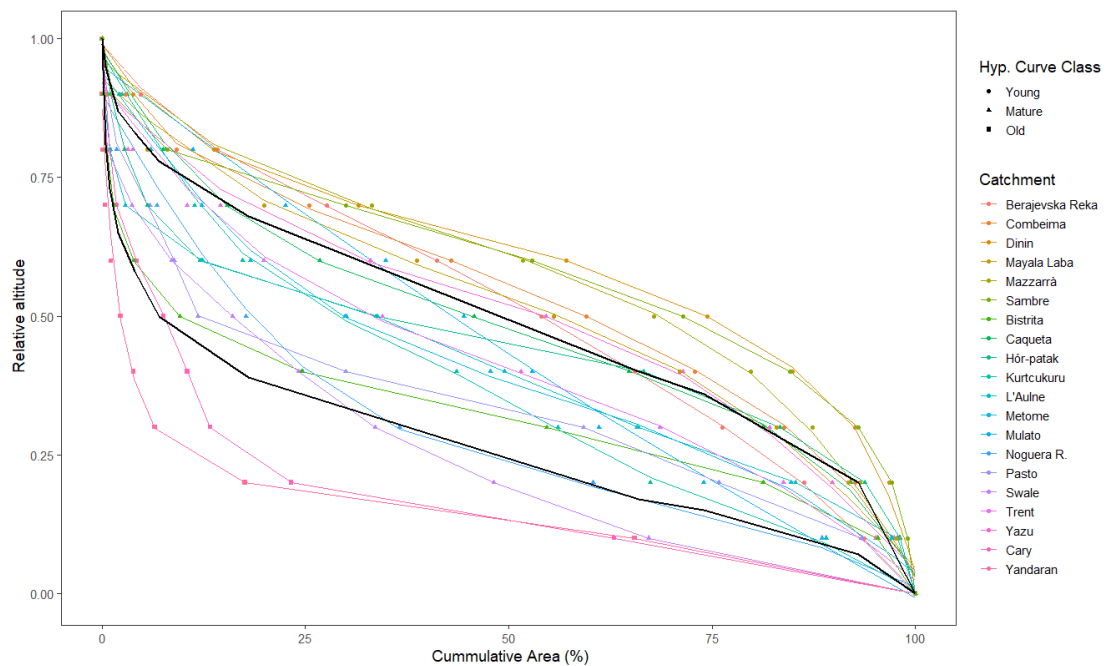


Figure 5-13 Hypsometric curves of the full set of catchments. The threshold between Young, Mature, and Old is delineated by the continues black lines.

The peak flow in catchments within each hypsometric curve category was compared by performing a Mann-Whitney U test. The analysis aimed to determine whether different categories of catchments based on their hypsometric curves have different hydrological responses. The null hypothesis is that the median of the peak flows is the same between hypsometric curves. 'Old curves', which have flatter catchments, have been removed from the analysis as there are only 2 catchments in this class. Figure 5-14 shows the variation of the peak flow between hypsometric curve classes. Results show that there is not a significant difference between hypsometric curve classes ( $W = 32$ ,  $p = 0.750$ ). A Levene's test also indicates that the variance between young and mature hypsometric curve classes are not significantly different ( $f = 1.451$ ,  $p = 0.245$ ).

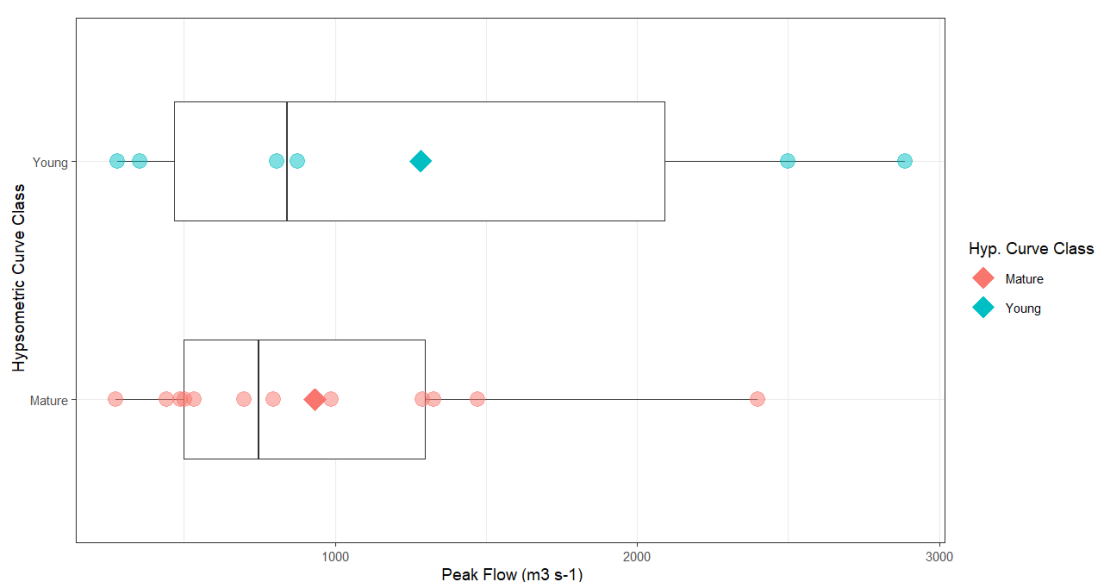


Figure 5-14 Box-plots showing the median of peak flow in each hypsometric curve class (black vertical line), mean peak flow in each area class (diamond), with boxes indicating interquartile range (IQR) of peak flow and coloured points indicating the peak flow of individual catchments.

Linear and polynomial regressions between peak flow and morphometric parameters were executed within each hypsometric group, as performed for size and shape classes, above (Figure 5-15). Results are presented in Table 5.8 and indicate slope in the linear model is highly correlated in both groups (Young  $r = 0.89$ ,  $p = 0.044$ , Mature  $r = 0.63$ ,  $p = 0.028$ ). Drainage density is also significantly negatively correlated to peak flow in the mature class ( $r = -0.70$ ,  $p = 0.024$ ) but

not correlated to young catchments. In the mature class, compactness index was correlated but to a lesser degree ( $r = -0.60$ ,  $p = 0.039$ ). Area was not correlated to peak flow in either group. As for the polynomial regression, similar to the cluster class analysis, most of the parameters in the Young class had a high  $r$ -value but not statistically significant. In contrast, in the Mature group, it was found that relationship between the compactness index and the peak flow was highly significant ( $r = 0.72$ ,  $p = 0.038$ ). As in the previous analysis, the partial F test suggested that none of the polynomial regressions has a statistically better fit to the data either for the Young and Mature class compared to the linear model.

Table 5.8 R and  $p$  values from the matrix correlation between parameters of the catchment and Peak flow classified by hypsometric curve classes.

| Peak Flow                  |                           |             |              |                  |             |                           |                                |
|----------------------------|---------------------------|-------------|--------------|------------------|-------------|---------------------------|--------------------------------|
| Catchment<br>Parameter     | Linear model              |             |              | Polynomial model |             |                           | F test<br>Model<br>differences |
|                            | Hypsometric Curve - Young |             |              |                  |             |                           |                                |
|                            | r                         | p-<br>value | Equation     | r                | p-<br>value | Equation                  | p-value                        |
| Area                       | 0.72                      | 0.170       | y=330+3x     | 0.93             | 0.133       | y=1100-9.8x+0.024x^2      | 0.149                          |
| Average Width              | 0.78                      | 0.117       | y=-130+180x  | 0.95             | 0.099       | y=1700-470x+43x^2         | 0.138                          |
| Compactness Index          | -0.14                     | 0.821       | y=2100-690x  | 0.44             | 0.806       | y=-56000+67000x-19000x^2  | 0.578                          |
| Drainage Density           | -0.64                     | 0.241       | y=9600-7700x | 0.64             | 0.586       | y=4500+1400x-4100x^2      | 0.978                          |
| Form Factor                | 0.30                      | 0.630       | y=310+2900x  | 0.30             | 0.913       | y=350+2300x+1400x^2       | 0.994                          |
| Mass Coef                  | 0.11                      | 0.889       | y=810+52x    | 0.74             | 0.672       | y=-700+1300x-190x^2       | 0.725                          |
| Slope                      | 0.89                      | 0.044       | y=99+35x     | 0.97             | 0.055       | y=790-40x+1.1x^2          | 0.140                          |
| Torrentiality Coef         | -0.22                     | 0.783       | y=3000-2200x | 0.73             | 0.688       | y=-66000+160000x-98000x^2 | 0.498                          |
| Hypsometric Curve - Mature |                           |             |              |                  |             |                           |                                |
| Area                       | 0.03                      | 0.937       | y=900+0.25x  | 0.52             | 0.387       | y=110x-0.047x^2           | 0.187                          |
| Average Width              | 0.13                      | 0.688       | y=780+24x    | 0.45             | 0.363       | y=-160+390x-28x^2         | 0.183                          |
| Compactness Index          | -0.60                     | 0.039       | y=3400-1400x | 0.72             | 0.038       | y=13000-14000x+3600x^2    | 0.122                          |
| Drainage Density           | -0.70                     | 0.024       | y=7500-5600x | 0.70             | 0.094       | y=13000-16000x+4300x^2    | 0.865                          |
| Form Factor                | 0.30                      | 0.348       | y=440+2600x  | 0.31             | 0.630       | y=990-3900x+17000x^2      | 0.767                          |
| Mass Coef                  | 0.74                      | 0.093       | y=600+63x    | 0.81             | 0.205       | y=760-98x+11x^2           | 0.411                          |
| Slope                      | 0.63                      | 0.028       | y=410+17x    | 0.64             | 0.093       | y=530+5.8x+0.16x^2        | 0.689                          |
| Torrentiality Coef         | -0.59                     | 0.071       | y=7100-7100x | 0.64             | 0.157       | y=57000-120000x+67000x^2  | 0.427                          |

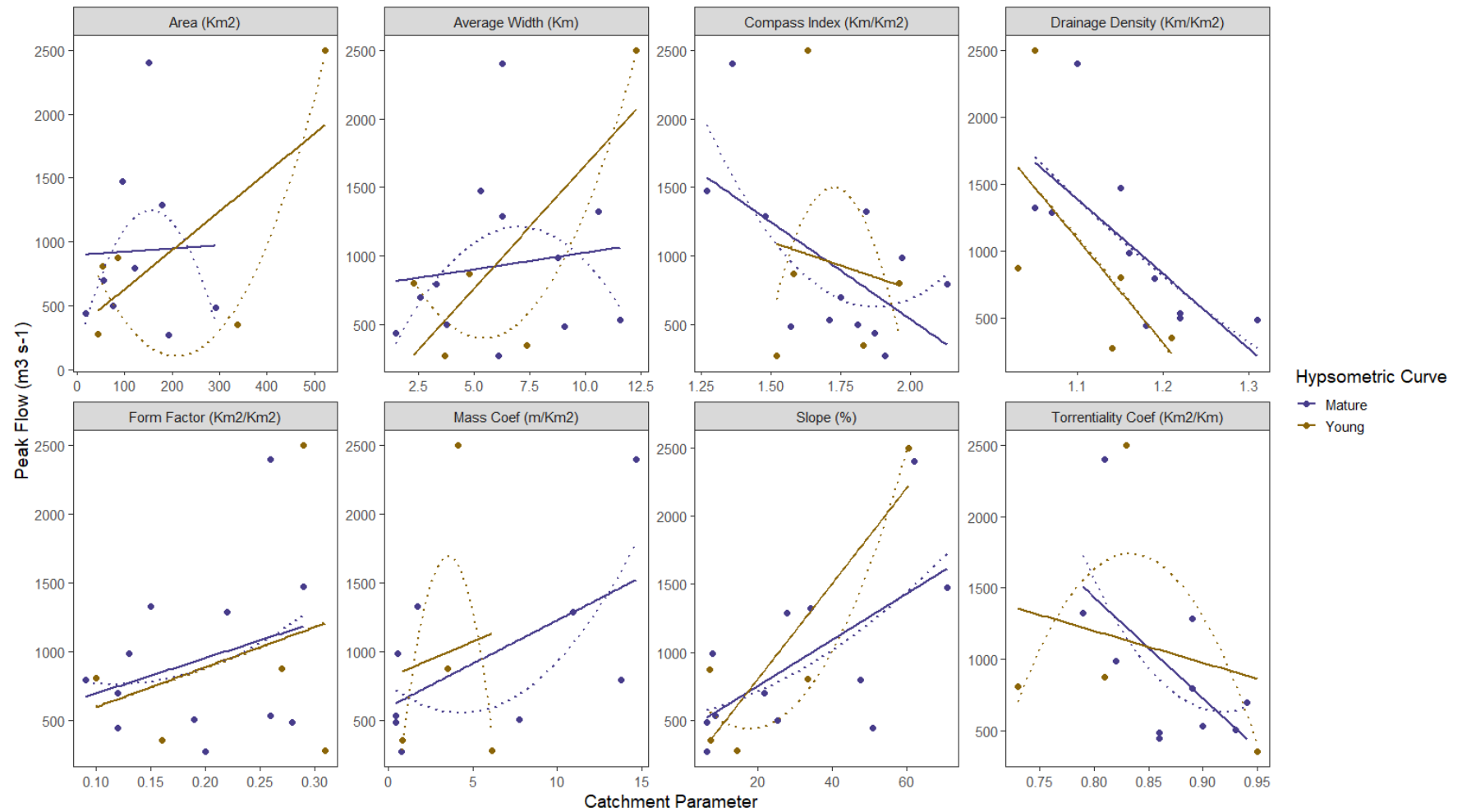


Figure 5-15 Scatter plot between peak flow and catchment parameters. Coloured points indicating the distribution of the data according to each hypsometric curve class. Linear and polynomial regression adjusted to the data for each class.



#### **5.4.6 Effect of rainfall type on peak flow and lag time**

In preceding sections, the analysis has considered a single left-skewed hyetograph. Here, the influence of four rainfall distributions (i.e. hyetographs) were considered and are described in section 3.7 (e.g. unimodal left-skewed, unimodal right-skewed, unimodal with centred peak and rectangular). The complete set of hydrographs calculated for every hyetograph distribution for each catchment are shown in Figure 5-16. Visually, it can be seen that many of the hydrographs within catchments are similar for different rainfall distributions. However, differences might be hidden in catchments such as Cary, L'Aulne, Metome, Sambre, Trent, Swale or Yandaran where the scale of the plot used for these catchments could cause the differences not to be seen. Despite the scale, what can be seen is in most of the catchments the higher peak flow is for the right-skewed distribution. However, it will be statistically assessed in the next section.

The shape of the hydrographs also seems to be consistent regardless of the rainfall distribution. For example, catchments such as Bistrita, Carry, Metome and Yandaran whose hydrographs present a lump in the rising limb for control rainfall [right-skewed rainfall] have similar patterns when using the other rainfall distributions. It was also expected that the rectangular hydrograph would have a lower peak flow than the other distributions but, this is only evident in some of the steepest catchments such as Combeima, Zayu, Mulato, and Caquetá. This suggests that changes in the rainfall distribution might be more evident in steep catchments rather than flatter catchments.

Figure 5-17 depicts the peak flow for each rainfall type on each catchment. The peak flow was standardized relative to the control rainfall [right-skewed rainfall]. Catchments such as Zayu, Mulato, Combeima, Caquetá, Swale and Bistrita catchments have greater variance between rainfall events and the highest peak flows across catchments are derived from right-skewed hyetographs, except for the Kurtcukuru catchment, which has its highest peak from the centred distribution. The lowest peak flows across all catchments come from the rectangular distribution except for Kurtcukuru, Hor-patak, Dinin, Cary, Barajevska, L'Aulne, Bistrita and Swale. There is a group of catchments (Yandaran, Trent, Sambre, Metome and L'Aulne) that are all in the sub-catchments size class where the variance between peak flows is insignificant ( $p > 0.89$ ). Finally, the large catchment area class (e.g. Bistrita and Swale) have similar peak flows for centred, right-skewed and rectangular distributions but the peak from the left-skewed distribution is more different from their mean.

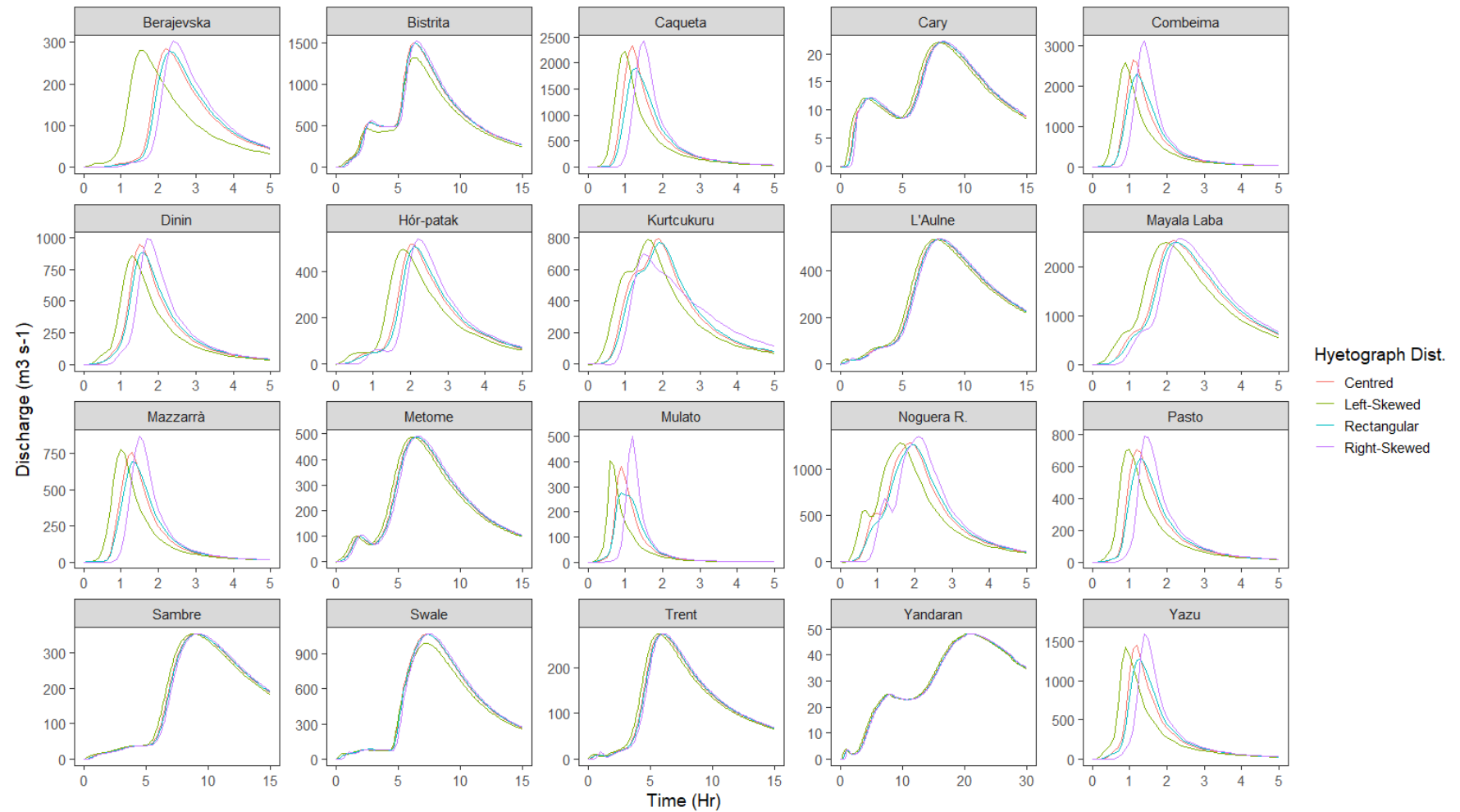


Figure 5-16 Hydrographs of the full set of catchments under 60 mm/hr rainfall event and four hyetographs distributions, unimodal left-skewed, unimodal right-skewed, unimodal with centred peak, and rectangular. The coloured lines are the hydrographs for each rainfall distribution.

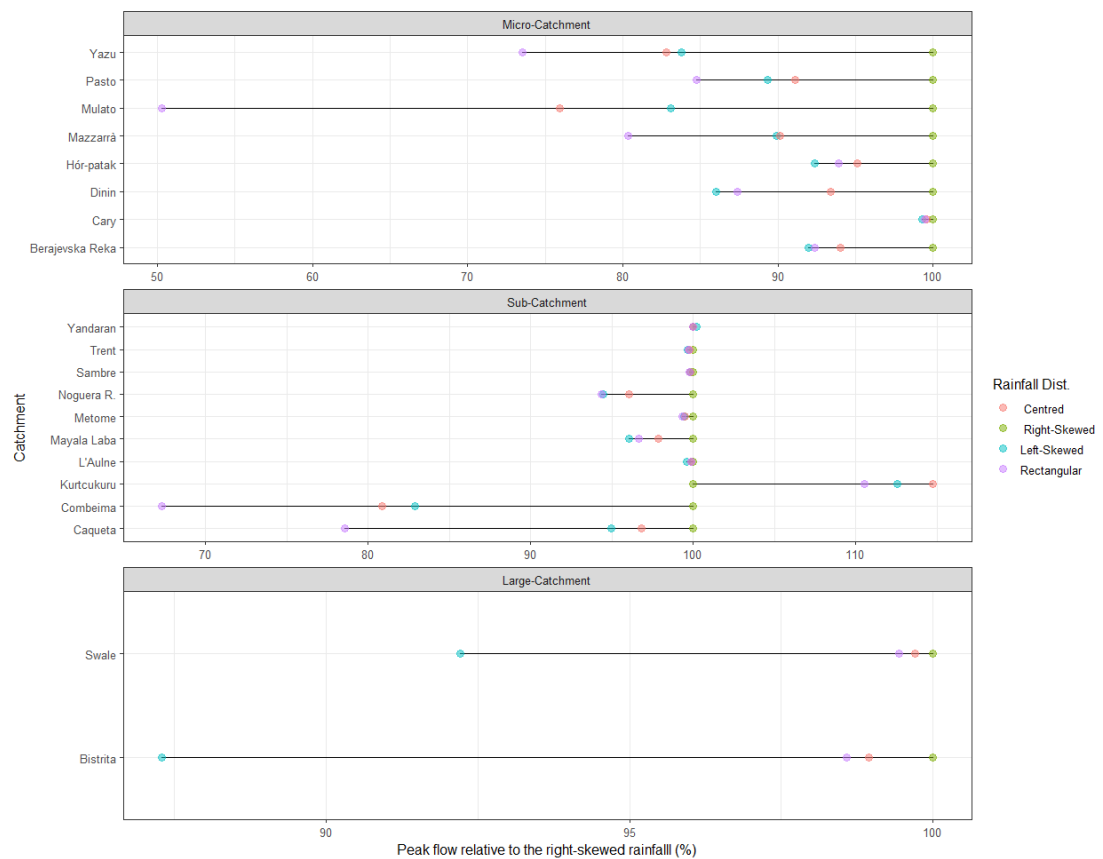


Figure 5-17 Percentage of the peak flow relative to the right-skewed rainfall in each catchment and for each rainfall distribution (coloured points). Catchments were classified by the catchment area classification for a better interpretation of the data.

The non-parametric Friedman's test was performed to explore the effect of the rainfall distribution on the peak flow of catchments. The hypothesis is that the peak flow for each catchment will be different depending on the rainfall distribution. The Friedman test shows that there is a significant difference between peak flows between the four rainfall distributions ( $\chi^2(3) = 37.26, p < 0.001$ ). Post-hoc analysis with Wilcoxon Signed Rank test was conducted to analyse the peaks of all catchments for all four rainfall distributions (Table 5.9). The centred rainfall distribution differs significantly from right-skewed ( $p < 0.01$ ) and rectangular ( $p < 0.01$ ) distributions. Right-skewed distributions also differ significantly to left-skewed ( $p < 0.01$ ) and rectangular ( $p < 0.01$ ) distributions. Other contrasts were not significantly different. Overall, the right-skewed distribution has the highest peak across all the distributions. The error bars also shows the variability of the

data, indicating with long error bars the type of rain with more spread out data, in this particular case the rectangular distribution Figure 5-18.

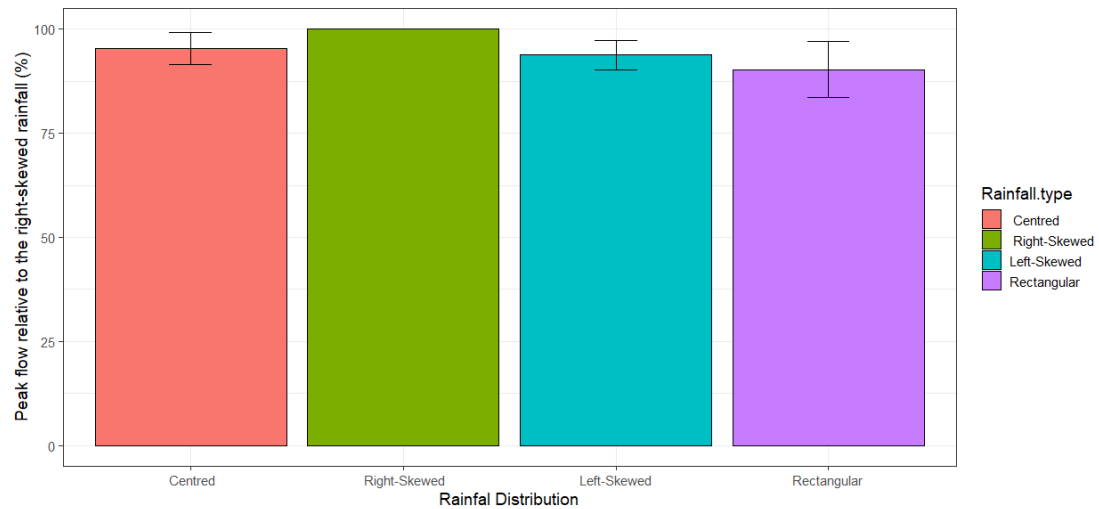


Figure 5-18 Bar graph showing the median of peak flow relative to the right-skewed rainfall in each rain distribution class for the 20 catchments. Error bars on top of each bar indicating the variability of the data.

Table 5.9 Wilcoxon Signed Rank multiple comparisons test of peak flow of four peaks rainfall type distribution showing the significance  $p$ -value for each comparison.

| Rainfall type | Centred | Right-Skewed | Left-Skewed |
|---------------|---------|--------------|-------------|
| Right-Skewed  | 0.00611 | -            | -           |
| Left-Skewed   | 0.11205 | 0.00611      | -           |
| Rectangular   | 0.00062 | 0.00356      | 1.00        |

Figure 5-19 depicts the lag time for each rainfall type on each catchment. The lag time was also standardized relative to the control rainfall [right-skewed rainfall]. Most catchments had the earliest time lag for the left-skewed rainfall distribution, except for the Kurtcukuru and Bistrita catchments, which have its highest time lag from the right and rectangular distribution respectively. The latest time lag comes from the right-skewed distribution, except for Kurtcukuru. The same non-parametric Friedman's test was performed using the lag time instead of the peak flow. The results show that there are significant differences between lag times from the four rainfall distributions ( $\chi^2(3) = 51.294$ ,  $p < 0.001$ ). The Post-hoc

analysis with Wilcoxon Signed Rank test deduced that all four rainfall distributions significantly differ from each other ( $p < 0.01$ )

Table 5.10. However, the most different is the left-skewed and right-skewed hyetographs ( $p < 0.01$ ) and the earliest onset events are generated by the left-skewed distributions.

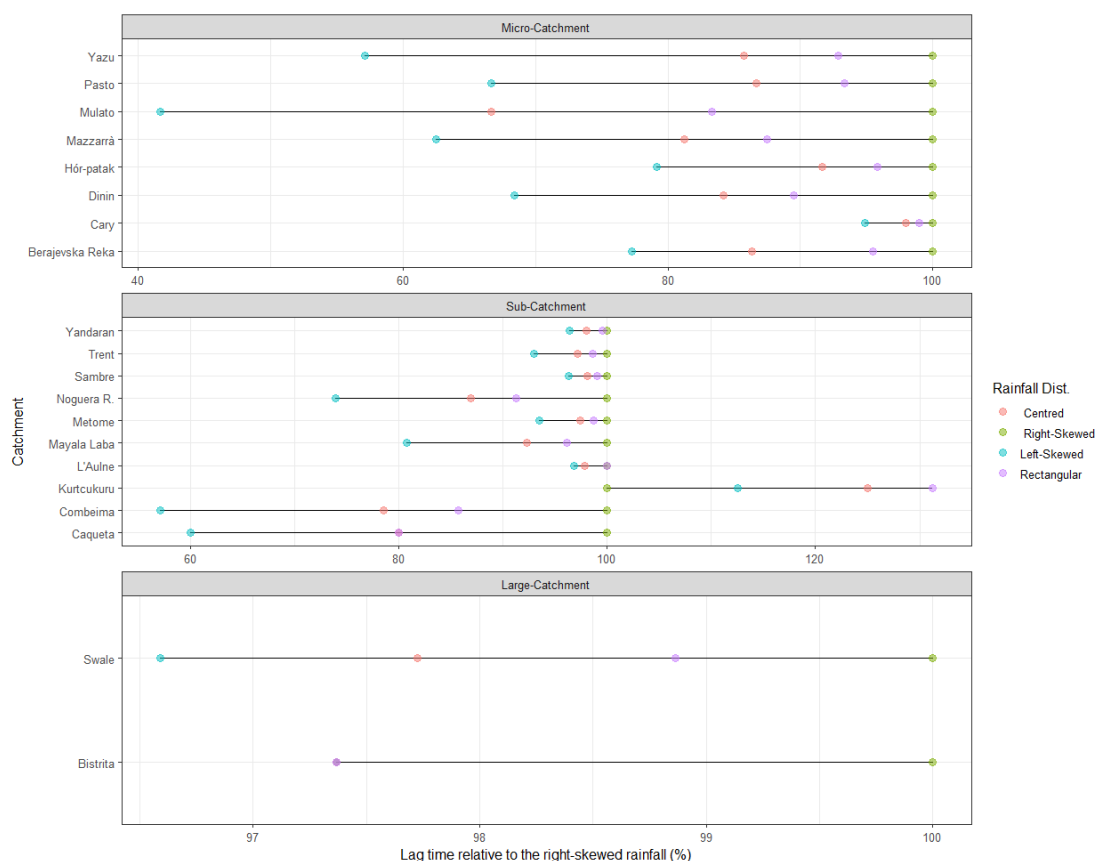


Figure 5-19 Percentage of the peak flow relative to the right-skewed rainfall in each catchment and for each rainfall distribution (coloured points). Catchments were classified by the catchment area classification for a better interpretation of the data.

Table 5.10 Wilcox Signed Rank multiple comparisons test of the time lag of four peaks rainfall type distribution showing the significance  $p$ -value for each comparison.

| Rainfall type | Centred | Right-Skewed | Left-Skewed |
|---------------|---------|--------------|-------------|
| Right-Skewed  | 0.00795 | -            | -           |
| Left-Skewed   | 0.00079 | 0.00203      | -           |
| Rectangular   | 0.00118 | 0.01335      | 0.00079     |

## **5.5 Discussion**

### ***5.5.1 Peak flow magnitude and variation between catchments and events.***

The hydrographs generated by IBER demonstrate that each modelled catchment behaves differently under identical rainfall conditions (Figure 5-2). In fact, the peak flow discharge varies both spatially and temporally when flowing downstream changing permanently in response to rainfall events (Beven and Carling, 1989). The characteristics of the discharge are not just determined by the climatological conditions but also by the intrinsic characteristics of the catchments (Charlton, 2007). Arnell (2014) states that peak flows are much more consistent in the same catchment generated by different events than for the same event between different catchments. The results here confirm these findings, with the difference between catchments being much greater than the difference between events (hyetographs) within catchments. Peak flows ranged from 22 to 2887 m<sup>3</sup> s<sup>-1</sup> (Cary and Combeima catchments, respectively). Although the peak flows are high given the torrential nature of the simulated rainfall event and the modelling is performed in an abstracted space, these peaks are not unrealistic relative to floods recorded in similar sizes of the catchment. For example, the River Findhorn in the UK registered a peak of 2402 m<sup>3</sup> s<sup>-1</sup> from a 782 km<sup>2</sup> catchment and the River Lyn in the UK registered a peak flow of 650 m<sup>3</sup> s<sup>-1</sup> from 101 km<sup>2</sup> catchment (Shaw, 2005, Ward and Robinson, 1967). Although the rainfall duration for these examples might be different, the magnitude of the hydrograph in terms of the peak is similar. The magnitude of the peak flow was expected to vary greatly between the catchments; however, the extent that this variability is related to morphometric characteristics was unknown and the focus of this chapter.

### ***5.5.2 Relationship of catchment parameters to peak flows and implications.***

Past work has suggested that there is a relation between the peak flow discharge and catchment area (Rodier and Roche, 1984, Shaw, 2005, Patton and Baker, 1976, Murphey et al., 1977, Adamson et al., 2009); however, no relationship between these two variables was found in this study when looking at all catchments together (e.g. Figure 5-5). This result is surprising because torrential rainfall was simulated to fall across the whole catchment area for the same length of time (1 hour rainfall event) and so, the catchment area is directly proportional

to the total discharge (i.e. the area under the hydrograph). A different modelling approach that did not have a consistent rainfall event across the whole catchment may lead to a different result and could increase the significance of the catchment area as a driving variable. It was also found that whilst area was not correlated to peak flow in any case, correlations with other morphometric parameters were stronger when catchments were split into size categories, indicating area does have importance to the hydrological response.

This study advocates that for this particular hydrological event and when looking at all the catchments together, the slope and drainage density are significant controls on peak flows ( $r = 0.62$ ,  $p < 0.001$ ;  $r = -0.70$ ,  $p = 0.003$ ). This can be seen by the fact that the highest peak flows are not from the largest catchments, even though the area in the abstracted model used here is directly related to the total volume of water moving through the catchment (Arnell, 2014). Instead, the highest peak flows are found in steeper catchments, resulting in a short overland time of concentration. The strong correlation between the drainage network and peak flow for the whole range of catchments is also interesting because the correlation is negative. This suggests that catchments with sparse drainage networks produce larger peak flows while catchments with dense drainage systems have lower peak flows. However, most of the studies suggest a positive correlation between peak flow and drainage density (Pallard et al., 2009, Murphey et al., 1977, Day, 1983).

The negative correlation between drainage network and peak flow does not reflect the results of others (Charlton, 2007, Day, 1983) who find from field measurements that catchments with dense drainage density values produce higher peaks and shorter travel times than those with more poorly developed drainage systems. This is because water reaches the channelized drainage network quicker, with the flow then more efficiently and rapidly evacuated through the catchment. Other modelling work supports the same hypothesis, that well drained catchments wash out water quicker, creating a higher peak value compared to catchments with poor drainage (Camino et al., 2018, Arnell, 2014, Ogden et al., 2011, Horton, 1932). The finding here is associated with the removal of two outliers which, if left in the analysis lead to an insignificant correlation between drainage density and peak flow (Appendix A). Without these outliers a steep negative relationship is found, which may be because of interactions between drainage density and other parameters, such as a weak but significant relationship between drainage density and torrentiality coefficient and form factor (Figure 4-1). However, it is clear regardless that drainage density does not have

a positive relationship with peak flow in this study in contrast to past work. In support of this, Pallard et al. (2009) argue that the relationship between drainage density and peak flow is affected by other catchment attributes, including large storage areas and (Knighton, 2014) argues that the correlation between discharge and drainage density can be impacted by further increases in precipitation. To establish the cause of this negative relationship requires further research that we suggest could focus on:

- modelling the same 60 mm torrential rain over longer periods (e.g. 2h, 4h, 6h).
- modelling the same torrential rainfall over a period of 1 hour but, distributing the rainfall in smaller areas of the catchment. This could avoid the potential impacts of having large volumes of water moving through the catchment at the same time.

Many of the correlations found in this study may be related to the intensity of the rainfall selected for this study (e.g. 60 mm h<sup>-1</sup>), especially because the rainfall was distributed equally throughout the entire catchment, which may confound correlations relative to events limited to only part of the catchments and subsequently moving through catchments. The F test helped to confirm that the majority of variables were related with linear regressions, which have a clear physical explanation. The polynomial correlations do not represent physical processes between variables but, instead more broadly indicate those cases where a linear relationship was not strong.

### ***5.5.3 Relationship of catchment parameters to peak flows for size class and implications.***

When catchments were classified according to catchment size, different relationships between parameters were found. Micro-catchments with areas below 100 km<sup>2</sup> had a strong correlation between peak flow and area, while sub-catchments with areas between 100 and 500 km<sup>2</sup> were not significantly correlated to area. Beven and Carling (1989) state that longer travel times and water storage within larger catchments might cause hydrological responses to rainfall events to be less clear than in smaller catchments. Larger catchments, therefore, have more opportunity for other variables to complicate the generation of peak flows in comparison to smaller catchments where area is the driving variable. Hewlett (1982) and Arnell (2014) argued for similar reasons that in relatively small, mainly



first-order catchments, the drainage network is not that important in controlling the peak flow. Beven and Carling (1989) also argue that the peak flow in small catchments is driven by the hillslope runoff generation. Relationships might also be affected by the duration of the rainfall event, which is not discussed in this research but, the effect of different rainfall intensities will be assessed and discussed in the next Chapter.

Although the area is important in driving the peak flow in the micro catchments, it was found that the slope was also significantly correlated to peak flows in these catchments. It was expected that micro catchments would also have a correlation between peak flow and drainage density but, the lack of data in this class (i.e. after removing outliers) was not enough to assess the correlation. In the case of the sub-catchments, slope, drainage density and torrentiality coefficient were highly significant. Even though slope and torrentiality coefficient were not correlated to each other for the whole set of catchments, these two parameters were highly correlated for sub-catchments, and both in some extent describe how steep or flat a catchment is. Torrentiality coefficient investigates the relationship between the number of first-order streams and the total area of the catchment area (Fuentes, 2004), indicating that the greater the number of first-order streams and the smaller the catchment area, the greater the torrential index (Díaz and Bermúdez, 1987). Normally, high values indicate a high susceptibility to erosion, as well as very short hydrological responses in catchments (Méndez et al., 2015).

The implications of dividing the dataset into categories is a reduction in the sample size, which affects the strength of correlations and abilities to interpret them. However, in doing so enabled the establishment of correlations not present in the overall dataset. Similarly, the removal of outliers to improve the ability to interpret relationships, also lowers the sample size. To improve correlations and understanding of the relationships found here, more sites could be included but, this has significant implications for modelling effort.

#### ***5.5.4 Relationship of catchment parameters to peak flows for cluster class and implications.***

A relationship was found between the drainage density and the peak flow for sub-catchments but not for micro-catchments as described above. In contrast, the classification of catchments by morphometric cluster classes, show that both cluster A and C had high negative correlations between peak flow and drainage

density. It is interesting to note that in cluster C most of the catchments are classified as sub-catchments and are predominately rounded in shape with dendritic drainage networks. In fact, the correlation between peak flow and catchment parameters for this class only differed slightly from the sub-catchment class given the overlap in contributing catchments. Area and peak flow were significantly correlated for cluster A, which is more aligned with the micro-catchment class. To some extent, this indicates the effect of the size on peak flow. Mass coefficient was also highly significant to peak flow, which suggests that the greater the mass coefficient value the greater the peak flow. Mass coefficient is normally used to understand how topography affects catchment erosion (Fuentes, 2004), with high values in mountainous catchments and low in flat catchments. It was also interesting to notice that catchments within cluster C had higher peak flows than catchments of cluster A, which agrees with (Smith and Ward, 1998) who states that rounded catchments normally have smoother peak flows compared to elongated catchments because the long path that water has to travel from remote areas.

#### ***5.5.5 Relationship of catchment parameters to peak flows for hypsometric curve class and implications.***

When classifying by the hypsometric curve, it was identified that young catchments had primarily low values of drainage density, which might indicate that the drainage system has not yet developed as much as in mature and old catchments. In comparison, old catchments had the highest drainage density values, which suggest that these catchments have well developed drainage networks. This is supported by the fact that drainage density was correlated to peak flow in mature catchments only and this was, again, a negative correlation indicating the more developed drainage network in the mature catchments, the lower the peak flows. Peak flows in young and mature catchments were strongly correlated to catchment slope but, with different degrees being stronger in young catchments than mature, which are characterised as having experienced more erosion and thus having lower overall topography i.e. shallower slopes, smaller elevation change across the catchment.

There is no doubt that hypsometric curves are an important parameter when characterising catchments. In this study, it was possible to identify the three types of curves that exist. However, when analysing peak flow in each class, it was not possible to determine significant differences between the two groups analysed.

This implies that hypsometric curves cannot be used to characterize the peak flow based on only these groups. This does not mean that this parameter is not important or irrelevant in the field of hydraulics and hydrology; on the contrary, what is suggested is it is a parameter that contributes to identifying other variables that control hydrological responses within these types of catchments. For example, the correlation of the catchment parameters with the peak flow for each of the hypsometric curves could infer that the slope of the catchment is a relevant parameter when determining differences in the magnitude of the flood peak. The correlation gradient for the young curves is greater than for the old catchments indicating larger increases in peak flow for relatively small changes in the slope. On the contrary, the relationship of the drainage density for both young and old curves had similar gradient but were slightly displaced relative to each other (i.e. parallel lines) indicating that changes in peak flow related to drainage density are similar in both catchment types. This clearly suggests that understanding morphometric variables can be important in understanding flood management, particularly when catchment groupings are analysed individually.

#### ***5.5.6 Effect of rainfall type on peak flow and lag time and implications***

The analysis of the effect of different distributions of torrential rainfall on catchments demonstrates that there are significant differences between all rainfall scenarios (Figure 5-18). In contrast to these results, a previous study with a similar approach indicated that there were no meaningful differences between hydrographs at catchment outlets when rainfall fell with differing hyetograph shapes (Collischonn et al., 2017). However, no significance levels were quoted in that paper and therefore, statistically significant differences may not have been detected visually. Also, whilst hyetographs led to statistically significant differences, they were not large differences as a proportion of the peak discharge, except for a couple of catchments.

The post hoc test for the lag time demonstrates that the earliest peak flows occur for left-skewed hyetographs, which might, therefore, be the most dangerous since they have the fastest hydrological response time. A short response was expected in all cases since flash floods generate high peaks in a short period (Ruiz-Villanueva et al., 2012, Gaume et al., 2009); however, in left-skewed rainfall events, most of the rainfall was concentrated in the first 15 minutes (Figure 3-10), which forces the catchments to evacuate most of the volume of the torrential rain towards the beginning of the event. In contrast, the right-skewed hyetograph

leads to generally higher peak flows when compared to other distributions. In Figure 5-16 it is noticeable that there is a slower hydrological response in the right-skewed hyetographs, with at least 45 minutes passing before peak flows occur. It is encouraging to compare this results with that found by Barbosa et al. (2018) who compared three catchments in Brazil and found that a right-skewed hyetograph produced the highest peak flow compared to other hyetograph distributions, including left-skewed, centred, shapeless and bimodal.

Catchments commonly have hydrographs with a positive skewness (Dingman, 2009). Consistent with this, here we found that all output hydrographs were positively skewed, regardless of catchment morphometry or hyetograph distribution. However, this effect might be attributed to the torrential event modelled. (Dingman, 2009) also states that the rising limb is steeper than the receding limb, which is in line with what we found here. In fact, the recession limb is steeper for right-skewed hyetographs than left-skewed. Although the shape of the hydrograph has been attributed to the shape of the catchment (Rinaldo et al., 1991), this research has all positively skewed hydrographs with a range of catchments shapes, which might indicate that the nature of the torrential event plays an important role.

Results from the rectangular hyetograph distribution were also interesting since more attenuated hydrographs were expected from this type of distribution. However, in most of the catchments, the reduction of the peak was not as great compared to the other three hyetographs. In fact, the peak flow is higher for rectangular hyetographs than left-skewed hyetographs in large-catchments. The result found in this section suggests that hyetographs do influence the timing and magnitude of peak flows but, as found by others, the variability between catchments for the same event, is much greater than for different events within the same catchment, For this reason, only one event type (unimodal, left-skewed) will be used in future analysis.

In terms of flood risk management, understanding the hydrological responses of certain types of rain plays a very important role. Based on this, measures to cope with floods can be designed, particularly to determine which type of rain can be more aggressive in different types of catchments. For example, knowing the maximum peak flow that can be generated by each type of rain helps to determine not only the magnitude of the flood but also to determine the measures necessary to face these events. Hence, computer modelling is of great importance since it is possible to infer the characteristics that different types of rain could have without

having to experience them. As explored in this research, knowing the hydrological responses of the catchments also contributes to determining the response time (i.e. time lag) that is fundamental in risk management. In fact, this research provides a more precise understanding of the effect of different rainfall distributions, concluding that for torrential one-hour rains, right-skewed hyetographs have larger peaks, however the most critical and shorter duration hydrological responses come from rains to the left-skewed hyetographs. These provide tools to design protection measures based on these two variables. However, even a deeper understanding of how the type of rain correlates with the parameters of the catchments is a field that must be developed and is proposed for future research.

## **CHAPTER 6. EFFECT OF NFM ON FLOOD PEAK AND LAG TIME ON CATCHMENTS**

### **6.1 Introduction**

NFM is defined by Dadson et al. (2017) as techniques used to manage flood risk by altering, or enhancing, natural process in a catchment and has received significant attention over the last two decades (Lavers and Charlesworth, 2018). NFM pays particular attention to reducing peak flows and slowing the flow (i.e. increasing the lag time) (Nisbet et al., 2011) but, also provides multiple benefits associated with woodland creation, re-naturalisation and wetland creation (SEPA, 2013). However, there remains little empirical evidence of NFM effectiveness in slowing the flow and reducing peak flows beyond a few small catchments in the UK (Nicholson et al., 2020).

There are few studies where the effectiveness of NFM approaches has been explored. An example is Nicholson et al. (2020), who took field measurements of runoff attenuation features (RAFs) and offline storage areas in the upper Belford Burn catchment (5.7 km<sup>2</sup>), Northumberland, UK. The study found that by storing 20,000 m<sup>3</sup> in offline storage, the peak flow was reduced by more than 30% downstream. Thomas and Nisbet (2007) carried out a modelling study in the River Cary, a tributary of the River Parrett in Southwest England, evaluating how NFM measures such as woodland planting can alleviate downstream flows. The study found that covering the floodplain by 50 ha of thick broadleaved woodland (in the 133 ha catchment), the flow velocity could be decreased by 60% to 70% and the peak flow delayed by 30 min. A modelling study by Acreman et al. (2003) also showed promising results for NFM measures on the River Cherwell, near Oxford, UK, reporting reductions in the peak flows of 10% to 15%.

Another case study was carried out by Wheeler et al. (2008) in the Pontbren catchment in the headwaters of the Severn in mid-Wales. The study found that deforestation over the last ten years has resulted in increased peaks flow by 6% to 18% but, modelling work suggested that planting tree shelterbelts in the lower parts of the catchment could reduce peak flows by 13% to 48%. Covering the whole catchment with woodland was estimated to reduce the peak flow by about 69% (Wheeler et al. 2008). The lag time also increased by 15 minutes for shelterbelts and 45 min for the scenario where the entire catchment was covered by woodland (Wheeler et al. 2008).

## **6.2 Aims Chapter 6**

In this chapter, tree planting (e.g. woodland creation) is the NFM measure of focus, with a range of coverages used across the 20 study catchments. The chapter describes and discusses the effectiveness of these NFM measures in reducing peak flows and lag times within catchments. It also assesses the effectiveness of woodland creation in reducing peak flows under a range of rainfall intensities. This is accomplished by fulfilling the following specific research objectives:

1. Use a hydraulic and hydrologic model (IBER) to calculate hydrographs across 20 catchments under a subset of NFM configurations, in response to modelled rainfall events.
2. To determine how peak flow and lag time in modelled catchments change as NFM coverage is increased from 0% to 100% of the catchment area.
3. To quantify how changes in peak flow and lag time compare between the modelled catchments in relation to their morphological characteristics.
4. To quantify the difference in peak flows of modelled catchments under a subset of NFM configurations for differing rainfall intensities (e.g. unimodal left-skewed of 30 mm hr<sup>-1</sup>, 60 mm hr<sup>-1</sup>, and 120 mm hr<sup>-1</sup>).

## **6.3 Methodology**

### **6.3.1 Methodological Overview**

This chapter is divided into two parts. Part 1 focusses on how NFM coverage in catchments alters their hydrological response to rainfall and part 2 focuses on how the effect of NFM on peak flow and lag time varies with rainfall intensity (Figure 6-1).

In part 1, the coupled hydraulic and hydrological model IBER (described in Section 3.5) was used to calculate a hydrograph at the outlet of each of the 20 catchments described in Section 4.3. A sequence of NFM coverages from 25% to 100% catchment coverage was investigated and compared to 0% coverage (i.e. control) presented in Chapter 5. NFM coverage increased from headwaters in a downstream direction (Figure 6-2). Particular attention was given to the effect of NFM on peak flow and lag time. The rainfall event used to perform these NFM

scenarios was the left-skewed rainfall event of 60 mm hr<sup>-1</sup> distributed uniformly across the whole catchment area.

In part 2, a similar analysis was performed but with three different rainfall intensities. The same NFM scenarios as mentioned above were used and hydrographs were, again, calculated at the outlet of each of the 20 catchments using IBER. Three unimodal left-skewed hyetographs of 30 mm hr<sup>-1</sup>, 60 mm hr<sup>-1</sup>, and 120 mm hr<sup>-1</sup> were applied. The NFM coverages were examined to evaluate how hydrographs change due to the range of rainfall intensities.

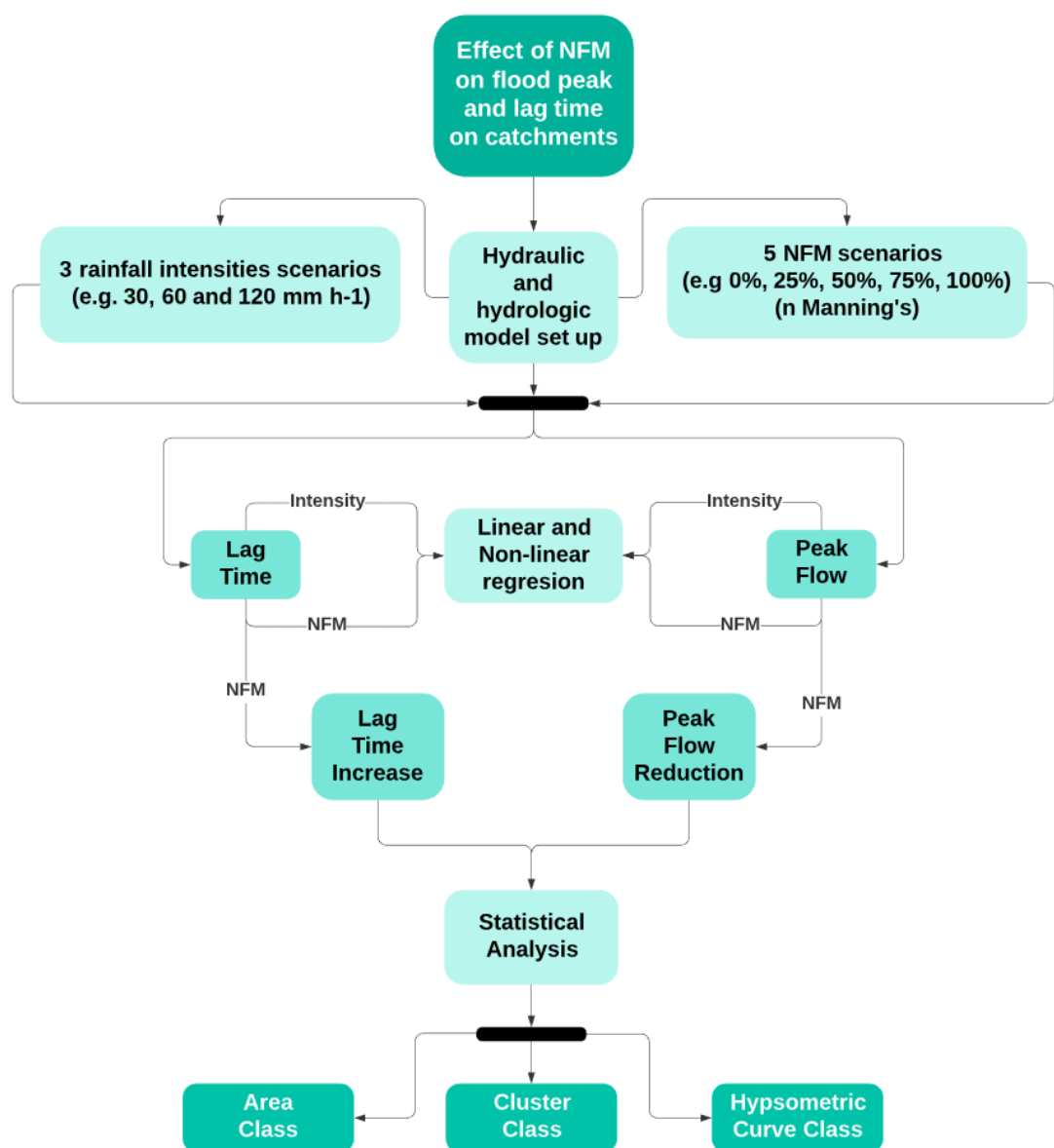


Figure 6-1 Effect of NFM on flood peak and lag time on catchments methodology flowchart. 5 NFM and 3 rainfall scenarios are configured to assess the effect of



these scenarios on peak flow and lag time. A non-parametrical test is used to determine differences between NFM scenarios, peak flow and lag time within a subset of catchments classes.

### ***6.3.2 Effect of NFM on flood peak and lag time on catchments.***

The first part of this chapter evaluates the effect of NFM on the flood peak and lag time between catchments. To evaluate the effect of NFM within a catchment, a set of scenarios with different NFM coverages were chosen. Five NFM scenarios were adopted by covering 0%, 25%, 50%, 75% and 100% of the catchment area with thick broadleaved woodland, shown in Figure 6-2 (see Section 3.5 for the hydraulic and hydrological model set up). The remaining areas were not covered by NFM and were instead, covered by pasture with high grass. The NFM coverages were designed from upstream to downstream dividing the area according to the percentages, mentioned above. This was decided as it allowed consistency between the 20 catchments. Chapter 7 explores the alternative placement of NFM.

To be able to model the NFM in IBER the Manning's  $n$  values for each particular land use cover had to be set. The NFM Manning's  $n$  values were set according to the study carried out by Thomas and Nisbet (2007). A Manning  $n$  value of 0.15 was selected to characterize the roughness of the broadleaved woodland. The remaining area had a Manning's  $n$  value of 0.035, corresponding to a pasture with high grass and/or cultivated areas with row crops (Chow, 1959). The main drainage system (river channel) of the catchment had a Manning's  $n$  value of 0.04, indicating a clean and winding channel with some pools and riffles (Chow, 1959) (Figure 6-2). The Manning's  $n$  value chosen for the channel ( $n = 0.04$ ) is larger than that for the floodplain ( $n=0.035$ ), as would be expected but it should be noted that this does not result in faster flow on the floodplain because the velocity is dependent on water depth relative to the roughness coefficient.

The Manning's  $n$  values used here are widely used in hydraulic modelling studies. For example, a study carried out in the Calder catchment in West Yorkshire (UK) evaluating a strategy to modulate flows through NFM gives a manning's  $n$  values of 0.035 for the floodplain grassland and between 0.1 and 0.2 for dense forest (Ferguson and Fenner, 2020a). Likewise, Dixon et al. (2016) in Lymington catchment used Manning's  $n$  values of 0.15 for 100 year forest growth and Manning's  $n = 0.05$  for the channel. Jones et al. (2008) reported a value of 0.04 for the drainage network in the Laurel Creek in the Grand River catchment in

Ontario, Canada where the author set values based on field measurements. However, Manning's n values can be subjective and are often altered when validating and calibrating hydraulic and hydrology models. For example, Medeiros et al. (2012) states that the values of forest based on field measurements is 0.061, much lower than the value of 0.144 suggested by the National Land Cover Dataset (NLCD) for the same area. Likewise, Bathurst (1986) uses values for overland flow based on measurements between 0.05 and 0.5. On the other hand, many studies use roughness as a calibrated parameter to input into feed the model (Mailapalli et al., 2008) sometimes using Lidar technologies (Mason et al., 2003), while others adjust the roughness values based on calibrated flow data (Cobby et al., 2003, Mason et al., 2003). This is typically done through sensitivity analysis (Timbadiya et al., 2011) or automated models included in some hydrological and hydraulic packages (Medeiros et al., 2012). These differences incorporate a degree of uncertainty into models and can reduce the physical meaning of Manning's n, hence here we have replicated the values used by other similar studies.

Additionally, the soil start condition was considered to be saturated soil with no infiltration into the subsurface (see Section 3.5.2). The same process was done for all 20 catchments selected in this study.

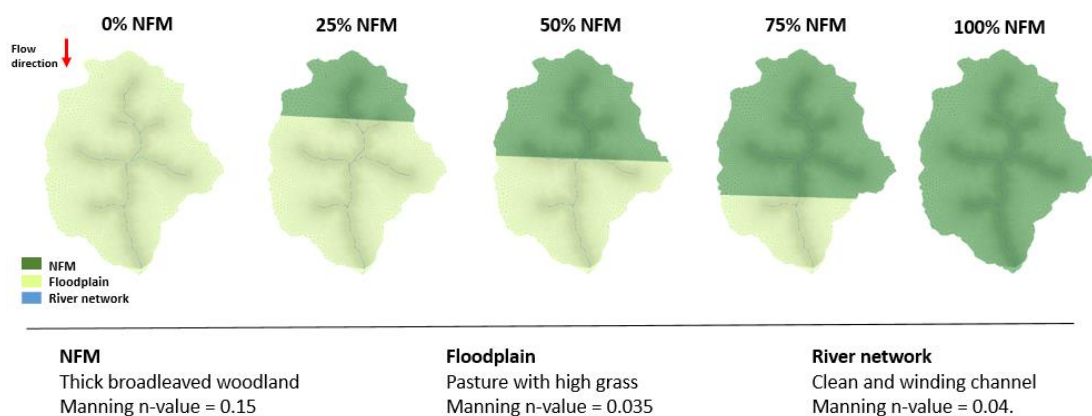


Figure 6-2 NFM scenarios. Scenario a) 100% area covered by pasture with high grass (manning n-value of 0.035) and drainage river network described by a clean and winding channel (manning n-value of 0.04). Scenario b) 25% thick broadleaved woodland (manning n-value of 0.15), remainder area (75%) covered by pasture with high grass (manning n-value of 0.035) and drainage river network (manning n-value of 0.04). Scenario c) 50% thick broadleaved woodland (manning n-value of 0.15), remainder area (50%) covered by pasture with high grass (manning n-value of 0.035), and drainage river network (manning n-value

of 0.04). Scenario d) 75% thick broadleaved woodland (manning n-value of 0.15), remainder area (25%) covered by pasture with high grass (manning n-value of 0.035), and drainage river network (manning n-value of 0.04). Scenario d) 100% thick broadleaved woodland (manning n-value of 0.15), and drainage river network (manning n-value of 0.04).

In total, four NFM scenarios and a control [0% NFM] were modelled for all 20 catchments using IBER. As a result, one hundred hydrographs were calculated and their peak flow and lag time calculated as in previous sections. The rainfall event used was the unimodal left-skewed of 60 mm hr<sup>-1</sup> distributed across the entire catchment area.

The resultant hydrographs from the IBER modelling were plotted for each catchment to make an initial visual assessment of changes in hydrographs due to NFM. Then, the peak flow and lag time versus NFM coverage were correlated for each catchment. Two regression models were fitted for peak flow magnitude across the four NFM coverages (i.e. linear and polynomial) in each catchment. The equation, significance and r values of each regression were calculated and displayed to identify which regression fitted better to the data. Both regression models were statistically compared performing a partial F test in r. The comparison aimed to identify which catchments adjust better to a linear regression; thus, no significant differences between models assumed that the regression between peak flow across all NFM is linear, whereas significant differences assumed that the regressions model is non-linear.

Catchments that adjusted better to a linear model were grouped into a new class named "Linear" and those with a non-linear relationship were named "Non-linear". A quantitative analysis was made for the morphological parameters of catchments within linear and non-linear groups to identify whether linear model catchments are, for instance, more or less steep or have higher or lower drainage density values compared to non-linear catchments. In addition, catchments that fitted better to a linear regression were used to correlate the gradient of the linear regressions to the morphological parameters of each catchment. This correlation was also evaluated to determine the regression of a better fit. This analysis, therefore, aimed to determine whether any of the parameters of the catchments has a particularly important influence on the slope of the linear regression.

The difference in peak flow and lag time between different NFM coverages for each catchment were calculated to determine the percent reduction (or increase) in peak flow and lag time for each NFM category. In terms of statistical analysis, as in Chapter 5, non-parametric tests were used as Shapiro-Wilk tests indicated that the data did not fit a normal distribution. In this particular case, all sets of catchments were assessed under a range of NFM configurations (i.e. treatments or dependent variable) having the peak flow and lag time as independent variables; therefore, a non-parametric test for repeated samples was used (Dytham, 2011). The non-parametric Friedman test for repeated measures was then performed to assess the statistical significance of NFM on peak flow and lag time. The test compares whether the peak flow reduction as a percentage of the control condition is significantly different between NFM coverages. The null hypothesis, in this case, was that the median of the peak flow reduction of each category of NFM across all catchments does not have significant differences. The Wilcoxon Signed Rank posthoc test was also performed to explore in more detail how NFM scenarios relate to each other and which NFM coverages are more similar/different. The Wilcoxon Signed Rank is an alternative to the paired Student's t-test (i.e. t-test for dependent samples when data is assumed to have a normal distribution) but for non-normally distributed data (Siegel, 1956). This test is used to do multiple comparisons between repeated measurements (i.e. treatments) to assess whether their population mean ranks differ. The output of the test is a matrix of the multiple comparisons possible indicating the statistical significance  $p$  values.  $P$  values indicating significant differences between repeated measures when  $p < 0.05$ . All analysis and plots were performed using the R software.

### ***6.3.3 Effect of NFM on peak flow varies by area and cluster class.***

To analyse how the effect of NFM on peak flow reduction varies between catchment size, the size classification range proposed by CIDIAT-MARNR (1984) and described in Section 3.4 was used. Since the effect of NFM on peak flow was already assessed, here the differences between peak flow reductions for each class was made. The statistical analysis slightly differs from the previous analysis; here repeated measures are also involved since the peak flow is evaluated for different NFM coverages. However, the analysed classes are independent of each other because catchments within the micro-catchments are different from the sub-catchments class, similar to the cluster group where catchments within clusters

are different. Therefore, individual independent tests were performed for each of the NFM coverages. Thus, a non-parametric test for independent samples (i.e. Mann-Whitney U test) was used for each NFM coverage, performing five independent analyses. The null hypothesis was that the median peak flow reduction is the same between micro- and sub-catchments. The test was repeated for each NFM scenario. In this case, the post-hoc Levene's test was performed to assess the variance of each class. This test was also performed five times being consistent with the number of Mann-Whitney U tests. In Chapter 5, no significant differences were found between the median of the peak flows in micro- and sub-catchments when no NFM was present on catchments (Figure 5-7); thus, this analysis aims to determine whether this remained the same with NFM coverage.

The same analysis was performed for each of the clusters of catchments identified and described in Section 4.3.2. The hypothesis analysed was that the effect of NFM on peak flow reduction depended on cluster class. In this case, previous results in Chapter 5 suggested that there are significant differences in peak flow for each cluster with no NFM (Figure 5-10). Analysis of NFM between clusters is important because clusters were statistically defined based on their morphological features. For example, cluster C contains catchments that are relatively large in size ( $> 100 \text{ km}^2$ ) with rounded shapes, while cluster A has smaller catchments with elongated shapes.

#### ***6.3.4 How the effect of NFM on peak flow and lag time varies with rainfall intensity across 20 catchments.***

The effect of NFM on the flood peak and lag time may vary with rainfall intensity. The same NFM scenarios as described above were used but with three unimodal left-skewed hyetographs of  $30 \text{ mm hr}^{-1}$ ,  $60 \text{ mm hr}^{-1}$ , and  $120 \text{ mm hr}^{-1}$  intensities. Hydrographs were calculated at the outlet of each of the 20 catchments. In total, four NFM scenarios and the control were modelled for all 20 catchments under the three intensities. As a result, three hundred and sixty hydrographs were calculated (5 NFM scenarios plus 3 intensities for 20 catchments) and their peak flow and lag time calculated as in previous sections.

The peak flow versus NFM coverage for the three rainfall intensities was plotted. Two regressions were fitted for each intensity and the  $r$  and significance  $p$  values calculated for each catchment. This analysis aims to determine whether the catchments that adjust to a linear or non-linear model are similar between

intensities. The lag time versus NFM coverage for the three rainfall intensities was also plotted, but no linear models were plotted in this case as significant relationships were not found.

Unlike other statistical analysis performed in this Chapter, here to assess the effect of NFM on the flood peak vary by rainfall intensity, the parametric two-way ANOVA for repeated measures was performed. No equivalent or reliable test was found for non-parametric data (Scheff, 2016). The two-way ANOVA for repeated measures is used for dependent analysis when involving more than two dependent variables (Dytham, 2011), in this particular analysis the two different treatments are NFM coverages and rainfall intensity. The test was performed based on the null hypothesis that the effect of NFM on peak flow depends on the rainfall intensity on catchments. The test, therefore, compares the main effects of the peak flow reduction as a percentage of the control condition for each NFM coverage, and for the three intensity levels. The significance  $p$  value is the output of the test indicating whether the variables compared are significantly different. Two  $p$  values are displayed, one for the NFM comparison and another for the intensities. To further explore the simple effects of each interaction between intensities and NFM scenarios the post-hoc Bonferroni multiple comparison tests were performed. The Bonferroni test is a multiple comparison test used when several dependent or independent statistical tests are being performed (Shaffer, 1995). The tests display the significant  $p$  values for each possible comparison between NFM coverages and between intensities. The analysis and plots were made using R.

#### ***6.3.5 Effect of NFM on peak flow varies by rainfall intensity and area and cluster class.***

How the effect of NFM on peak flow reduction varies with rainfall intensity for different catchments classifications (e.g. size, cluster, hypsometric curve) was explored. The analysis was qualitative, looking at the main differences in peak flow reduction across all NFM scenarios and intensities, as well as area and cluster classes.

## **6.4 Results**

### ***6.4.1 Effect of NFM on flood peak and lag time on catchments.***

Figure 6-3 depicts the hydrographs as a result of the  $60 \text{ mm hr}^{-1}$  rainfall event under a set of NFM configurations. The horizontal axis is the duration of the event in hours and the vertical axis is the discharge in  $\text{m}^3 \text{ s}^{-1}$ . NFM coverage has an impact on the peak flow and lag time of catchments, with a clear visual trend of decreasing peak flow as NFM coverage increases. However, the relationship with lag time is more complex and; for example, catchments such as Berajevska Reka, L'Aulne, Cary and to a lesser degree Yandaran have lag times that increase as NFM coverage increases. However, in other catchments including Metome, Noguera R., Kurtcukuru, Dinin and Trent the lag time decreases as NFM increases. These trends will be explored further, below.

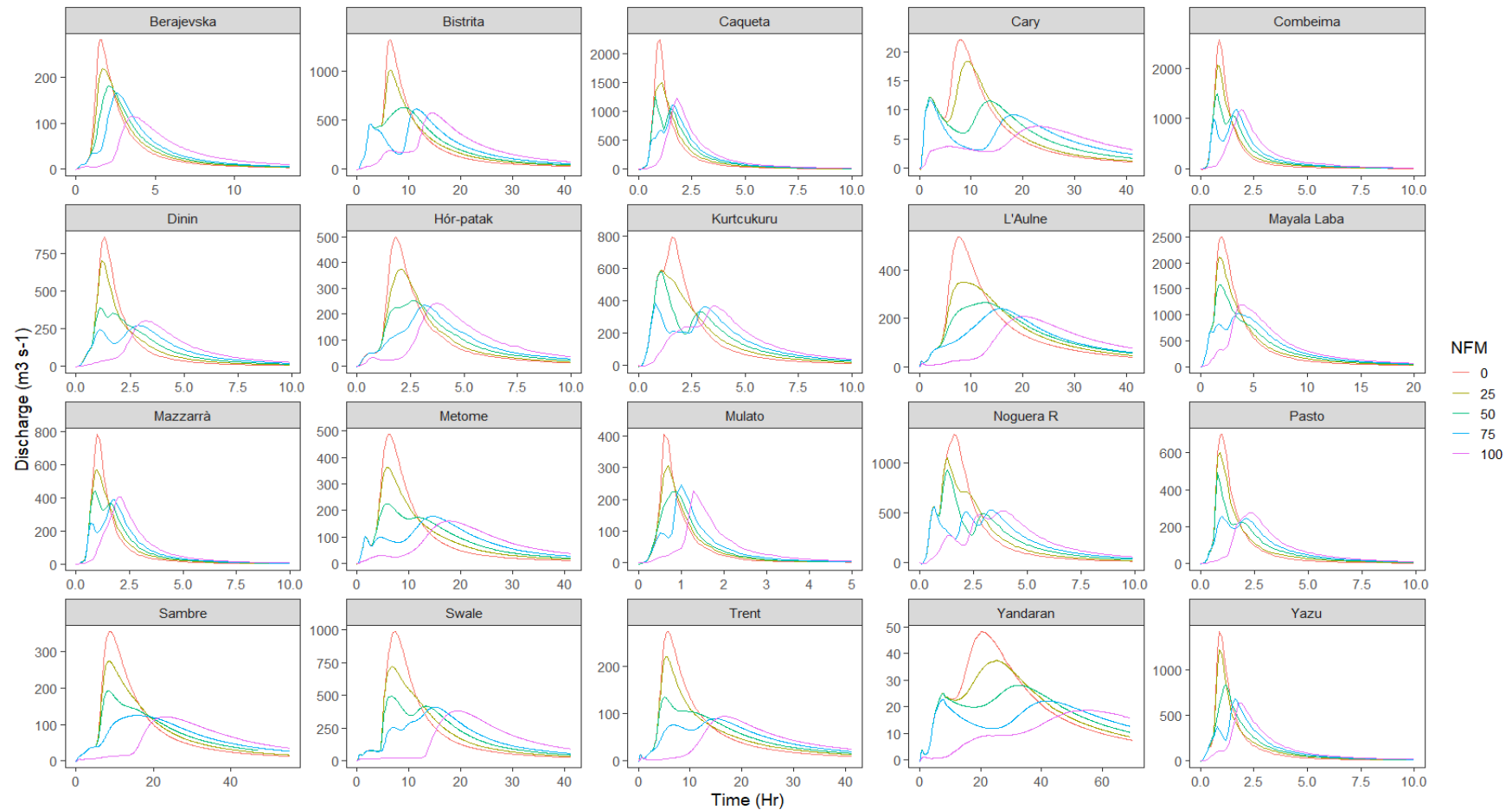


Figure 6-3 Output hydrographs from the hydraulic and hydrological modelling by IBER. All scenarios were performed under a 60 mm h<sup>-1</sup> left-skewed rainfall event. The coloured continuous lines are the hydrographs for each NFM coverage (e.g. control [0%], 25%, 50%, 75%, 100%). In all cases, the areas of NFM had Manning's n values of 0.04 indicating thick broadleaved forest, and areas without NFM had Manning's n values of 0.035 indicating remainder areas covered by pasture with high grass. The drainage network had Manning's n values of 0.04 indicating clean, winding channel.



Hydrographs from the 50% to 75% NFM coverages tend to have a bimodal peak. This is likely to be due to the spatial distribution of NFM coverage, moving from the upstream to downstream areas of the catchment. The NFM coverage in these cases uncouples the upstream from downstream regions, delivering two peaks of water. However, in some cases this is not the case; for instance, Berajevska Reka, L'Aulne, and Sambre have a unimodal hydrograph for all NFM coverages.

To visually demonstrate how a bimodal hydrograph is formed during the rainfall event, Dinin catchment is used as an example. Figure 6-4 is a time-lapse of the rainfall event in this catchment under the two NFM scenarios. From the 75% NFM scenario, it can be seen that flow is retained upstream where 75% of the catchment is covered by trees, while downstream most of the water from the rainfall event has been drained creating the first peak of the hydrograph. After this, the remaining water upstream is released more slowly, creating a second peak. The same trend can be seen with the 50% NFM coverages. In the 25% NFM scenario, flow is also retained upstream in the 25% of the catchment covered by trees; however, the resultant hydrograph is unimodal because the area without NFM is large and still dominates the hydrograph. The unimodal peak is most likely to occur when there is not NFM coverage (0% NFM).

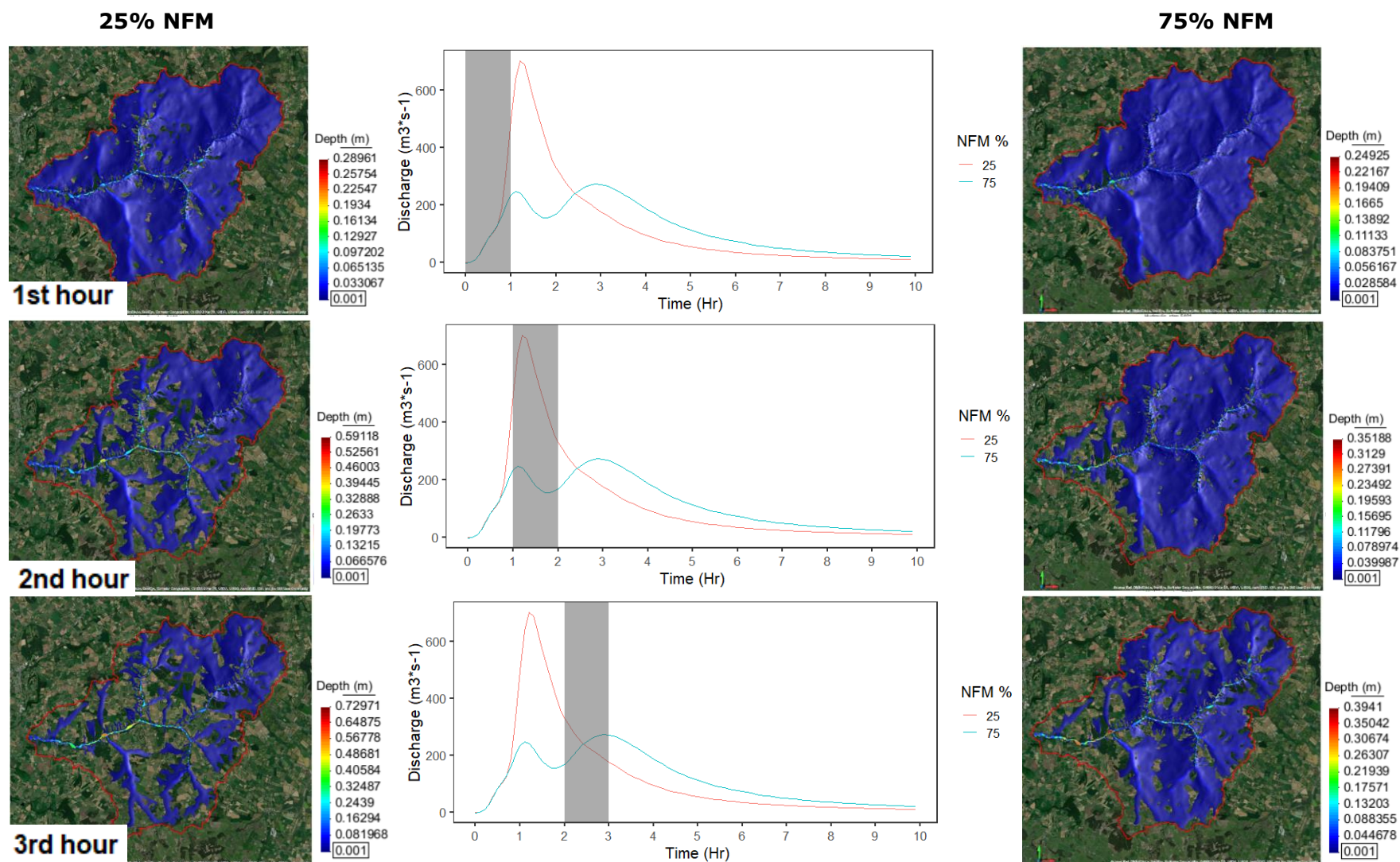


Figure 6-4 Time-lapse of the hydraulic and hydrological modelling by IBER of Country Kilkenny catchment for the 25% NFM and 75% NFM scenarios. The time-lapse just represents the initial period of the rainfall event. This graph describes the differences in hydrographs due to the percentage of NFM in each scenario. The interesting aspect of this is the scenario of 75% is that water is retained upstream where 75% of the catchments is covered by trees, while downstream most of the water from the rainfall event has been washed up creating the very first peak of the hydrograph. After this, the remained water upstream is released smoothly creating a second peak.

Two regression models, linear and polynomial were fitted to the data to assess the correlation between peak flow and NFM coverage (Figure 6-5). The  $r$  and  $p$ -value, and equation of each regression were calculated to estimate the strength of each model (Table 6.1). The figure below shows that there is an overall negative correlation between peak flow and NFM, indicating that as NFM coverage increases, peak flows get lower. However, the strength and gradient of the correlation varies between catchments, being steeper in Combeima, Mayala Laba and Yazu, indicating greater reductions with NFM, and shallower in Cary and Yandaran, indicating NFM has a relatively smaller impact. Linear regression had significant correlations between NFM coverage and peak flow ( $p < 0.05$ ) and was strong across all catchments ( $r > 0.87$ ), with the exception of Mulato and Caquetá, which were insignificant ( $p = 0.054$ ,  $p = 0.098$ ) (Table 6.1). The polynomial model also demonstrated significant correlations ( $p < 0.05$ ) for all catchments, except for Kurtcukuru and Pasto ( $p = 0.067$ ,  $p = 0.071$ ). However, the  $r$  values for the polynomial regressions were stronger for significant correlations compared to the linear model ( $r > 0.93$ ).

The partial F test allowed determination of whether each regression was statistically different (Table 6.1). The  $p$  values show that there was no significant difference between linear and non-linear regressions for the catchments Trent, Dinin, Sambre, L'Aulne, Berajevska Reka, Pasto, Noguera R., Bistrita, Kurtcukuru, Mayala Laba, and Yazu ( $p > 0.05$ ). This indicates that these catchments fit a linear model. In contrast, regression models for Cary, Metome, Swale, Yandaran, Hór-Patak, Mazzarrà, Combeima, Mulato and Caquetá were significantly different ( $p < 0.05$ ) and so these catchments are represented by non-linear (polynomial) models.

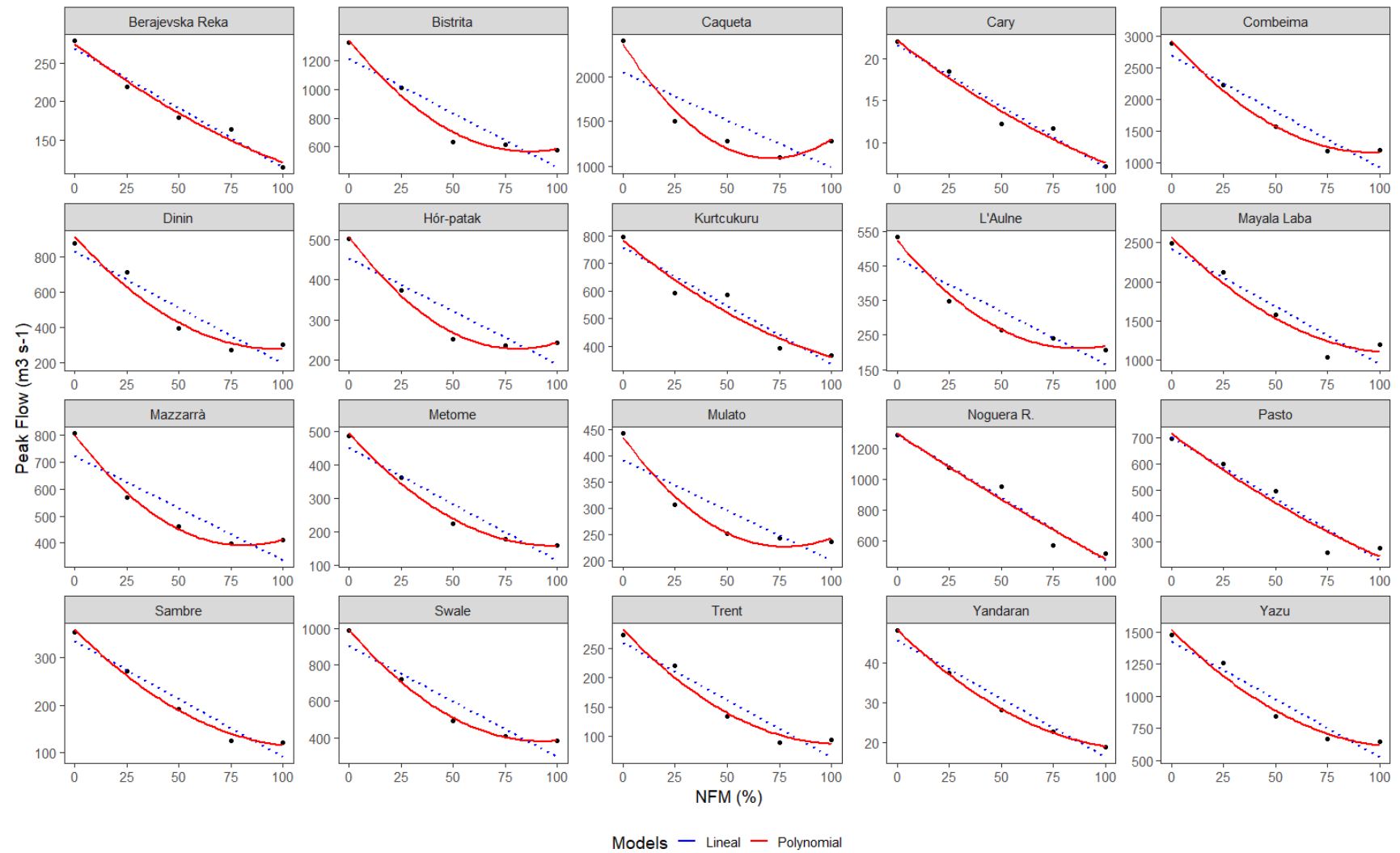


Figure 6-5 Scatter plot of the peak flow and five NFM scenarios for the full set of catchments. Linear and polynomial regression adjusted to the data.

Table 6.1 R, p values, and equation from the linear and polynomial models between peak flow and NFM scenarios for each catchment. The last column indicates the p-value from the differences between models.

| Peak Flow              |       |         |               |                  |         |                         |                   |
|------------------------|-------|---------|---------------|------------------|---------|-------------------------|-------------------|
| Linear model           |       |         |               | Polynomial model |         |                         | Model differences |
| Catchment              | r     | p-value | Equation      | r                | p-value | Equation                | p-value           |
| <b>Berajevska Reka</b> | -0.98 | 0.002   | $y=270-1.5x$  | 0.98             | 0.022   | $y=270-2x+0.0051x^2$    | 0.457             |
| <b>Bistrita</b>        | -0.92 | 0.029   | $y=1200-7.6x$ | 0.97             | 0.023   | $y=1300-18x+0.1x^2$     | 0.075             |
| <b>Caquetá</b>         | -0.81 | 0.098   | $y=2000-11x$  | 0.98             | 0.021   | $y=2400-36x+0.25x^2$    | 0.030             |
| <b>Cary</b>            | -0.98 | 0.004   | $y=22-0.15x$  | 0.96             | 0.030   | $y=22-0.19x+0.00044x^2$ | 0.004             |
| <b>Combeima</b>        | -0.95 | 0.013   | $y=2700-18x$  | 0.99             | 0.007   | $y=2900-36x+0.19x^2$    | 0.038             |
| <b>Dinin</b>           | -0.94 | 0.020   | $y=830-6.3x$  | 0.96             | 0.041   | $y=910-13x+0.066x^2$    | 0.179             |
| <b>Hór-patak</b>       | -0.90 | 0.039   | $y=450-2.6x$  | 0.99             | 0.009   | $y=510-7x+0.043x^2$     | 0.023             |
| <b>Kurtcukuru</b>      | -0.96 | 0.011   | $y=760-4.2x$  | 0.93             | 0.067   | $y=780-6.2x+0.02x^2$    | 0.547             |
| <b>L'Aulne</b>         | -0.92 | 0.028   | $y=470-3.1x$  | 0.98             | 0.018   | $y=520-7.2x+0.042x^2$   | 0.059             |
| <b>Mayala Laba</b>     | -0.95 | 0.015   | $y=2400-15x$  | 0.95             | 0.050   | $y=2600-27x+0.12x^2$    | 0.288             |
| <b>Mazzarrà</b>        | -0.90 | 0.037   | $y=720-3.9x$  | 0.99             | 0.004   | $y=800-10x+0.062x^2$    | 0.010             |
| <b>Metome</b>          | -0.95 | 0.012   | $y=450-3.4x$  | 0.99             | 0.007   | $y=490-6.8x+0.035x^2$   | 0.039             |
| <b>Mulato</b>          | -0.87 | 0.054   | $y=390-1.9x$  | 0.98             | 0.021   | $y=440-5.4x+0.035x^2$   | 0.045             |
| <b>Noguera R.</b>      | -0.98 | 0.004   | $y=1300-8.2x$ | 0.96             | 0.042   | $y=1300-8.9x+0.0079x^2$ | 0.864             |
| <b>Pasto</b>           | -0.96 | 0.009   | $y=700-4.7x$  | 0.93             | 0.071   | $y=720-5.9+0.012x^2$    | 0.742             |
| <b>Sambre</b>          | -0.97 | 0.007   | $y=340-2.5x$  | 0.99             | 0.010   | $y=360-4.4x+0.019x^2$   | 0.090             |
| <b>Swale</b>           | -0.94 | 0.016   | $y=900-6.1x$  | 1.00             | 0.002   | $y=990-13x+0.071x^2$    | 0.008             |
| <b>Trent</b>           | -0.95 | 0.013   | $y=260-2x$    | 0.97             | 0.029   | $y=280-3.7x+0.018x^2$   | 0.167             |
| <b>Yandaran</b>        | -0.98 | 0.010   | $y=46-0.29x$  | 1.00             | 0.001   | $y=48-0.5x+0.0021x^2$   | 0.007             |
| <b>Yazu</b>            | -0.96 | 0.010   | $y=1400-9x$   | 0.97             | 0.029   | $y=1500-16x+0.071x^2$   | 0.206             |

Catchments within each type of regression model were evaluated to determine if these catchments are consistently contained within other classes used in this investigation (i.e. area size, cluster, and hypsometric class). Table 6.2 shows all the catchments and the corresponding values for each parameter, as well as the size, hypsometric curve and regression type grouping. We found that no obvious consistent clustering of catchments that fit the linear and nonlinear regression type; the catchments were totally mixed in other classes.

Table 6.2 Catchment parameter and area size, cluster, hypsometric curve and regression type classes.

| Catchment              | Size            | Cluster   | Hypsometric Curve | Regression Type |
|------------------------|-----------------|-----------|-------------------|-----------------|
| <b>Berajevska Reka</b> | Micro-Catchment | Cluster B | Young             | Linear          |
| <b>Bistrita</b>        | Catchment       | Cluster C | Mature            | Linear          |
| <b>Dinin</b>           | Micro-Catchment | Cluster B | Young             | Linear          |
| <b>Kurtcukuru</b>      | Sub-Catchment   | Cluster A | Mature            | Linear          |
| <b>L'Aulne</b>         | Sub-Catchment   | Cluster C | Mature            | Linear          |
| <b>Mayala Laba</b>     | Sub-Catchment   | Cluster C | Young             | Linear          |
| <b>Noguera R.</b>      | Sub-Catchment   | Cluster C | Mature            | Linear          |
| <b>Pasto</b>           | Micro-Catchment | Cluster A | Mature            | Linear          |
| <b>Sambre</b>          | Sub-Catchment   | Cluster C | Young             | Linear          |
| <b>Trent</b>           | Sub-Catchment   | Cluster B | Mature            | Linear          |
| <b>Yazu</b>            | Micro-Catchment | Cluster C | Mature            | Linear          |
| <b>Cary</b>            | Micro-Catchment | Cluster A | Old               | Non-linear      |
| <b>Caqueta</b>         | Sub-Catchment   | Cluster C | Mature            | Non-linear      |
| <b>Combeima</b>        | Sub-Catchment   | Cluster C | Young             | Non-linear      |
| <b>Hór-patak</b>       | Micro-Catchment | Cluster A | Mature            | Non-linear      |
| <b>Mazzarrà</b>        | Micro-Catchment | Cluster A | Young             | Non-linear      |
| <b>Metome</b>          | Sub-Catchment   | Cluster C | Mature            | Non-linear      |
| <b>Mulato</b>          | Micro-Catchment | Cluster A | Mature            | Non-linear      |
| <b>Swale</b>           | Catchment       | Cluster C | Mature            | Non-linear      |
| <b>Yandaran</b>        | Sub-Catchment   | Cluster A | Old               | Non-linear      |

The two types of regression were also visually evaluated to determine if, for example, they contained flatter or steeper catchments, or if they are wider or more elongated catchments. No obvious relationship between the linear and non-linear regression types exists. To further explore this, the gradient of linear regressions (i.e. slope of linear regression) between the peak flow and NFM coverage was related to the catchment parameters (Figure 6-6 Table 6.3). Only the catchments that fit linear regressions were used in this analysis. The results indicated that the average slope of the catchment was positively and strongly correlated to the slope of the linear regression ( $r = 0.74$ ,  $p = 0.010$ ). A partial F test suggested that this relationship was best represented by a linear relationship. This strong linear correlation indicates that increasing NFM leads to larger incremental decreases in peak flows in steeper catchments.

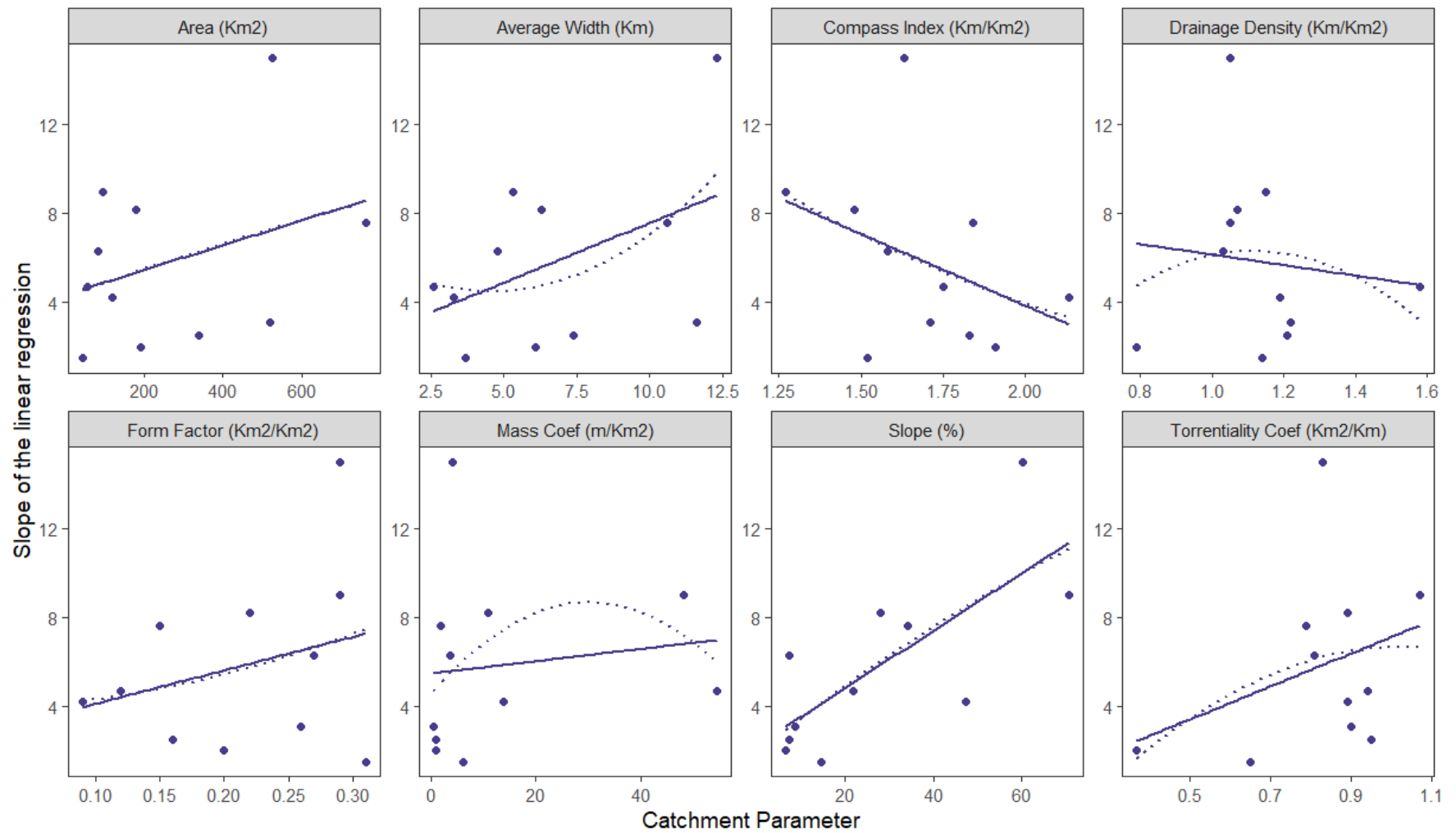


Figure 6-6 Scatter plot of the peak flow and parameters of the catchment for the catchments that fit linear regressions . Linear (solid line) and polynomial (dotted line) regression adjusted to the data.

Table 6.3 R and *p* values from the matrix correlation between the gradient of the linear model and parameters of the catchment and classes of catchments (e.g. area size, cluster, hypsometric curve, and type of regression).

| Catchment<br>Parameter    | Slope of the linear model |         |                  |         |                                |
|---------------------------|---------------------------|---------|------------------|---------|--------------------------------|
|                           | Linear model              |         | Polynomial model |         | F test<br>Model<br>differences |
|                           | r                         | p-value | r                | p-value | p-value                        |
| <b>Area</b>               | 0.34                      | 0.314   | 0.34             | 0.621   | 0.978                          |
| <b>Average Width</b>      | 0.46                      | 0.157   | 0.50             | 0.321   | 0.542                          |
| <b>Compactness Index</b>  | -0.38                     | 0.247   | 0.38             | 0.529   | 0.907                          |
| <b>Drainage Density</b>   | -0.11                     | 0.740   | 0.24             | 0.781   | 0.545                          |
| <b>Form Factor</b>        | 0.29                      | 0.393   | 0.29             | 0.706   | 0.914                          |
| <b>Mass Coef</b>          | 0.13                      | 0.694   | 0.25             | 0.768   | 0.548                          |
| <b>Slope</b>              | 0.74                      | 0.010   | 0.74             | 0.043   | 0.877                          |
| <b>Torrentiality Coef</b> | 0.35                      | 0.297   | 0.37             | 0.561   | 0.720                          |

Linear regression was also used to investigate the effect of the NFM on the lag time (Figure 6-7). A significant positive correlation was found for 7 catchments (Berajevska Reka, Bistrita, Hór-patak, L'Aulne, Metome, Mulato and Yazu). These 7 correlations are also strong, with *r* values between 0.95 and 0.99. Some catchments have what appear to be anomalous values in otherwise clear trends, such as Caqueta 50% NFM, Kurtcukuru 75% NFM, Yandaran 75% NFM and Combeima 50% NFM (Figure 6-7). These values are present in catchments with hydrographs that have dual peaks (see Figure 6-3) and, as explained above, the first peak appears in some hydrographs with 50 and 75% NFM distributions with a later higher, second peak. For many catchments, including those with unimodal distributions, the lag time is shorter for 25% and 50% NFM coverage compared to the control [0% NFM], such as Dinin, Mayala Laba, Mazzarra, Metome, Sambre, Swale, Kurtcukuru and Trent. These catchments were therefore assessed using the catchments parameters, and most of the catchments had high values of factor form (indicating elongated catchments) with low values of drainage density and torrentially coefficient.



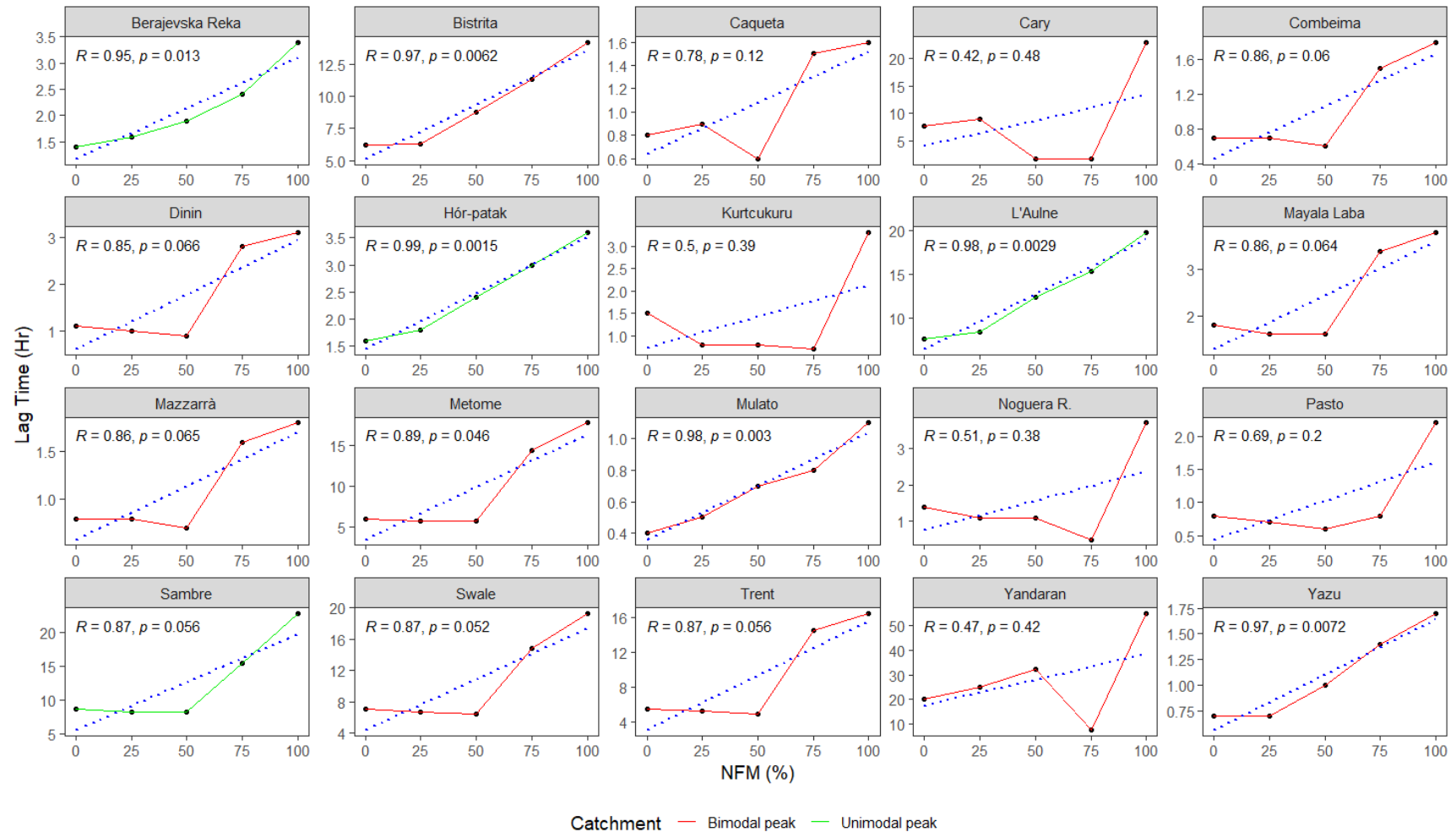


Figure 6-7 Scatter plot of the time lag and five NFM scenarios for the full set of catchments. Linear regression adjusted to the data including its correspondent r and p values (dotted blue line). The continuous green line shows the trend of the lag time through the NFM scenarios. Coloured lines indication catchments with unimodal and bimodal peak.

To further assess the effect of NFM on peak flow, the peak flow reduction was calculated as a percentage compared to the peak flow under control conditions [0% NFM]. Figure 6-8 shows the cumulative peak flow reduction and mean peak flow, for the five NFM coverages. Figure 6-8 confirms that peak flow reduced with increasing NFM coverage but, also shows that the percentage reduction is greatest between 25% to 50% NFM coverage. The reduction between 50% to 75% and, particularly between 75% to 100% NFM, is less strong.

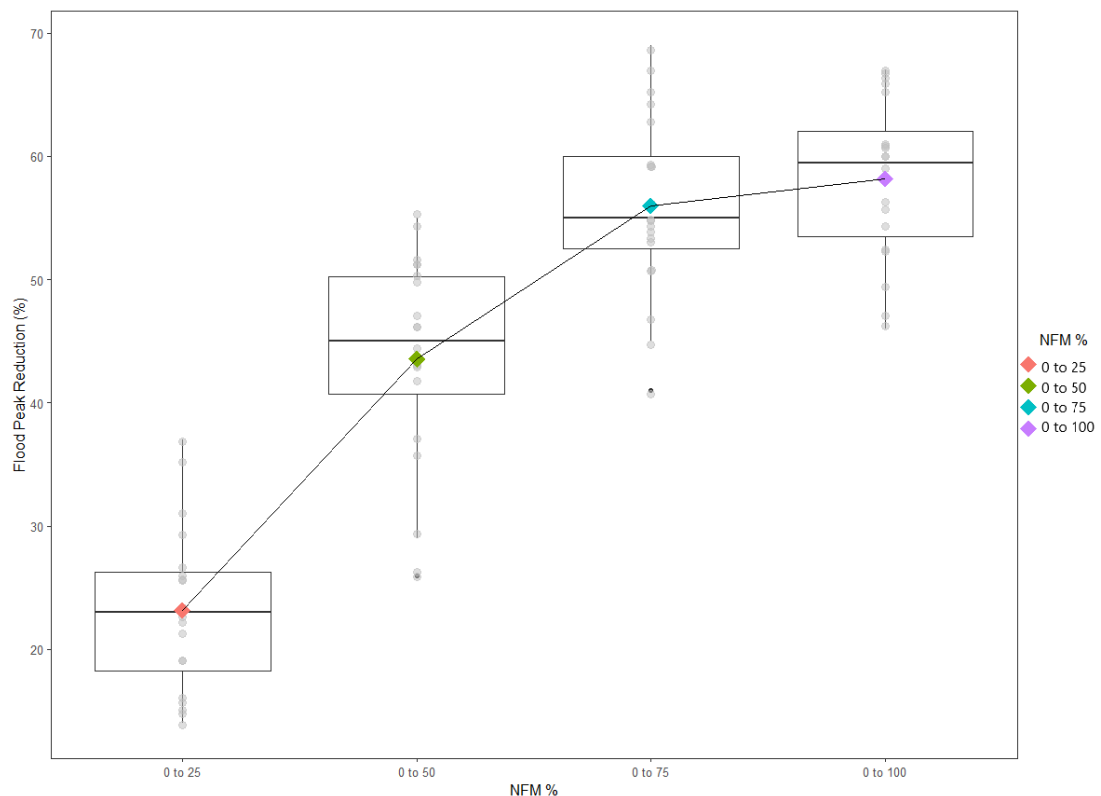


Figure 6-8 Accumulative peak flow reduction, median peak flow (horizontal black line), mean flood peak (coloured diamonds), across 20 catchments and five NFM scenarios.

The non-parametric Friedman's test was performed to explore the effect of the NFM on the peak flow reduction on catchments. The hypothesis analysed is that the median of the peak flow reduction of each category of NFM across all catchments is equal. The Friedman test shows that there are significant differences between peaks from the four NFM coverages ( $\chi^2(3) = 52.025$ ,  $p < 0.001$ ). Post-hoc analysis with Wilcoxon Signed Rank test was conducted to analyse the medians of the peak flow reduction as a percentage of the control conditions for

all catchments, for all four NFM categories (Table 6.4). 100% NFM coverage differs significantly from 25% and 50% coverage, and 25% NFM differs significantly from 50% and 75% NFM ( $p < 0.01$ ). However, 75% NFM was not significant different to 100% NFM ( $p > 0.05$ ).

Table 6.4 Significance P values for the Wilcoxon Signed Rank multiple comparisons test of peak flow of four NFM categories.

| <b>NFM</b>             | <b>[0% to 100% NFM]</b> | <b>[0% to 25% NFM]</b> | <b>[0% to 50% NFM]</b> |
|------------------------|-------------------------|------------------------|------------------------|
| <b>[0% to 25% NFM]</b> | 0.00053                 | -                      | -                      |
| <b>[0% to 50% NFM]</b> | 0.00062                 | 0.00078                | -                      |
| <b>[0% to 75% NFM]</b> | 1.00                    | 0.00053                | 0.00053                |

The effect of NFM on the lag time was also analysed in Figure 6-9. The results of the Friedman's test indicate that the lag time is significantly different with different NFM coverages ( $\chi^2(3) = 44.231$ ,  $p < 0.001$ ). The Wilcoxon Rank Test was performed to explore in more depth the differences between NFM scenarios Table 6.5. The results indicate that there was not a significant difference between 25% and 50% NFM ( $p > 0.05$ ) but that all other contrasts were significantly different ( $p < 0.01$ ). The 25% and 50% NFM coverages indicate that there is not much impact on lag time, in fact half of the catchments in 25% scenarios had earlier lag time compared to the control [0% NFM] while 13 catchments presented earlier lag times for the 50% scenario. Interestingly, this effect is seen in the same NFM scenarios where the impact on peak flow reduction is greater; 25% and 50%.

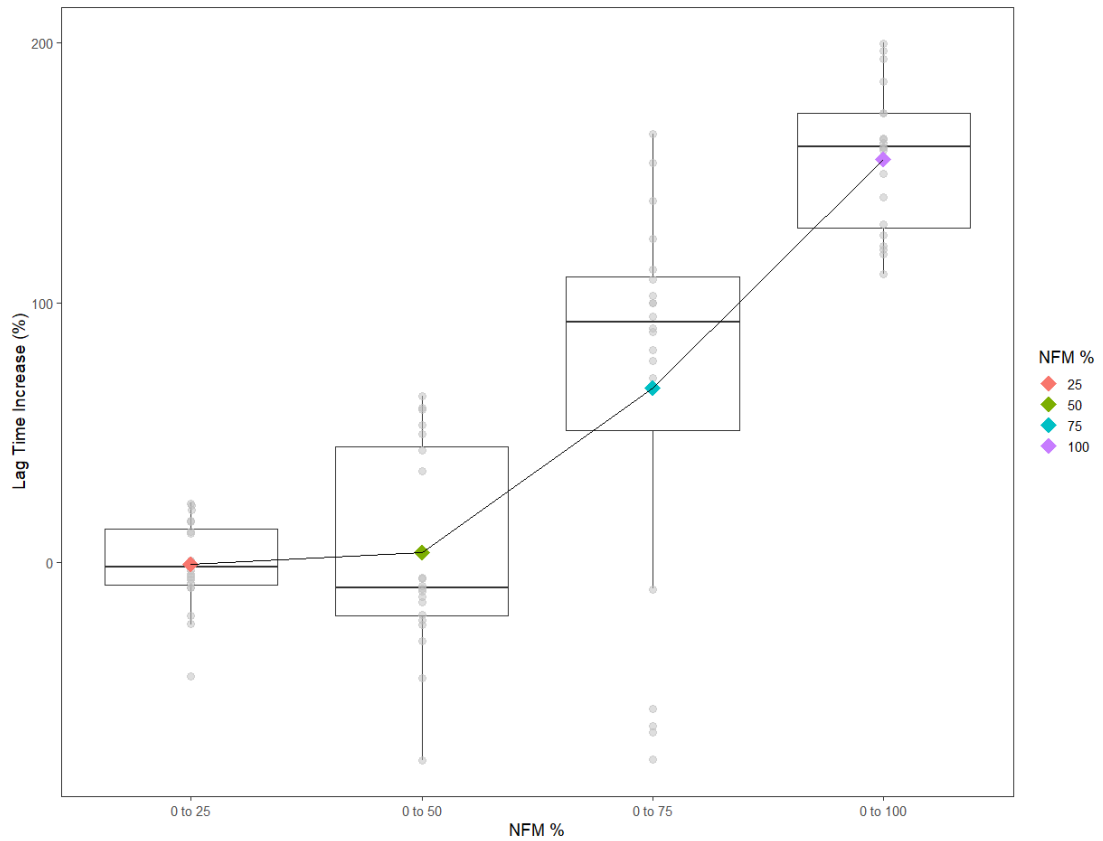


Figure 6-9 Lag time percentage increase, median lag time (horizontal black line), mean lag time (coloured diamonds), across 20 catchments and five NFM scenarios.

Table 6.5 Wilcoxon Signed Rank multiple comparisons test of lag time increase of four NFM categories.

| NFM             | [0% to 100% NFM] | [0% to 25% NFM] | [0% to 50% NFM] |
|-----------------|------------------|-----------------|-----------------|
| [0% to 25% NFM] | 0.00053          | -               | -               |
| [0% to 50% NFM] | 0.00053          | 1.00000         | -               |
| [0% to 75% NFM] | 0.00053          | 0.02028         | 0.02040         |

#### 6.4.2 Effect of NFM on flood peak vary by area, cluster and hypsometric curve class.

Although no statistical difference in peak flow or lag time was found between micro- and sub-catchments in chapter 5, the catchment area has previously been shown to correlate to peak flow for micro-catchments ( $r = 0.803$ ; Table 5.3). Therefore, here the effect of NFM on peak flow within area classes was assessed.

'Large-catchments' have been removed from the analysis as this class only contains 2 catchments. Figure 6-10 shows that when area classes are considered separately, the overall peak flow still decreases with increasing NFM, which is very similar to when all the catchments have been assessed together (i.e. Figure 6-8). Overall, results indicate that the percentage flow reduction is greater for sub-catchments than micro-catchments in all NFM comparisons. However, the mean and median of the peak flow reduction for each class size in each NFM scenario vary. It was expected to have a larger variance for the sub-catchments class across all NFM because in Chapter 5 it was found that even though there were not significant differences between both classes the variance was greater for sub-catchments. Conversely, here the variance seems to be greater for micro-catchments compared to sub-catchments. The expected results could be seen just in the 0 to 50% NFM scenario.

The Mann-Whitney U test shows that micro-catchments and sub-catchments are not significantly different in any of the NFM scenarios ( $p > 0.05$ ). Although the variance is larger for micro-catchments relative to sub-catchments in the 50% scenario, and larger for sub-catchments than micro-catchments in the 75% scenario, the results of a Levene's test indicate that the variance of both classes is not significantly different ( $p > 0.05$ ) in all NFM scenarios.

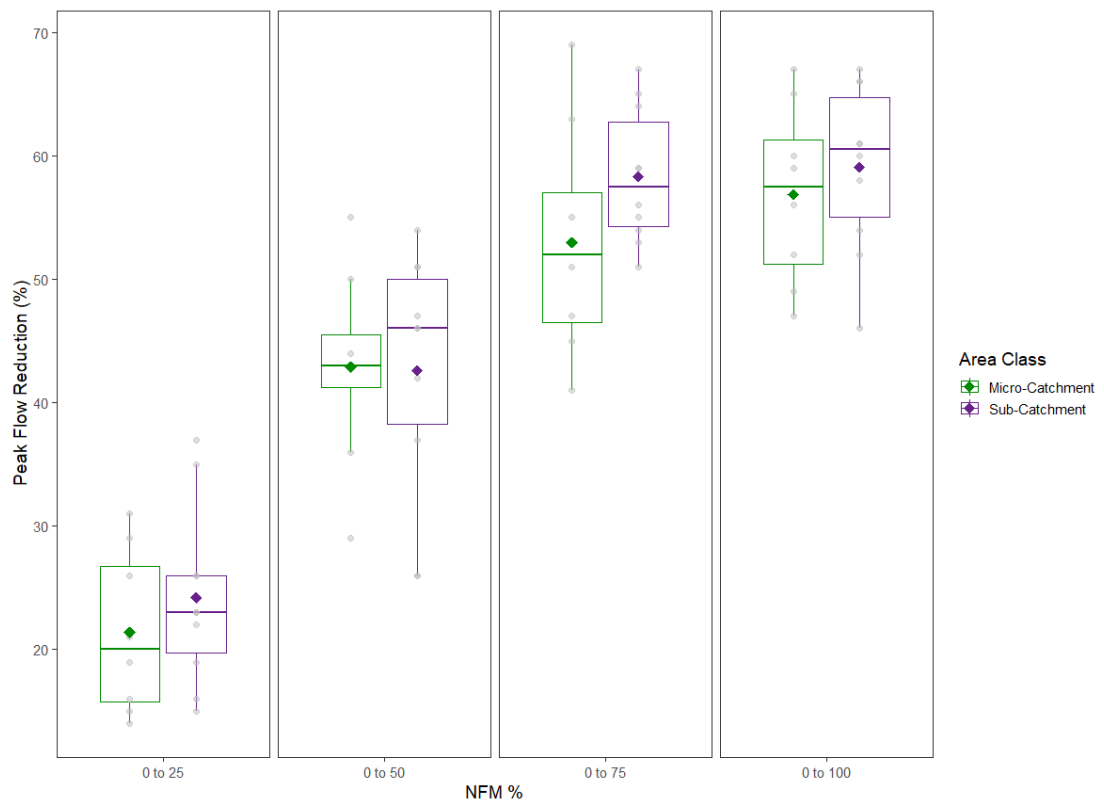


Figure 6-10 Box-plots showing the median of peak flow reduction in each area class (horizontal line) for each NFM set compared to the control [0% NFM]. Mean peak flow reduction in each area class (diamond), with boxes indicating the interquartile range (IQR) and grey points indicating the peak flow reduction of all individual catchments.

To expand the analysis of the effect of the NFM on peak flow reduction, the same analysis above was made for the catchment clusters determined in Section 4.3.2. In chapter 5 a statistical difference between cluster A (small and elongated) and C (large and rounded) was found when peak flow was compared. Once again, cluster B, which has intermediate sized catchments, has been removed from the analysis as it only contained 3 catchments. Figure 6-11 depicts individual box-plots for peak flow reduction and NFM for cluster A and cluster C. The results indicate that there was a greater peak flow reduction in cluster C than cluster A except for the scenario 0 to 25. Similar to previous analysis, the variance for the cluster A was expected to be smaller than cluster C but the results reflect the opposite. Cluster A as mentioned above has smaller catchments and it was found to have smaller variance compared to the cluster C when peak flow was analysed (see Section 5.4.4). The similarities between cluster A and the micro-catchment

class might confirm that there are larger differences in the peak flow reduction for smaller catchments when increasing the coverage of NFM.

No evidence of significant differences were found by performing the Mann-Whitney U test ( $p > 0.05$ ) for 25%, 50% and 100% NFM coverage. However, significant differences were found for the 75% NFM coverage between clusters ( $W = 8$ ,  $p = 0.009$ ). The Levene's test indicates that the variance of both cluster classes is not significantly different ( $p > 0.05$ ) in all NFM scenarios.

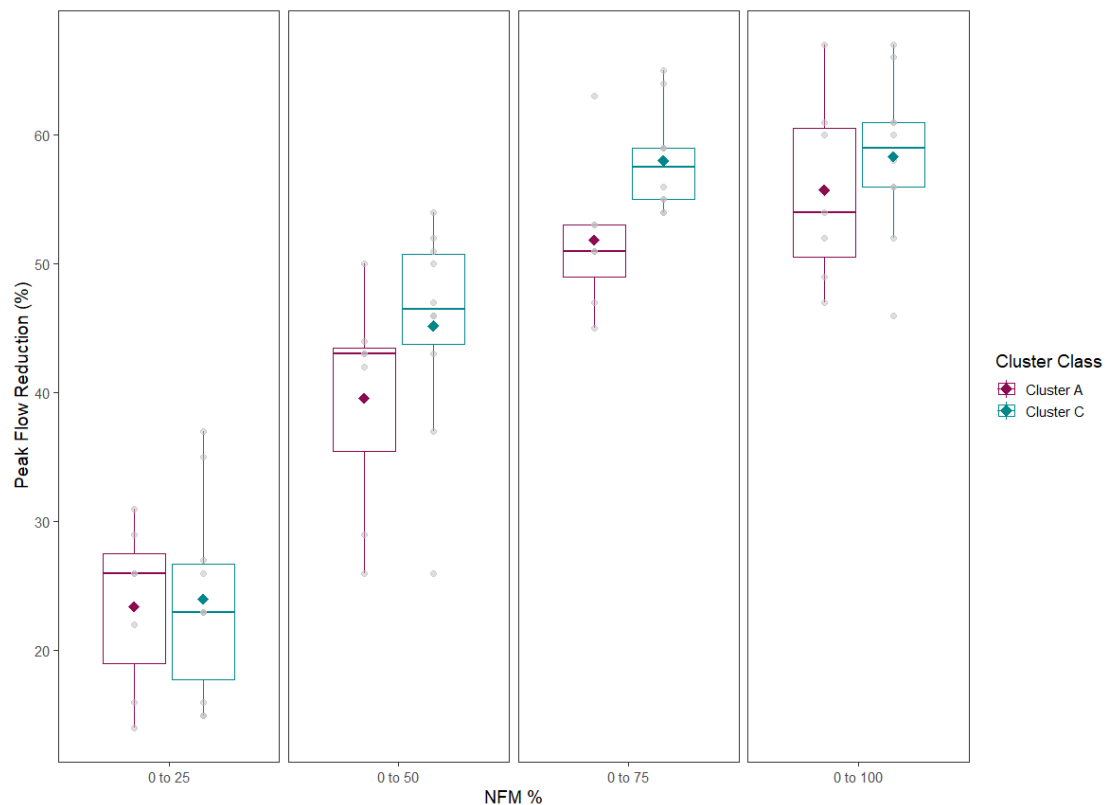


Figure 6-11 Box-plots showing the median of peak flow reduction in each cluster (horizontal line) for each NFM set compared to the control [0% NFM]. Mean peak flow reduction in each area class (diamond), with boxes indicating the interquartile range (IQR) and grey points indicating the peak flow reduction of all individual catchments.

The same analysis was performed for linear and non-linear catchments and hypsometric curves (Figure 6-12). The results show that there were significant differences in the peak flow reduction between linear and non-linear catchments

for 25% NFM ( $W = 13$ ,  $p = 0.008$ ) and no significant differences for the other NFM scenarios ( $p > 0.05$ ). A Levene's test also indicates that the variance between linear and non-linear catchments is not significantly different for any of the NFM scenarios ( $p > 0.05$ ), except for 50% NFM ( $f = 5.496$ ,  $p = 0.031$ ). In terms of the hypsometric curve, no evidence of significant differences was found for the peak flow reduction between curves in any of the NFM scenarios ( $p > 0.05$ ), and no significant differences by performing the Levene's test in any of the scenarios evaluated.

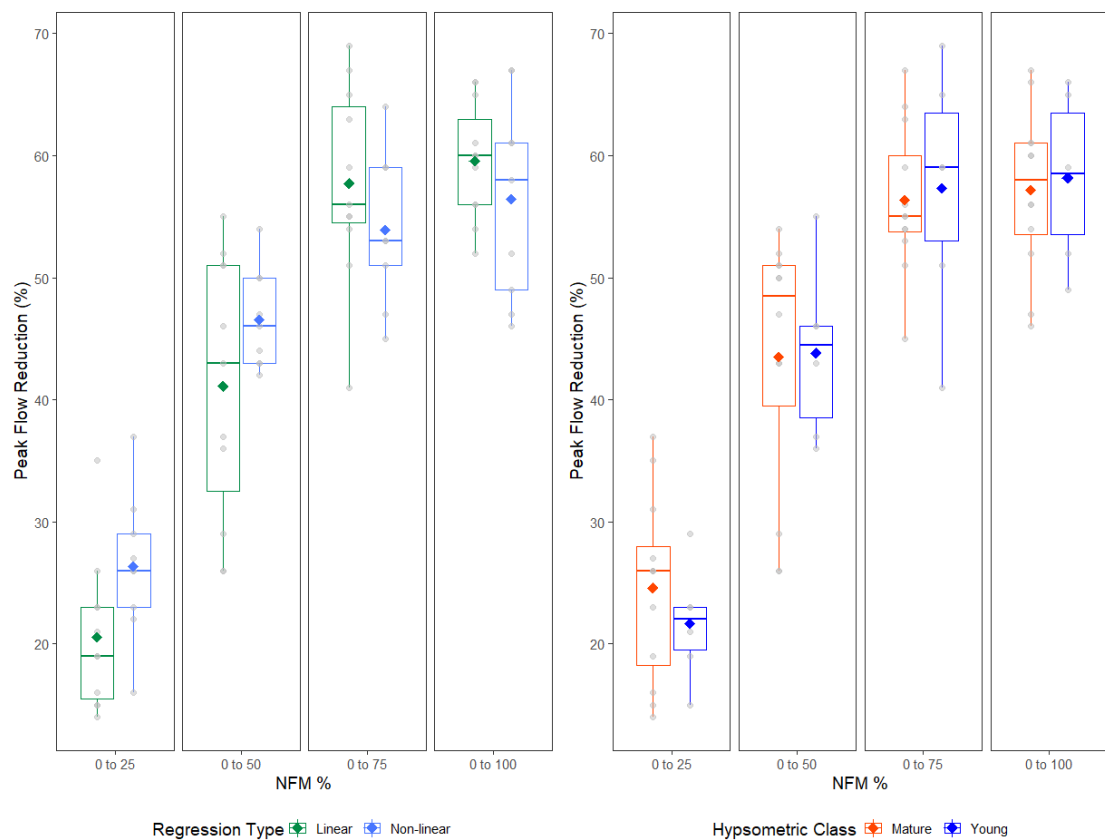


Figure 6-12 Box-plots showing the median of peak flow reduction in each regression type and hypsometric curve (horizontal line) for each NFM set compared to the control [0% NFM]. Mean peak flow reduction in each area class (diamond), with boxes indicating the interquartile range (IQR) and grey points indicating the peak flow reduction of all individual catchments.



#### ***6.4.3 The effect of NFM on flood peak flow and lag time with varying rainfall intensity across 20 catchments.***

The second part of this chapter examines the effect of NFM coverage on the peak flow and lag time depending on a range of three rainfall intensities. Figure 6-13 shows the scatter plot of the peak flow across all NFM scenarios and each rainfall intensity for each catchment. Two regression models (e.g. linear and non-linear) were fitted to the data and the  $r$  and  $p$  values calculated to evaluate the strength of the relationship. The overall negative trends indicate that peak flow generally decreased with NFM coverage regardless of the intensity of rainfall. The linear regression for the  $120 \text{ mm h}^{-1}$  scenarios had a steeper slope than for lower intensities, indicating higher peak flows for  $120 \text{ mm h}^{-1}$  scenario, as would be expected. It also indicates that reductions in peak flow with NFM coverage were greater for higher intensity events. The analysis of the linear and non-linear regression models indicates that most catchments had high  $r$  values ( $r > 0.9$ ) in both models. However, results from the linear model indicated that Caquetá and Mulato were the only catchments that were not significantly correlated in none of the three intensity scenarios.

As for the non-linear model, correlations were not significant for Caquetá, Dinin, Kurtcukuru, L'Auline, Mayala Laba, Pasto, and Yandaran in the  $30 \text{ mm h}^{-1}$  scenario while just Kurtcukuru and Pasto were also not significant in the  $60 \text{ mm h}^{-1}$ . Likewise, Dinin, Kurtcukuru and Pasto were not significantly correlated in the  $120 \text{ mm h}^{-1}$  scenario. What the correlations suggest is that these catchments had a linear trend between peak flow and NFM. However, to determine which regression had statistical better fit the partial F test was used. The results from the tests are also shown in Table 6.6. Results indicate that Combeima-Hor-patak, Mazzarrà, Metome and Sambre had better fit with non-linear model in the  $30 \text{ mm h}^{-1}$  ( $p < 0.05$ ). As for the  $120 \text{ mm h}^{-1}$  scenario Caquetá, Combeima, Hór-patak, Mazzarrà, Metome, Mulato, Swale and Yandaran were found to have a better fit for the non-linear model. The remaining catchments for the three scenarios show a linear trend across all NFM. What these results suggest is that there is an effect of the rainfall intensity in the peak flow for the range off NFM configurations because the number of catchments that fitted better to a non-linear model has increased with the increase of the rainfall intensity.

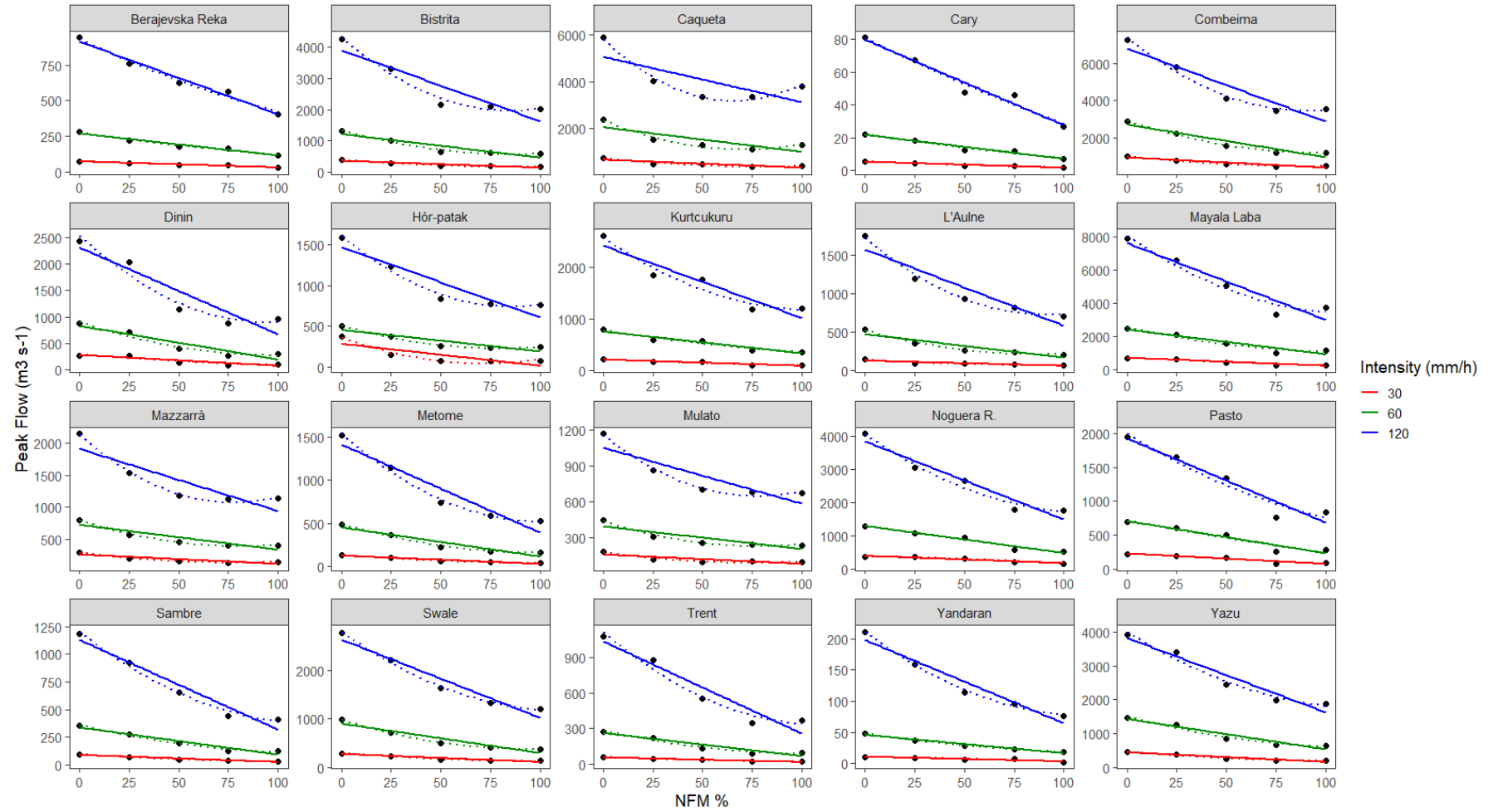


Figure 6-13 Scatter plot of the peak flow and all NFM configurations and three intensities. The coloured lines are the linear regression model fitted. The r value was calculated for each linear regression.

Table 6.6 R and equation from the lineal model between peak flow and NFM scenarios for each catchment and for the three intensities.

| Catchment              | Peak Flow           |         |                  |         |                          |                     |         |                  |         |                          |                      |         |                  |         |                          |
|------------------------|---------------------|---------|------------------|---------|--------------------------|---------------------|---------|------------------|---------|--------------------------|----------------------|---------|------------------|---------|--------------------------|
|                        | Intensity 30 mm h-1 |         |                  |         |                          | Intensity 60 mm h-1 |         |                  |         |                          | Intensity 120 mm h-1 |         |                  |         |                          |
|                        | Linear model        |         | Non-linear model |         | F test Model differences | Linear model        |         | Non-linear model |         | F test Model differences | Linear model         |         | Non-linear model |         | F test Model differences |
|                        | r                   | p-value | r                | p-value | p-value                  | r                   | p-value | r                | p-value | p-value                  | r                    | p-value | r                | p-value | p-value                  |
| <b>Berajevska Reka</b> | -0.98               | 0.003   | 0.98             | 0.036   | 0.826                    | -0.98               | 0.002   | 0.98             | 0.022   | 0.457                    | -0.99                | 0.001   | 0.99             | 0.016   | 0.455                    |
| <b>Bistrita</b>        | -0.90               | 0.037   | 0.99             | 0.020   | 0.054                    | -0.92               | 0.029   | 0.97             | 0.023   | 0.075                    | -0.91                | 0.031   | 0.99             | 0.022   | 0.066                    |
| <b>Caquetá</b>         | -0.86               | 0.063   | 0.97             | 0.066   | 0.133                    | -0.81               | 0.098   | 0.98             | 0.021   | 0.030                    | -0.73                | 0.164   | 0.99             | 0.012   | 0.013                    |
| <b>Cary</b>            | -0.98               | 0.004   | 0.98             | 0.033   | 0.520                    | -0.98               | 0.004   | 0.96             | 0.030   | 0.004                    | -0.98                | 0.003   | 0.98             | 0.034   | 0.767                    |
| <b>Combeima</b>        | -0.94               | 0.018   | 1.00             | 0.009   | 0.036                    | -0.95               | 0.013   | 0.99             | 0.007   | 0.038                    | -0.94                | 0.019   | 0.99             | 0.011   | 0.046                    |
| <b>Dinin</b>           | -0.92               | 0.028   | 0.93             | 0.127   | 0.568                    | -0.94               | 0.020   | 0.96             | 0.041   | 0.179                    | -0.93                | 0.024   | 0.97             | 0.051   | 0.201                    |
| <b>Hór-patak</b>       | -0.82               | 0.041   | 0.99             | 0.028   | 0.044                    | -0.9                | 0.039   | 0.99             | 0.009   | 0.023                    | -0.92                | 0.028   | 0.99             | 0.013   | 0.042                    |
| <b>Kurtcukuru</b>      | -0.96               | 0.009   | 0.97             | 0.064   | 0.646                    | -0.96               | 0.011   | 0.93             | 0.067   | 0.547                    | -0.94                | 0.017   | 0.97             | 0.054   | 0.272                    |
| <b>L'Aulne</b>         | -0.89               | 0.045   | 0.95             | 0.095   | 0.255                    | -0.92               | 0.028   | 0.98             | 0.018   | 0.059                    | -0.94                | 0.020   | 0.99             | 0.013   | 0.054                    |
| <b>Mayala Laba</b>     | -0.96               | 0.009   | 0.97             | 0.065   | 0.646                    | -0.95               | 0.015   | 0.95             | 0.050   | 0.288                    | -0.95                | 0.012   | 0.98             | 0.041   | 0.264                    |
| <b>Mazzarrà</b>        | -0.89               | 0.045   | 1.00             | 0.007   | 0.017                    | -0.9                | 0.037   | 0.99             | 0.004   | 0.010                    | -0.88                | 0.050   | 1.00             | 0.007   | 0.016                    |
| <b>Metome</b>          | -0.94               | 0.016   | 0.99             | 0.011   | 0.050                    | -0.95               | 0.012   | 0.99             | 0.007   | 0.039                    | -0.96                | 0.010   | 1.00             | 0.006   | 0.034                    |
| <b>Mulato</b>          | -0.85               | 0.071   | 0.98             | 0.039   | 0.071                    | -0.87               | 0.054   | 0.98             | 0.021   | 0.045                    | -0.88                | 0.052   | 0.99             | 0.012   | 0.027                    |
| <b>Noguera R.</b>      | -0.96               | 0.010   | 0.99             | 0.027   | 0.191                    | -0.98               | 0.004   | 0.96             | 0.042   | 0.864                    | -0.96                | 0.008   | 0.99             | 0.025   | 0.195                    |
| <b>Pasto</b>           | -0.96               | 0.011   | 0.96             | 0.086   | 0.995                    | -0.96               | 0.009   | 0.93             | 0.071   | 0.742                    | -0.96                | 0.010   | 0.97             | 0.064   | 0.545                    |
| <b>Sambre</b>          | -0.96               | 0.008   | 1.00             | 0.005   | 0.039                    | -0.97               | 0.007   | 0.99             | 0.010   | 0.090                    | -0.97                | 0.005   | 1.00             | 0.010   | 0.095                    |
| <b>Swale</b>           | -0.94               | 0.017   | 0.99             | 0.022   | 0.101                    | -0.94               | 0.016   | 1                | 0.002   | 0.008                    | -0.97                | 0.006   | 1.00             | 0.003   | 0.026                    |
| <b>Trent</b>           | -0.97               | 0.006   | 0.99             | 0.022   | 0.211                    | -0.95               | 0.013   | 0.97             | 0.029   | 0.167                    | -0.96                | 0.011   | 0.98             | 0.031   | 0.197                    |
| <b>Yandaran</b>        | -0.95               | 0.015   | 0.96             | 0.086   | 0.559                    | -0.98               | 0.010   | 1                | 0.001   | 0.007                    | -0.97                | 0.005   | 1.00             | 0.002   | 0.022                    |
| <b>Yazu</b>            | -0.95               | 0.014   | 0.98             | 0.037   | 0.209                    | -0.96               | 0.010   | 0.97             | 0.029   | 0.206                    | -0.97                | 0.007   | 0.99             | 0.024   | 0.225                    |

The effect of NFM configuration on the lag time for the range of intensities is plotted in Figure 6-14. Linear models were not fitted to the data as the previous analysis indicates that linear regression does not fit the data due to anomalous values associated with double-peaked distributions (see Section 6.4.1, Figure 6-7). This analysis aimed to examine whether the trend of the lag time with NFM coverage changes due to the rainfall intensity. In general, trends were similar across rainfall intensities indicating that lag time is delayed to a greater degree for the lower rainfall intensity and to a lesser degree for the higher intensity. However, the effect of intensity on lag time across NFM seems to be non-additive since lines are not parallel. This might indicate that there is an additional effect on the lag time caused by the intensity level, which is addressed in the next section.

There were clear differences in the lag time due to the NFM coverage. These changes occurred in the same catchments identified in section 6.4.1 (Figure 6-14), which were double-peaked hydrographs that complicate the lag time measurement. Interestingly, these catchments had lower lag time values for  $60\text{mm h}^{-1}$  and  $120\text{mm h}^{-1}$  than the  $30\text{mm h}^{-1}$  in the 75% NFM scenario. These results indicate that lag time for this particular coverage and for these particular catchments, had a shorter peak flow response for lower intensity values. Catchments that had shorter lag times for the 25% and 50% NFM compared to the control (0% NFM) in the  $60\text{ mm h}^{-1}$  scenario showed the same trend for  $30\text{ mm h}^{-1}$  and  $120\text{ mm h}^{-1}$ .

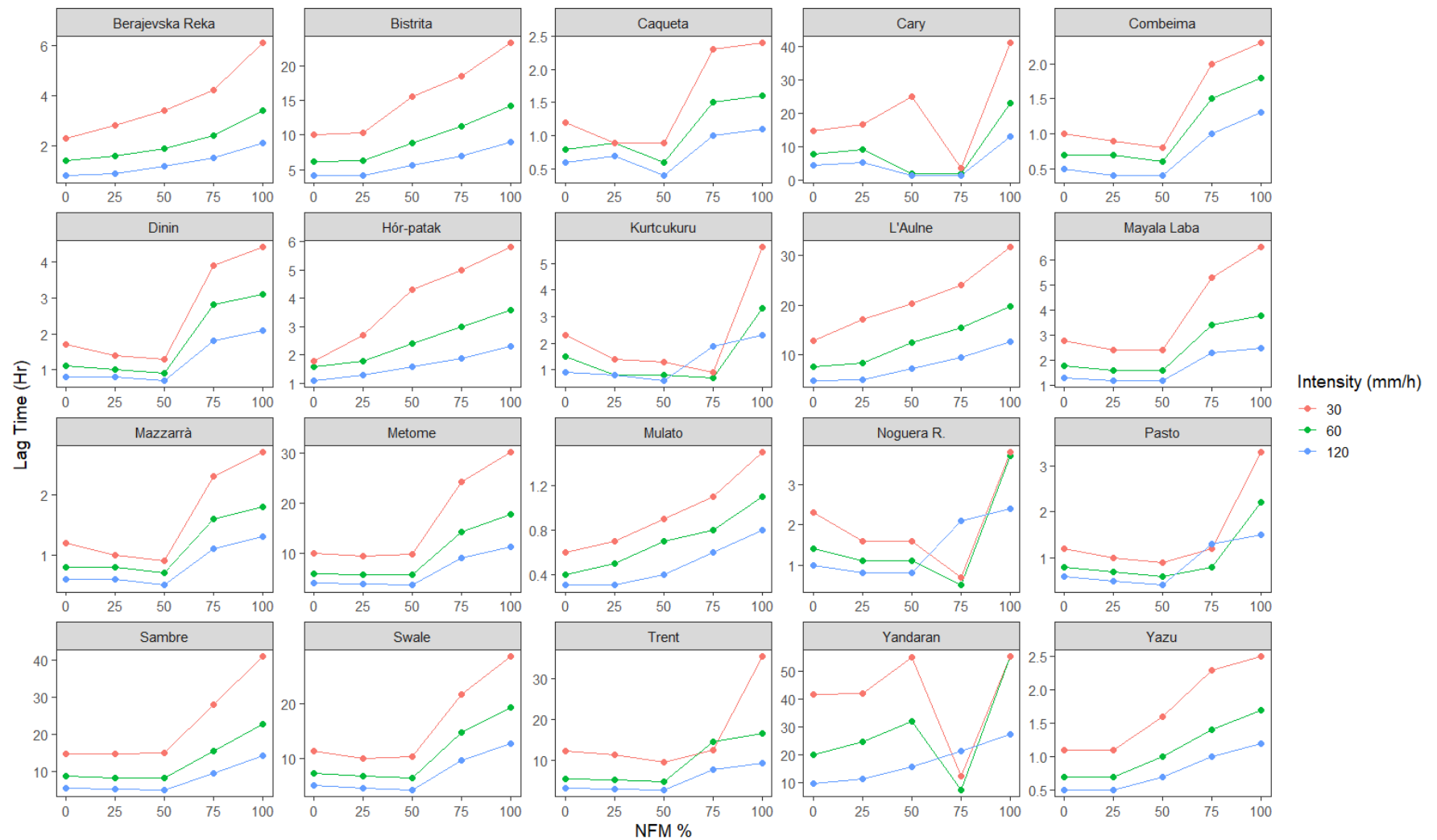


Figure 6-14 Scatter plot of the lag time and all NFM configurations and three intensities. The coloured lines are the trend lines through each NFM and intensities.

To assess how the effect of NFM on the peak flow varies with intensity, the percentage reduction in peak flow was investigated. Figure 6-15 shows the boxplot of the peak flow reduction across all NFM and three intensities. The trend indicates a positive increase in peak flow reduction while the NFM increases and for the three intensities. The boxplots also indicate that the variance is greater for the 30 mm h<sup>-1</sup> than the 60 and 120 mm h<sup>-1</sup> scenarios from 25% to 75% NFM. Overall, the 120 mm h<sup>-1</sup> scenarios have lower relative reductions in peak flow than the 30 and 60 mm h<sup>-1</sup> for all NFM scenarios, being most evident in the 100% NFM coverage.

How the impact of NFM on peak flow reduction varies with intensity was statistically assessed by evaluating the null hypothesis that the effect of NFM on peak flow reduction depended on the rainfall intensity (Figure 6-15). The two-way ANOVA for repeated measures was performed. The results reveal that there were significant effects of NFM scenarios ( $F(3, 57) = 98.94, p = 0.01, \eta^2=0.71$ ) in reducing the peak flow, but no significant effect of rainfall intensities ( $F(2, 38) = 0.74, p = 0.483$ , Greenhouse-Geisser  $p = 0.59, \eta^2=0.008$ ) in the peak flow reduction. The Bonferroni post-hoc tests was performed twice to analyse; first, the simple effect of the peak flow reduction for each intensity across each NFM scenario ( Table 6.7 ) and second, the simple effect of the peak flow reduction of the three intensities in each NFM scenario (Table 6.8). The results of the first test show that there was no significant differences in peak flow reduction for the 75% NFM and 100% NFM coverages for the 30 mm h<sup>-1</sup> intensity ( $p = 0.21856$ ) and no significant differences for the same scenarios with other intensities ( $p = 1, p = 0.89$ ). The other possible combinations between intensity and NFM scenarios had significant differences ( $p < 0.05$ ).

The Bonferroni test for simple effects of peak flow reduction of each rainfall intensity in each NFM category (Table 6.8) has revealed that there was no significant effect on peak flow reduction for the 25% NFM and the 50% NFM for the three intensities ( $p > 0.05$ ). However, significant differences were found between 60 and 120 mm h<sup>-1</sup> for the 75% NFM ( $p = 0.0068$ ). The 100% NFM scenario differs significantly ( $p < 0.05$ ) from 60 mm h<sup>-1</sup> to 120 and 30 mm h<sup>-1</sup>.

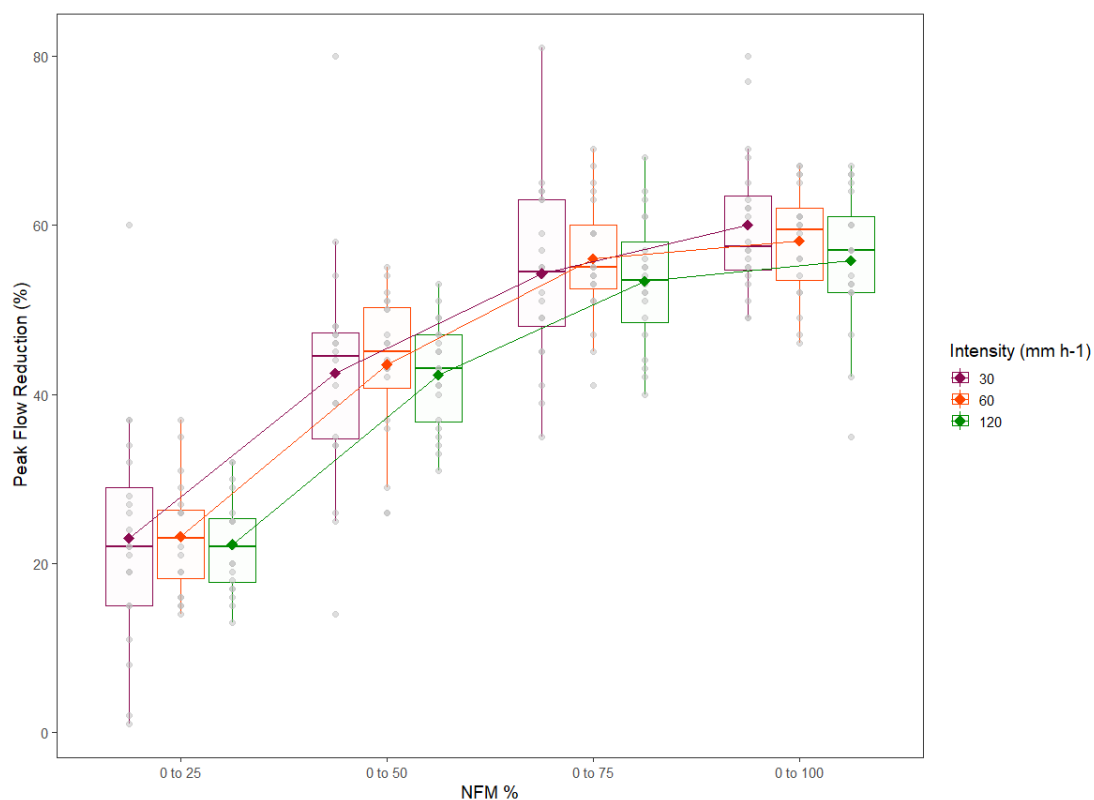


Figure 6-15 Effect of NFM on the peak flow reduction vary by intensity. The colours of the boxplots represent the three rainfall intensities.

Table 6.7 Significance P values for the Bonferroni multiple comparisons test for simple effects of peak flow reduction of each intensity across four NFM categories.

| Intensity 30 mm h <sup>-1</sup>  |                  |                 |                 |
|----------------------------------|------------------|-----------------|-----------------|
| NFM                              | [0% to 100% NFM] | [0% to 25% NFM] | [0% to 50% NFM] |
| [0% to 25% NFM]                  | 6.30E-09         | -               | -               |
| [0% to 50% NFM]                  | 4.90E-05         | 2.10E-06        | -               |
| [0% to 75% NFM]                  | 0.21856          | 7.70E-08        | 0.00063         |
| Intensity 60 mm h <sup>-1</sup>  |                  |                 |                 |
| NFM                              | [0% to 100% NFM] | [0% to 25% NFM] | [0% to 50% NFM] |
| [0% to 25% NFM]                  | 1.10E-10         | -               | -               |
| [0% to 50% NFM]                  | 1.20E-05         | 1.90E-08        | -               |
| [0% to 75% NFM]                  | 1                | 2.40E-10        | 6.20E-05        |
| Intensity 120 mm h <sup>-1</sup> |                  |                 |                 |
| NFM                              | [0% to 100% NFM] | [0% to 25% NFM] | [0% to 50% NFM] |
| [0% to 25% NFM]                  | 4.00E-10         | -               | -               |
| [0% to 50% NFM]                  | 1.50E-05         | 3.30E-09        | -               |
| [0% to 75% NFM]                  | 0.89             | 3.50E-10        | 5.90E-05        |

Table 6.8 Significance P values for the Bonferroni multiple comparisons test for simple effects of peak flow reduction of each rainfall intensity in each NFM category.

| [0% to 25% NFM] |      |    | [0% to 50% NFM] |      |    | [0% to 75% NFM] |        |    | [0% to 100% NFM] |        |        |
|-----------------|------|----|-----------------|------|----|-----------------|--------|----|------------------|--------|--------|
| Intensity       | 120  | 30 | Intensity       | 120  | 30 | Intensity       | 120    | 30 | Intensity        | 120    | 30     |
| 30              | 1    | -  | 30              | 1    | -  | 30              | 1      | -  | 30               | 0.054  | -      |
| 60              | 0.84 | 1  | 60              | 0.61 | 1  | 60              | 0.0068 | 1  | 60               | 0.0081 | 0.8868 |

#### **6.4.4 Effect of NFM on peak flow reduction under three rainfall and catchment size and cluster class.**

The effect of NFM on peak flow reduction for different rainfall intensity differs between micro- and sub-catchments (Figure 6-16). The figure below shows the individual boxplots for each area classes and the three rainfall intensities. The graph for the micro-catchment shows that the intensity of 30 mm h<sup>-1</sup> had an overall higher peak flow reduction across all NFM scenarios compared to 60 and 120 mm h<sup>-1</sup> rainfall intensities. The 30 mm h<sup>-1</sup> intensity had the lowest values for sub-catchments, decreasing the peak flow reduction considerably compared to the other intensities. The 120 mm h<sup>-1</sup> had the lowest peak flow reduction across all NFM scenarios for micro-catchments, while the sub-catchments had similar peak flow reductions as 60 mm h<sup>-1</sup>.



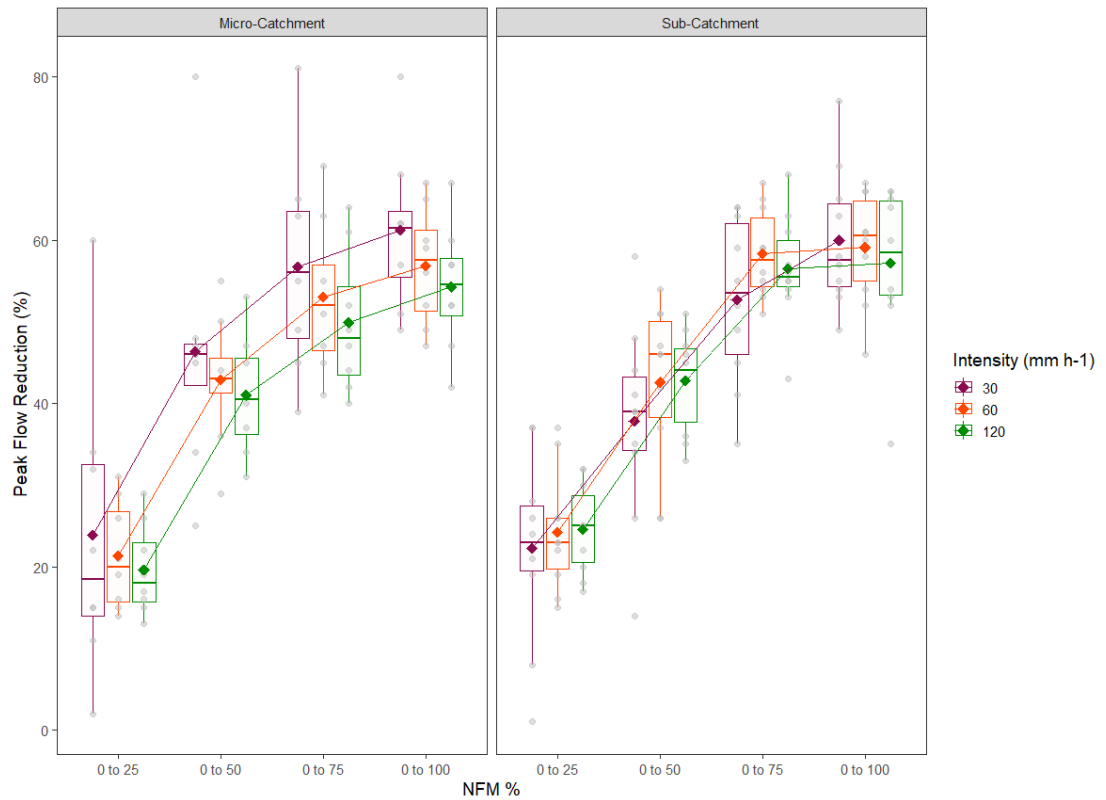


Figure 6-16 Effect of NFM on the peak flow reduction vary by intensity and area classes. The colours of the boxplots represent the three rainfall intensities.

The difference in the effect of NFM coverage on peak flow reduction with differing rainfall intensities was also compared between catchment clusters (Figure 6-17). The figure below shows that the catchments within cluster A have higher peak flow reduction for the rainfall event of 30 mm h<sup>-1</sup> than the 60 and 120 mm h<sup>-1</sup>. The mean peak flow reduction is similar for 60 and 120 mm h<sup>-1</sup> intensities in all NFM scenarios. Conversely, the 30 mm h<sup>-1</sup> and 60 mm h<sup>-1</sup> intensity rainfall had similar peak flow reduction for cluster C. The lowest peak flow reduction was for the 120 mm h<sup>-1</sup> in all NFM scenarios.

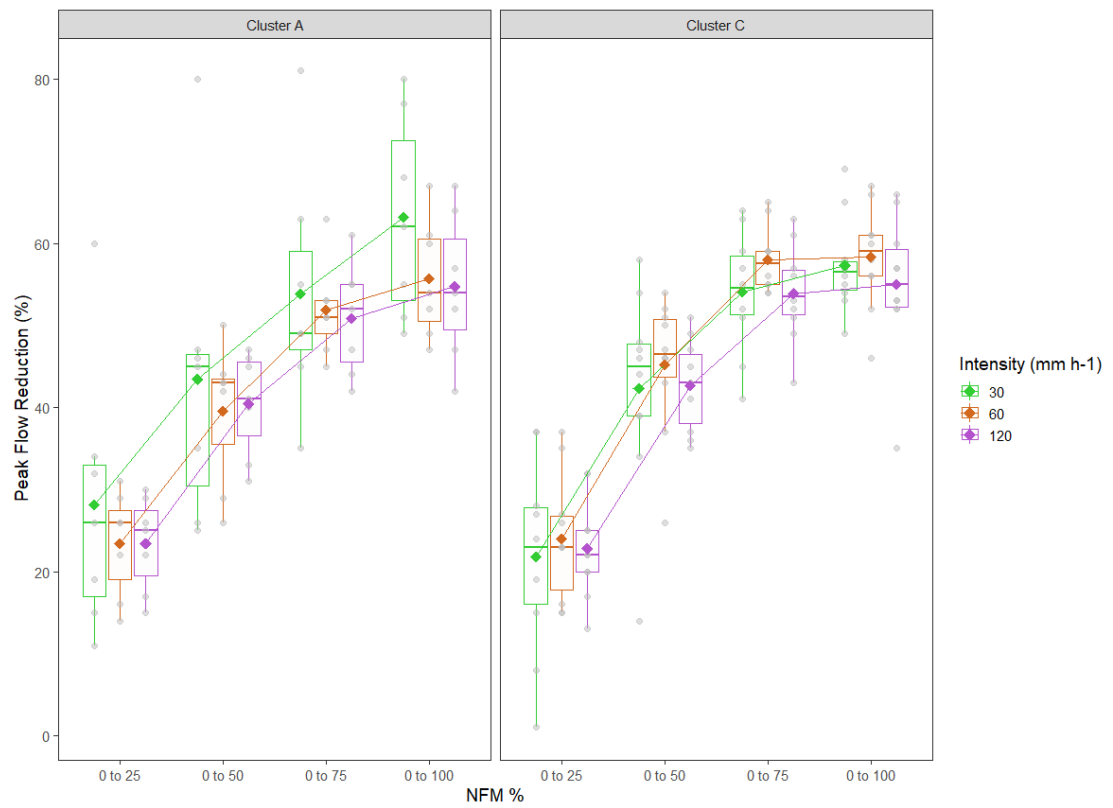


Figure 6-17 Effect of NFM on the peak flow reduction vary by intensity and Cluster classes. The colours of the boxplots represent the three rainfall intensities.

## **6.5 Discussion**

### ***6.5.1 Effect of NFM on peak flow and lag time on catchments.***

This chapter has described how a modelling approach can be used to assess the effectiveness of NFM in catchments of differing shape. The use of NFM is capable of reducing and delaying the flood peak downstream in all catchments (Figure 6-3) and peak flows progressively decrease as NFM is increased. However, increasing NFM does not always increase lag times. A partial F test comparing the better fit model between linear and non-linear regressions indicates that 11 out of 20 catchments have peak flows that decrease linearly with increasing NFM; however, in 9 catchments a non-linear regression was a better fit, indicating that in these cases the effectiveness of NFM plateaued at higher catchment coverages (Table 6.1). These two groups of catchments were analysed together and separately to look for particular morphological or physiological characteristics that determine NFM effectiveness (i.e. substantial decreases in peak flows). There were no clear relationships between the catchments in these two regression groups and other statistically determined clusters (i.e. area, cluster, hypsometric curve) (Table 6.2). However, catchments that better fitted to a linear model had lower values of mass coefficient, indicating landscapes with steep, mountainous terrain (Fuentes, 2004). Although the mass coefficient is related to the steepness of a catchment, catchments with linear decreases in peak flow with increasing NFM had mixed values of catchment slope. Drainage density also had lower values for linear models which are usually associated with a slow hydrological response (Linsley et al., 1977). Drainage density is important as NFM is thought to be more effective in catchments with slower hydrological responses (Díaz and Bermúdez, 1987).

In fact, those catchments that had better fit with the linear regression had a significant correlation between the catchment slope and the slope of a linear regression between NFM and peak discharge. It seems that from the seven parameters used to characterise catchments, the average slope of the catchment is the most important parameter in influencing the peak flow, including how NFM alters it. This implies that in these catchments, declines in peak flow as NFM coverage increases are greater when catchments are more mountainous, with high slopes. The average slope of catchments are considered a relevant parameter mainly due to their influence on overland flow velocities (David and Davidova, 2014), discussed further in Chapter 5.

The relationship between lag time and NFM was not clear for most catchments (Figure 6-7). Counter-intuitively, some catchments had a faster hydrological response (i.e. shorter lag time) when NFM coverage was increased. These catchments had bimodal hydrographs (Figure 6-3). The bimodal peak in these catchments was more evident for 50% and 75% NFM coverage but, the hydrograph becomes unimodal when the catchment is fully covered with NFM (or when it has no NFM coverage). The high peak flows in these catchments are possibly attributed to the distribution of the NFM (i.e. from headwaters to downstream; Figure 6-2) since areas with no NFM are closer to the catchment outlet thus water would drain faster. Catchments with bimodal distributions typically had higher form factor values, thereby being elongated in shape. This is in contrast to the work of (Smith and Ward, 1998, Arnell, 2014) who note that elongated catchments normally have smoother peak flows compared to rounded catchments because the water from remote areas takes longer to arrive at the catchment outlet. However, here it is argued that a heavy rainfall event across the entire catchment could lead to shorter lag times, regardless of catchment shape, if NFM (or other measures) disconnect regions of the catchment and where the magnitude of peak flows is attributable to contributing area and drainage density (Arnell, 2014, Rinaldo et al., 1991).

The approach of this study can identify the peak flow reduction for a set of NFM distributions across catchments by contrasting the control scenario [0% NFM] to 25%, 50, 75, and 100% NFM. Across all measures, it was found that there were statistically significant differences in peak flow reduction (Figure 6-8) but that there was not a significant difference between 75% and 100% NFM (Table 6.4). Therefore, the results here suggest that placing NFM in more than 75% of a catchment will make only marginal difference to peak flows over 75% NFM, at least when distributed headwards and then progressing downstream. This also suggests that the most downstream 25% of the contributing area, which is generally flatter, is not able to significantly contribute to a decrease in peak flows and so is not necessarily a good area for NFM placement.

From the range of NFM scenarios assessed, it can be seen that the flood peak could be significantly reduced up to 68% for 100% NFM and up to 23% for 25% NFM (Figure 6-8). The rates of peak flow reduction appear to be high but, these results are in line with other work such as by in the upper Belford Burn catchment and by Wheeler et al. (2008) in the Pontbren catchment, and to a lesser degree, with that of Acreman et al. (2003). Furthermore, when peak flow reduction is standardised by catchment size, greater reductions in peak flow are found for

catchments between 100 and 600 km<sup>2</sup>, and reductions are less for catchments smaller than 100 km<sup>2</sup> (Figure 6-10).

The effect of the catchment size on peak flow reduction implies that the catchment area does have a fundamental role in implementing flood management measures. The results here suggest that when torrential rain falls in relatively small catchments, NFM has a smaller impact in reducing the peak flows. However, the efficiency in reducing the peak remains considerable in either type of catchment. Additionally, the percentages of NFM coverage across the catchment also contribute to determining the percentage efficiency in the peak flow reduction. Similar to this, the analysis of the clusters determined that in general small and elongated catchments have a greater potential for reducing the peak of the flood. As such, the reduction in peak flow is intrinsically linked to the morphological and physiographic characteristics of the catchments but, also the percentage of coverage and spatial distribution of the NFM in the catchment.

To identify impacts of catchment morphometry it was necessary to split the dataset into catchment classes providing a deeper understanding of the hydrological responses of the catchments due to the effect of NFM. However, this also reduced the number of data points used to generate relationships, with implications for interpretation. However, the approach itself provides important potential insights for flood management, and could provide the basis of a tool to define and adjust potential strategies for flood management based on the reduction efficiency, coverage percentages, and spatial positioning of the NFM.

#### ***6.5.2 The effect of NFM on flood peak due to a range of rainfall intensities.***

Figure 6-13 shows that declines in peak flow as NFM coverage increases are greater (i.e. the trend is steeper) for larger rainfall intensities. This implies that in absolute terms, NFM was more effective at reducing peak flows for larger events, which is in contrast to other work that suggests that NFM is less effective for larger events (McIntyre and Thorne, 2013). However, if peak flow reduction is standardised as a percentage of the control conditions, there are no statistical differences between rainfall intensities (Figure 6-15), indicating that peak flow reduction is equally attributed to NFM coverages regardless of event intensity. To further explore this result, catchments were separated into size classes and it was found that micro-catchments had greater reductions in peak flow at lower intensity

events ( $30\text{mm h}^{-1}$ ) in comparison to the larger events but, there was no difference for sub-catchments. This indicates that rainfall intensity, at least in this abstracted modelling environment with uniform rainfall across entire catchments, did not significantly impact NFM effectiveness except in the smallest catchments, where effectiveness was reduced as rainfall intensity increased. It should also be noted that all three rainfall events modelled are extreme rainfall events and, if compared to smaller events of more regular (i.e. annual) return periods, NFM may be more effective at these smaller events. All results shown are subject to the modelling assumptions and, are likely to be different if other hydrological processes, such as infiltration, were included. This is likely to be more significant for smaller rainfall events as there might be significantly different runoff between soil types and land use coverage, whereas for large events, such as those modelled here, the runoff is higher regardless of grassland or forest cover (Birkinshaw et al., 2014). However, future work could usefully address this limitation.

### **6.5.3 Summary**

Overall, these results indicate that NFM can be effective at reducing peak flows regardless of catchment shape and morphology, and rainfall intensity but, is likely to have a greater impact in catchments that are relatively large (between 100 and 600 km<sup>2</sup>), with rounded shapes and low drainage density indicating slow drainage to the channel network. Furthermore, steep catchments that generate relatively high peak flows are more likely to have greater peak flow reductions. The impact on lag time is more complex as NFM can disconnect areas of the catchment, creating a bimodal hydrograph. Whilst this is a result of the abstract nature of catchment, rainfall and NFM placement modelling in this chapter, it does identify a potential issue with NFM as misplaced NFM could potentially cause similar events in reality. The results also indicate that NFM within the 25% of the catchment nearest the catchment outlet is unlikely to have a significant impact on peak flows when NFM is configured from upstream to downstream. Therefore, the placement of NFM in a catchment is critical and could make the difference between a substantial positive impact reducing peak flow, and a negligible impact or worse, a decrease in lag time, albeit with a smaller peak.

## **CHAPTER 7. OPTIMISING NFM PLACEMENT TO MAXIMISE THE EFFECTIVENESS.**

### **7.1 Introduction**

NFM is a significant component of current environmental policy in the UK (Environment Agency, 2010, SEPA, 2015, Lavers and Charlesworth, 2018, Environment Agency, 2017) due to the increased frequency and intensity of rainfall (Quintero et al., 2018, Sayers et al., 2015, Lehmann et al., 2015). As such, it has become particularly relevant as a climate change adaptation measure (Iacob et al., 2014). For example, hillside afforestation for NFM has been proposed as a flood mitigation method to slow the flow (Sharp, 2014) and it has been progressively applied in the UK (Thomas et al., 2017). Although scientific evidence suggests that tree planting is an effective method of reducing peak flows and runoff (Neary et al., 2009, Thomas and Nisbet, 2007), as well as enhancing ecosystems (Wheater et al., 2010, Collentine and Futter, 2018), there is a significant gap and considerable uncertainty about where NFM is best placed in catchments (Iacob et al., 2014, Dixon et al., 2016). For example, Lane (2017) states that determining the best location for an allocation of NFM within a catchment can be arduous and complex, generally requiring detailed modelling and good calibration data, and if incorrectly cited could aggravate downstream flooding. Dixon et al. (2016) also state that the most relevant aspect attempting to reduce the peak flow is not just the catchment area but the spatial configuration of the woodland coverage.

The hydrological response of a catchment to rainfall is a key factor in determining where tree planting is likely to be most effective, depending on flow pathways and variable time scale (Nicholson et al., 2020). To determine spatial location of trees on catchments, hydraulic and hydrological models have been used, which are capable of reflecting the characteristics of the landscape, as well as the hydrological response (Plate, 2009). However, the complexity of such models and the input data requirements can limit their applicability and utility. Different approaches have been found in an attempt to investigate the effect of the spatial configuration of tree planting on peak flow reduction. For example, Thomas and Nisbet (2007) used a modelling approach in the Parret catchment, UK, to determine the impact of planting 50 ha of woodland in a reach of the River Cary (2.2 km). Dixon et al. (2016) in the Lymington catchments, UK (98 Km<sup>2</sup>) used a modelling approach to study individual segments of the river network, as well as

individual catchments, and then a combination of sub-catchments to cover the entire catchment area.

Another study carried out by Salazar Galán et al. (2012) using three different flow routing models, simulated the afforestation of three catchments (e.g. Poyo, Upper Iller and Kamp) to observe the effect of tree planting in different landscape configurations and for a sub set of rainfall events. In the Poyo catchment (184 Km<sup>2</sup>), forest coverage was increased from 1% to 28% in agricultural areas, while in the Upper Iller (954 Km<sup>2</sup>), the total area covered was 620 km<sup>2</sup>, corresponding to increase from 32 to 65% of the total area in steep topographies. In the Kamp catchments, slope categories were planted with pine trees to take into account their differences in runoff generation, with forest area increased from 14 to 23 % on steep slopes, and from 33 % to 63 % on intermediate slopes. The study found that for small storms the Poyo and Kamp catchments had 30% peak flow reduction whereas the Upper Iller catchments had only 5%. The study also concluded that the peak flow reduction is affected by the magnitude of the event, the higher the event magnitude, the lower the peak flow reduction. A different approach was carried out by McVicar et al. (2007) in the Coarse Sandy Hilly Catchment (113,000 Km<sup>2</sup>) in North China, where observations from paired catchments were evaluated, with increasing woodland in upstream areas by 20% reducing downstream peak flows by up to 14.1%.

The review of the literature related to the NFM has shown that the reduction of the peak flow could be achieved by using different methods; however, relatively few have detailed the strategies for the location of the NFM in the catchment. Lavers and Charlesworth (2018) argue that the techniques currently used for NFM are not new in terms of international agricultural land drainage and catchment management practices and, as such, are well understood. However, the best placement of NFM continues to be a field in need of development and research (Connell, 2008, Hankin et al., 2016). The Environmental Agency of England also encourages the use of hydraulic and hydrological programs to seek alternatives that contribute to the understanding of NFM and determine the best place to locate the NFM (Environment Agency, 2017).

In the UK in 2012, SEPA and the Scottish Forestry Commission conducted a national study to identify potential areas for NFM (SEPA, 2015). As a result, four fundamental parameters were determined to have a greater impact on reduction of runoff: land cover, type of soil, slope, and precipitation. The methodology was based on method of the Environment Agency to identify watersheds sensitive to



land use change (DEFRA, 2008), identifying the areas within a catchment that most contribute to the generation of terrestrial flows. Therefore, it is considered that the slope of the catchment is one of the main morphological parameters that determine the hydrological response. This is also based on the main findings of past chapters of this thesis, that determined that the slope and the drainage network are key parameters in controlling the hydrological responses. Therefore, in this chapter the effect of the positioning of the NFM in different ranges of slope in the hydrographic catchment will be analysed.

On the other hand, the Natural Flood Management Handbook by SEPA encourages the use of spatially distributed hydrological models with a physical and semi-physical basis that can be used to give an indication of the sensitivity to NFM measurements at different locations within a catchment (Forbes et al., 2015, SEPA, 2015). Flood risk is determined by the volume of water reaching the outlet of a river system, which is partly determined by the contribution of the flood peaks of individual sub-catchments (Blanc et al., 2012b). It is argued that the estimated travel time it takes for precipitation to travel out of the catchment varies depending on the particular conditions of the catchment. Hydrological principles tell us that slowing the progression of flood water from areas that contribute the most to peak flooding can help desynchronize the flow that subsequently contributes to a flood reduction effect (Lane, 2017, Blanc et al., 2012b). In this sense, this research will use the travel time approach to identify the peaks that most contribute to the generation of the flood. Then NFM will be placed to slow down the flow which will be modelled in IBER.

## **7.2 Aims Chapter 7**

It is clear from past work in this thesis that the placement of trees is important to the resulting impact on peak flows. Therefore, this chapter will use a coupled hydraulic and hydrological model (IBER) and a water routing tool (r.travel time) to determine where NFM within catchments is likely to have the best performance in reducing peak flows. Previous chapters of this thesis have placed NFM arbitrarily in the catchment, from the headwater and expanding in a downstream direction. In this chapter, the spatial location of NFM (tree planting) is considered, with a range of areal coverages strategically placed across a sub-set of six catchments using two approaches (e.g. average slope of the catchment and travel time). This chapter describes and discusses the effect of NFM location in reducing peak flows and lag times between catchments and explores methods for optimising the

placement of NFM. This will be accomplished by fulfilling the following specific research objectives:

1. Use a coupled hydraulic and hydrologic model (IBER) to calculate hydrographs across six catchments, under a subset of NFM configurations, in response to a modelled rainfall event.
2. To determine how peak flow and lag time in modelled catchments changes with the addition of NFM placement.
3. To quantify the difference in hydrograph peak flow and lag time between modelled catchments with alternative NFM placing, and models of NFM coverage from 0% to 100% catchment coverage reported in Chapter 6.

## **7.3 Methodology**

### ***7.3.1 Methodological Overview***

This chapter considers two approaches for modelling NFM placement. Approach 1 focusses on the slope of the catchment and how NFM placed in particular slope classes can alter the hydrological response of catchments. This is a novel approach that has not been used previously or seen in the literature review. There is a lack of methodologies for the positioning of the NFM in the literature that makes this a field of potential research. Therefore, the methodology is based on its own initiative based on the fact that in this study the slope of the catchment has proven to be one of the most relevant variables in the hydrological response of the catchment. Approach 2 considers the travel time of water across catchments as a method of desynchronising hydrographs, potentially optimising NFM placement, and maximising reductions in peak flows and lag time across catchments.

For approach 1, the coupled hydraulic and hydrological model IBER was used to calculate a hydrograph at the outlet of each catchment used in this chapter. Six catchments were selected from the cluster analysis in Chapter 4, representing a range of shapes, slopes and catchment sizes (Section 4.3; Figure 4-5). This decision was also based on the model set up time and the computational time since this approach involves modelling 7 scenarios for each catchment making modelling 20 catchments unfeasible in the timeframe. Two catchments from each cluster were selected; these catchments were Kurtcukuru, Pasto, Barajevo, Dinin, Mayala Laba and Metome (

Table 7.1). For example, Pasto and Kurtcukuru are smaller in size with elongated shapes while Mayala Laba and Metome are rounded in shape but relatively large. Dinin and Barajevo are relatively small in size, rounded and moderately sloped. NFM was spatially located in areas of similar slope using the slope classification proposed by Curtis et al. (1965) and described below. The percentage NFM coverage therefore varied depending on the area of each slope class in each catchment, discussed further below. The new catchment coverage of NFM based on slope classes was compared to 0% NFM coverage (i.e. control conditions), which were presented in Chapter 6.

Table 7.1 Catchments selected to be modelled using the sloping approach.

| <b>Catchment</b>       | <b>Area (Km<sup>2</sup>)</b> | <b>Average Slope (%)</b> | <b>Cluster</b> |
|------------------------|------------------------------|--------------------------|----------------|
| <b>Pasto</b>           | 56.3                         | 21.7                     | Cluster A      |
| <b>Kurtcukuru</b>      | 120.6                        | 47.5                     | Cluster A      |
| <b>Dinin</b>           | 85.6                         | 7.2                      | Cluster B      |
| <b>Berajevska Reka</b> | 44.5                         | 14.5                     | Cluster B      |
| <b>Metome</b>          | 291.9                        | 6.4                      | Cluster C      |
| <b>Mayala Laba</b>     | 522.7                        | 60.4                     | Cluster C      |

In approach 2, GRASS GIS software was used to run a flow routing tool (r.traveltime), which is a deterministic model that simulates the travel time of a unit of water falling on each cell in the catchment (Maidment, 1996). Therefore, a set of values were calculated for each cell across a catchment, which represent the time it takes for water falling in that cell to reach the catchment outflow. Histograms of travel times across a catchment were then used to strategically place NFM in an attempt to desynchronise areas of similar travel times that could generate high peak flows. These targeted NFM areas were then modelled in IBER to generate a new set of hydrographs for these particular scenarios. A full description of the methodology of this approach is described in section 7.3.3.

It should be noted that differences in these two modelling approaches (i.e. using IBER and r.traveltime) render them not easy to directly compare. IBER models hydrographs using a coupled hydraulic and hydrological model (detailed in Chapter 4) using a robust mathematical approach, solving the two-dimensional depth-

averaged Shallow Water Equations (SWE) where rainfall is modelled as lasting for one hour across the entire catchment, but with varying intensity. As such, backwatering effects and relative water volumes feedback through the system, altering peak flows and hydrograph shapes. In contrast, *r.traveltime* is a simplified model that assumes that the rainfall is invariant and distributed equally across the whole catchment area (Maidment, 1996). Thus, the velocity varies in each cell but does not vary through time. The model uses slopes and path-lengths (e.g. flow direction and flow accumulation) to model preferential flow paths and so also does not include interactions between bodies of water moving through the system. For these reasons the *r.traveltime* output of a travel time map (i.e. time-area curve) does not necessarily represent the hydrograph of the same event modelled in IBER; hence the need to use both models.

### **7.3.2 Slope approach**

The slope of the catchment was used as a parameter to define areas where NFM could be allocated. These areas were defined according to the classification of slope established by Curtis et al. (1965) (Table 7.2). As explained in section 3.4, this classification was defined as a function of the frequency of occurrence of particular slope angles in river catchments. This classification is robust and has been based on the morphological characteristics of the catchments of several countries as well as on 17 previous classifications. Therefore, it is considered that this classification defines the morphological characteristics of the study catchments in terms of the slope and can be used to define the ranges where to establish the NFM. This classification has seven different ranges of slope, which makes it possible to evaluate the catchments in various scenarios and determine how sensitive is the positioning of the NFM in certain spatial locations based on the ranges of slope. ArcGIS was used to calculate the slope map of each catchment from the DEM. Seven NFM scenarios were considered, which were placing NFM in areas with slope magnitudes in the ranges: < 2%, 2 to 8%, 8 to 15%, 15 to 30%, 30 to 40%, 40 to 60% and >60% (Figure 7-1). Since each catchment has different morphological parameters (e.g. area and average slope), the NFM percent coverage differed between catchments and was dependant on the total area of each slope range in each catchment (Table 7.3).

Table 7.2 Definitions of slope classes, adapted from (Young and Clayton, 1972).

| <b>Description</b> | <b>Slope gradient classes (%)</b> |
|--------------------|-----------------------------------|
| Flat               | < 2%                              |
| Undulated          | 2-8%                              |
| Moderately sloping | 8-15%                             |
| Hilly              | 15-30%                            |
| Moderately steep   | 30-40%                            |
| Steep              | 40-60%                            |
| Very steep         | >60%                              |

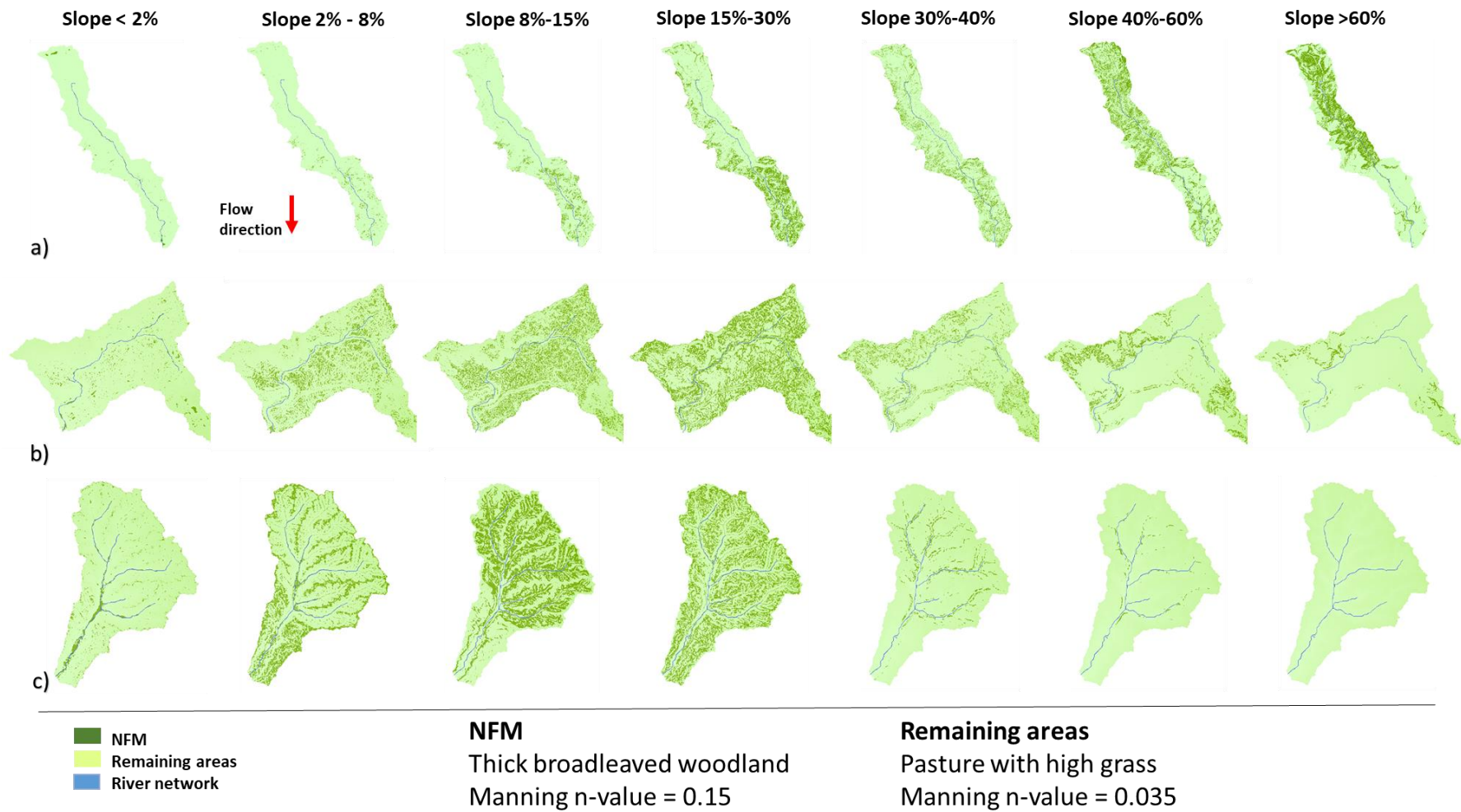
Table 7.3 Percentage of NFM in each slope class on catchments.

| <b>Slope Classes</b> | <b>Percentage of NFM</b> |              |                   |              |                    |               |
|----------------------|--------------------------|--------------|-------------------|--------------|--------------------|---------------|
|                      | <b>Kurtcukuru</b>        | <b>Pasto</b> | <b>Berajevska</b> | <b>Dinin</b> | <b>Mayala Laba</b> | <b>Metome</b> |
| <b>&lt; 2%</b>       | 1.0%                     | 3.2%         | 4.7%              | 12.7%        | 0.7%               | 17.5%         |
| <b>2-8%</b>          | 2.5%                     | 14.2%        | 21.6%             | 52.9%        | 1.0%               | 58.4%         |
| <b>8-15%</b>         | 7.0%                     | 25.3%        | 37.1%             | 28.3%        | 2.1%               | 24.8%         |
| <b>15-30%</b>        | 21.0%                    | 34.0%        | 30.9%             | 5.8%         | 8.8%               | 4.0%          |
| <b>30-40%</b>        | 14.2%                    | 10.7%        | 4.4%              | 0.0%         | 9.4%               | 0.2%          |
| <b>40-60%</b>        | 26.7%                    | 9.6%         | 0.9%              | 0.0%         | 27.0%              | 0.0%          |
| <b>&gt; 60%</b>      | 27.3%                    | 2.7%         | 0.0%              | 0.0%         | 51.4%              | 0.0%          |

As in previous chapters, NFM was considered to be tree planting, represented in the model with increased roughness values, slowing the flow. All Manning's n values have been used consistently in all chapters as follow: the Manning's n-value for NFM was 0.15, defined as a broadleaved woodland; areas not covered with NFM had Manning's n values of 0.035, representing pasture with high grass, and; the drainage river network had Manning's n of 0.04, representing a clean and winding channel with some pools and shoals. The new set of NFM coverages were set up in IBER as a hydraulic input. The rainfall event used in all cases was the left-skewed rainfall event of 60 mm hr<sup>-1</sup> distributed uniformly across the whole catchment area, directly comparable to the results of Chapter 6. IBER was used to calculate hydrographs from the set of NFM scenarios. Special attention was given to the peak flow and lag time, which were then contrasted with the scenarios explored in Chapter 6 (e.g. 0%, 25, 50, 75, and 100% NFM).

The difference in peak flow between different NFM coverages for each catchment was calculated to determine the percentage reduction in peak flow for each NFM category. The analysis aimed to find the best performance scenario of NFM. The peak flow reduction was also correlated to NFM coverage and for the slope classes. Linear regression was fitted and the  $r$  and significance values of each regression were calculated and displayed to identify which regression was significant and strongly correlated to the data.

Considering that in this method, the percentage of NFM is variable in all catchments and therefore there is no control of the area of NFM, the data was standardized by dividing the percentage of NFM by the percentage reduction in the peak flow. This index was named the "efficiency index" and determines how efficient the percentage of NFM in catchments is in reducing peak flows. Therefore, high percentages of NFM coverage with small percentages of peak flow reduction lead to low values of the efficiency index indicating low efficiency. In contrast, low NFM coverage with high flow reduction reflects high values in the index indicate higher efficiency. This index will help to have a better cross catchment comparison. Finally, this index was also correlated with the average slope of the catchment to evaluate the efficiency of the NFM categories on different slopes. A linear regression was adjusted to measure the degree of correlation of the variables.



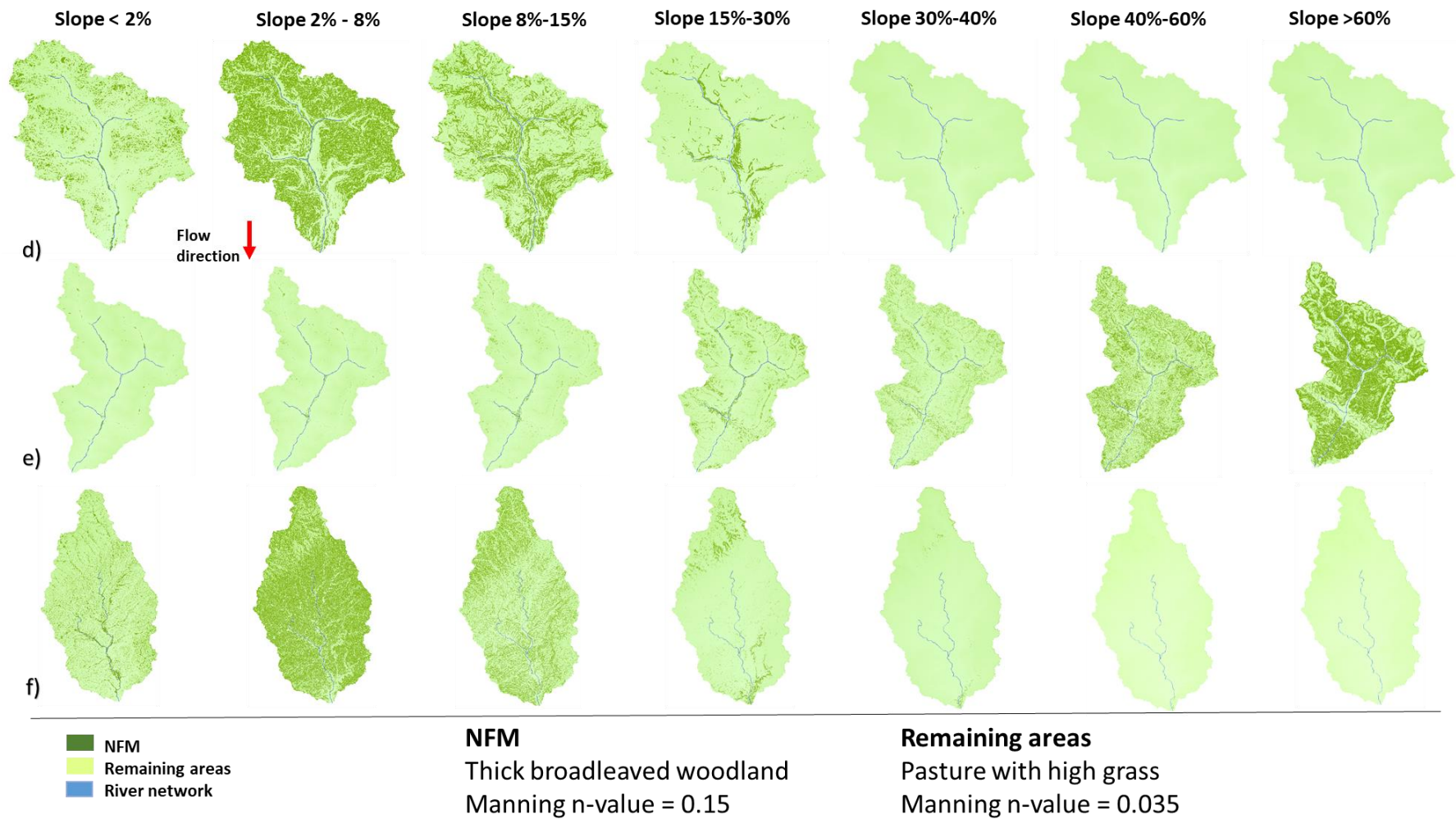


Figure 7-1 NFM scenarios based on the slope classification < 2%, 2 to 8%, 8 to 15%, 15 to 30%, 30 to 40%, 40 to 60% and >60%. a) Kurtcukuru, b) Pasto, c) Berajevska, d) Dinin, e) Mayala Laba, f) Metome. NFM described as thick broadleaved woodland with manning n-value of 0.15, drainage river network (manning n-value of 0.04), and areas with no NFM covered by pasture with high grass with manning n-value of 0.035.



### 7.3.3 Travel time approach

To calculate the travel time of water within the catchment, the tool *r.traveltime* was used. The tool has been developed for the GRASS GIS software (Neteler et al., 2012). The travel time calculation is described by Melesse and Graham (2004) and Muzik (1996) and briefly described here. The *r.traveltime* command works under the formulation of the kinematic wave described by to calculate the travel times across catchments. The algorithm of *r.traveltime* uses the DEM to start computing the travel time of each raster cell from the catchment outlet toward headwaters. Overland flow travel time in a grid cell (equation 7.4) was approximated using the Manning equation (Equation 7.1) and continuity equation (Equation 7.2) and used to determine the average flow velocity through the channel reach (Equation 7.3).

Equation 7.1

$$V_c = \frac{S^{1/2}}{n} y^{2/3}$$

Equation 7.2

$$Q = V B y$$

Equation 7.3

$$V_c = \left[ \frac{\sqrt{S}}{n} \left( \frac{Q}{B} \right)^{2/3} \right]^{-3/5}$$

Equation 7.4

$$tc = \frac{L^{0.6} n^{0.6}}{i_e^{0.4} S^{0.3}}$$

Where  $V_c$  is the channel flow velocity ( $\text{m s}^{-1}$ ),  $S$  is the slope,  $n$  is Manning's  $n$ , and  $y$  is the hydraulic radius in meters (Equation 7.1).  $Q$  is the cumulative discharge in  $\text{m}^3 \text{s}^{-1}$ , and  $B$  is the channel width in meters (Equation 7.3).  $tc$  is the travel time in seconds,  $i_e$  is the rainfall intensity in  $\text{m s}^{-1}$ ,  $L$  is the length of the overland flow in the grid in meters (Equation 7.4).

Additional parameters used in *r.traveltime* include a flow direction map and flow accumulation map, both of which were created in GRASS GIS using the

r.watershed and r.fill.dir commands. The Manning's n input values for surface roughness, described above, were also created in GRASS GIS using the r.mapcalc tool. The rainfall intensity used was the 60 mm hr<sup>-1</sup>. Sensitivity analysis was conducted to determine how the input parameters of r.traveltime such the threshold value for stream network delineation (i.e. minimum number of cells (threshold) that classify cell as a channel) and roughness to determine how the output travel time histogram changes (See Appendix B).

The model output was used to delineate areas of the catchment with similar travel times and slow them down. To achieve this, the travel time map was exported to ArcGIS and the histogram of the travel times across the catchment was calculated. The histogram shows the distribution of times that it takes water in every cell to reach the catchment outlet. Peaks in the histogram indicate multiple cells that have the same travel time (to the nearest second), indicating water falling in these cells will all arrive at the catchment outlet at the same time. Thus, these peaks were targeted as the cells that could most contribute to creating the flood peak. Figure 7-2 shows the graphical diagram of the histogram of travel time where the objective is to flatten the peaks, equalising the travel times so there is a more uniform distribution across the catchment. The total number of the cells in the histogram can be used to calculate the area of the catchment by multiplying the total number of cells by the DEM's cell size (in this case, 12.5 m x 12.5 m). 25% of the total area of the catchment was defined for NFM placement, which was then comparable to the results of Chapter 6 which included 25% catchment planting arbitrarily in the most upstream region.

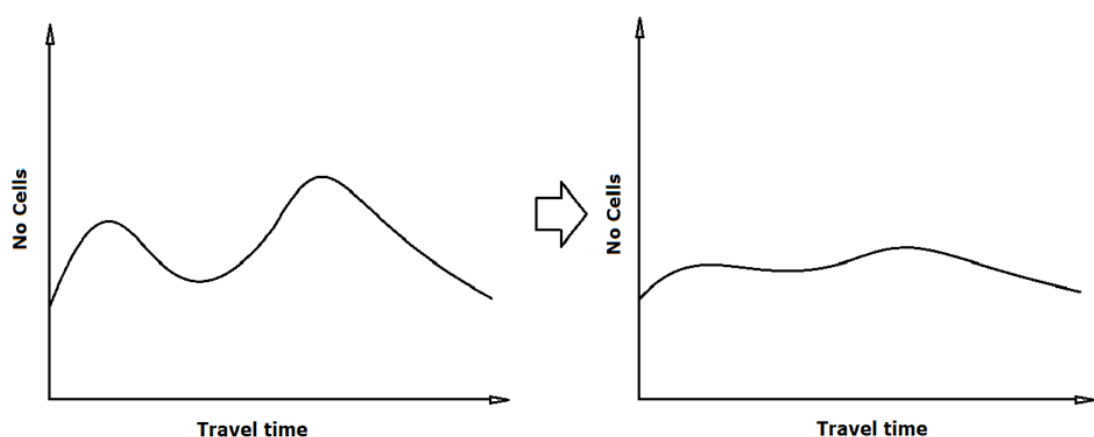


Figure 7-2 Graphical diagram of the travel time approach. The aim is to alter remove peaks, representing relatively large areas draining at the same time; for example, turning a histogram like on the right-hand side to something more like the left-hand side.

To identify the peak of the histogram but also to account for 25% of the catchment area, the histogram was classified using the quantile method in ArcGIS (Lantada and Núñez, 2004). The method divides the histogram into defined sections where each section has the same number of cells; therefore, cells with high frequency (peaks) will be grouped into narrower sections. The method helps to classify the peaks of the histograms, since the greater the number of classes, the greater the precision in identifying them. In this sense, the histogram was divided into 20 sections, each representing 5% of the total catchments cells, and therefore also 5% of the total catchment area (Figure 7-3). Five classes with the highest peaks were used to complete 25% of the total area targeted to slow the flow down.

Once the classes were identified, the cells of each section in the catchments were spatially located and plotted (Figure 7-3). The NFM was then applied to these sections and set up and run in IBER to generate hydrographs for comparison with model runs in Chapter 6. A flow chart of the travel time methodology is shown in Figure 7-4.

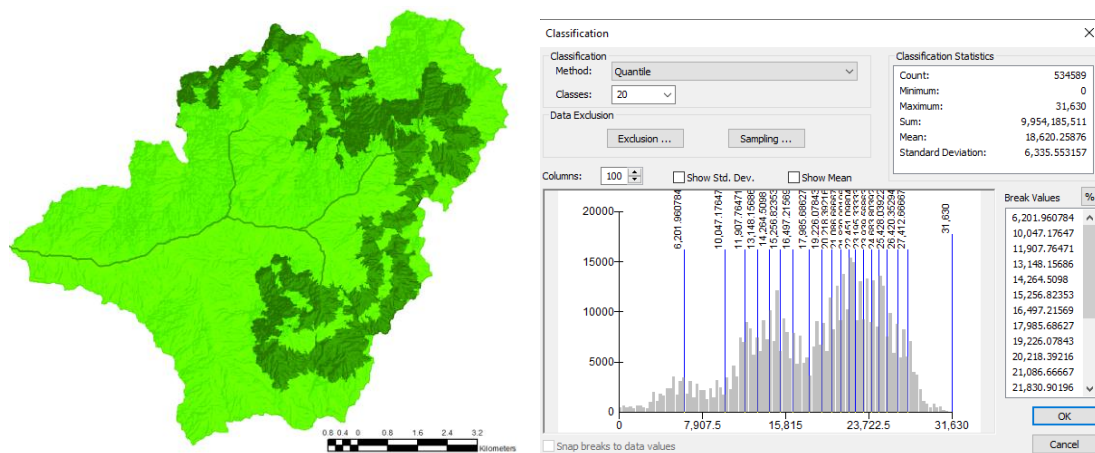


Figure 7-3 Potential NFM placing (dark green colour) and the histogram of the travel time output. The histogram shows the 20 classes used to identify the highest peaks of the histogram.

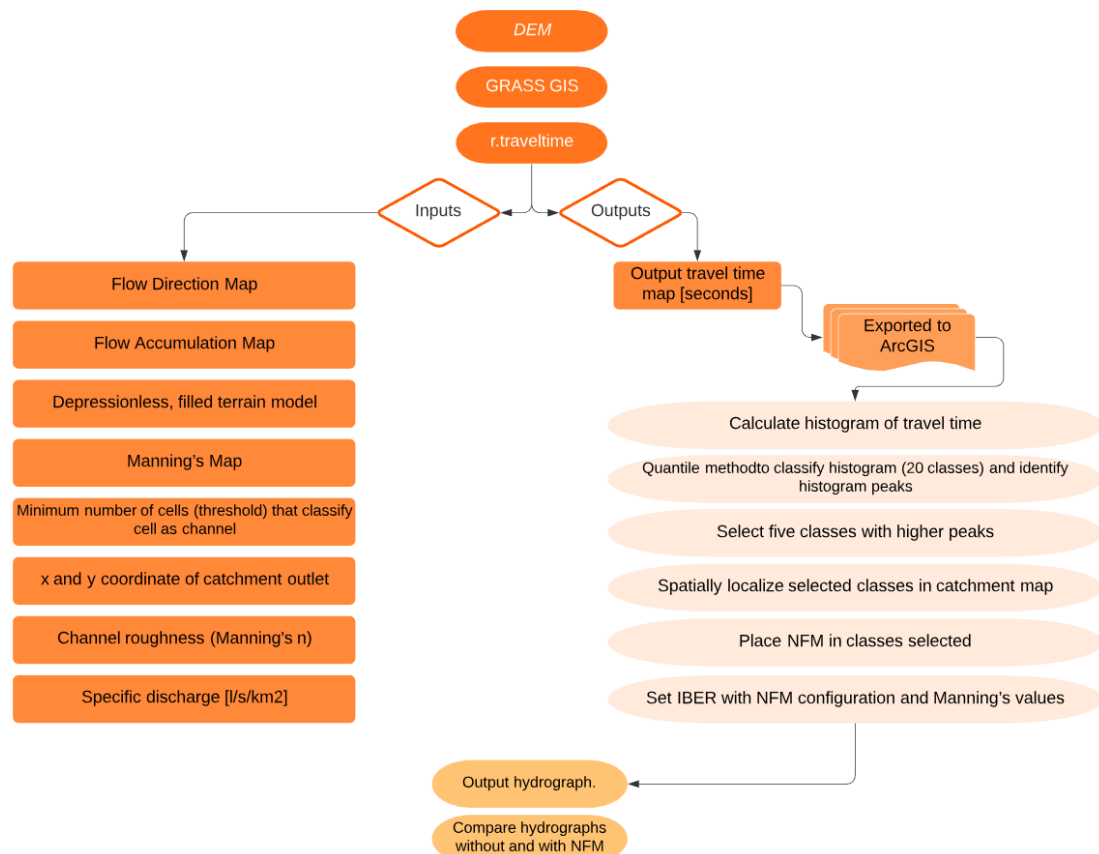


Figure 7-4 Travel time methodology flowchart. Hydraulic and hydrological inputs and spatial information are inputted into r.travelttime model in GRASS GIS, generating the travel time map based on catchment features. The travel time map is used to identify cells that contribute to the peak flow and slow them down. Modelling will be done using the identified cells as a new set of NFM to determine the potential to benefit from NFM.

## 7.4 Results

### 7.4.1 Slope

Table 7.4 depicts the catchments modelled from cluster A and the percentage coverage within each slope class where NFM was situated in the model runs. Hydrographs from Chapter 6 (e.g. control [0%], 25%, 50%, 75%, 100%) and hydrographs generated in this chapter from slope coverages are displayed for comparison (Figure 7-5).

The analysis of the hydrographs for the Kurtcukuru catchment reveals that there was an overall decrease in the peak flow and an increase in lag time when NFM was situated on any slope category. The highest peak reduction was when NFM was situated on slopes between 15-30%, leading to a 20.2% reduction in peak flow. This represented tree planting over 21% of the total area of the catchment. For comparison, 25% NFM coverage of the most upstream region of the catchment, presented in Chapter 6, led to a 26% reduction in peak flow. In no case did NFM coverage on particular slope categories lead to as large of a peak reduction as the 25% NFM coverage presented in Chapter 6. The smallest percentage reduction (10.3%) in peak flow occurred when NFM was placed on slopes greater than 60%, despite the fact that 27.3% of the catchment area was in this category. Similarly, the lag time increase ranged from 2.2% (>60%) to 35.6% (15-30%). Two other slope ranges also had a lag time increase over 15%; <2 and 2-8% (22.2%, 15.6%, respectively). These two slope ranges do not cover large areas but do have some of the largest lag time increases (see Table 7.4)

In the Pasto catchment (Figure 7-5), NFM coverage of slopes between 2-8% and 8-15% (covering 14.2% and 25.3% of the catchment, respectively) had the greatest impact on peak flows. The peak flow reduction was 32% and 31.5% respectively, which is comparable to the reduction associated with 50% NFM in Chapter 6 (29% reduction). Also of interest is that despite the scenarios of 30-40%, 40-60% and >60% covering 10.7%, 9.6% and 2.7% of the total catchment area, respectively, they had no discernible impact on the peak flow. The lag time showed the greatest increase for the 8-15% scenario (48%), with equal increases of 36% for NFM on slope categories 2-8% and 15-30%. The <2% scenario did not have an effect on the lag time (0%).

Table 7.4 Peak flow reduction and lag time delay for catchments within cluster A, including the percentage of the area with NFM between slope classes.

| Slope Classes | Kurtcukuru |                                             |               |                         |                    | Pasto    |                                             |               |                         |                    |
|---------------|------------|---------------------------------------------|---------------|-------------------------|--------------------|----------|---------------------------------------------|---------------|-------------------------|--------------------|
|               | % of NFM   | Peak Flow (m <sup>3</sup> s <sup>-1</sup> ) | Lag time (Hr) | Peak Flow Reduction (%) | Lag Time Delay (%) | % of NFM | Peak Flow (m <sup>3</sup> s <sup>-1</sup> ) | Lag time (Hr) | Peak Flow Reduction (%) | Lag Time Delay (%) |
| < 2%          | 1.0%       | 677.2                                       | 1.8           | 14.9%                   | 22.2%              | 3.2%     | 561.77                                      | 0.8           | 19.5%                   | 0.0%               |
| 2-8%          | 2.5%       | 670.3                                       | 1.7           | 15.7%                   | 15.6%              | 14.2%    | 474.34                                      | 1.1           | 32.0%                   | 36.0%              |
| 8-15%         | 7.0%       | 662.0                                       | 1.6           | 16.8%                   | 8.9%               | 25.3%    | 477.88                                      | 1.2           | 31.5%                   | 48.0%              |
| 15-30%        | 21.0%      | 634.8                                       | 2.0           | 20.2%                   | 35.6%              | 34.0%    | 551.23                                      | 1.1           | 21.0%                   | 36.0%              |
| 30-40%        | 14.2%      | 698.8                                       | 1.6           | 12.2%                   | 8.9%               | 10.7%    | 691.47                                      | 0.8           | 0.9%                    | 0.0%               |
| 40-60%        | 26.7%      | 684.1                                       | 1.6           | 14.0%                   | 8.9%               | 9.6%     | 701.53                                      | 0.8           | 0.0%                    | 0.0%               |
| > 60%         | 27.3%      | 713.6                                       | 1.5           | 10.3%                   | 2.2%               | 2.7%     | 700.20                                      | 0.8           | 0.0%                    | 0.0%               |

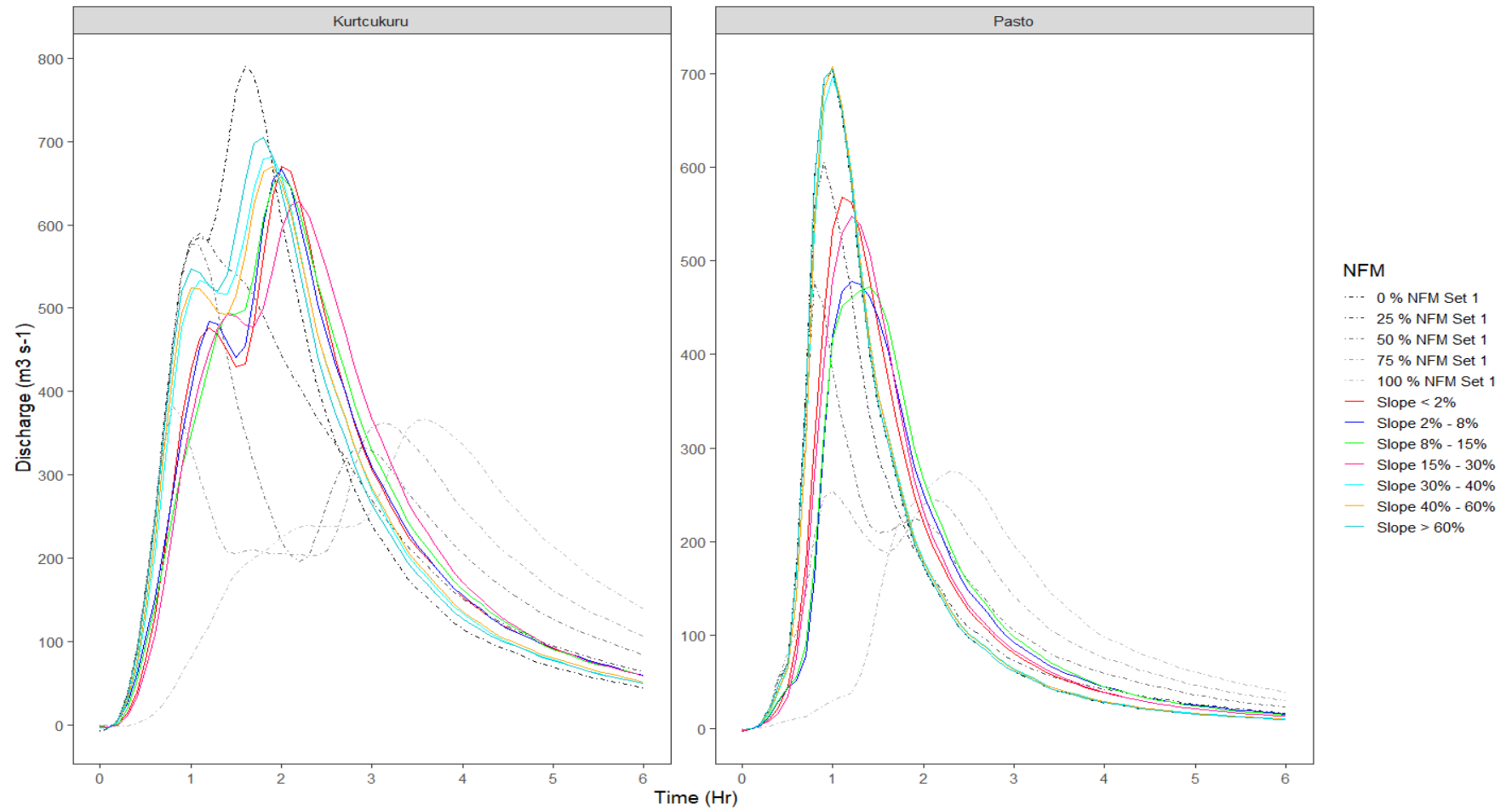


Figure 7-5 Output hydrographs from the hydraulic and hydrological modelling by IBER of the cluster A catchments (i.e. Kurtcukuru and Pasto). The greyscale dashed lines are the hydrographs for each NFM coverage (e.g. control [0%], 25%, 50%, 75%, 100%). The coloured continuous lines are the hydrographs for each NFM coverage considering the slope of the catchment.

In cluster B, the Berajevska Reka catchment had the highest peak flow reductions when NFM was situated on slopes of <2% (covering 4.7% of catchment area) and 2-8% (21.6% of catchment area) (Figure 7-6). The percentage reduction in peak flow when NFM was placed on slopes <2% was 33.4%, which is comparable to the 50% NFM scenario in Chapter 6 (36% reduction) despite the fact that only 4.7% of the catchment was covered. The smallest reduction in the peak flow was for planting on slopes between 8-15% and 15-30%, although these two scenarios had aerial coverages much greater than for other scenarios (Table 7.5). The greatest lag time increase was associated with NFM on slopes <2%, leading to a 50.6% increase in lag time. The scenarios between 8-15% and 15-30% had similar lag time increases (15.3%, 15.3%) which are comparable with the lag time for the 25% NFM coverage in chapter 6 (15% increase).

Similarly in the Dinin catchment, the peak flow was mostly mitigated by NFM located between slopes of <2% (26.1% reduction) and 2-8% (43.8% reduction) (Table 7.5). Although the 2-8% slope coverage reduced peak flows, it had a lesser impact on peak flows than the 50% coverage in Chapter 6 (55% reduction) despite covering 52.9% of the total catchment area. This scenario also had the biggest lag time increase (87.7%) which is longer lag time than scenarios with 25% and 50% NFM coverage in Chapter 6.

Table 7.5 Peak flow reduction and lag time delay for catchments within cluster B, including the percentage of the area with NFM between slope classes.

| Slope Classes | Berajevska |                                             |               |                         |                    | Dinin    |                                             |               |                         |                    |
|---------------|------------|---------------------------------------------|---------------|-------------------------|--------------------|----------|---------------------------------------------|---------------|-------------------------|--------------------|
|               | % of NFM   | Peak Flow (m <sup>3</sup> s <sup>-1</sup> ) | Lag time (Hr) | Peak Flow Reduction (%) | Lag Time Delay (%) | % of NFM | Peak Flow (m <sup>3</sup> s <sup>-1</sup> ) | Lag time (Hr) | Peak Flow Reduction (%) | Lag Time Delay (%) |
| < 2%          | 4.7%       | 185.9                                       | 2.1           | 33.4%                   | 50.6%              | 12.7%    | 646.4                                       | 1.5           | 26.1%                   | 41.5%              |
| 2-8%          | 21.6%      | 197.4                                       | 2.0           | 29.3%                   | 43.5%              | 52.9%    | 491.9                                       | 2.0           | 43.8%                   | 87.7%              |
| 8-15%         | 37.1%      | 244.5                                       | 1.6           | 12.4%                   | 15.3%              | 28.3%    | 799.6                                       | 1.3           | 8.6%                    | 23.1%              |
| 15-30%        | 30.9%      | 248.3                                       | 1.6           | 11.0%                   | 15.3%              | 5.8%     | 940.2                                       | 1.1           | 0.0%                    | 4.6%               |
| 30-40%        | 4.4%       | 274.2                                       | 1.4           | 1.8%                    | 1.2%               | 0.0%     | 943.2                                       | 1.1           | 0.0%                    | 0.0%               |
| 40-60%        | 0.9%       | 278.8                                       | 1.4           | 0.1%                    | 1.2%               | 0.0%     | 943.1                                       | 1.1           | 0.0%                    | 0.0%               |
| > 60%         | 0.0%       | 279.3                                       | 1.3           | 0.0%                    | 0.0%               | 0.0%     | 943.1                                       | 1.1           | 0.0%                    | 0.0%               |

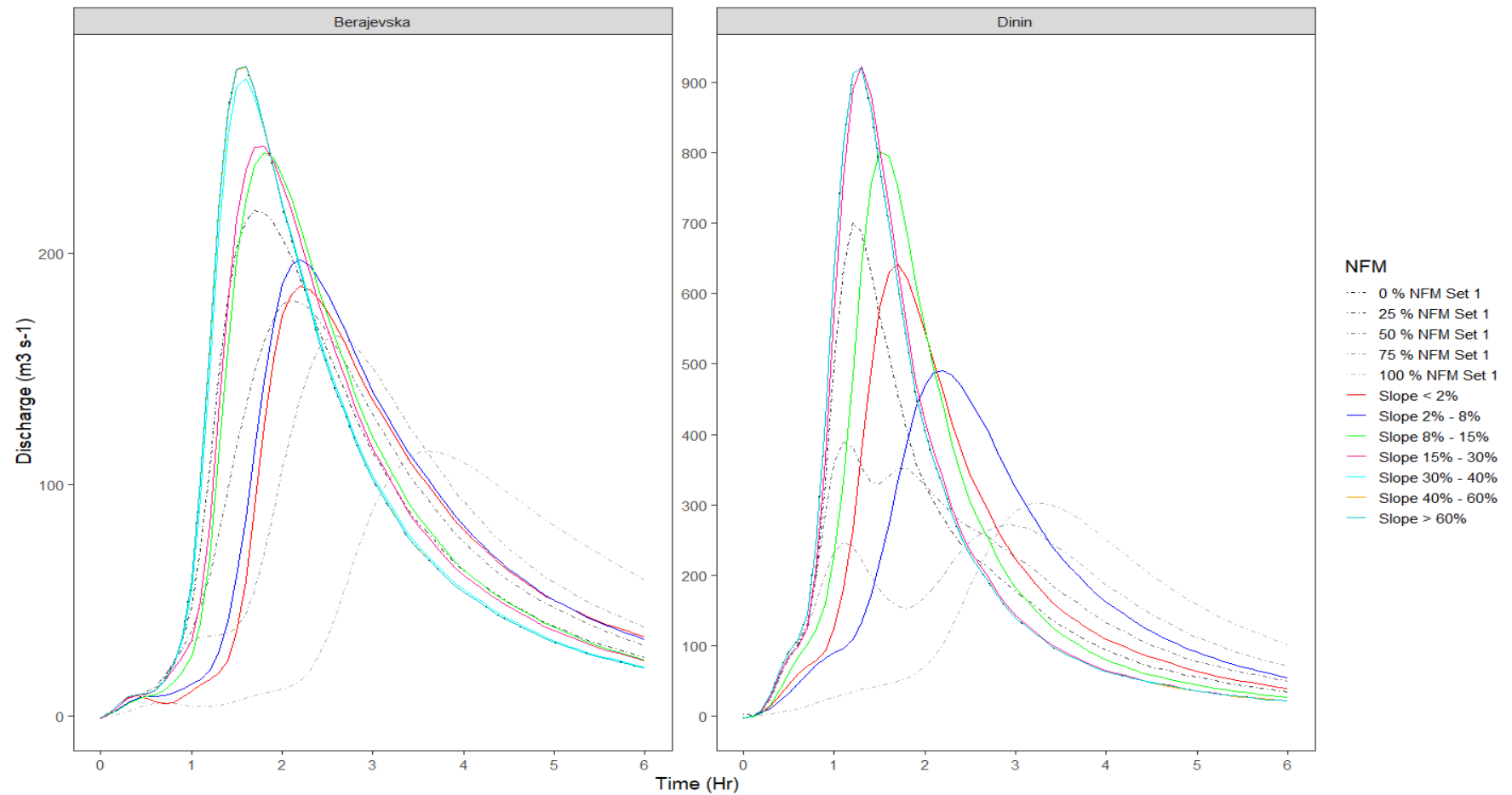


Figure 7-6 Output hydrographs from the hydraulic and hydrological modelling by IBER of the cluster B catchments (i.e. Berajevska Reka and Dinin). The greyscale dashed lines are the hydrographs for each NFM coverage (e.g. control [0%], 25%, 50%, 75%, 100%). The coloured continuous lines are the hydrographs for each NFM coverage considering the slope of the catchment. All scenarios were performed under a 60 mm h-1 left-skewed rainfall event.



The cluster C catchment Mayala Laba had the largest reduction in peak flow when NFM was placed in areas with slopes 15-30%; representing 8.8% of the total catchment area (Figure 7-7). Despite covering a smaller total area, this scenario had better performance (21.7% reduction) than the 25% NFM coverage from Chapter 6 (15%% reduction), but not as high as the 50% NFM coverage (37%% reduction). The second best performance was for planting on <2% slopes, which covered only 0.7% of the catchment area but reduced peak flows (17.1%) to a similar degree as 25% coverage in Chapter 6 (15%). In contrast, NFM in areas of slopes >60%, which covered 51.4% of the catchment area, reduced peak flows by only 4.2%, which is considerable smaller than 50% NFM coverage in Chapter 6 (37%). Lag time had similar increases for the <2%, 8-15%, 40-60%, and >60% slope categories (21.9%) regardless the substantially different BFM coverages in each of those scenarios.

The peak flow comparison for Metome catchment shows that the scenarios of <2% (18% of catchment area) and 2-8% (58% of catchment area) had the greatest reductions in peak flow (42% and 42.6%, respectively) (Table 7.6). It is interesting to notice that these two scenarios had similar peak flow reduction, despite substantially different aerial coverage (covering 17.5% and 58.4% of the catchment, respectively). The scenario of 8-15% had 15.6% reduction with 24.5% NFM coverage, however, this slope range had lower peak flow reduction compared to the 25% in chapter 6 (26% reduction). Lag time also showed the greatest peak reduction when NFM was placed in areas with slopes <2% and 2-8%, with increases of 67.2% and 77.2%, respectively.

Table 7.6 Peak flow reduction and lag time delay for catchments within cluster C, including the percentage of the area with NFM between slope classes.

| Slope Classes | Mayala Laba |                    |               |                         |                    | Metome   |                    |               |                         |                    |
|---------------|-------------|--------------------|---------------|-------------------------|--------------------|----------|--------------------|---------------|-------------------------|--------------------|
|               | % of NFM    | Peak Flow (m3 s-1) | Lag time (Hr) | Peak Flow Reduction (%) | Lag Time Delay (%) | % of NFM | Peak Flow (m3 s-1) | Lag time (Hr) | Peak Flow Reduction (%) | Lag Time Delay (%) |
| < 2%          | 0.7%        | 2070.3             | 2.1           | 17.1%                   | 21.9%              | 17.5%    | 283.3              | 10.0          | 42.0%                   | 67.2%              |
| 2-8%          | 1.0%        | 2202.2             | 1.9           | 11.8%                   | 10.5%              | 58.4%    | 280.2              | 10.6          | 42.6%                   | 77.2%              |
| 8-15%         | 2.1%        | 2127.6             | 2.0           | 14.8%                   | 16.2%              | 24.8%    | 421.9              | 6.9           | 13.6%                   | 15.6%              |
| 15-30%        | 8.8%        | 1956.9             | 2.1           | 21.7%                   | 21.9%              | 4.0%     | 470.1              | 6.1           | 3.7%                    | 2.2%               |
| 30-40%        | 9.4%        | 2270.4             | 1.9           | 9.1%                    | 10.5%              | 0.2%     | 487.9              | 6.0           | 0.0%                    | 0.6%               |
| 40-60%        | 27.0%       | 2306.3             | 2.1           | 7.7%                    | 21.9%              | 0.0%     | 488.1              | 6.0           | 0.0%                    | 0.0%               |
| > 60%         | 51.4%       | 2393.6             | 2.1           | 4.2%                    | 21.9%              | 0.0%     | 488.0              | 6.0           | 0.0%                    | 0.0%               |

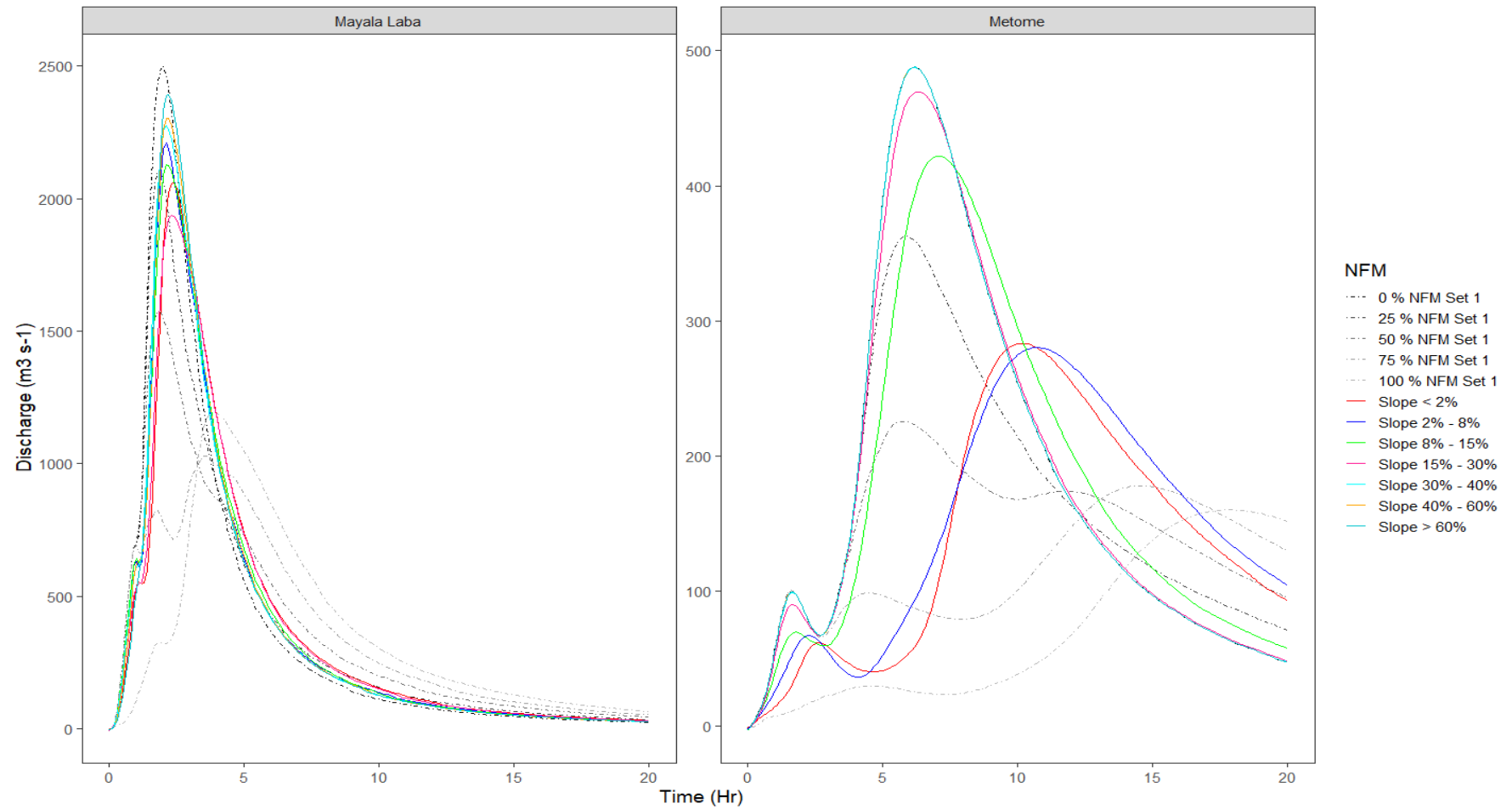


Figure 7-7 Output hydrographs from the hydraulic and hydrological modelling by IBER of the cluster C catchments (i.e. Mayala Laba and Metome). The greyscale dashed lines are the hydrographs for each NFM coverage (e.g. control [0%], 25%, 50%, 75%, 100%). The coloured continuous lines are the hydrographs for each NFM coverage considering the slope of the catchment. All scenarios were performed under a 60 mm h<sup>-1</sup> left-skewed rainfall event.

#### **7.4.2 Effect of NFM placement on specific slopes**

To further assess the effect of NFM placement on specific slopes, the peak flow reduction was calculated as a percentage difference from the peak flow under control conditions [0% NFM] (Figure 7-8). In general across catchments, peak flow reduction was greatest when NFM was placed in areas where the slope is 2-8%, followed by slopes < 2%. The results also show planting NFM on slopes of 2-8% had the greatest variance in percent reduction, most likely associated with the variation in area covered between catchments. The NFM coverage percentage bar graph shows that there are two catchments (e.g. Dinin and Metome) with NFM percentages greater than 50% in the 2-8% slope ranges that help define this range with the highest percentage of peak flow reduction. However, it cannot be stated that the percentage of reduction is solely due to the percentage of NFM in the catchments but rather to the range of slopes in which the NFM was established. For example, Mayala Laba and Kurtcukuru have percentages of 51.4% and 27.3% coverage in slope ranges greater than 60%, but the reduction in peak flow is much less than Dinin and Metome. Similarly, the Pasto catchment has the same reduction percentage (32%) in two different slope scenarios (2-8% and 8-15%), but the percentage of NFM from one scenario to another varies almost twice. The steepest slope ranges (e.g. 40-60% and >60%) had percentage reductions calculated for just three catchments since the slopes of other catchments did not extend this steep, which can be seen in the median of the boxplots for both scenarios indicating 0%.

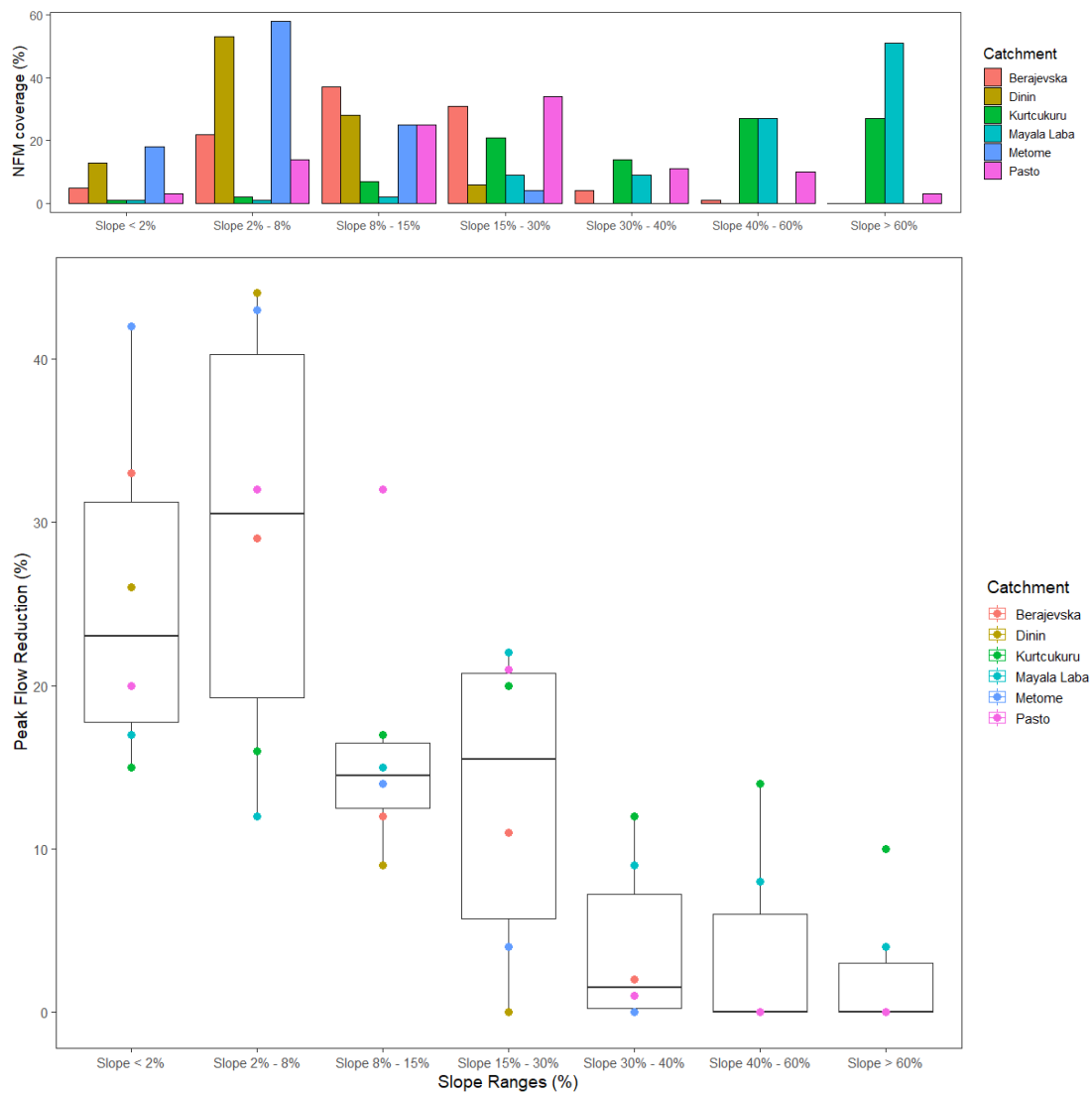


Figure 7-8 Peak flow reduction, median (horizontal black line) across 6 catchments and seven NFM scenarios. On the top, the percentage of NFM in each catchment and for each slope range.

Linear regression was used to investigate the effect of NFM coverage on peak flows across different slopes (Figure 7-9). A significant positive correlation was found for 3 slope ranges (<2%, 2-8%, and 40-60%) when plotting NFM aerial coverage with peak flow reduction. These three correlations are also strong, with  $r$  values between 0.83 to 0.94, implying that reductions in peak flow increase with aerial coverage. In contrast, the other slope categories did not have significant correlations although this is affected by the relatively small sample size. Despite not being significant all slope classes generally had higher peak reductions when aerial coverage was greater, except 8 – 15%, where there is no clear relationship between NFM coverage and peak flows.

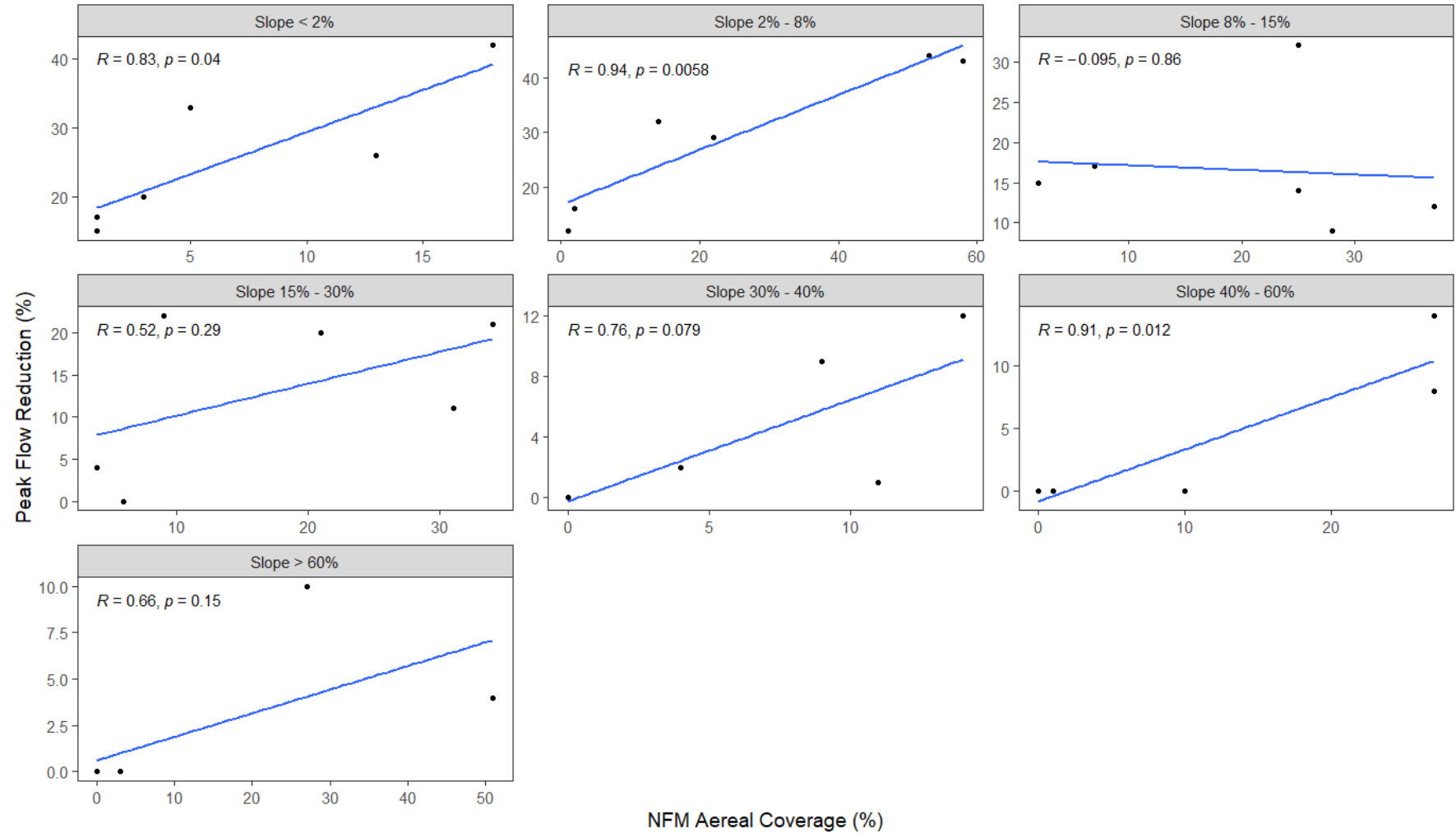


Figure 7-9 Scatter plot of the peak flow reduction and the NFM aerial coverage for 6 catchments. Linear regression adjusted to the data.

The peak flow reduction was standardized with respect to the NFM coverage area. This 'efficiency index' reduces the confounding impact of differing aerial coverages throughout standardisation. The index values therefore indicate how big of a reduction in peak flow is expected for an increase in NFM aerial coverage, here applied separately to each slope category. In this way, high percentages of NFM coverage with small percentages of flow reduction lead to high values, indicating low efficiency. In contrast, low NFM values with high flow reduction values reflect low values in the index that indicate higher efficiency. Figure 7-10 shows the efficiency index for each range of slope. This index shows that the hydrographic catchments have greater efficiency in reducing the peak flow when NFM was placed in areas where the slope is <2%. The results also show that the index increases when the NFM is planted in higher slope categories. This indicates that regardless of the percentage of NFM coverage in the catchment, the reduction in peak flow has a greater effect when NFMs is planted in catchments with lower slopes.

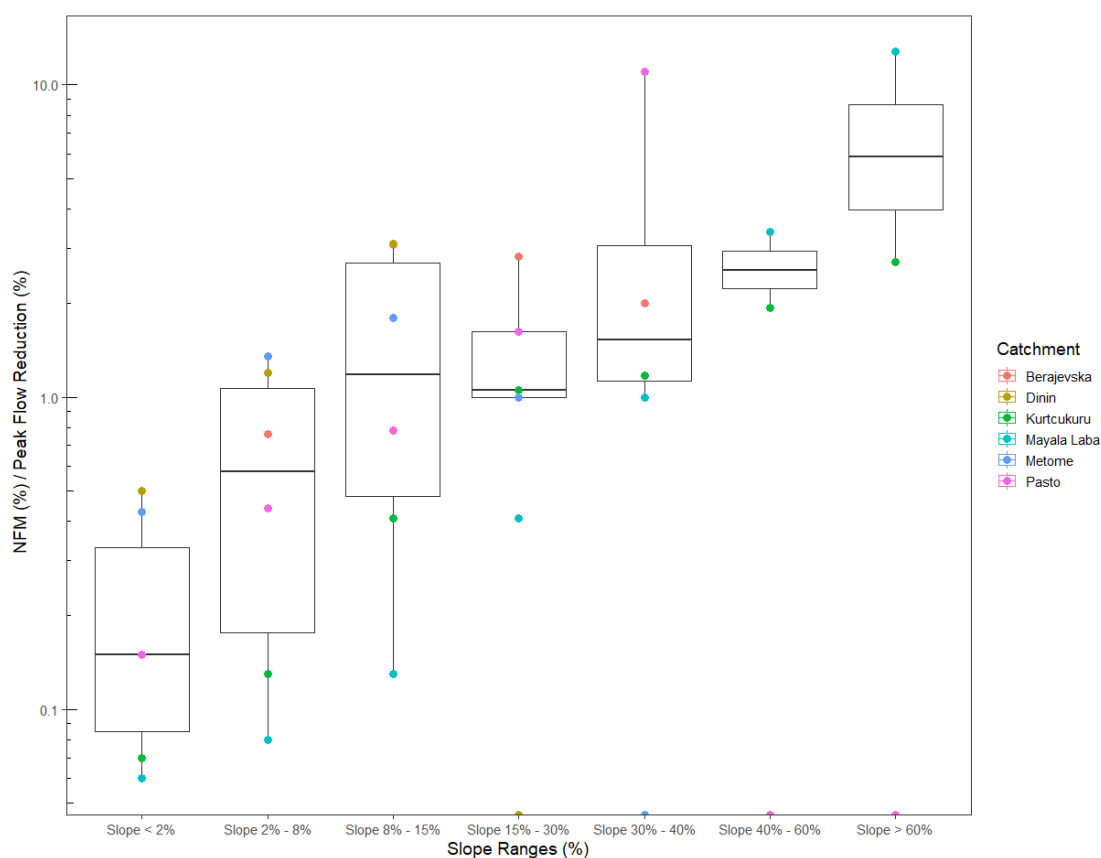


Figure 7-10 Efficiency index (e.g. NFM coverage area divided by peak flow reduction) median (horizontal black line) across 6 catchments and seven NFM scenarios of slope ranges.

The efficiency index between the percentage of NFM coverage and the reduction in peak flow was further evaluated by considering the mean slope of each catchment. Figure 7-11 shows the efficiency index in each slope category for each catchment plotted against the average slope of that catchment. Significant negative correlations are found in categories <2%, 2 – 8% and 8 – 15%, which indicates that NFM planted in these catchment regions are more efficient when the average slope of the catchment is large. In contrast, the relationship is positive for slope ranges greater than 40%, indicating that there is less efficiency in reducing the peak flow when the average slope of the catchments is smaller. The other slope ranges were not significantly correlated.

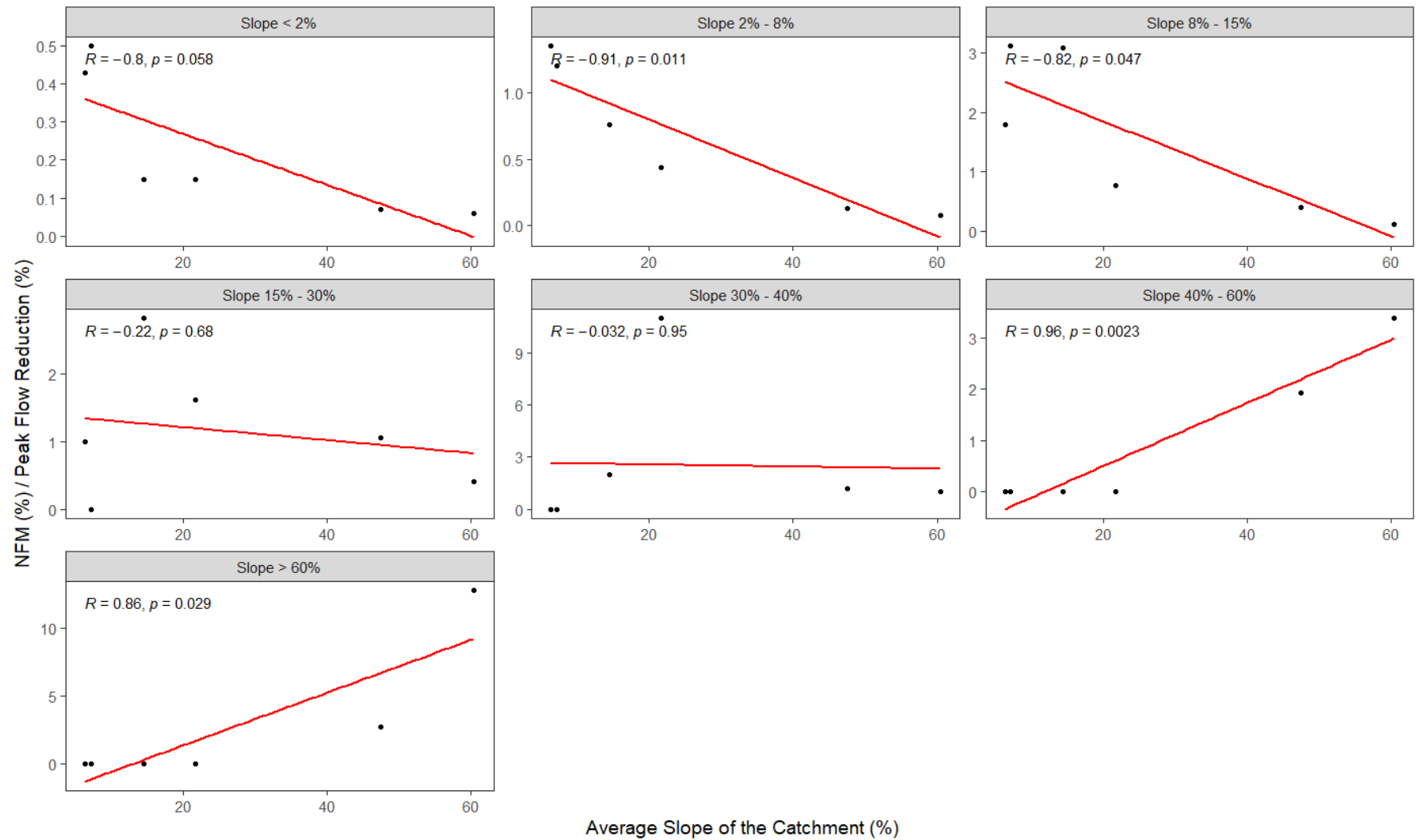
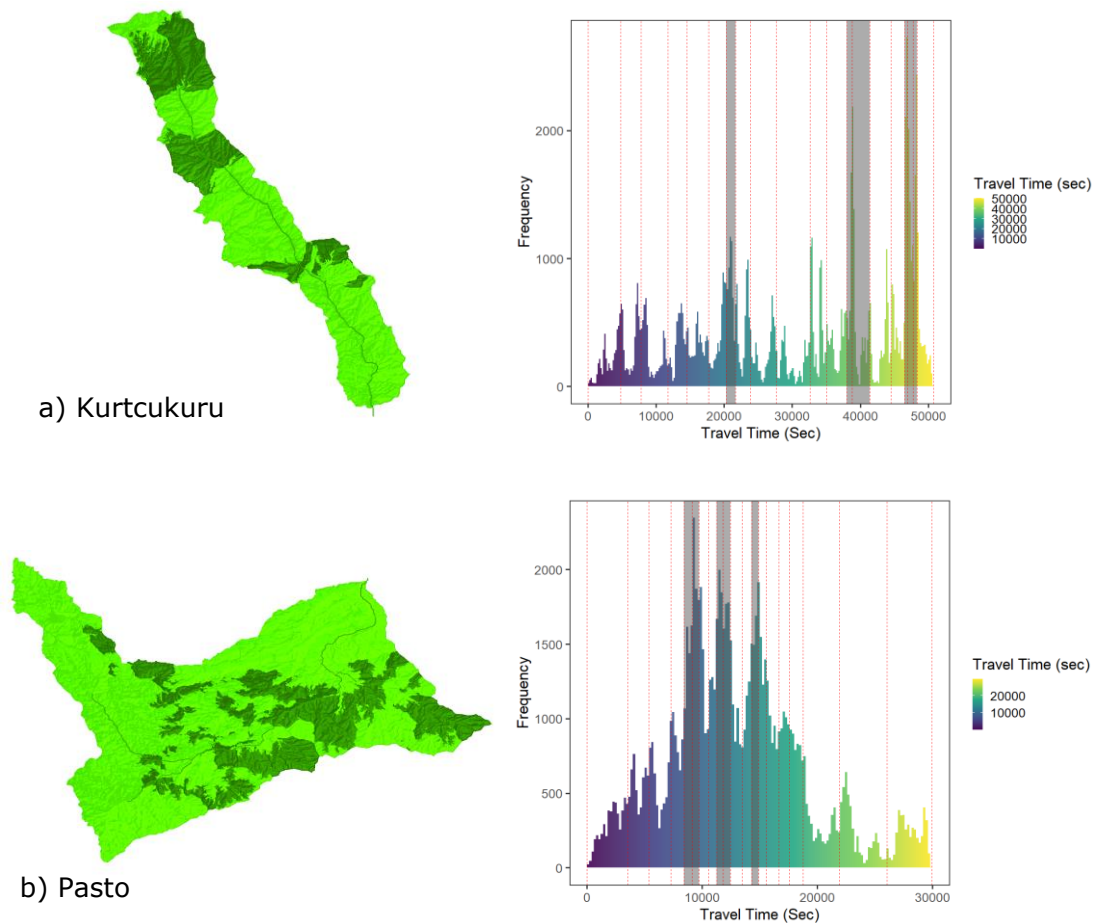


Figure 7-11 Scatter plot of percentage of NFM / the peak flow reduction and the average slope of 6 catchments. Linear regression adjusted to the data.



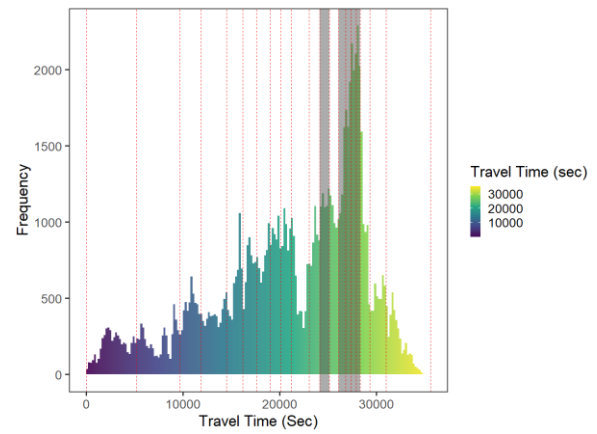
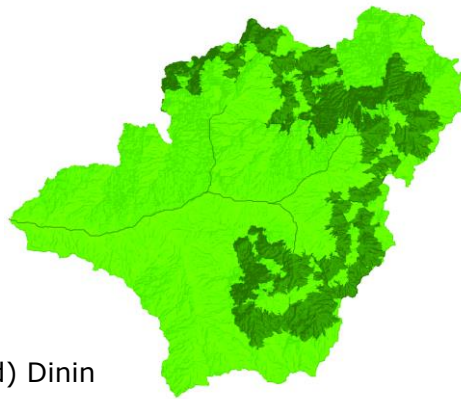
### 7.4.3 Travel time

The `r.traveltime` tool was used to calculate the travel times in the six study catchments, and to produce histograms of travel times for each catchment (Figure 7-12). The histograms were divided into 20 quantiles representing 5% of the total cells of the travel time map as well as 5% of the total area of the catchment and five of these were selected to remove obvious peaks and equalise the histogram. Figure 7-12 also shows the areas that were covered with NFM in each catchment, representing 25% of the catchment area based on the quantiles selected on histograms. The dark green colour represents the areas with NFM while the light green is the areas without NFM.

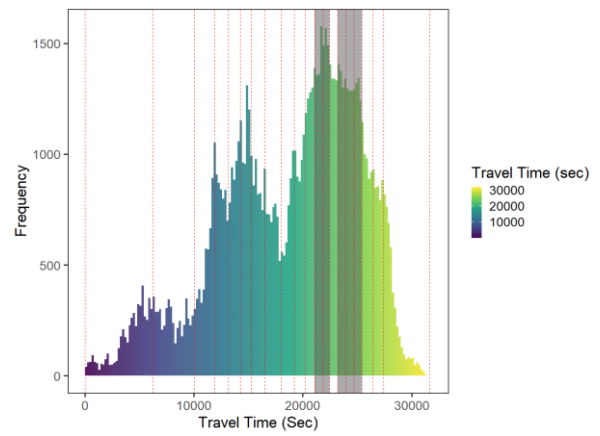




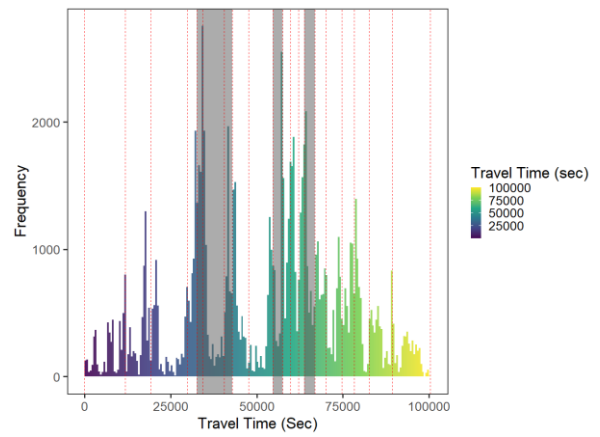
c) Berajevska Reka



d) Dinin



e) Mayala Laba



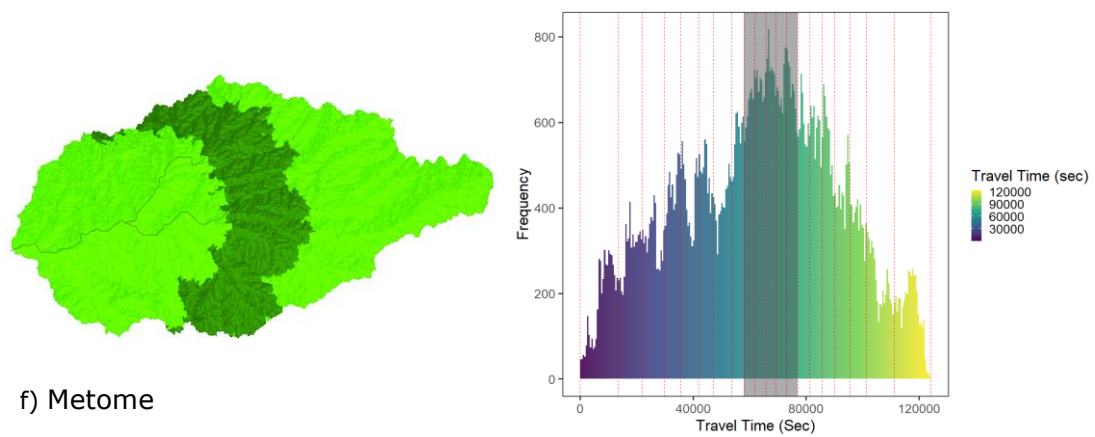


Figure 7-12. Areas of where NFM (dark green) has been placed on catchments based on the peaks of the travel time histograms. Histograms of the travel time from the r.traveltime on GRASS GIS, the red dashed lines represent the quartiles (20 Classes), and the grey band are the targeted pixels with more frequency. (a) Kurtcukuru, (b) Pasto, (c) Berajevska, (d) Dinin, (e) Mayala Laba, (f) Metome.

As an example, Figure 7-13 shows the hydrographs of Berajevska catchment with 0% NFM and the 25% NFM based on different travel times from the IBER model. The hydrograph with NFM is wider and flatter than without NFM, therefore having a lower peak flow and delayed lag time. Berajevska catchment had peak flow in the scenario without NFM is around  $280 \text{ m}^3 \text{ s}^{-1}$  whereas in the scenario with NFM the peak is about  $220 \text{ m}^3 \text{ s}^{-1}$ . Lag time was 1.4 hr for the scenario without NFM and 2 hr for the scenario with NFM.

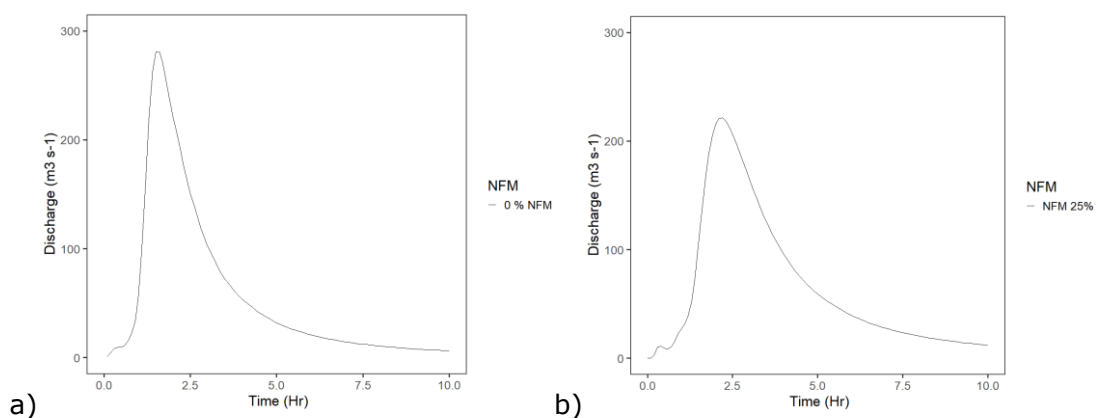


Figure 7-13 Hydrographs from the IBER model for the two scenarios without (a) and with (b) NFM intervention, distributed in 25% of the catchment according to the travel time method.

Figure 7-14 shows the equivalent output hydrographs for all six catchments in comparison to hydrographs from Chapter 6 (e.g. control [0%], 25%, 50%, 75%, 100%). Results show an overall reduction in peak flow in all catchments when 25% of NFM was planted in areas of consistent travel time. Peak flow reduction ranged from 11% (Mayala Laba) to 37% (Dinin) catchments. These two catchments have the highest and lowest slopes, respectively (see Table 7.5 and Table 7.6). Dinin catchment had the greatest peak flow reduction (37%) but had the smallest change in lag time (9%) (Table 7.7). Metome catchment had both a high peak flow reduction (28%) and lag time delay (71%).

The peak flow reduction was similar in all cases to that observed when 25% NFM was placed the most upstream portion of the catchment in Chapter 6, with the exception of the Dinin catchment, where peak flow was reduced to a greater degree by the arbitrary placement of NFM in Chapter 6. In contrast, the lag time increased to a much greater degree when NFM was placed in areas to equalise travel times than where placed in Chapter (Figure 7-14, Table 7.7). It is also interesting to see that Kurtcukuru catchment had a bimodal hydrograph when 25% NFM is placed with the travel time approach, differing from 25% NFM in Chapter 6, although a bimodal distribution did occur when larger areas were planted in Chapter 6.

Table 7.7 Peak flow reduction and lag time delay for the 6 catchments modelled using the lag time criteria.

| Catchment          | Control [0% NFM]   |               | Peak Flow Reduction (%) | 25% NFM Travel Time |               | Lag Time Delay (%) |
|--------------------|--------------------|---------------|-------------------------|---------------------|---------------|--------------------|
|                    | Peak Flow (m3 s-1) | Lag time (Hr) |                         | Peak Flow (m3 s-1)  | Lag time (Hr) |                    |
| <b>Kurtcukuru</b>  | 795.5              | 1.5           | 30%                     | 557.2               | 2.0           | 33%                |
| <b>Pasto</b>       | 698                | 0.8           | 17%                     | 582.4               | 1.3           | 60%                |
| <b>Berajevska</b>  | 279.1              | 1.4           | 21%                     | 221.4               | 2.0           | 42%                |
| <b>Dinin</b>       | 943.1              | 1.1           | 37%                     | 598                 | 1.2           | 9%                 |
| <b>Mayala Laba</b> | 2498.1             | 1.7           | 11%                     | 2211.4              | 2.9           | 69%                |
| <b>Metome</b>      | 488.1              | 6.2           | 28%                     | 349                 | 10.6          | 71%                |

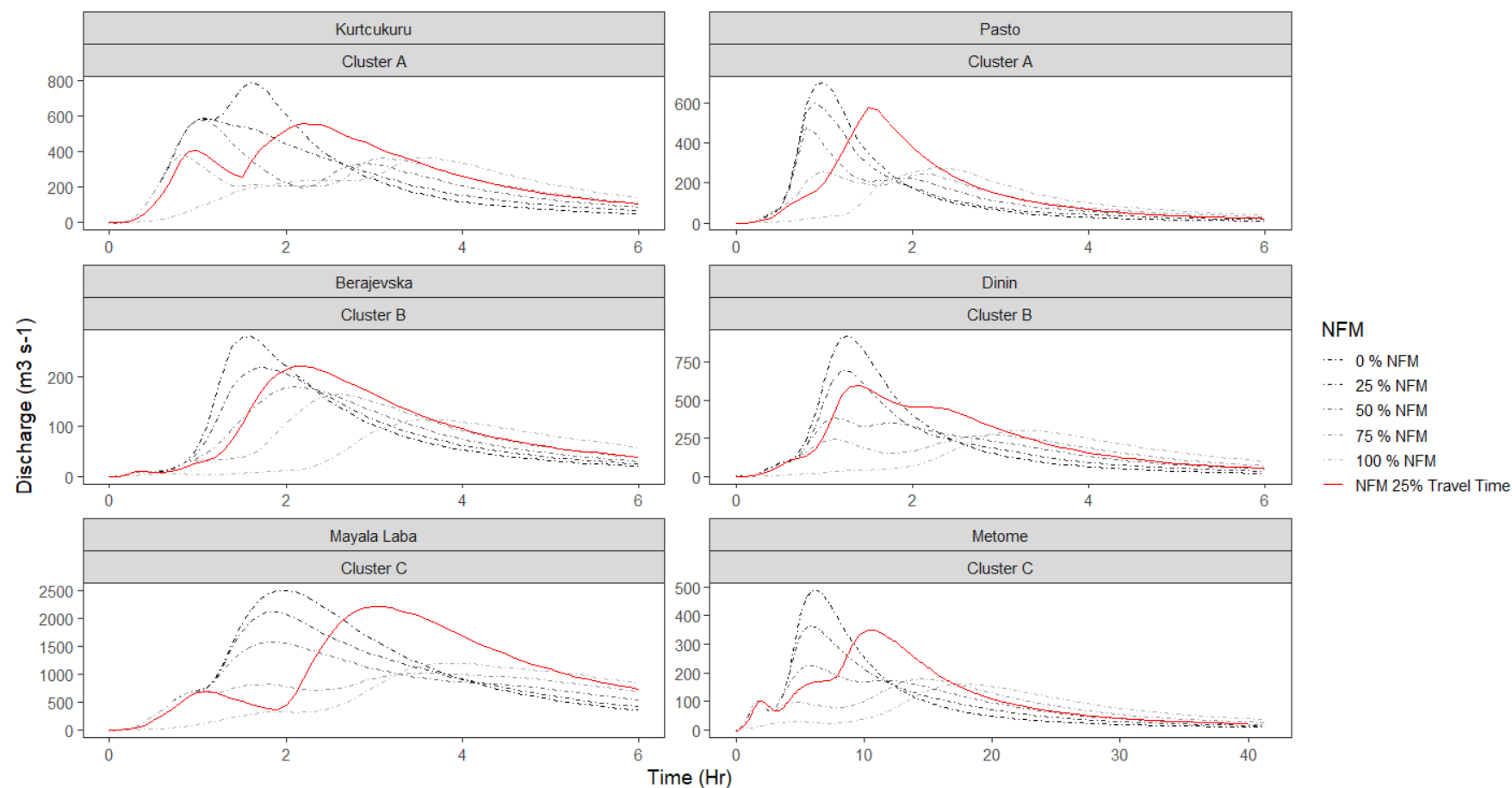


Figure 7-14 Output hydrographs from the hydraulic and hydrological modelling by IBER. The greyscale dashed lines are the hydrographs for each NFM coverage (e.g. control [0%], 25%, 50%, 75%, 100%). The red continuous red lines are the hydrographs for the scenario of NFM coverage considering the travel time approach. All scenarios were performed under a 60 mm h<sup>-1</sup> left-skewed rainfall event

## **7.5 Discussion**

### **7.5.1 Slope**

The slope approach appears to reduce the peak flow to a greater degree than planting in areas of the catchment with distance from outlet, as done in Chapter 6. However, the results are catchment specific with different slope classes having bigger impacts than others depending on which catchment is used and the area of NFM in each class. In general, there is a greater reduction in peak flow when NFM is placed in areas with slopes <2% and 2-8%. For example, planting in these regions in Barajevo (29%) and Pasto (33%) led to reductions in peak flow comparable to 75% catchment coverage in Chapter 6, despite only covering 5% and 14% of the catchment, respectively. This is in agreement with Thomas and Nisbet (2007) who argue that woodland is likely to be more efficient on the floodplain where slopes are relatively low. The efficiency index was able to corroborate that the scenario with the greatest efficiency in reducing the flow is when the NFM is located in lower slope magnitudes. The reduction of peak flows through preferential planting in relatively shallow slopes is likely to be because the flood wave celerity decreases in flatter landscapes, resulting in slower flow velocities. Sholtes and Doyle (2011) state that the peak discharge generated where slopes are steep tend toward a kinematic type flood wave and are less likely to be attenuated by hydraulic resistance. Moreover, flatter areas often coincide with floodplains that allow water to spread out, increasing the local resistance to the flow and reducing the flow velocity (Cowan, 1956). Reddy (2005) suggest that floodplains should be the focus of flood control measures.

The reduction in peak flow is presumably influenced by the percentage of NFM coverage, which is reflected in the greater variance of data between groups when there is a larger range of catchment sizes (Figure 7-8). For example, the 2-8% slope range has the greatest variance because the catchment coverage varies widely between catchments (from 1% to 58.4%). The peak flow reduction when planting on specific slopes is aligned to the findings of Dixon et al. (2016) in the Lymington catchment, UK, where floodplain restoration at the sub-catchment scale with 20% to 35% catchment tree planting, could lead a reduction in the peak flow up to 20%. Dixon et al. (2016) argue that flood measures have large variability in peak reduction depending on where the measure is located but, that variability is also due to the timing of runoff contribution reaching the catchment outlet. Nisbet and Thomas (2006) also suggest NFM measures will require less tree planting in areas downstream than in the headwater because the flow

resistance is higher. In contrast, (McVicar et al., 2007) suggest that in general, woodland on slopes less than 26% have the most significant impact on downstream hydrographs.

Although there is variation in peak flow reduction, the percentage of reduction shows that NFM measures have a positive effect on peak flows, which is in line with other studies. Farley et al. (2005) in 26 catchments found that covering between 20 and 40% of the catchment with eucalyptus could potentially reduce runoff by up to 75%. The author also found that 5 years after planting, there were 15% reductions in runoff increasing to 50% reductions when plants were 10 years old. Jacob et al. (2014) also summarise the performance of 25 catchments with a variety of afforestation percentages as well as for two return periods ( $T_r$ ) (<2 years and 50–200 years). Although the location of the measures on catchments was not fully provided, the study found that peak flow were reduced by increasing the percentage of afforestation, with greater proportional reductions recorded for small, frequent flood events ( $T_r = 2$  years) in comparison to larger floods ( $T_r = 50\text{--}200$  years). A modelling study by Sharp (2014) in the Eddleston Water catchment (69 km<sup>2</sup>) in the Scottish Borders, suggested that afforesting 15% of the catchment area could reduce the peak flow considerably at the catchment scale.

Therefore, these results confirm that NFM placement is critical in maximising the positive impacts of NFM and incorrect placement can lead to only marginal reductions in peak flows. Focusing on discrete areas of relatively low slopes has the potential to improve performance but this is complicated by areas of catchment within each slope category. The results presented here were also quite catchment specific and a greater number of catchments would need to be modelled and analysed to draw out general trends, or morphological characteristics, that could be used to infer what slopes will work best in which catchments.

### **7.5.2 Travel time**

The travel time approach demonstrated that there were large areas within catchments that had similar travel times, which presumably contribute to peaks in the hydrographs. Overall, the 25% of NFM distributed based on travel time had similar results to the 25% distributed in Chapter 6 which, in contrast to the slope results, could indicate the location of NFM is not as significant as first assumed. However, it is clear from the analysis in Chapter 6 and in response to slope, above,

that this is not the case. Therefore, for these 6 catchments, spatial location is important but our use of the travel time did not focus on planting on the optimal locations. The formation of small early peaks, before a larger peak flow in the hydrographs of the Kurtcukuru and Mayala Laba catchments, may indicate that planting on particular travel time regions can have a disproportionate impact on flow distribution. In addition, these two catchments had NFM localized more towards the lower part of the catchment, where the slopes were more gentle, which were shown in the slope analysis to be particularly significant. Therefore, it may not be the conceptual approach that is problematic but, instead, the method used to determine where to spatially locate NFM to equalise travel times. This is because it is not realistic to assume that NFM's ability to adjust the travel time is equal in all area of the catchment, demonstrated by the analysis of efficacy, above.

Whilst the placement of NFM using the travel time approach did not have major advantage in reducing the peak flow over the distribution used in Chapter 6, it did have a much greater impact on lag times. Lag times were on average 47% longer when the travel time was used to locate tree planting, which makes logical sense as the approach specifically aims to slow down the flow (i.e. increase travel times) (

Figure 7-14 and Table 7.7 ). Therefore, the method of selecting travel time regions to plant in this study, delayed the peak more than it reduced the peak.

It is hypothesised here that because NFM was focused in regions of similar travel time, the peak was substantially delayed but, only slightly reduced because the travel time was delayed by the same amount through the entire region. A better approach would be to focus some NFM in the region of the peak, but also plant NFM elsewhere to ensure that the peak flow is broken up and not simply delayed. Achieving this is complex and is made more challenging here because *r.traveltime* and IBER represent the catchments differently, with histograms of travel time not accounting for interacting water volumes. To further develop this concept and approach, the travel time derived from each cell across a catchment needs to be derived from the coupled hydraulic-hydrological model in a more sophisticated form than *r.traveltime*, which will mean that the histogram of travel times could be directly related to the hydrograph. In this case, the travel times that contribute to the peak flow could be identified and targeted for NFM to reduce peak flows. Unfortunately, performing such a model would currently be computationally expensive using IBER, potentially requiring the model to be run separately for each individual cell in the catchment. However, the benefits could be significant



because, whilst the model would be catchment specific requiring a DEM, the conceptual framework and modelling approach would be universal and offer an option for a genuine optimisation of NFM placement as, theoretically, a perfectly equalised travel time histogram (i.e. horizontal line) should represent the lowest peak flow as all 'cells' across a catchment would arrive at the outlet at a different time.

Although the `r.traveltime` code provides useful output to better understand the water travel time through the catchment, an advanced mathematical approach could be used to perfectly equalise the histograms through high spatial granularity, and altering Manning's  $N$  with more granularity. Whilst this would be an interesting mathematical challenge, it has several limitations in terms of practical application, especially given the abstracted nature of the modelling required. In this case, roughness should theoretically decrease with travel time from the catchment outlet in an upstream direction and, thus, water near the outlet will take longer to leave the catchment while water from the upstream area will travel faster. `R.traveltime` is also beneficial as a starting point for integrating the travel-time calculation into a coupled hydrological-hydraulic model so as to account for backwatering effects.

Whilst such modelling approaches are developed, a simpler method could be to focus planting on broad regions of similar travel times, whilst also considering and preferentially planting on lower slopes. This allows a combination of both slope and travel time work and a focusing on areas of the catchment where it has been shown that it is more efficient to plant trees to reduce peak flows.

## CHAPTER 8. GENERAL DISCUSSION

### 8.1 NFM impacts on peak flow and lag time

#### ***8.1.1 The significance of catchment characteristics to peak flow and lag time.***

Hydraulic and hydrological modelling with IBER allowed the calculation of hydrographs at the outlet of 20 hydrographic catchments in response to a torrential rain event ( $60 \text{ mm h}^{-1}$ ). The peak flow varied considerably between catchments because of the variability in physiological and morphological characteristics between catchments (Ward and Robinson, 1967, Barry and Chorley, 2009). In particular, the peak flow was significantly related to the mean slope of catchments and the drainage network (see Table 5.3). The correlation between peak flow and drainage density showed a high negative correlation that contradicts most studies that suggest that catchments with dispersed drainage networks produce lower maximum flows, while catchments with dense drainage systems have larger maximum flows (Pallard et al., 2009, Murphey et al., 1977, Day, 1983). This negative correlation might be justified due to the rainfall event used in this research, Knighton (2014) suggest that flow is affected by large volumes of rain and also for large storage areas that can invert the correlation of these two variables. However, we suggest further research to validate this result. The slope of catchments is a determining variable in the hydrodynamic equations used in the model, and is significant because of its influence on flow velocity (David and Davidova, 2014). The slope not only determines how fast the river or a drainage channel conveys water, but also the velocity of surface runoff (Alexander, 2001). Therefore, the slope of the catchment influences the hydrological response to precipitation events.

Catchments with steep slopes typically result in rapid runoff responses and consequently higher peak discharges (Elmoustafa, 2012). This investigation determined that the peak flow increases with the mean slope of the catchment. In contrast, the area of the catchment, which was expected to have a strong relationship with the peak flow because rainfall was uniform over the entire catchment area, did not correlate to peak flow. This is in contrast to past work that has suggested catchment area is an important determinate of hydrograph characteristics (Costa, 1987, Rodier and Roche, 1984, Baker et al., 1988, Adamson et al., 2009, Murphey et al., 1977, Griffiths and McKerchar, 2008). These studies link peak flow to the catchment area but, none have focused on the effects of morphology on surface flow in the context of average catchment slopes and for

extreme rainfall events. Most studies instead link peak flow to return periods (Francés et al., 2008, Reszler et al., 2018), flood volumes (Sodnik and Mikoš, 2006, Gaál et al., 2015), precipitation and main-stem channel length (Burgers et al., 2014, Barlow et al., 2014, Woltemade and Potter, 1994), or channel slope (Benson, 1964, Leopold and Wolman, 1957, Bridge, 1993).

Whilst not significantly correlated to peak flow, the area was important in the analysis because correlations between peak flow and other variables were stronger when catchments were split into sub-groups based on their area. For example, the area and slope of catchments were highly correlated to peak flow for micro-catchments, whereas for sub-catchments the equivalent correlations were insignificant (see Table 5.5). A study carried out by Gaál et al. (2015) in 330 catchments in Austria explored the peak-volume relationship of hydrographs and found that relationships between peak flow and total water volume were more consistent for smaller flood time scales than catchments with a larger flood response. Figure 8-1 shows a schematic flood peak-volume relationship adapted from Gaál et al. (2015). This indicates that scale is an important variable in controlling the hydrological response of catchments, and it may modulate the importance of other physiographical features in catchments, as found here. Woltemade and Potter (1994) state that small catchments (less than 10 km<sup>2</sup>) peak flow attenuation is reduced by the fact that there is an absence of well-developed floodplains, as well as a short travel time of flood waves to the catchment outlet. In contrast, large catchments tend to have high flows attenuated via complex hydraulic processes at larger scales, associated with channel network and channel-floodplain connectivity. Kirkby et al. (2005) also argue that water storage in catchments can contribute significantly to hydrological response, and increases as a function of catchment area. This not only highlights the importance of certain variables at particular scales but, also suggests that catchment area plays an important role in the characterisation of hydrological responses.

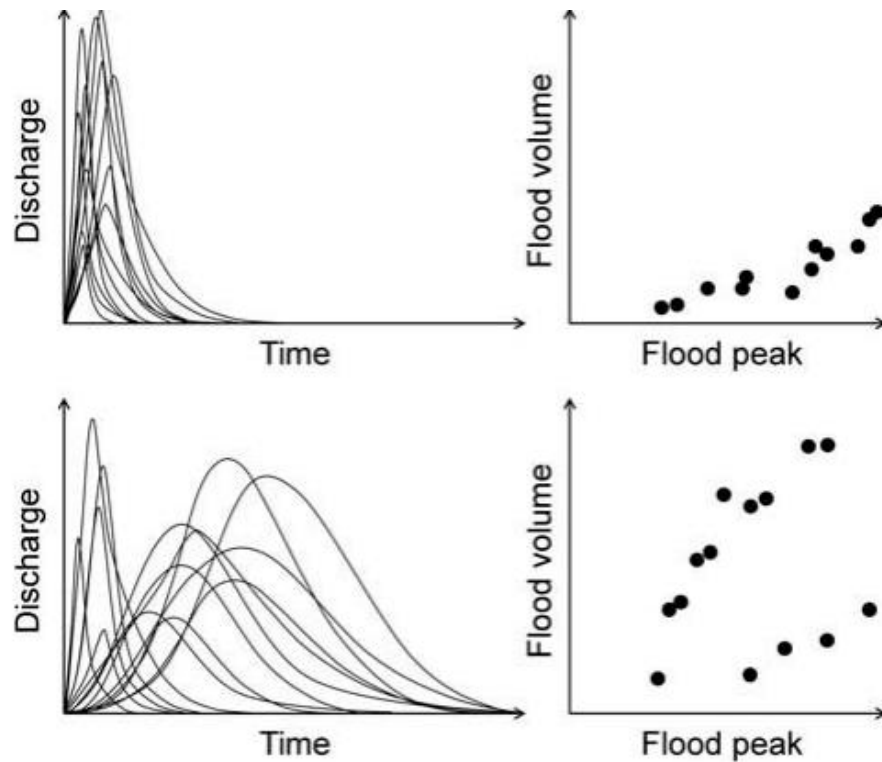


Figure 8-1 Schematic of flood peak–volume relationships. Top: consistent relationship (strong type of association). Bottom: not consistent relationship (weak type of association). Adapted from (Gaál et al., 2015).

A significant negative correlation between lag time and the average slope of the catchment was found, indicating lag time decreases as slope increases (see Table 5.4). This correlation is interlinked with the relationship between peak flow and slope since catchments with steeper slopes have shorter response times and, therefore, shorter lag times. A similar high correlation between these variables was found by Abdulkareem et al. (2019) in the Kelantan river catchment in Malaysia in a study that analysed the relationships between catchment parameters and lag time and time of concentration. Changes in the lag time and time of concentration were evaluated on three different years as catchments had undergone intense land use/land cover changes. High correlations were found in three of the catchments and for all the three years analysed ( $r > 0.84$ ) whilst one catchment had a weaker correlation ( $r = -0.48$ ).

In general, the design of the methodology allowed the detection of differences between the hydraulic and hydrological analysis at different scales, and that the strength of correlations between the peak flow and the morphological and

physiological variables of the catchment varies with the scale of the analysis. In this sense, we suggest that when using uniformly distributed rainfall events, it is best to avoid large catchments (e.g.  $> 100 \text{ km}^2$ ) as the large scale may mask or reduce the strength of correlations due to the effect of areas of accumulation in the catchment. Goodrich et al. (1995) argue that the spatial variability of rainfall in large-scale watersheds is important and, to replicate real-world events, requires a good spatial approximation to obtain adequate results from hydrological models. In addition, larger catchments are less likely to experience uniform rainfall over the entire area so normally this assumption is violated (Rajurkar et al., 2002). Larger catchments are also more likely to experience rainfall events of a longer duration than smaller catchments because moving storms will pass smaller catchments more quickly than larger catchments. Conversely, for small catchments it is more common to assume uniform rainfall to model hydrological responses. However, this is not always the case because the distribution of rainfall is highly related to several factors, including regional atmospheric dynamics, ocean circulation, catchment topography and the influence of catchment configuration (Olivares et al., 2012, Terassi and Galvani, 2017, Sharon, 1972). Modelling at the sub-catchment scale could generate hydrological responses that deviate significantly from reality, adding uncertainty to the model and therefore to the flood management measures that are generated from the results. As the findings of this work are developed beyond the abstracted scenarios used here and towards physical reality, consideration of different rainfall durations will be important. The effect of the 1 hour rain duration rainfall events used in this study is reflected in the hydrographs of the river catchments. Figure 5.2 shows that the effect of torrential rain generates hydrographs of more than 40 hours in some cases, particularly in large catchments because the flood wave has to travel further. In small catchments, surface runoff is of shorter duration due to the shorter distances it has to travel to the catchment outlet.

### ***8.1.2 The significance of NFM on peak flows and lag times***

The IBER model enabled an analysis of the effect of various NFM scenarios on hydrographs. The initial results showed a reduction in peak flow as vegetation cover increased from 25% to 100% (see Figure 6-5). For example, across all catchments an average peak flow reduction of 23% was recorded when the most upstream 25% of the catchment was covered in NFM, whereas a 43% average reduction was recorded for 50% catchment coverage. These values are large but

comparable to other modelling studies; for example, Ferguson and Fenner (2020b), (Ferguson and Fenner, 2020a) in the Cam and Ely river catchments in Cambridgeshire, UK (18 Km<sup>2</sup>), where covering 45% of the upper catchment with trees could lead to a peak flow reduction of 17% and a lag time delay of 30 min for a rainfall event with a 5 year return period. In the same catchments and rainfall scenario, covering 79% of all arable land with trees led to a peak flow reduction of 33.2% and 45 min of peak flood delay (Ferguson and Fenner, 2020a). Most of the literature reviewed concludes that there a reduction in peak flow can be expected when implementing NFM strategies. However, the efficiency of this reduction is linked to numerous factors related to the hydrological response of catchments, such as the type of management strategy, the morphological and physiological characteristics of the catchment, and the NFM coverage areas.

The reduction of peak flow with NFM scenarios varied significantly between catchments. In eleven catchments, the peak flow declined linearly as catchment coverage of tree cover increased, whereas the rest had polynomial declines in peak flow, indicating that decreases got smaller at higher catchment coverages of NFM (see Table 6.1). Given conditions were consistent between catchments, the variation in the impact of NFM between catchments was due to their morphological and physiological characteristics. However, neither of the two groups of catchments (linear and polynomial) aligned with the categories determined in the research (e.g. size class, hypsometric curve, shape cluster). This suggests that the reduction of peak flow due to the implementation of NFM is strongly determined by catchment characteristics but that other catchment classifications, or more likely, a combination of the classifications used here, are needed to fully identify specific categories of hydrological responses. This is further evidenced by the fact that catchment area was only significant as a controlling variable on other correlations. When looking at correlations within the linear and polynomial groups separately, it was found that those more strongly associated with a linear decline in peak flow, had greater reductions in peak flow when catchment slopes were high. To fully explore such relationships a larger sample size is needed because as more categories are added the sample size in each decreases.

The relationship between lag time and NFM was more complex than for the peak flow. The lag time varies considerably with NFM between catchments and, counter-intuitively, has faster lag times with increasing NFM in some cases (see Figure 6-7 and Figure 8-2). However, increasing lag times tended to be associated with disconnection of regions of catchment because the location of NFM in this study sometimes lead to a bimodal distribution. This is interpreted as meaning the

closest areas to the catchment outlet, which were not covered with NFM except in the 100% scenario, start having a proportionally large contribution to the rising limb relative to the remaining NFM-covered area, due to the assumption of evenly distributed rainfall across the catchment. Although an earlier peak is created in this scenario, the magnitude of the peak flow values is always lower compared to the control scenario, indicating that the flood event at the outlet would be less aggressive. However, further research into the implications of disconnecting areas of catchment through large-scale tree planting would be useful as the creation of rapid onset small peak flows could have implications for management.

As shown here, the desynchronisation of parts of the catchment through NFM could significantly impact hydrographs, albeit in this specific case the change is potentially undesirable. Metcalfe et al. (2018) argues that the effect of NFM on the flood peak is mostly due to the desynchronization of particular areas in the catchment and, by focusing NFM in regions of particular importance, peak flows can be reduced. However, the results presented do differ from Ferguson and Fenner (2020a) in the Cam and Ely River catchments, where no differences in outlet hydrograph shape were observed between covering the upstream and downstream 45% of the catchments. Connell (2008) in the River Maddach, Wales, did not observe changes in output hydrograph shape between models of three floodplain areas with four woodland scenarios. Therefore, the desynchronisation of parts of catchments is not a guarantee, even with substantial tree coverage, and is dependent on catchment morphology and hydrology.

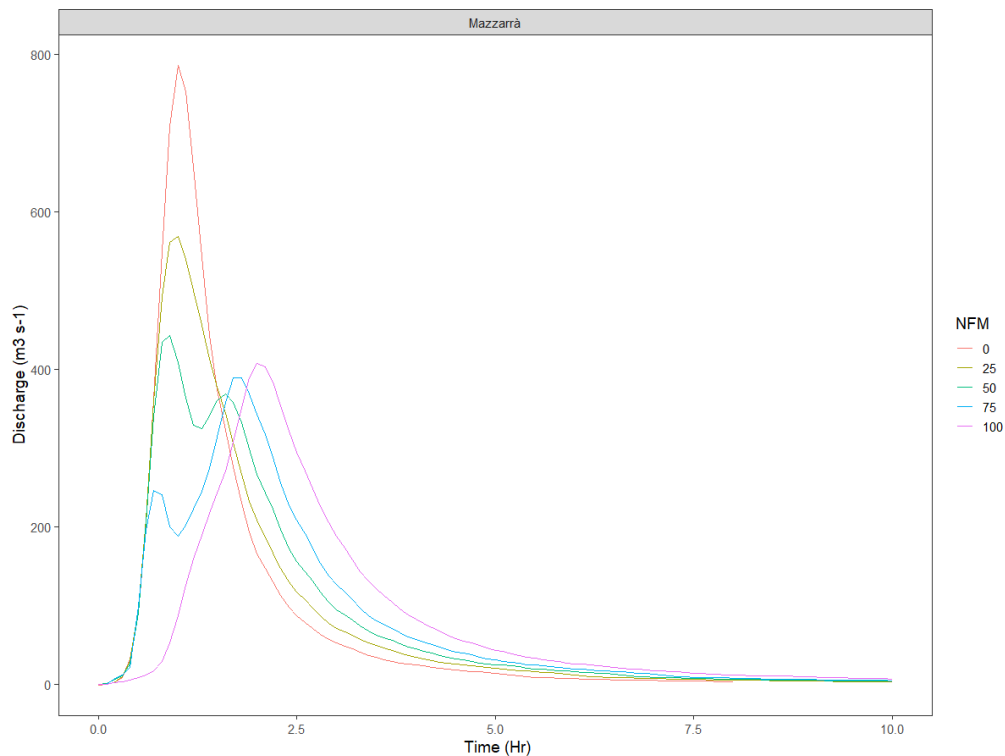


Figure 8-2 NFM hydrographs for the Mazzarrà catchment showing the creation of an earlier peak as well as a bimodal peak caused by the distribution of NFM.

The effect of NFM on modelled peak flows will also be impacted by the choice of Manning's  $n$  values (Spada et al., 2017). It is widely known that Manning's  $n$  values are used to characterize the roughness of the terrain (Hatzigiannakis et al., 2016). Manning's  $n$  coefficients are usually determined from flow measurements (Corato et al., 2015) when known discharge data is available from nearby stations (Ervine and MacLeod, 1999) and used to predict previous or future events (Ferguson, 2010, Narsimlu et al., 2015). In other cases, the Manning's  $n$  values are calculated using a survey of the topography the channel bed. However, values are regularly adjusted in hydraulic modelling to calibrate models. In this research, consistency in conditions between catchments in order to identify the role of catchment morphology was paramount and so specific Manning's  $n$  values, taken from other similar studies, are used to represent NFM. A sensitivity analysis could be carried out to determine the significance of the chosen Manning's  $n$  values on peak flows and lag time; however, the consistency across catchments mean that the observed trends between catchments – the focus of this PhD – are unlikely to change.

Although Manning's  $n$  values are very important, the use of accurate values within a catchment is not feasible given that roughness will change over very small



scales, in relation to soil types, vegetation, topography and channel bed configurations (De Doncker et al., 2009). De Doncker et al. (2009) carried out a Manning's  $n$  sensitivity analysis using different techniques in the Biebrza River and the River Aa in Belgium. De Doncker et al. (2009) found that the Manning  $n$  coefficient also varies according to the season, thus values increase from May until September and decrease from October. Therefore, the selection of Manning's  $n$  values is always a simplification of reality and selection depends on the aims and objectives of the study.

Therefore, the results of this research are largely controlled by the experimental design and the establishment of tree cover from the upper part to the lower part of the catchment. The original design aimed to understand the reduction of peak flows by proportional increases in vegetation cover. Whilst the findings do not provide a complete answer to this question, this methodological design did allow a better understanding of how hydrological responses in catchments depends on the spatial location of NFM and the desynchronization of particular areas. In this sense, the analysis of NFM cannot be solely based on the percentage coverage or reduction of the peak flow.

### ***8.1.3 The impact of increasing NFM coverage on peak flows and lag times***

The percentage reduction in peak flows is greater when NFM coverage was between 25 and 50% of the catchment, as opposed to higher coverages (Figure 6-8). In fact, the percent reduction in peak flow when 75% of the catchment is covered in NFM is, in many cases, more effective than covering the entire catchment. This indicates that the remaining 25% did not contribute significantly to the reduction of the hydrograph peak, indicating NFM location is critical in being an effective peak reducing strategy. (Kirkby et al., 2005) states that rainfall in areas close to the outlet of the catchment has a higher effective intensity due to the short travel times, and will be less affected by drainage networks and storage capacities in the catchment. However, here the NFM was distributed from upstream to downstream and so the 25% from 75% to 100% represents the most downstream area of the catchment. Had NFM increased in the other direction (with the most upstream left to last), a markedly different set of results is likely. Therefore, the variation in the percentage reduction of peak flow between NFM scenarios is likely associated with two key factors: the morphological characteristics of the catchment and the spatial location of the NFM in the catchment.

Despite there being no statistical differences between micro and sub-catchments, the overall percentage reduction in peak flow was lower for the micro-catchments than for the sub-catchments (Figure 6-10), potentially indicating that NFM coverage is less efficient in reducing flows in small catchments. This differs from (Kay et al., 2019), who suggest that NFM interventions are likely to be most effective in smaller catchments based on reviewing published evidence of the flood response in UK catchments. However, this affirmation is based on a group of catchments whose area is less than 100 km<sup>2</sup> excluding a large range of catchments configurations. In contrast, Hankin et al. (2017) argue that NFM measures are likely to be effective at larger scales if NFM is installed widely across catchments, taking into account the synchronisation of flood waves. A similar result was evidenced when the percent reduction in peak flow was compared between catchment shapes, with reductions greater in catchments characterised by being large and rounded (Cluster C) compared to smaller, elongated catchments (Cluster A) (Figure 6-11). Despite partially standardising for catchment area by looking at percentage reductions in peak flow, it is clear that area and shape are important. So far, no studies have addressed the relative significance of NFM in different catchment configurations, with the majority of studies focused on particular NFM measures for specific, real-world catchments. As such, there is limited work to directly corroborate the findings here.

In this study, the differences in the percent reduction for different types of catchments are linked to the spatial location of the NFM (i.e. headwaters to downstream). For example, covering 25% of an elongated catchment in NFM would likely lead to a higher percentage of the drainage network within the NFM area than more rounded catchment, shown in Figure 8-3. The experimental design of this investigation implies that the hydrological responses and, therefore, the output hydrographs, are highly influenced by the distribution of the NFM. It is then suggested to use other criteria for the experimental design of further studies that will not be influenced by the shape of the catchment. The hypsometric curves of the catchment could be used to establish different NFM percentages based on the differences in the catchment elevation. The results could therefore be contrasted with those of this investigation to determine if the desynchronization of the areas is due to particular distributions of the NFM.

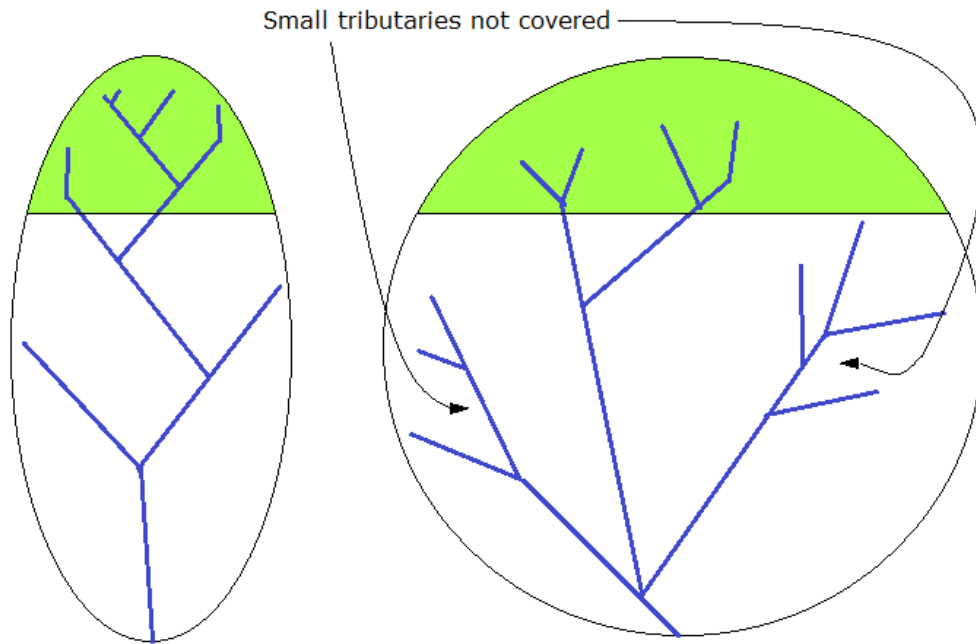


Figure 8-3 Conceptual figure explaining the differences of covering 25% of NFM in two different catchments shape and their interaction with drainage density.

The review of the existent literature suggests that NFM functions differently in different river catchments, mainly due to the morphological peculiarities of each catchment and the flood management measures used in each study. Therefore, some differences can be seen between other studies and this research. However, it is not recommended to generate standard rules to define the effectiveness of NFM based on a specific case study. Approaches such as those carried out in this research using 20 synthetic catchments and a variety of NFM scenarios can contribute to finding patterns or ranges of peak reduction in catchments. These results might be useful to compare similar studies that used similar conditions such as rainfall events or NFM distributions. However, it may not be possible to formulate a single and definitive rule of thumb for the establishment of NFM measures. However, in these cases it may be possible to identify the characteristics of catchments that are unlikely to follow more generalised rules, for example because of particular combinations of size, shape, drainage density, rainfall type or other parameters.

#### **8.1.4 Significance of rainfall intensity and distribution to modelling results**

In this study, rainfall was distributed evenly over the total area of the modelled catchments. Losses due to infiltration or evapotranspiration were not incorporated into models and therefore, the net rainfall corresponds to the total amount of fallen water in the entire catchment. Implications of not modelling infiltration will be discussed in next section. The precipitation was spatially distributed evenly over the catchment to ensure consistency between catchments. For example, Nguyen et al. (2016) states that distributed rainfall across catchments allows for capturing the impact of modifying particular model parameters, such as DEM resolution, mesh resolution, channel and floodplain roughness (Manning  $n$ ), as well as to calibrate hydrological models. However, rainfall distributed over entire catchments is rare, particularly in large catchments, as confirmed by Woltemade and Potter (1994) who state that the most extreme convective storms usually cover only a small proportion of catchments. Other studies have found great variability in output hydrographs depending on rainfall intensity and duration, as well as its spatial distribution. For example, (Kirkby et al., 2005) found that differences in runoff generation were mainly due to storm area effects and Wilson et al. (1979) performed rainfall-runoff modelling in the Rio Fajardo catchment, Puerto Rico (68.6 Km<sup>2</sup>), concluding that the spatial distribution of rainfall had a significant influence on the volume of surface runoff, lag time and peak flow. However, this simplification allowed examination of geomorphic factors without adding complexity, with the result being that outlet hydrographs likely had shorter lag times and some phenomena associated with catchment morphology and NFM, such as bimodal peaks, would likely present differently with unevenly distributed rainfall.

There was a reduction in peak flow due to NFM regardless of the intensity of rainfall. The peak flow declined to a greater extent as NFM increased when rainfall intensity was higher (e.g. 120mm h<sup>-1</sup>). However, when peak flow reduction is standardised as a percentage of the control peak flow (i.e. 0% NFM), the reduction for each NFM increment is similar (see Figure 6-15). These results in part differ from Ferguson and Fenner (2020a) who argue that the potential for peak attenuation decreases for higher intensity rainfall events. This view is also supported by (Kay et al., 2019) who suggest that NFM is likely to be more effective at lower rainfall return periods (e.g. 10 years). The difference between the results of this study and these other studies is likely related to the area of the catchment. As mentioned above these studies were based on catchments where the area was

less than 100 km<sup>2</sup>, therefore the conclusions are limited to a reduced number of catchment types. Here again, the importance of an analysis by classes or categories can be ratified. In fact when the effect of the NFM in the reduction of the peak was analysed for different intensities and by sub-classes, it was found that the micro-catchments had greater reductions in peak flow when lower rainfall intensities were studied. From these analysis it was also noticed that the peak flow variation was greater for larger intensities. This is in disagreement with the proposal of (Woltemade and Potter, 1994) who state that catchments that only offer minimal attenuation produce peak flows that present greater variance due to rainfall intensity and duration.

## **8.2 NFM placement in catchments**

### ***8.2.1 Optimising the placement of NFM***

It was clear from the results of Chapter 6 that the spatial location of NFM in a catchment is important. Through the use of the tool *rtraveltime* it was possible to estimate the travel time of distributed flow in the catchments, and to target NFM in areas with similar travel times that contribute to peak flows. Despite being conceptually promising, the results were disappointing, with only limited benefits over the arbitrary placement of NFM in previous chapters. However, the promise of the method is evidenced by the much greater increases in lag times relative to other NFM placement scenarios. The greater effect on the lag time is due to the fact that the NFM is focused on the areas that generate the peak, and delay that peak significantly by desynchronizing these areas from the rest of the catchment. However, by only planting areas of similar travel time, the peak itself is not significantly reduced because these areas still have similar travel times, albeit slower.

From a mathematical point of view, the map of travel times could be optimized, equalizing the histogram of travel times so that all cells in the catchment drain through the outlet at different times. By altering the roughness of each cell on a continuous scale for equalizing travel times would result in the output hydrograph having a smooth trend with an extended, flattened peak and would represent the theoretical, optimal conditions and the lowest possible peak flow for the conditions. However, this is a complex mathematical task and, from a hydraulic perspective, not easy to model since changing the roughness coefficient in one cell alters the travel times in all linked upstream cells. As such, this relatively simple concept

would be highly modelling intensive. This is also not a practical solution because subtly tuning roughness or slope to optimise travel times is not possible in reality, and any model of travel time will necessarily be a simplification with other factors – not least the non-uniform distribution of precipitation, potentially negating the benefits of such an approach. Therefore, optimising travel times would be an interesting academic continuation of this study, and could yield important insight into hydrological response but, is unlikely to be practically possible.

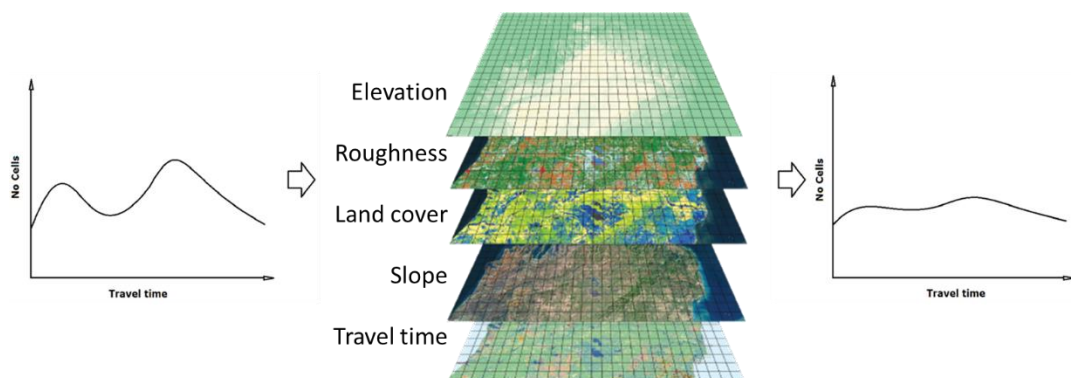


Figure 8-4 Graphical diagram of the travel time approach. The travel times could be mathematically optimised but the solutions will not be feasible because to achieve this the roughness's values in each cell should change which is not happening in the real life.

An alternative approach would be to use the travel time method to develop generic rules for optimised placement, or to generate broad regions for targeting NFM in specific catchments, but acknowledging that this would not be a true optimisation of placement. In this vein, it was found that focusing NFM on particular slopes could yield substantial reductions in peak flow, whilst covering much smaller areas of catchments in NFM in comparison to upstream placement. The analysis was complicated by the inevitable fact that different catchments had differing coverages of slope magnitudes but, clearly indicated that focusing NFM on low slopes, less than 8%, led to greater relative reductions in peak flows than when focused on steeper slopes. (Thomas and Nisbet, 2007) argue that NFM measures installed in the floodplain area where slopes are relatively low are more efficient in terms of peak flow reduction. Similarly, Dixon et al. (2016) in the Lymington catchment, UK, found that floodplain restoration could lead up to 20% attenuation of peak flows.

The fact that flow is reduced to a greater extent in areas with lower slopes is because flow resistance is greater on slopes of less inclination (Bates and Pilgrim, 1983, Cowan, 1956). From the hydraulic and functional point of view, this is in agreement with the function of flood zones which act as natural components of the catchment that decrease flow velocity and alter flood dynamics (Woltemade and Potter, 1994). Wong et al. (2015) state that the floodplain topography is the main element controlling flood wave propagation. Features of the floodplain cause flow velocities to decrease compared to in-channel flows and, thus these areas act as a storage reservoir (Bhowmik and Stall, 1979, Bates and Pilgrim, 1983, Wong and Laurenson, 1983). Storage areas are important in catchments, significantly contributing to reducing peak flows and, therefore, catchments without functioning floodplains can have larger peak flows (Woltemade and Potter, 1994). In addition, Connell (2008) found that by covering floodplains with dense forest, the flow velocity could be reduced by as much as half compared to an area of grassland. A forested floodplain reduces flow velocity, contributing to storage, because the linear kinematic energy becomes turbulent in motion (Fischer-Antze et al., 2001). However, it has also been argued that for high magnitude and low frequency rainfall events, the peak flows are not attenuated to the same degree as smaller events because the total discharge becomes dominated by overbank flow, with the entire floodplain delivering flood water much like a channel (Woltemade and Potter, 1994).

Although NFM has been proven to be more efficient in floodplains, its establishment is conditioned by several aspects that play an important role and make it difficult to freely implement. Land use and land ownership are two such factors. Land use conflicts are beyond the scope of this research; however, other research has focused on these areas of research and models of NFM optimisation could be extended to include land use information, discussed further in section 8.2.3.

### **8.2.2 NFM efficiency**

In investigating the role of slope in modulating the impact of NFM, an efficiency index was calculated in which the percentage of NFM was divided by the peak flow reduction. Using this metric indicated that there is greater efficiency in reducing peak flows when NFM is established on slope magnitudes  $<2\%$  and that the efficiency decreases as slope magnitude increases (Figure 7-10). Most of the literature reviewed does not evidence the use of a particular metric to quantify the

impact of NFM: generally the analysis is based on determining the percentage reduction in peak flow. This research therefore contributes with a novel metric that allows normalisation of NFM in relation to the hydrological responses of each catchment. It is then possible to determine the impact of different distributions of NFM in different configurations in catchments, which therefore helps to optimize positioning within catchments. In this sense, this metric could help answer the concerns of (Kay et al., 2019) who argue that there is no clarity in relationships between the type of hydrological response of a catchment and its practical potential for establishing NFM measures.

### ***8.2.3 Practical challenges of optimising NFM placement***

Whilst the abstract modelling above has led to the development of conceptual and numerical modelling approaches for rationalising where to place NFM in catchments, there are also practical challenges to placement (Kay et al., 2019). In particular, there are social, economic and spatial planning considerations that need to be made, as well as the requirement for land owner permission (Waylen et al., 2017). Research by Holstead et al. (2017) on farmer's perception of NFM in Scotland, and based on interviews, workshops and online surveys, found that there are six main criteria to enable the NFM implementation. These were economy, public perception, catchment planning, advice availability, policy and tradition. Results show that about 53% of the farmers considered their land too valuable to install NFM measures, while 38% affirm that the lack of funding is one of the main barrier to implementation (Holstead et al., 2017). It was also found that 64% of farmers had not implemented NFM and have not had enough advice about NFM, and 59% of the farmers did not know about NFM. There are also questions surrounding the ability of establishing NFM in some areas and the time taken for NFM to establish and have its desired impact. (Ferguson and Fenner, 2020a) argue that NFM interventions have significant barriers associated with the time taken for trees to mature. Since the effects of NFM are normally seen in the long term, especially in tree planting (Farley et al., 2005), and restoration projects generally do not include monitoring programs on the same time scale (Wells et al., 2020), it is very difficult to gather evidence on the efficacy of the NFM that serves to generate security among farm owners when implementing NFM in their territories (Wells et al., 2020, Waylen et al., 2017). Dadson et al. (2017) affirms that the major issue in the implementation of NFM is the lack of robust evidence of their functionality and efficacy.



Land ownership is also a key factor in the implementation of NFM. In particular, farmers with small landholdings are generally reluctant to convert their productive land into a NFM scheme, because of the financial implication (Holstead et al., 2017). This is a particular issue in the UK because land holdings tend to be small (UK average 86.4 ha) (DEFRA STATISTICS, 2020), and so large scale NFM or river restoration, and a holistic management approach, is likely to require the collaboration, co-operation and agreement of many individual private landowners (Wingfield et al., 2019). Such practical and social challenges turn the implementation of NFM beyond a technical problem (Wells et al., 2020), into something more complex. However, the incorporation of NFM into public policy with economic incentives means that NFM measures are increasingly being accepted by the community (Collentine and Futter, 2018). A three year project carried out in the River Stroud and River Frome catchments (250 km<sup>2</sup>) in the southern Cotswolds, UK, was based on community participation in implementing 400 flood mitigation interventions (Short et al., 2019). The project was based on building trust among landowners about the benefits of NFMs that would later enable their adoption. Likewise, the commitment of local people in the generation of knowledge has been considered key in the adoption of measures that have generated not only environmental benefits, but also cultural and social ones (Short et al., 2019).

Having a tool that could optimise NFM placement and demonstrate in a modelling framework why NFM should be targeted in a particular area, could therefore be a useful tool for stakeholder engagement and education. In addition, being able to use NFM efficiently, potentially planting smaller areas of the catchment but delivering significant peak flow reductions, would be beneficial in reducing potentially contentious land use decisions. The results of this research provide insight into the potential of NFM in different areas of the catchment. These results are the outcome of a hydraulic and hydrological modelling process involving considerable human and computational effort and highly specialised knowledge. At this time, this research is addressed to an academic community, however, the findings found here can be used and automated to develop a tool that uses these examples to assess the potential of NFM. In this regard, non-academic audiences that need to see the potential of those solutions in a visual and friendlier way could use this tool, which, in turn, would help build trust and promote the acceptance of NFM measures.

### **8.3 Abstracted models and scenarios**

#### **8.3.1 Model set up and modelling effort**

The sensitivity analysis of the IBER model contributed to defining fundamental parameters such as the mesh size and the time step to be used in the model. These two parameters are considered fundamental in modelling because these directly affect the quality and precision of the results, as well as the computational time (Bladé et al., 2014). The sensitivity analysis for the mesh size determined that there were no significant differences in the peak of the hydrograph (e.g. < 1%) between elements of 100, 200 and 300 metres in micro and sub-catchments. In contrast, the same analysis for large catchments indicated that peak flow increased between 3 and 8% (see Figure 4-10). Therefore, mesh size is clearly important, but the significance is dependent on the catchment size.

Here, a mesh size of at least 10 metres along the drainage network contributed to obtaining greater precision in the results than a uniform coarse mesh over the entire catchment. Results indicated that a coarser resolution outside of the drainage network did not significantly affect the output hydrographs but, instead contribute to saved computational time. The effect of mesh size was also evaluated by including a channel with 2 metre resolution along the main network. The results indicated that for a catchment of 54.8 km<sup>2</sup> the computational time could be 40 times longer for a 2 m resolution in comparison to 10 m, which was not feasible for this study, with numerous scenarios to be evaluated. The analysis also determined that peak flow differences were on the order of 5%, which for this study were deemed insignificant relative to the benefits of reduced computational times, although for others this decision will depend on the model aims.

The sensitivity analysis of the step time was also key to the configuration of the IBER model. The test determined that in micro and sub-catchments, the computational times did not vary significantly when the time step was altered (see Figure 4-15). However, for large catchments, the computational time increased substantially when configuring the model with a time step of 5 min. Although the sensitivity analysis of the mesh size and time step enabled an estimate of the total time to model the set of catchments, the sensitivity analysis was carried out using the simplest scenario, which implied that the computational times for the catchments were underestimated for complex scenarios. Whilst having a higher resolution time-step did improve the precision of the results, the volumetric differences in the hydrograph, and the magnitude of the peak flow, was not

significantly impact (Figure 4-14) and so, here, computational times was saved by accepting a slight decrease in precision.

The analysis of two types of mesh: a coarse mesh and a more refined mesh that also included a 2 m channel along the main river, yielded results with significant differences. The coarse mesh with 171812 elements was solved by the model in 1 hour and 24 minutes while the more refined mesh with 972211 element took 54.8 hours. Without a doubt, the coarser mesh has a higher efficiency because the number of elements in the mesh is much lower than the refined mesh. This can be verified in Figure 5-4 where it is seen that the computational time adjusts to a linear regression as a function of the number of elements. However, the differences were not significant when the two outlet hydrographs of each model were evaluated and the peak flow and lag time were compared. Therefore, the choice of the mesh size had significant implications for computational time but not for the output hydrographs in these cases. However, this may not be true in all studies. The refined mesh generates more reliable results, but at the cost of a longer computational time, but as in the case of this investigation, where more than 300 simulations were carried out, the choice of a refined mesh is not a viable option. To perform this analysis, the refined mesh was carried out in a micro-catchment (Mazarra) with an area of 54 Km<sup>2</sup>, but if the same analysis with a 2 m channel was applied to a catchment like Bistrita with an area of 759.7 km<sup>2</sup> the computational time would be 205 hours instead of 12 hours. Therefore, the choice of an element size will depend on the scope and precision that an investigation requires.

### ***8.3.2 The implications of modelling abstracted catchments***

This research has been based on the hydraulic and hydrological modelling of synthetic catchments that reflect physiological parameters of natural catchments but are, ultimately, abstracted. The decision to use abstracted catchments was made because it increases the likelihood of isolating important determinates of hydrological response from inherent variability and small-scale processes and factors (such as subtle changes in roughness) that are present in real-world catchments, and cannot be suitably modelled (Nguyen et al. (2016)). Therefore, the method has enabled me to make assertions about general trends that are relevant to all catchments, allowing discussions about under-pinning, fundamental controls on NFM efficacy. However, the downside of this approach is that the results are not replicating any particular catchment and the incorporation of real-

world variability could significantly complicate or change the relationships identified here. However despite this fact, the model results do provide useful information about generic trends, which are necessary for developing widely applicable rules for use in multiple catchments.

Including additional variables in the model could change the modelling results but, would also complicate the ability to generate widely applicable, fundamental relationships. For example, variables representing vegetation cover, infiltration and roughness in catchments are highly significant but, also catchment specific and so, difficult to incorporate in a meaningful, abstracted way in our catchments. The assumptions made in this research regarding the infiltration imply a fully saturated soil for all catchments and scenarios, which means that all runoff was generated by saturation excess overland flow (SEOLF). As mentioned above, this assumption was made on the basis that variable infiltration rates across catchments would complicate the ability to compare between catchments and because the inclusion of infiltration when infiltration rates are not known, increases the uncertainty of the model. The likely result of not including infiltration is an over-estimation of the peak flow but, this impact will be more limited for extreme rainfall events, as is the focus of this study, where infiltration would be expected to be limited.

There is no doubt that the infiltration plays an important role in the hydrological response of a catchment. Hankin et al. (2019) argue that to model the effects of tree planting on peak flows, understanding of the impacts on surface roughness and infiltration rates are necessary. Similarly, (Calder and Aylward, 2006, Wahren et al., 2012) argue that forested areas have a higher infiltration capacity compared to bare soils and therefore, could help mitigate peak flows. (Kirkby et al., 2005) suggest that infiltration in different areas of catchments contributes significantly to decreases in runoff and is more evident as catchment areas increase. The infiltration rate in catchments could also be a source of runoff downstream by infiltration excess overland flow (IEOLF), also known as Hortonian overland flow. It is argued that the effect of IEOLF is related to the soil conditions and climate (Simmers, 2003, Ormaza, 2018). For example, Bull et al. (2000) argue that the IEOLF tends to represent a minor contribution in the temperate region compared to semi-arid regions. Ormaza (2018) also suggest that in semi-arid regions, the peak of hydrographs tend to be unimodal with a very quick response due to the runoff caused by IEOLF reaching channels quicker than the SEOLF (Camarasa-Belmonte, 2016). Therefore, infiltration is a variable that has to be carefully analysed since the type of soil plays an important role in the infiltration rate.

Likewise, the subsurface flow is another variable that is directly related to the capacity of the soil and is hydrologically important but, likely to be highly catchment-specific and beyond the scope of this work. This parameter could also mask the impact of catchment shape in these abstractions. Therefore, the role of infiltration and sub-surface flows are likely to be important when trying to recreate real-world catchments but, here that was not the aim. Instead, the significance of the variables (e.g. Manning's  $n$ , infiltration, rainfall duration) is limited by focusing on a short, intense rainfall event occurring on fully saturated surfaces, enabling focus on the significance of catchment shape and topography in abstracted conditions.

The infiltration of the catchment also varies with respect to the intensity of the rainfall (Saghafian et al., 2008, Amini et al., 2011, Olang and Fürst, 2011). (Noori et al., 2016) argue that infiltration is more sensitive for smaller rainfall events than for intense, short-duration rains. (Noori et al., 2016, Abdulkareem et al., 2019) both argue that during very intense rainfall events the rate of precipitation could overwhelmingly exceed the infiltration capacity and therefore, the soil surface begins to behave in a similar way to impermeable surfaces. Similarly, antecedent moisture conditions are important as previous rainfall events can saturate soils, leading to overland flow during subsequent rainfall events (Titmarsh et al., 1995, Connolly et al., 1997). As intense, short-duration rainfall was modelled in this study, the role of infiltration is likely less significant than it would be if modelling smaller events. It has been also demonstrated that the velocity of the flow is more important in determining the volume of water that infiltrates into the soil than the water depth (Mudd, 2006). If infiltration was included, the impacts of NFM would likely be greater, reducing peak flows and lag times to a greater degree than modelled here; however, trends associated with the placement of NFM and trends between catchments are thought to remain as documented here.

In addition to infiltration, other hydrological phenomena, including interception and transpiration were not considered in this research. A large number of studies recognize these as important variables in determining the hydrological response of rainfall events (Marchi et al., 2010, Acreman and Holden, 2013, James and Roulet, 2009). In this research, NFM associated with broadleaved tree planting was parametrised by solely changing Manning's  $n$ . Sivapalan et al. (2005) argues that evapotranspiration impacts flood generation by altering the progress of rainfall to the channel network, reducing water volumes in the channel, and altering antecedent conditions in catchments, which will also change seasonally

with vegetation life cycles. Evaporation is of greatest significance in large catchments, with large storage areas and more prolonged rainfall events. Acreman and Holden (2013) state that evaporation increases once the rainfall event has finished and the remaining water in the catchment will experience different rates of evaporation dependent on microclimate. This effect has the potential to decrease the flood magnitudes, particularly in hot climates where water storage on floodplains could be evaporated (Zwarts et al., 2006). Here, there was no consideration of climate in the abstracted modelling space and so whilst evapotranspiration may have altered absolute values, it is unlikely it would have significantly altered trends between catchments.

Although the design of the methodology for this research was a simplification of reality, the results provide a novel insight into the potential benefits of NFMs for a wide range of catchment configurations. This research, nevertheless, does not ignore the importance of other variables that play an important role in fluvial and hydrological dynamics. For the case of individual catchment studies, we recommend that future modelling could usefully apply the lessons learned in this study to real-world catchments, incorporating infiltration rates, variable catchment roughness for land use and NFM measures, as well as the soil antecedent conditions. These incorporations could determine whether the methods developed here hold true in calibrated and validated models replicating real-world conditions. However, when the research approach is based on a large group of catchments, assigning variables to the model (e.g. infiltration) would not be recommended, since assuming homogeneous conditions for all catchments is unrealistic. This could generate counterproductive results, for example, the slope of each catchment would influence infiltration rates and this would generate more uncertainty in the model and make the determination of over-arching general trends difficult. In this sense, our recommendation to the wider scientific community is that a simplified model can generate an approximate estimate of the hydrological responses, but when it is necessary to study a particular catchment, a model with sufficient information that represents real conditions should be generated.

## **8.4 Beyond slowing the flow**

### **8.4.1 Other NFM methods**

This research has focused on the use of tree planting to slow overland flow after intense rainfall events, and has found that it is possible to reduce peak flows in different morphological configurations of catchment with large coverages of NFM (25% catchment area and over). When flow reduction is not possible through the establishment of large areas of tree cover, other NFM options and alternatives could be used, including offline storage areas, leaky dams, ponds, and bunds. In terms of the hydrological and hydraulic modelling approach, most of these measures could be included in the model by setting up adequate hydrodynamic conditions. It could be expected that increasing the number of measures the ability of the catchment to decrease the peak flow would increase. For example, (Samra, 2017) has shown that incorporating different measures into a model, the percentage flow reduction can be maximised. However, the study did not consider where to place NFM in catchments.

Some NFM alternatives could offer smaller intervention coverages compared to planting trees, with significant impacts on hydrological response. The efficiency of such schemes is largely based on the number of measures throughout the catchment (Lane, 2017, Wilkinson et al., 2019). Measures such as ponds have to be able to store a certain volume of water to be effective (Samra, 2017), as well as be numerous enough to reduce the flood peak (Wilkinson et al., 2019). Wilkinson et al. (2019) argue that the implementation of large offline storage areas can lead to regulatory issues, such as the Flood and Water Management Act 2010 in the UK, which imposes a capacity beyond which regulation is required (Environment Agency, 2017). It is also argued that the implementation of these measures disproportionately affects some catchment land owners whilst others benefit (Holstead et al., 2017, Waylen et al., 2017, Spray et al., 2016).

Therefore, given the policy significance of tree planting in the UK, the potential to disperse trees through catchments limiting impacts on a single land-owner, and the potential benefits of tree planting on peak flows, the modelling performed here remains important in informing future flood mitigation methods. However, future modelling could usefully incorporate offline storage in areas of catchments, coupled with tree planting, to maximise potential benefits and determine where different NFM methods could be best located.

#### **8.4.2 Holistic catchment management**

There is no doubt that natural flood management is gaining importance due to the environmental benefits it can provide (Iacob et al., 2014). However, it should not be ignored that the problems of flooding have historically been dealt with predominantly using grey infrastructure. This grey infrastructure remains an important component of many catchments and will continue to fulfil an important function for which they were designed. The implementation of grey infrastructure has been widely criticized for a lack of consideration of catchment functioning and its often negative impacts on habitat and conditions at lower flows (Dixon et al., 2016). However, the transition to more sustainable and natural measures does not seek to replace existing infrastructure but, to establish a synergy with NFM (Kay et al., 2019). The argues that many European projects currently work hand in hand with grey infrastructure to reduce flood peaks. For example, a project developed in Waldringfield in Suffolk, UK, integrated pre-existing grey structures (e.g. brick wall along the canal) with the implementation of a new wetland behind the wall. The project proved to be a great model for partnership working (Environment Agency, 2017).

Currently there is focus on "next generation infrastructure," which consists of the harmony between green and grey infrastructure (Browder et al., 2019). This new concept is in its early stages as the interaction between the two infrastructures is imprecise due to the inherent complexity of most natural systems (Browder et al., 2019). Likewise, the implementation of green structure still needs to be established as a robust measure for flood management. In this sense, it is considered that green infrastructure has challenges that must be specified to achieve harmony with grey infrastructure. Having a conducive public policy to finance the implementation of NFM, and also establish long-term monitoring programmes, is considered essential considering the problems discussed above. The High Level Panel on Water (HLPW) convened by the States Nations and the World Bank concluded that natural solutions can help with the modern challenges of climate change and water problems in river catchments, particularly if it creates a match with grey infrastructure (HLPW, 2018).



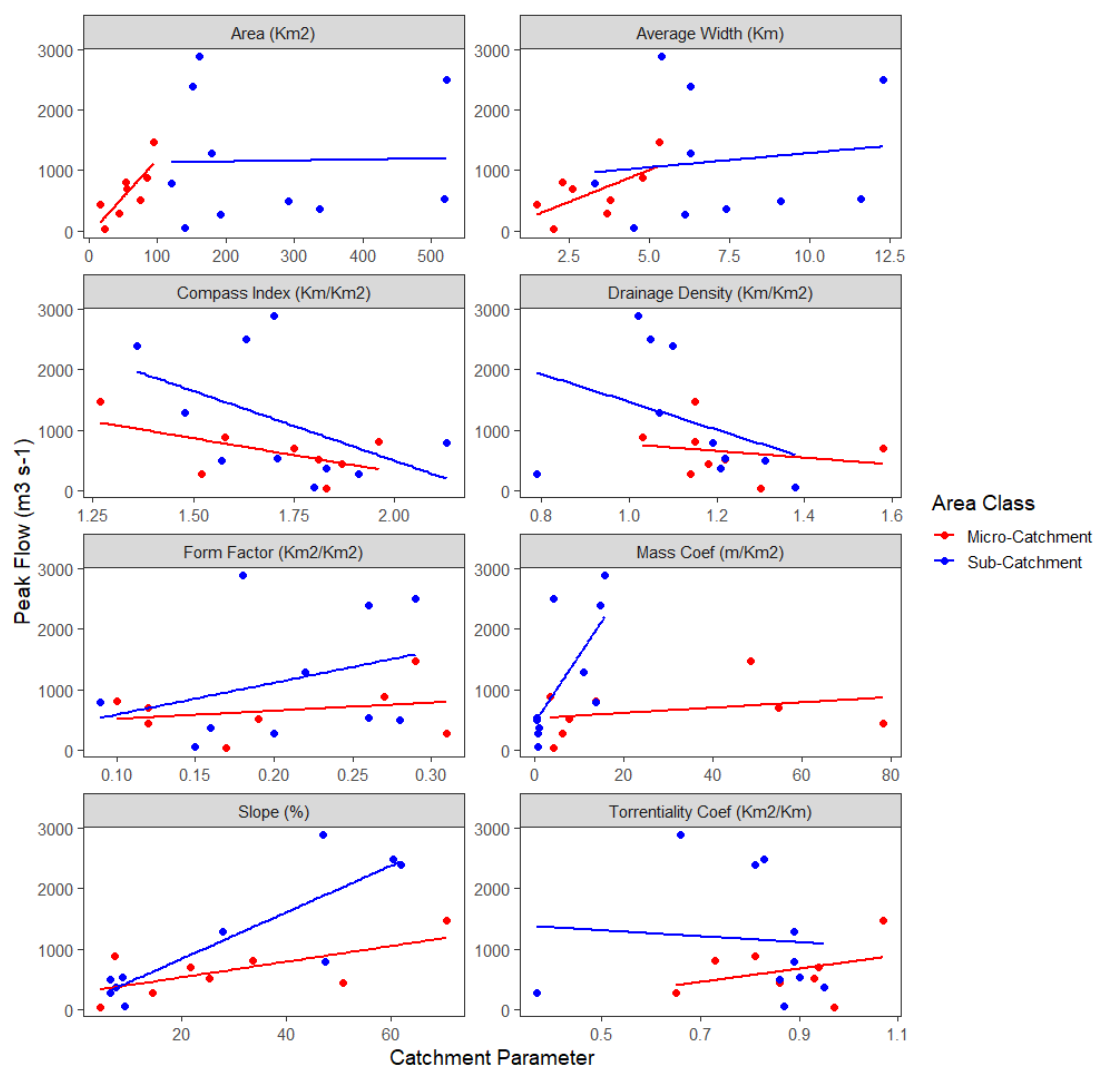
## **CHAPTER 9. CONCLUSIONS**

This PhD has used modelling of synthetic catchments to explore the efficacy of NFM and shows that tree planting can significantly reduce peak flows and increase lag times in catchments. The magnitude of these changes is dependent on catchment characteristics, although relationships are not simple. The benefit of using synthetic catchments and abstracted rainfall events is that the importance of catchment characteristics can be untangled from the inherent complexity of the natural system but, as document here, some of the decision in abstracting the modelling lead to unrealistic situations in the real World. In particular, the increase in NFM coverage from the upstream to downstream of the catchment leads to hydrological effects, such as bimodal hydrograph distributions that are unlikely to occur in reality. However, such findings do allow a better understanding of the interplay between NFM, catchment hydrology and rainfall events and do demonstrate the significance of NFM placement in desynchronising parts of the catchment.

By focusing NFM in areas that contribute disproportionately to generating peak flows could be a method of more efficiently placing NFM in catchment, ultimately reducing coverage whilst maximising flood benefit. Identifying where in catchments green infrastructure could be placed for maximum benefit, and considering which catchments and events are most likely to see significant reductions in peak flows, also enables identification of situations where tree planting may not have desired effects. It is in these regions other methods, including grey infrastructure, may be needed to protect vulnerable areas. Whilst it is clear that before implementation of schemes, bespoke modelling of catchments, validated and calibrated on monitoring data is needed, the findings document here demonstrate the potential benefits and advances that could be made by future research focusing more broadly at hydrological responses of a large range of necessarily simplified catchments. The rules generated from such modelling could offer useful tool for land-owner engagement and could lead to better optimising of tree planting schemes in the landscape.

## APPENDIX A

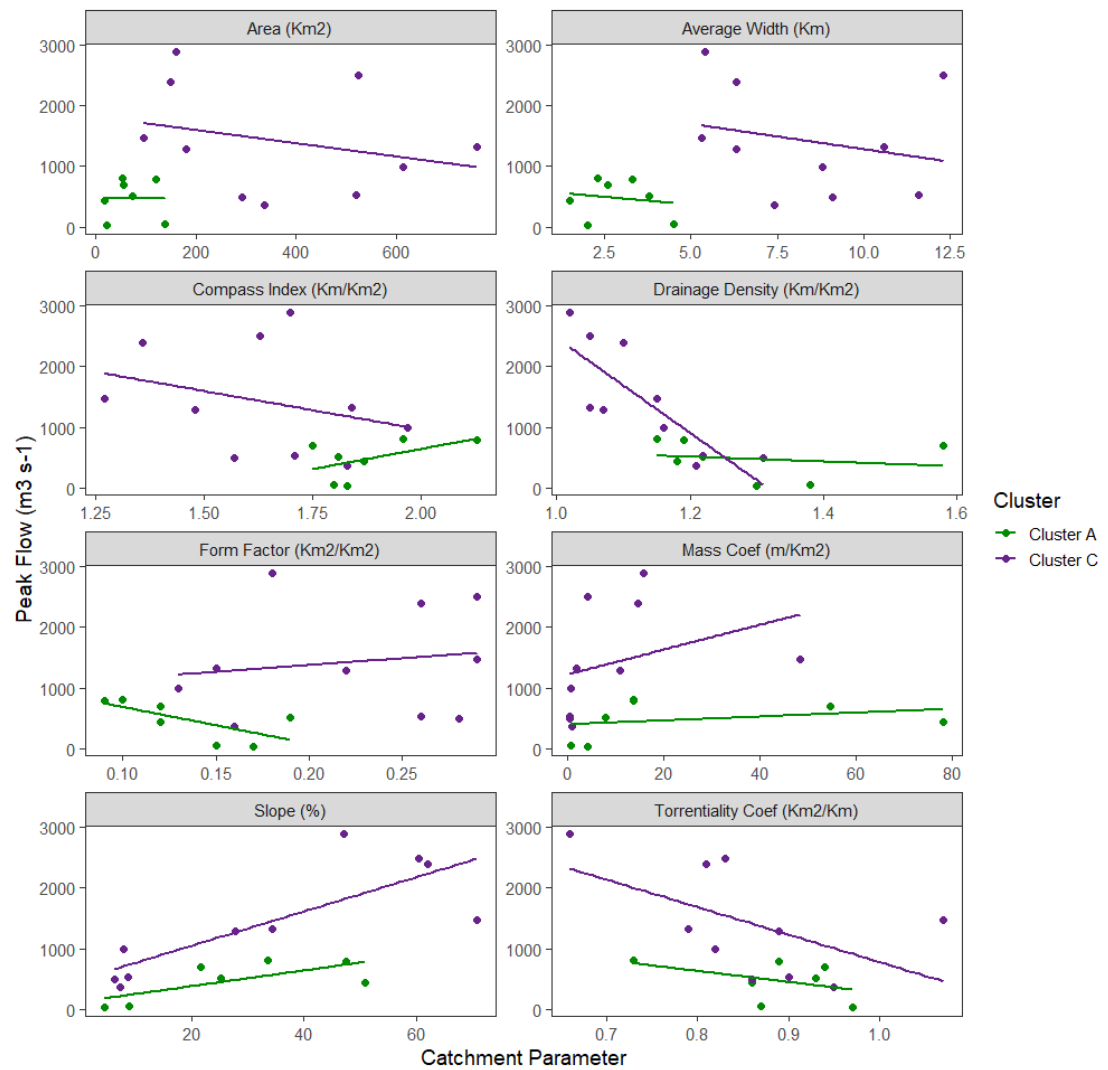
The figure below shows the relationship between peak flow and catchment parameters for the a of catchment classifications. The whole data set has been considered with no outliers removed. Equivalent figures with outliers removed is presented in Figure 5-5.



Appendix A 1 Scatter plot between peak flow and catchment parameters. Coloured points indicating the distribution of the data according to each size class. Linear regression adjusted to the data for each area class.

Appendix A 2 R and p values from the matrix correlation between parameters of the catchment and Peak flow classified by Catchment Area.

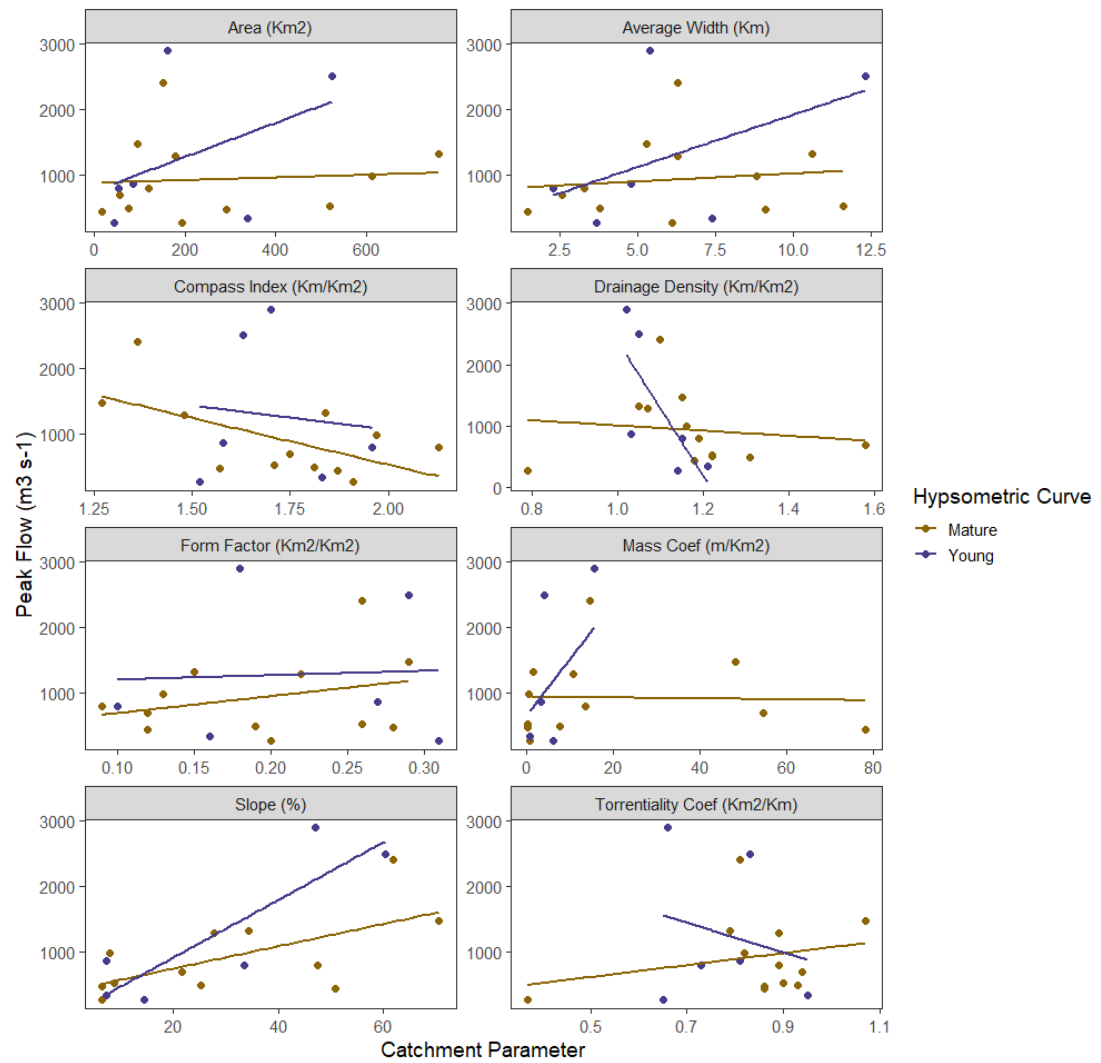
| <b>Peak Flow</b>               |                        |                |                      |                |
|--------------------------------|------------------------|----------------|----------------------|----------------|
| <b>Catchment<br/>Parameter</b> | <b>Micro-Catchment</b> |                | <b>Sub-Catchment</b> |                |
|                                | <b>r</b>               | <b>p-value</b> | <b>R</b>             | <b>p-value</b> |
| <b>Area</b>                    | 0.80                   | 0.016          | 0.02                 | 0.950          |
| <b>Average Width</b>           | 0.66                   | 0.077          | 0.13                 | 0.710          |
| <b>Compactness Index</b>       | -0.58                  | 0.130          | -0.49                | 0.150          |
| <b>Drainage Density</b>        | -0.21                  | 0.620          | -0.37                | 0.300          |
| <b>Form Factor</b>             | 0.26                   | 0.540          | 0.32                 | 0.360          |
| <b>Mass Coef</b>               | 0.29                   | 0.490          | 0.71                 | 0.022          |
| <b>Slope</b>                   | 0.67                   | 0.070          | 0.87                 | 0.001          |
| <b>Torrentiality Coef</b>      | 0.35                   | 0.400          | -0.08                | 0.820          |



Appendix A 3 Scatter plot between peak flow and catchment parameters. Coloured points indicating the distribution of the data according to each cluster class. Linear regression adjusted to the data for each cluster class.

Appendix A 4 R and p values from the matrix correlation between parameters of the catchment and Cluster A and C.

| <b>Catchment<br/>Parameter</b> | <b>Peak Flow</b> |                |                  |                |
|--------------------------------|------------------|----------------|------------------|----------------|
|                                | <b>Cluster A</b> |                | <b>Cluster C</b> |                |
|                                | <b>r</b>         | <b>p-value</b> | <b>r</b>         | <b>p-value</b> |
| <b>Area</b>                    | 0.02             | 0.970          | -0.28            | 0.440          |
| <b>Average Width</b>           | -0.16            | 0.730          | -0.24            | 0.510          |
| <b>Compactness Index</b>       | 0.52             | 0.230          | -0.31            | 0.380          |
| <b>Drainage Density</b>        | -0.18            | 0.690          | -0.81            | 0.005          |
| <b>Form Factor</b>             | -0.69            | 0.093          | 0.15             | 0.670          |
| <b>Mass Coef</b>               | 0.29             | 0.530          | 0.34             | 0.340          |
| <b>Slope</b>                   | 0.70             | 0.079          | 0.08             | 0.005          |
| <b>Torrentiality Coef</b>      | -0.43            | 0.330          | -0.54            | 0.100          |

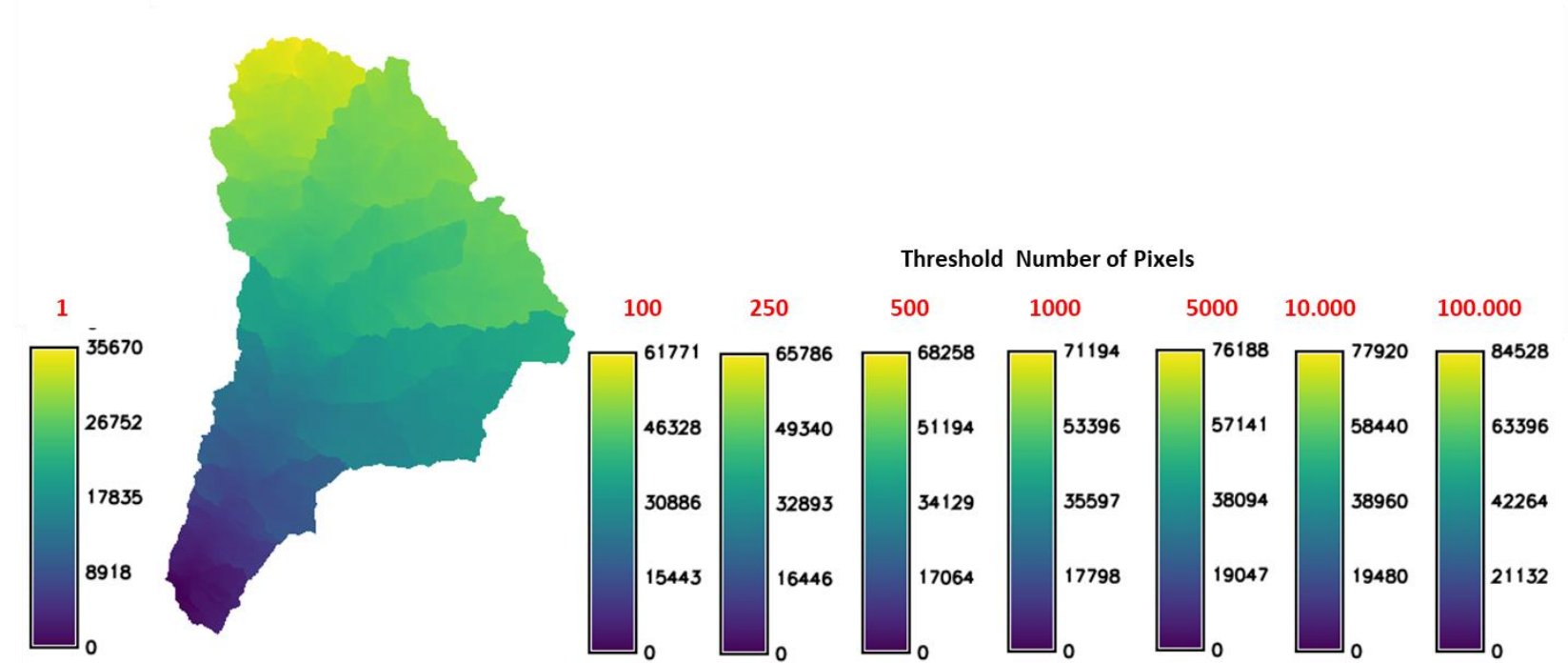


Appendix A 5 Scatter plot between peak flow and catchment parameters. Coloured points indicating the distribution of the data according to each hypsometric curve class. Linear regression adjusted to the data for each class.

Appendix A 6 R and p values from the matrix correlation between parameters of the catchment and Peak flow classified by hypsometric curve classes.

| <b>Catchment<br/>Parameter</b> | <b>Peak Flow</b>                     |                |                                       |                |
|--------------------------------|--------------------------------------|----------------|---------------------------------------|----------------|
|                                | <b>Hypsometric Curve -<br/>Young</b> |                | <b>Hypsometric Curve -<br/>Mature</b> |                |
|                                | <b>r</b>                             | <b>p-value</b> | <b>r</b>                              | <b>p-value</b> |
| <b>Area</b>                    | 0.08                                 | 0.800          | 0.44                                  | 0.380          |
| <b>Average Width</b>           | 0.13                                 | 0.690          | 0.50                                  | 0.310          |
| <b>Compactness Index</b>       | -0.60                                | 0.039          | -0.11                                 | 0.840          |
| <b>Drainage Density</b>        | -0.13                                | 0.700          | -0.75                                 | 0.086          |
| <b>Form Factor</b>             | 0.30                                 | 0.350          | 0.05                                  | 0.930          |
| <b>Mass Coef</b>               | -0.03                                | 0.920          | 0.45                                  | 0.370          |
| <b>Slope</b>                   | 0.63                                 | 0.028          | 0.87                                  | 0.025          |
| <b>Torrentiality Coef</b>      | 0.25                                 | 0.430          | -0.23                                 | 0.660          |

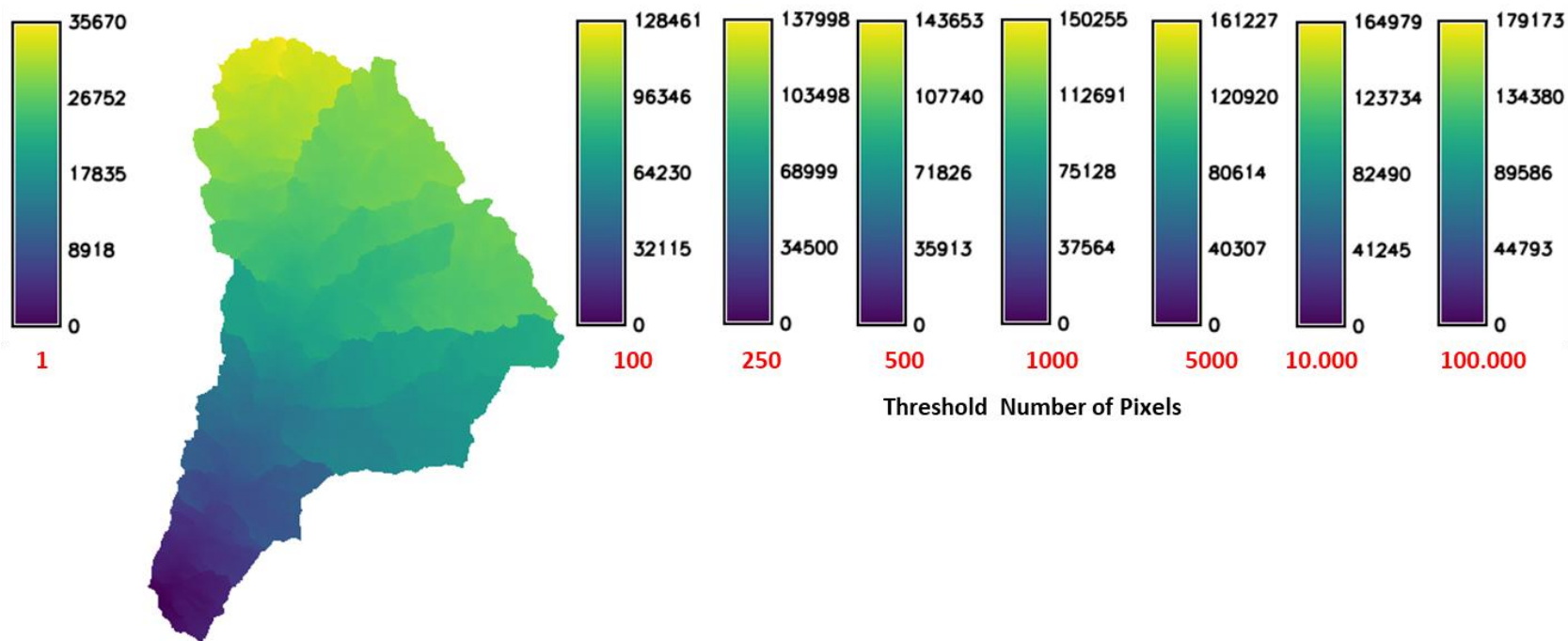
**APPENDIX B .**



Raster pixel resolution =12m  
Roughness = 0.01  
Specific Discharge [l/s/km\*\*2] = 16.660  
surface runoff: 16600.000000 l/s/km\*\*2 = 1.660000e-005 m/s = 59.760000 mm/h

Appendix B 1 Travel time sensitivity analysis varying the threshold number of pixels from 1 to 10000. Roughness values n = 0.01.





Raster pixel resolution =12m

Roughness = 0.035

Specific Discharge [ $\text{l/s/km}^2$ ] = 16.660

surface runoff:  $16600.000000 \text{ l/s/km}^2 = 1.660000\text{e-}005 \text{ m/s} = 59.760000 \text{ mm/h}$

Appendix B 2 Travel time sensitivity analysis varying the threshold number of pixels from 1 to 10000. Roughness value  $n = 0.035$ .

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