Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

DO TREES IN UK-RELEVANT RIVER CATCHMENTS INFLUENCE FLUVIAL FLOOD PEAKS?

A SYSTEMATIC REVIEW

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Executive Summary

The effect of trees on flooding is much debated. In the aftermath of widespread flooding in Cumbria during December 2015 much attention focussed on whether natural solutions, in particular tree planting in upstream catchments, can have a role in reducing flood risk. Despite multiple literature reviews investigating links between land use and river flows, the link between forests and river flooding remains conflicted. There is a need to provide a robust review of the available evidence to support future planning and decision making. A systematic review, producing an unbiased and transparent assessment that can be easily interrogated and reproduced, has been identified as the most effective way to contribute to the debate. This report presents the results of the initial literature search and qualitative data analysis.

This review sought to capture qualitative findings from peer-reviewed studies focussing on the impact of trees on river flooding. It specifically did not focus on the impacts of trees on intermediate processes (*e.g.* rainfall interception, groundwater recharge or overland flow). Whilst the role of these processes in determining hydrological response is recognised, it was agreed that inferred findings should not be included in the review as these do not necessarily translate to a substantive influence of river flooding. We also did not include the effect on river flooding of trees or woody debris within river channels.

The electronic reference database Web of Science was searched using a text string developed by the project team and advisory group in order to capture as much of the relevant literature as possible. Studies relevant to UK-catchments were selected on the basis of geographic location using the Köppen climate classification. Reference screening found 72 papers containing information likely to be of relevance to this review, and from these 71 case studies were analysed. Qualitative statements relating to the effect of trees on river flooding were extracted from each case study. Further information was extracted to understand whether the study was based on purely observational data or model output and whether the influence on flood peak was dependent on the size of flood event.

Considering all statements together, distinguishing only on the basis of increasing or decreasing cover, there is broad support for the conclusion that trees influence flood peaks. Increasing the amount of tree cover results in a decreasing flood peak, and decreasing the amount of tree cover results in an increase in the flood peak. However, if a distinction is made between studies based on observations and those based on model output the conclusion is less clear. The majority of statements supporting both the relationship between increasing tree cover and decreasing peak flows, and decreasing tree cover and increasing peak flows are based on model outputs.

If the observation-based statements are considered in isolation, the results of analysis are more mixed. There remains a majority of statements showing increasing cover to decrease flood peaks but notable numbers supporting the opposite effect or no influence, resulting in no overall significant difference. No clear difference was found between the number of observation-based statements indicating an increase in flood peak due to decreasing cover and those reporting no influence on flood peak, although none reported a decrease. Distinguishing further on the basis of flood

magnitude, all statements that distinguish between small and large flood events (defined qualitatively) indicate that the peak flows of small flood events are reduced by increasing tree cover. However the majority of statements from observed case studies report that the peak flows of large flood events are not influenced by the presence or absence of trees in the catchment. It is worth noting that in both cases the number of statements involved is small.

It has not been possible to explore the role of effect modifiers, which can be expected to exert a large influence on the studied relationships. In particular, it is known that factors such as the extent of forest cover change, the type of forest involved, the age of the forest and the nature of forestry management practices can act to modify the magnitude and even the direction of change to peak flows. This becomes more of an issue with observational studies since such factors are easier to control or be discounted by modelling.

These findings help to explain why there is continuing debate associated with this topic and how it is possible for strongly held yet differing views on the influence of trees on peak flows to exist. Greater consideration of the influence of effect modifiers in the reviewed studies should help to clarify the results, although important questions are likely to remain. This is especially the case regarding the effects of tree cover on large flood peaks and in large catchments, where there is a paucity of observed data to test and validate models.

Increasing the number of observational studies would help to address the gap but presents a number of significant challenges, including: accurately measuring changes to large peak flows; controlling for land use and management changes, as well as background shifts in weather; and not least, maintaining long-term funding for data collection to capture changes to infrequent, large peak flows. This report presents some initial thoughts on the requirements of future studies and identifies some areas for further research.

Contents

1 Introduction

Widespread flooding across Cumbria and other parts of northern Britain in December 2015, caused by record-breaking rainfall at the beginning of the month (Met Office, 2016), left over 5,000 homes inundated and 43,000 homes without power (BBC, 2015). Local businesses were also badly affected. Much of the subsequent media attention focussed on whether natural solutions can help reduce floods (*e.g.* Biggs, 2016, Lean, 2016, Webster, 2016), particularly whether afforestation of the upstream catchment could assist with flood management. However, the effect of trees on flood risk is much debated, reflecting the diversity of evidence and expert opinion. Multiple literature reviews looking at the impact of land use on river flows have been carried out (*e.g.* Bruijnzeel (2004), Bowling *et al.* (2000), Calder (2005), Eisenbies *et al.* (2007), O'Connell *et al.* (2004), van Dijk and Keenan (2007) and Dadson et al., (2017)) each with its own scope. However the link between forests and river flooding remains inconsistent. The requirement to provide clarity with respect to the evidence that links the presence of trees in a catchment to river flooding is becoming increasingly necessary, especially in regards to the catchment-based approach to flood risk management.

It is generally accepted that forests can influence rainfall-generated flooding through the mechanisms of interception, infiltration into the soils, and increasing available storage. Factors such as forest type, forest age, catchment size, and management regime are likely therefore to influence the hydrological response. However a number of complicating factors have prevented development of a unified position. First, climatic effects can be difficult to separate from those of terrain or land-use. Climate change and variability are important factors for example in the Meuse catchment, northwest Europe, climate change (driving a strong increase in annual and winter precipitation) has been found to surpass land use change as the dominant control on the frequency of high-flow events (Ward *et al.,* 2008). Secondly, there are many other catchment characteristics, such as pedology, geology, channel network density, geomorphology and antecedent conditions, plus their interactions, which influence flood generation.

Distinguishing the effect of these from the effect of trees, which may also differ in location to the expected benefit, is challenging. Consequently, comparisons between catchments are problematic, even when they are adjacent. Many statistical analyses have been undertaken to relate flood magnitude to characteristics of a catchment for example the Flood Studies Report (NERC, 1975) and Flood Estimation Handbook (IH, 1999), though these two studies did not consider forest cover. Where forest cover has been used, co-variance between predictor variables has been found. For example, in the Irish Flood Study (OPW, 2014), strong correlations were also noted between average annual rainfall, forest cover and altitude (because forestry has tended to be undertaken in wet, upland areas). Forest cover did not add any additional explanation of variations on flood peaks to that provided by rainfall and altitude. The final outputs of such work tend only to focus on significant relationships as these produce methods for river engineering design (thus excluding trials of other variables that were not significant) producing a publication bias.

The complexity inherent in the influences on river flooding makes the formation of a clear opinion difficult, and whilst there is pressure to reduce the flood risk to communities and investigate the potential for natural measures to contribute to this, the lack of a robust review is causing confusion. A systematic review of written evidence has been identified as the most effective way to contribute to the debate and is anticipated to provide both clarity on the existing evidence and help inform current and future decision making. A key benefit of the systematic review approach is that it can provide a mechanism for producing an unbiased and transparent assessment that can be easily interrogated, reproduced and updated.

The first step in achieving this overall aim is to capture as much of the relevant literature as possible and summarise the various findings, and that is what this report sets out to do.

2 Study Overview

2.1 Terminology – Papers, Case studies and Statements

This review distinguishes between the papers identified through the screening process (Section 3.4, **Table 3**), the case studies identified in each paper (Section 4, **Table 5**) and the qualitative statements presented in relation to each case study (Section 4.4, **Figures 3**, **4** and **5**). The numbers of papers, case studies and statements reported in the review can differ from each other. Definitions of each are provided below and it is important to bear these in mind when reading this report.

- **Paper**. This refers to an individual publication (in this case from the peer-reviewed literature) identified through searching online databases. Each paper can be identified by a reference and those included in the analysis of this review are listed in Appendix B.
- **Case study**. A single paper can contain information from more than one study each with different characteristics. For example, one paper may compare the results of one experiment in one location with the results of another experiment in another location. Each experiment is treated as separate case study.
- **Statements**. The statements are the pieces of information reported for each case study. An individual case study may make a single statement regarding the effect of trees on river floods, or may make multiple statements (e.g. effect X was observed under certain conditions whereas effect Y was observed under different conditions). It is these statements that form for the final numbers presented in this review.

2.2 Study aims and objectives

The overarching aim of this review was to assess the influence of trees on river floods in catchments that are in the UK or comparable climates to those in the UK. Trees can influence flood characteristics in a variety of ways, such as delaying the flood peak and extending the duration of high water level conditions. However, this review looks specifically at the influence of trees on peak flows, often measured as maximum discharge and measured in cubic metres of water per second (m^3/s). The primary question posed is ‘Do trees in UK-relevant river catchments influence fluvial flood peaks?’. It specifically did not focus on the impacts of trees on other hydrological processes (*e.g.* groundwater recharge or overland flow) or studies inferring impacts from tree-scale process based studies (e.g. interception or evapotranspiration measurements). This review focuses on studies where there is direct evidence of the relationship between the increasing or decreasing cover of trees on flood peaks downstream of the forested areas within a hydrological catchment.

The original intention of this study was to carry out full quantitative data extraction from all literature found to meet the review criteria. However, as the work proceeded it became clear that the initial scoping phase was uncovering more studies than expected. In addition to this, the project team carried out a trial data extraction exercise at an early stage in the process and this revealed the considerable complexity involved in confidently extracting data from papers in a form whereby quantitative comparisons could be made. This was largely due to the variety of metrics used in the quantification of trees and floods. As a result of both of these developments, each of which was uncertain at the project outset, it was agreed between the project team and the funder (CEH) that the expected scope of the review should be revised.

A systematic approach, as set out by the CEE (Collaboration for Environmental Evidence, 2013), was adopted and documented at all stages. Details of the references passing or failing the inclusion/exclusion criteria (Section 3.3) at each stage of the process have also been captured in a spreadsheet and electronic database. The electronic database is a key output of this study enabling future updates and analysis. The opportunity to undertake a meta-analysis and to investigate other features of floods (e.g. timing and duration) remains open for the future.

To achieve the study aim, this review set out to meet the following four objectives:

1. An extensive search, using search terms agreed by the advisory group, for all potentially relevant peer-reviewed literature available through the online reference database, Web of Science.
2. Assessment of all relevant literature following systematic screening according to criteria agreed by the advisory group. All literature identified as relevant has been stored in a database.
3. Extraction of contextual information and where presented qualitative statements regarding the influence of trees on flood peaks from each of the screened references.
4. Analysis of the qualitative statements (extracted in objective 3) and a summary of the overall review findings.

2.3 The scope of this review

This review:

- considered peer-reviewed literature on the assumption that the peer review process acts as a quality control across all studies.
- focused on the impact of trees on river flooding.
- looked specifically at river floods resulting from above average rainfall as opposed to groundwater or seawater flooding.
- captured qualitative study findings in a structured manner so that the addition of quantitative results in the future is straightforward.

This review did not:

- consider the impact of trees on intermediate processes (*e.g.* rainfall interception, groundwater recharge or overland flow).
- consider the effect of trees or woody debris occurring or placed within river channels and their role in flooding.
- carry out independent quality assessment of each study (beyond the peer-review process).

3 Methodology

3.1 Identifying the review question and search terms

The review question is central to the review process and determines the search terms that are subsequently used to identify relevant literature. The key elements of the question were structured using the Population, Intervention, Comparison and Outcome (PICO) framework (**Table** 1) as recommended by the CEE. An iterative process of refining the question and PICO structure was carried out to identify the optimum question going forward and several versions of the framework were trialled before the final version was agreed (see Appendix A for details).

The scope of the literature search was defined by the question ‘Do trees in UK-relevant river catchments influence fluvial flood peaks’ and the searches and screening were carried-out using all the search-terms listed in Table 1.

Due to time constraints, data extraction and analysis were limited to information reported on the flood peak, and this report presents results relating to that aspect of flood characteristics.

The search-terms were combined using the Boolean operators ‘AND’ and ‘OR’ into the text string below that was used to search the topic (which looks for text matches in either the title, abstract or keywords) of references in the Web of Science database:

((Landscape OR river OR catchment OR basin OR *stream* OR channel OR watershed) AND (Planting OR *forest* OR tree* OR wood* OR logging OR "land use" OR regenerat* OR fell* OR timber OR plantation OR clear-cut* OR scrub OR coppic* OR “land cover”) AND (*flow* OR level OR flood OR discharge OR runoff OR yield OR volume OR duration OR hydrolog* OR inundat*))

The search was limited to studies published in English, and no restriction was imposed on the basis of age of study.

3.2 Data sources

This review has sought to capture as much of the relevant literature as possible, whilst acknowledging that there is a limit to the resources available to do this. Effort was focussed on identifying relevant references in Web of Science, regarded as one of the most comprehensive electronic reference databases. Our search was constrained to English language papers. A key assumption going through this process was that the majority of relevant peer-reviewed literature is present in Web of Science and will therefore be picked up by our search terms. The advisory board have also submitted relevant literature, which has been subject to the same set of inclusion/exclusion criteria.

It should be noted that whilst every effort has been made to ensure this review captures all the relevant literature, some studies may have been missed and others may be published in the future. For instance an investigation of Natural Flood Management in Cumbria has recently been published by JBA Consulting, but this was not in time for inclusion in this review. We therefore propose that the database we have constructed and used for our analysis can be updated as additional evidence becomes available. We are also concerned that there may be a bias in the literature favouring publication of positive results and that those studies with null results may not be deemed noteworthy and therefore fail to be published.

Table 1 *Elements of the systematic review in the PICO structure. The * character denotes a wildcard so that for example *forest* will pick up all occurrences of the word forest as well as afforestation, deforestation, forestry etc.*

Population	**I**ntervention	**C**omparison	**O**utcome
UK-relevant river catchments	Trees (afforestation, deforestation, management)	Before and after studies, Paired catchment studies	Fluvial flood characteristics
landscape river catchment basin *stream* channel watershed	planting *forest* tree* wood* logging "land use" regenerat* fell* timber plantation clear-cut* scrub coppic* “land cover”	Comparison terms were not used to constrain the literature search, but were considered during screening and data extraction.	*flow* level flood discharge runoff yield volume duration hydrolog* inundat*

3.3 Study inclusion/exclusion criteria

All literature, regardless of source, was subject to the agreed inclusion/exclusion criteria, to determine whether or not it met the selection criteria for the review. For a study to have been included in this review, it needed to have met the following criteria:

Data: Must be based upon quantitative data, even though the statements captured were qualitative i.e. studies based upon a survey of stakeholder opinion cannot be included.

Population*:* UK-relevant river catchments. The definition of ‘UK-relevant’ is countries with the same Köppen climate classification (Kottek et al., 2006) as the UK

(Cfb and Cfc). The project team and advisory group have discussed a possible additional geographic constraint based on proximity to the UK for reasons of differences in tree species and forest management regime, however rather than introducing this as an inclusion/exclusion criteria the location of each study will be extracted and spatial analysis can be carried out later in the process. UK-relevant areas are shown in **Figure 1** and are listed in **Table 2**.

Exposure/Intervention: Trees – Distinction was made between trees and other types of vegetation, however all trees in all growth stages (including natural regeneration or succession as well as planned planting or removal) will be considered.

Comparator: Before and after studies, Paired catchment studies.

Outcomes: Fluvial flood characteristics – *e.g.* peak flow, time to peak.

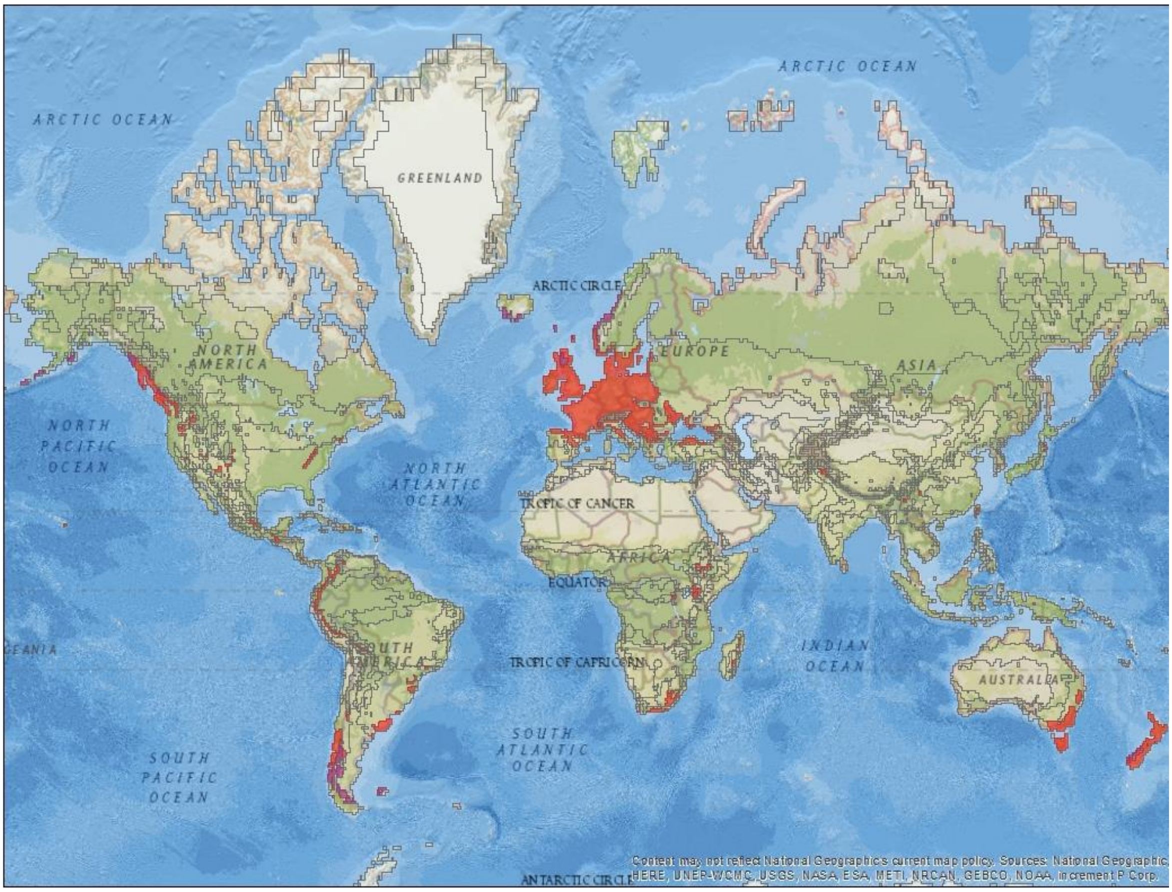

Figure 1 Regions of the world with the same Köppen classification as the UK (areas shaded red). Sources. Basemap: National Geographic, Esri, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp. Köppen climate layer: Kottek, *et al.* 2006: Rubel and Kottek, 2010.

Table 2 *UK-relevant areas and their inclusion in the systematic review.*

Included country	**Included area/region**[*1]	**Possible**[*2]
Belgium	France (except Mediterranean coast)	Areas of Italy
Denmark	Northern Spain	Areas of North America
England	Northern Switzerland	Areas of South America
Germany	South Eastern Australia and Tasmania	Bosnia and Herzegovina
Hungary	Southern Sweden	Croatia
Luxembourg	Southern/Western Norway	Eastern Austria
New Zealand	Western and Central Czech Republic	Eastern Romania
Northern Ireland		Macedonia
Poland		Serbia
Republic of Ireland		Slovenia
Scotland		South Eastern South Africa
The Netherlands		South Western Chile
Wales		Western Canada
		Western Latvia
		Western Lithuania
[*1]include and refine manually		
[*2]include only if a prominent study becomes apparent		

3.4 Screening process

Geographical and inter-disciplinary differences in the terminology used in environmental sciences cause difficulties when searching for relevant information and result in very large numbers of references being returned by database searches. The initial Web of Science search identified 19,337 potentially relevant references (**Table 3**). To maintain both the breadth of search and feasibility of delivery of this review, a computer-based automated method of filtering articles was developed. The process carried out in MS Excel mimics that which would be carried out by the reviewer and consists of the following steps:

1. **Country Screen** – Titles were screened for the list of countries outside of the UK-relevant area AND screened against the list of countries within the UK-relevant area. Where a reference title or abstract included a non-UK-relevant area AND did NOT include a UK-relevant area, that reference was excluded. All other references were retained.
2. **Warning word Screen** – Titles were screened for warning words that identified if a study focussed solely on non-flood issues such as nutrients, carbon or ecology rather than the physical hydrological aspects of river floods.

All those references that contained a warning word AND NOT a flood word were identified. These references were discarded.

3. **Keyword Screen** – Titles were screened for the presence of each of the key search terms. In this case they were split into 3 groups (tree words, river words, flood words). Those references that contained any word from any one of the groups were identified. These references were retained except in the case that a title contains only a river word, and not a tree word or flood word. Trials indicated that references containing only a river word in the title were not relevant to this review. These references were discarded. In addition, references whose titles do not contain any keywords were discarded.

The automatic screening process was conservative – i.e. only removing references where conditions were met. If there was uncertainty then the reference was included for manual checking at a later stage.

Table 3 *Numbers of papers identified during the search and screening process*

Stage	**Number of papers**	
Web of Science search	19337	
Automated screening	5198	
Title and Abstract Screen	462 + 37 (see note)	* An additional 37 papers were included at this stage, identified during previous work by Andrew House.
Full Review	72	

The database searches and subsequent automatic filtering returned 5198 results. The principal reviewer checked the titles of these results and excluded those which did not match the inclusion criteria. Those that passed this stage of the screening went on for full text screening, which was carried out in parallel by 3 reviewers. Where the full text was found to meet the inclusion criteria, qualitative data extraction was carried out and the results captured in a database.

3.5 Qualitative data extraction

Qualitative data were extracted from those papers that passed the title and abstract screens. The categories for this process were identified by the project team during trial data extraction which was carried out on a subset of 6 papers. During this stage, information about the country location, type of study, comparison, basis of result and influence on peak flow were extracted into a database. To make subsequent analysis easier, the data extracted were constrained to pre-defined levels (**Table 4**).

The project team and advisory group recognised the potential for greater confidence to be associated with observation-based studies rather than those based on model outputs. Models can be used for extrapolating beyond the data available and can therefore be useful for giving an indication as to what a response might be to a scenario outside of the observed dataset. However the model setup and parameters used, which are typically informed by process understanding, comparable studies or expert judgement, strongly influence the output from the model. Confidence in the model output, especially when outside of the observed data range with which the model is calibrated, can therefore be a subject for debate. To enable a distinction to be made between observed and modelled studies during analysis, data from all qualifying studies, whether based on either observations and/or model output, were extracted and the basis for result was recorded using an appropriate category (e.g. observed/modelled/combination).

Table 4 *Information extracted from each case study*

	Country	**Study Type**	**Experimental Design**	**Comparison**	**Basis of result**	**Influence on flood**
Levels	Various	Single site	Single catchment	Increasing cover	Model – process	Increase
		Multiple site	Paired catchment	Decreasing cover	Model – statistical	Decrease
					Combined model and observation	No influence
					Observation	Inconclusive
						Not reported

In the subsequent analysis, studies showing either no influence or an inconclusive result were grouped together as having no influence. Similarly, process and statistical models were not differentiated but grouped together as simply ‘model’. If the paper reported results that were a combination of modelled and observed data, and having read the paper it was not possible to clearly distinguish which the results were based on, then these studies were classed as a combination of model and observation and were discounted at this stage. With further work, it may be possible to disentangle the results and conclusions in these studies according to the observed and modelled portions of the work (See Appendix C for list of papers affected). It may be possible to include them at a later stage following more detailed analysis. The case studies were finally split into two groups: those in which the comparison involved increasing the amount of tree cover (e.g. afforestation) and those in which the comparison involved decreasing the amount of tree cover (e.g. logging or forest fire).

3.6 Data analysis

Some of the references selected were found to present more than one result and corresponding conclusion, so rather than summarise results according to the number of papers, we identified each result as a separate case study. Therefore one paper could include more than one case study.

Case studies were separated into two groups according to whether they reported the effects of increasing tree cover (e.g. afforestation) or decreasing tree cover (e.g. deforestation). The qualitative statements associated with each case study were then extracted. The statements (i.e. the findings in relation to the influence on fluvial flood peak) were categorised according to their reported effect on flood peak as either increasing, decreasing or having no influence on flood peak. Where a single statement was made about the influence this was captured as a general effect, however where the statement differentiated between the effect on large and small floods, these were captured separately.

All subsequent analysis was carried out on the statements, using the vote account method to assess the numbers of statements reporting a particular influence on flood peak. While we recognise the limitations of a vote account method (Stewart, 2010), it is the most suitable for the data collected in this review.

Analysis was then carried out in three stages using the following groupings of the results:

1. All data split into two groups – increasing cover and decreasing cover
2. As above with sub-grouping according to observed or modelled results
3. As above with additional sub-grouping according to the magnitude of flood event

For the purpose of this review, flood event magnitude was categorised according to the qualitative statements identified. We do not therefore present a quantifiable definition of what is meant by a small or large flood event. We recognise that development and inclusion of a suitable method for quantifying event size will be an important activity in subsequent work.

We used the chi-square test of independence to determine whether or not peak flow was affected by the change in tree cover. Significant effects were inferred at the 0.05 level.

4 Results and analysis

4.1 Number of papers and case studies identified

72 papers were identified during the search and screening process as meeting the inclusion criteria and qualitative data extraction was carried out on each (**Table 5**). This was a greater number of papers than initially expected and this result illustrates the breadth of the literature search.

One of these papers, which presented results based on sediment as a proxy for flood flows, was discounted due to uncertainty over how the results could be considered alongside traditional flow metrics. From the 71 papers remaining, 80 case studies were identified, of which 9 had results based on a combination of observation and model. These were not included for the reason presented in Section 3.5. All papers that contributed to the results and analysis are listed in Appendix B.

***Table 5** Numbers of papers identified at each stage of the review process*

Stage	**Number**	
Full Review	72	* 1 study based on sediment as a proxy for flow was removed due to uncertainty over how it could be included alongside other studies.
Number of papers going forward	71	
Number of case studies	80	* The number of case studies is greater than the number of papers because several papers reported more than one case study result.
Number of case studies going forward for analysis	71	* 9 case studies based on a combination of observation and model output were excluded from the final analysis (see Section 3.5)

4.2 Geographical distribution of case studies

Case studies from 14 countries, plus a number of multiple country studies (9 of 71), are included in the analysis (**Figure 2**). The majority of case studies are from European countries (51 of 71) with a further 11 from Australia, New Zealand and Canada.

In the analysis carried out, no further distinction is made on the basis of location. All case studies were considered equal regardless of their country of origin.

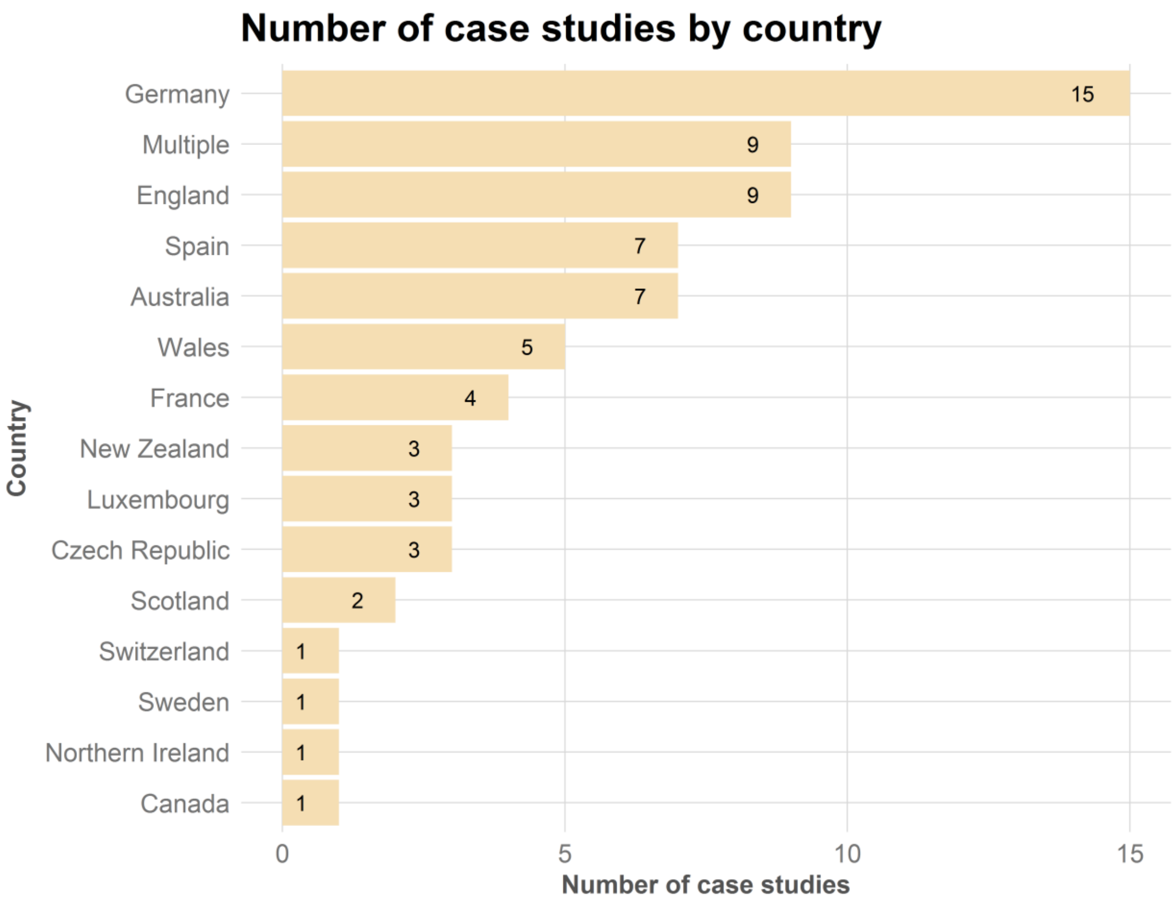

***Figure 2** Case studies according to country location*

4.3 Number of case studies according to qualitative criteria

Contextual information about each case study was collected (**Table 6**). Study type, either single or multiple site, was used to capture whether the case study dealt with one geographic region (e.g. one catchment or two neighbouring catchments) or compared results from catchments in different regions (e.g. the response of a catchment in France compared to the response of a catchment in Germany). The majority of case studies report results for a single site (57 of 71) rather than multiple sites (14 of 71) (**Table 6**).

A distinction was also made between case studies based on a single catchment and those using a paired catchment methodology. Paired catchment studies, in which one catchment acts as a control whilst the other is manipulated, are often considered superior to single catchment studies but are more expensive and potentially difficult to deliver due to issues around identifying two catchments with similar conditions and duplication of monitoring infrastructure. Single catchment studies typically look for the hydrological response of a catchment over time as a manipulation is carried out and relate this to driving mechanisms (e.g. rainfall and land cover). The majority (56 of 71) of case studies considered were carried out on single catchments. 15 case studies presented results from paired catchment studies.

A greater number of case studies related to increasing tree cover (45 of 71) rather than for decreasing cover (26 of 71). The number of results based on observational and model studies was approximately equal (34 observation studies and 37 model studies).

Table 6 *Summary of case studies according to qualitative criteria*

	Level	**Number of case studies**
Study Type	Single Site	57
	Multiple Site	14
Experimental Design	Single Catchment	56
	Paired Catchment	15
Comparison	Increasing cover	45
	Decreasing cover	26
Basis of results	Model	37
	Observation	34

In addition to instances where a single paper presented multiple case studies, in some cases, single case studies presented multiple statements such as a certain effect on a small flood and another effect on a large flood. These were captured as discrete statements (85 in total) and it is these statements that are presented in the following analysis.

4.4 Analysis of Statements

As described in Section 2.1 the main analyses carried out in this review consider the number of statements regarding the influence of trees on river floods. The results of those analyses are presented in the following sections.

4.4.1 Effect of trees on flood peak: Combined Results

Considering all statements together, distinguishing only on the basis of increasing or decreasing tree cover, there is broad support for the conclusion that trees influence flood peaks. Increasing the amount of tree cover results in a decreasing flood peak, and decreasing the amount of tree cover results in an increase in the flood peak (**Figure 3**).

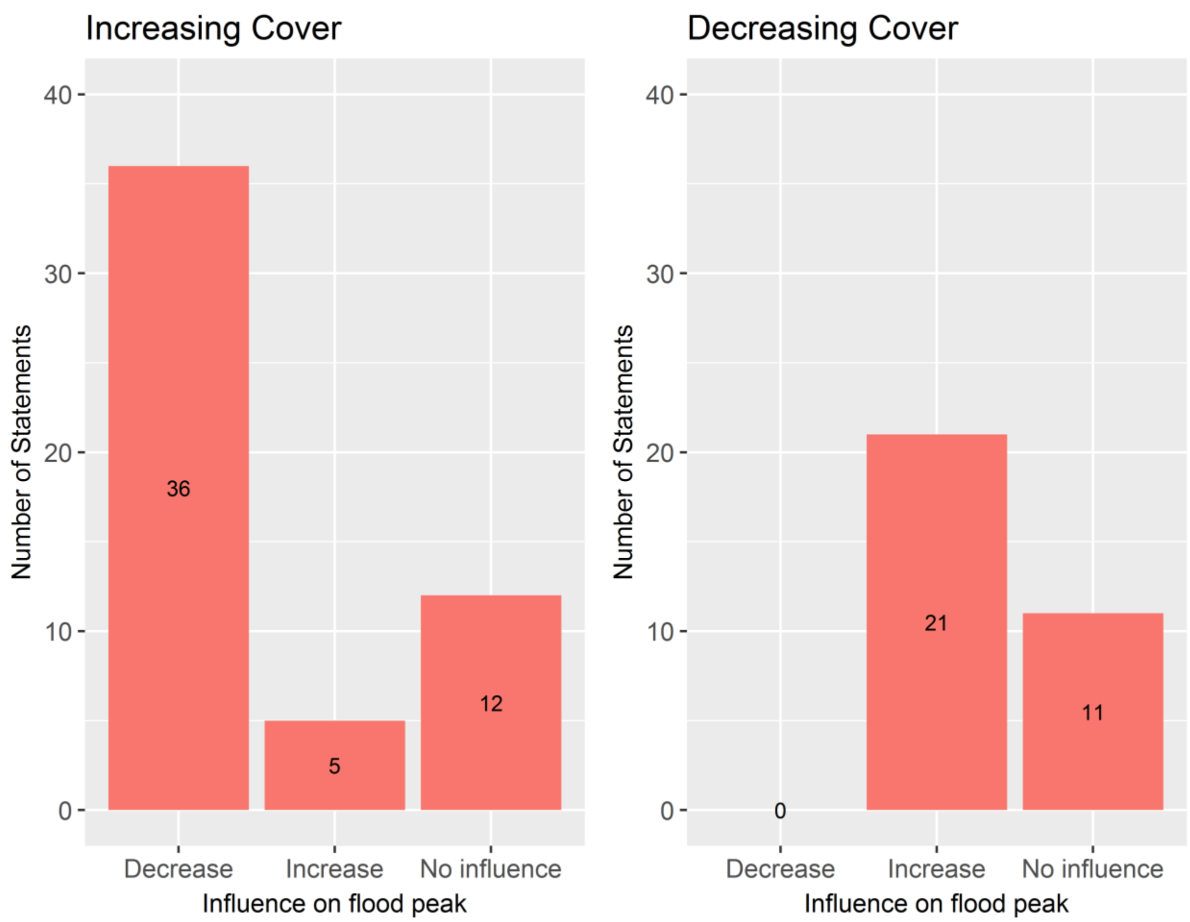

Figure 3 *Results of combined analysis of all statements, distinguishing solely on the basis of increasing or decreasing tree cover.*

The effect of increasing tree cover ($\chi 2$ =27.63, df= 2, p<0.051) is significant, in particular due to the large number of statements reporting a decrease in flood peak. The effect of decreasing cover ($\chi 2$= 29.85, df= 2, p<0.051) is significant, primarily because of large numbers of statements reporting either increasing peak flows or no influence on peak flows and the absence of any statements reporting a decrease in peak flows.

4.4.2 Effect of trees on flood peak: Observed versus modelled results

With a distinction between observational and modelled results, it is apparent that the conclusion is less clear (**Figure 4**). The majority of statements supporting both the relationship between increasing tree cover and decreasing peak flows, and decreasing tree cover and increasing peak flows are based on model outputs.

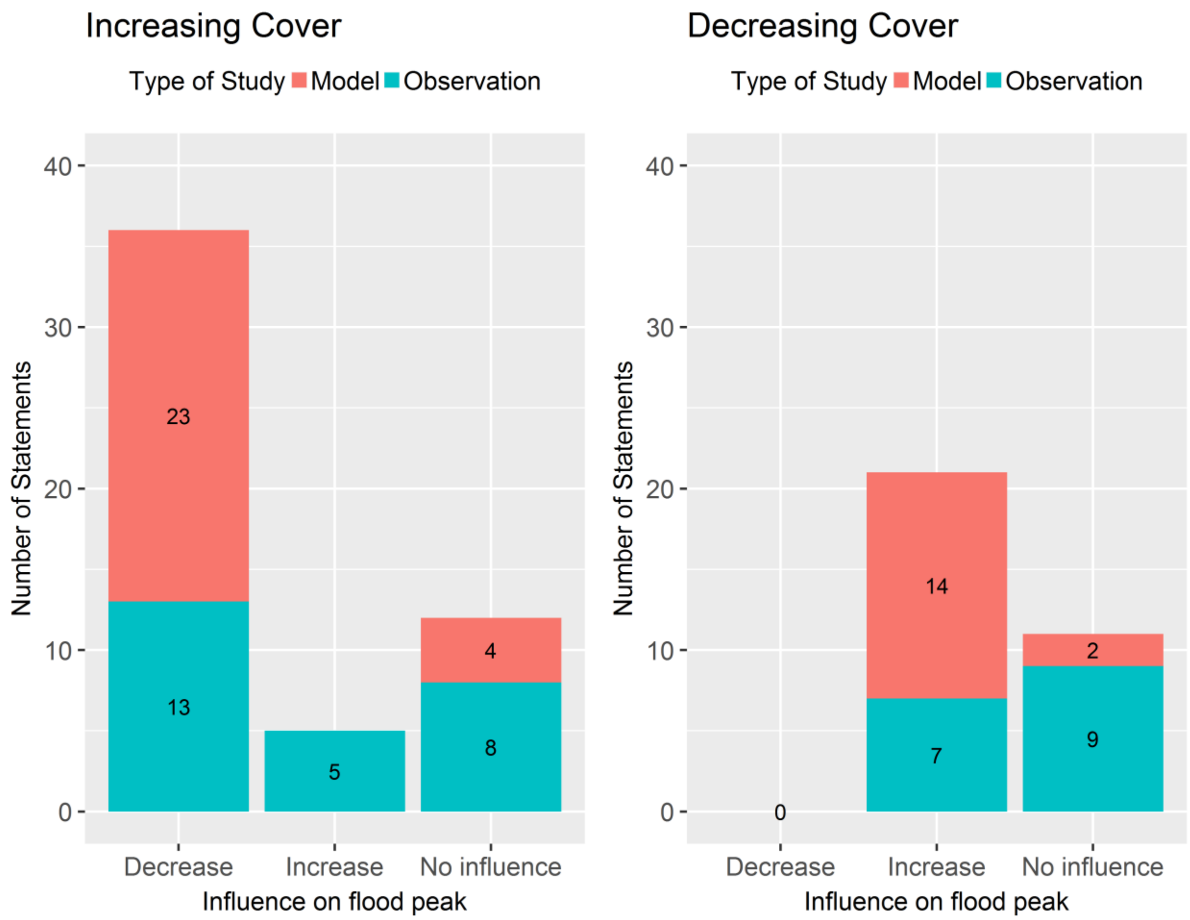

***Figure 4** Results of combined analysis of all statements, distinguishing both on the basis of tree cover and basis of result (type of study).*

If the observational results are considered in isolation, the results of analysis indicate that the relationship between increasing tree cover and flow ($\chi 2 = 3.75$, df= 2, $p<0.05$) is not significant and the effect of increasing cover was randomly distributed across the peak flow categories. For decreasing tree cover ($\chi 2 = 8.43$, df= 2, $p>0.05$), there is a significant difference between categories of influence on flood peak, arising largely as a result of the lack of recorded statements for peak flow decrease. However the number of observation-based statements reporting a flow increase due to decreasing cover was similar to the number reporting no influence, and it is not possible to reach a clear conclusion on this basis. Note that the majority of statements reporting an increase in flood peak as a result of increasing cover attribute this to pre-afforestation drainage[1].

4.4.3 Effect of trees on flood peak: Observational versus modelled results for different flood magnitudes

A final set of analyses was carried out with an additional distinction of flood magnitude (**Figure 5**). This was not possible for all case studies as in each case (increasing and decreasing flow) the majority of case studies reported a single (not distinguishing between large and small events) qualitative statement on the effect of trees on peak flows. Where a case study didn't distinguish on the basis of event magnitude, a single statement was recorded as 'General'. Where a study reported flood magnitude, it was typically described in terms of either a small or large event. In this situation, a single case study would produce two statements, one relating to the effect on small events and the other relating to the effect on large events. Our analysis uses the same categories to distinguish between floods of different magnitude.

Considering floods categorised as 'General', the results are similar to those presented in Section 4.6 in that the dominant influence of model results is apparent. If observed and modelled studies are considered together then the effects on general flood events supports the conclusion that increasing tree cover reduces flood peaks, and decreasing tree cover increases flood peaks.

Still considering observed and modelled studies together, all statements relating to the effects of increasing cover on small events report a decrease in flood peak, whilst for large events the majority of statements indicate no influence with a smaller number reporting a decrease. The results for decreasing cover are similar in that the majority of statements relating to small events report a increase in flood peak, whereas for large events the majority of statements indicate no influence.

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[1]This additional note was included at the special request of the advisory group, as the result of increasing tree cover resulting in an increase in river flooding was felt to have the potential to be interpreted without the necessary context. It is acknowledged that subsequent work is required to account for the effect of pre-afforestation drainage and many other potential effect modifiers across all the studies reported in this review.

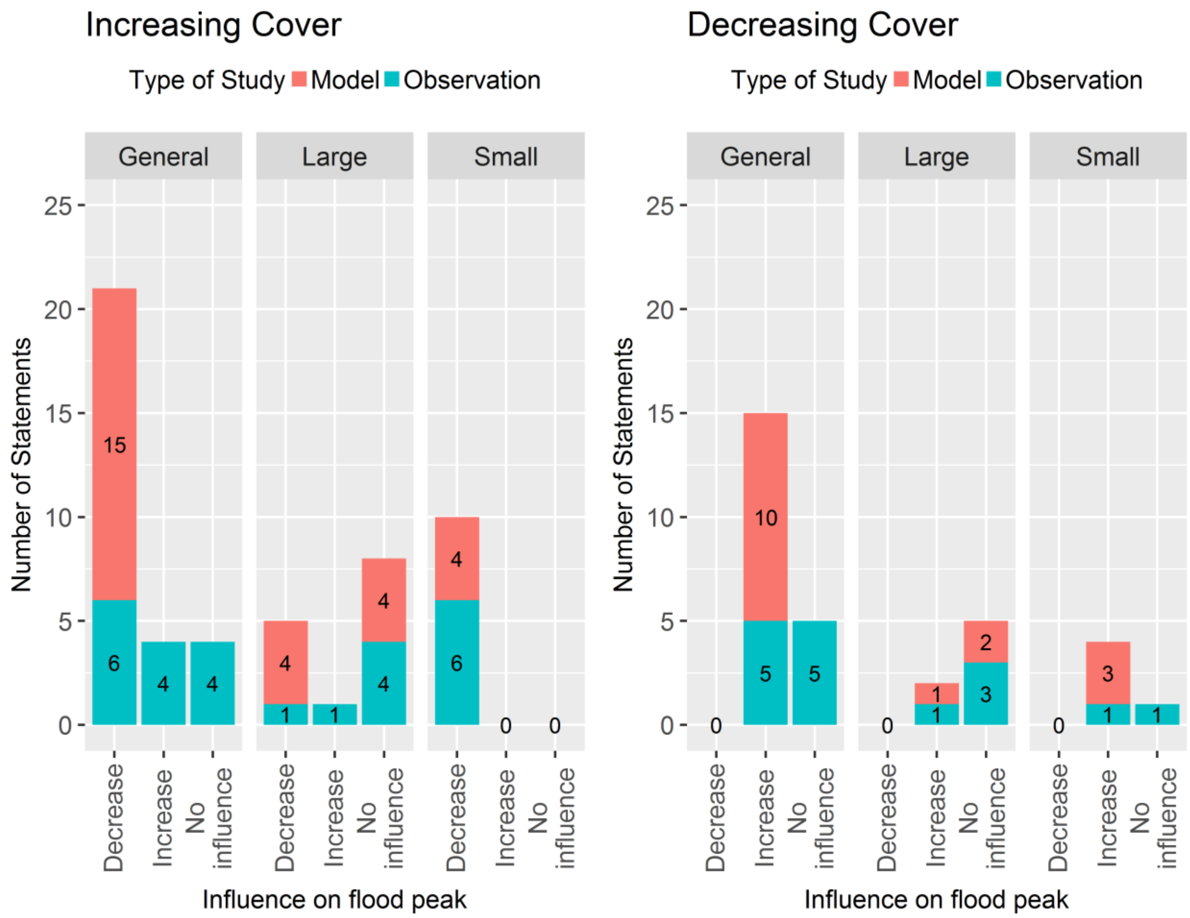

Figure 5 *Results of combined analysis of all statements, distinguishing on the basis of tree cover, basis of result (type of study) and flood magnitude.*

However, if observation-based statements are considered without modeled studies then the evidence of the influence of trees on flood peaks is less conclusive. Distinguishing further on the basis of flood magnitude, all statements that distinguish between small and large flood events (defined qualitatively) indicate that the peak flows of small flood events are reduced by increasing tree cover. However the majority of statements from observed case studies report that the peak flows of large flood events are not influenced by the presence or absence of trees in the catchment. It is worth noting that in both cases the number of statements involved is small.

5 Summary and concluding remarks

5.1 Evidence summary

This review has carried out a search of peer-reviewed literature to identify any published studies of the effects of trees on river flooding. The search criteria identified those studies with similar climatic characteristics as UK catchments, but discounted those that did not specifically report the impact of decreasing or increasing cover on river floods, or that focused on the impacts of trees on other hydrological processes or inferred impacts from tree-scale process based studies. Overall 71 papers covering 71 valid separate case-study sites, were identified, with the majority of case study sites being located in Europe (51), and 17 of these were in the UK. The review did include both model-based and observational studies, and found approximately equal numbers of case studies based on observed (34) and modelled (37) results. Study type was mainly single site (57) and single catchment (56), and the majority of study's investigated the effect of increasing cover (45).

5.2 Results synthesis

Analysis of the overall results reported in the literature reviewed indicates that of the case studies assessing increasing tree cover (45) the majority of statements indicate a significant reduction in fluvial flood peaks (36), compared to a lesser number (12) reporting no influence, and a much lesser number (5) reporting an increase. Of those case studies assessing a decrease in cover (32), no statements evidenced a decrease in flood peaks, while the significant majority (21) found an increase in fluvial floods compared to a lesser number (11) finding no influence.

Additional analysis sought to distinguish between results from observed and modelling studies and found the overall pattern was less clear. The majority of statements supporting both the relationship between increasing tree cover and decreasing peak flows (23 of 36), and decreasing tree cover and increasing peak flows (14 of 21) are based on model outputs. If observational results are considered in isolation the majority of statements (13) found increasing tree cover to decrease flood peaks but notable numbers found the opposite effect (5) or no influence (8), resulting in no overall significant difference. No clear difference was found between the number of observation-based statements indicating an increase in flood peak due to decreasing cover (7) and those reporting no influence on flood peak (9), although none reported a decrease.

Further distinction was made between the size of flood peak, however it was not possible to classify results across all case studies as results were not reported in a suitable form. Of those investigating increasing cover (45) 24 provided some evidence on the size of flood. For large floods the results were not conclusive, with the majority of statements (8; 4 observation, 4 model) indicating no influence compared to those reporting a decrease (5), which were primarily from model studies (4). For small floods the results were much more consistent, with all 10 statements indicating a decrease. Of those studies investigating decreasing cover (32) only 12 provided information on which we could assess flood size. The majority of statements (5 of 7) indicated no influence on large floods, and an increase (4 of 5) in small floods.

These results suggest that while overall the generally accepted relationship between increasing cover and decrease in floods, or decreasing cover and increase in floods is well represented in the overall literature base, this relationship is influenced by both i) the type of study used and ii) the size of flood. In the first case if only observed studies are considered, the evidence that increasing tree cover reduces floods is less conclusive. Models by contrast, only show increasing cover to result in a decrease or no influence on floods. In the second case, we find that the evidence is uncertain for the impact of increasing cover on large floods, but consistent across study types for showing increasing cover reduces small floods. This leads to a number of statements that can be based on the evidence considered that can be used to answer the primary question:

- Overall the evidence suggests increasing tree cover decreases flood peaks and that decreasing cover increases flood peaks
- Further distinction between observed and model based studies and comparative results between the two types is less clear. Importantly, given the main summary, only modelled results were found to provide significant evidence that increasing cover reduces food peaks.
- The relative impacts of whether change in cover has variable impacts on the size of flood considered is difficult to quantify and robustly consider given the lack of suitable information reported in the literature, but there is consistent and strong evidence that increasing cover reduces small floods.

These findings help to explain why there is so much debate associated with this topic and how it is possible for strongly held yet differing views on the influence of trees on peak flows to exist. In developing this review, the advisory group supported making a distinction between observed and modelled studies, and size of flood, and these results clearly demonstrate that different conclusions can be reached depending upon whether or not model results are included in analysis alongside observations, and what size of flood is considered.

5.3 Discussion on results

Here we explore further the three main areas of discussion that came about when considering the review results with the advisory team. These three areas reflect key areas of uncertainty and differences in individual scope, but all were areas that were agreed upon as being important to consider the implications and relevance of this review going forward.

5.3.1 Effect modifiers

This was perhaps the most discussed topic, as it was clear to all concerned that there are a wide range of effect modifiers beyond simply increasing or decreasing cover, changes to the landscape structure and functioning that affect the resultant hydrology and impact on flood peaks. It was also an area that could not be systematically assessed due to the lack of consistent reporting of such factors within the literature. It has thus not been possible to explore the role of effect modifiers, which can be expected to exert a large influence on the studied relationships, but could not be systematically assessed here. It is likely, for example, that observational studies finding increasing cover to increase peak flows could be attributed to the specific effect of pre-planting forest drainage. It is also possible that studies reporting no influence of trees on flood peaks could result from a low level of change in tree cover, a very young forest, or the opposing effects of simultaneous phases of forest development within a catchment, such as forest growth and harvesting. Likewise, differences in underlying soils, geology, weather and physiographic factors will affect the hydrological response to changes in tree cover, and modifiers such as these must be given due consideration.

The fact remains that the evidence is simply not suitable to provide a systematic appraisal of effect modifiers without attempting to provide some form of relative confidence framework whereby both the robustness of method and quality of reporting is assessed, and results compared in an objective way. This would involve a more detailed systematic review and significant effort to develop objective, systematic and defensible criteria. A more workable approach going forward would be focused upon making a systematic and considered list of these factors, and using this list to set out more systematic reporting requirements for studies into the effects of changing tree cover on hydrology.

5.3.2 Model vs Observed

The review has clearly identified differences in the results reported in observation and modelling-based studies and that the reported results between the two types of study were less consistent. We have not attempted to use rigorous systematic review techniques to objectively apply some form of quality control or scoring, whereby methods could be comparatively assessed, and do not thus attempt to comment on what method is best or most accurate. Each method has its own cost and value, with observations providing the data required to parameterise and calibrate models but being very costly and limited in time, while models provide the opportunity to analyse extreme flood events that are not likely to be captured in limited monitoring programmes but which one can never truly validate, as no observations exist. Additionally this would also raise the question about which model is most suitable. While such a discussion could be raised in the area of water resources where there are numerous industry applied models based on extensive development and calibration to observations, the limited data on flood flows from forested areas has certainly led to a comparative lack of certainty over whether there are suitably calibrated models for such applications. This is an area for further discussion among hydrological modellers. What is clear is that there is a need for more observations to better calibrate models and to inform the development of models that better reflect the range of processes and effect modifiers involved (e.g. forest drainage, compaction) that become increasingly difficult to focus on in real-world monitoring and which might never be specifically monitored during extreme events.

Possible reasons for the difference in results between observational studies and modelling studies might include:

- Hypothesis-led monitoring (e.g. Trees have an impact on flows) sets up experiments to isolate variables of interest (trees and river flows) from a variety of other influences (e.g. variability in rainfall, urban development, farming practices) and test their relationship through measurements. For example, to examine the effect of trees on floods, experiments involving long term monitoring allow us to examine statistics relating to peak river flows before and after trees are added/removed. If this is not possible, peak river flow statistics from paired catchments (ideally similar catchments but with different levels of tree cover) might be compared. Note that in both cases, for robust statistics comparing peak river flows with- and without-trees, several years of monitoring may be required. For higher flood peaks with a return period of (say) 30 years, at least 30 years of monitoring is preferable. During that period, the experimental design would require no other changes be made to land-cover or other catchment properties (in practice this is hard to enforce). An added difficulty is that a tree cover is not static but grows through time and is subject to phased management interventions such as thinning, felling and re-design.
- Modelling studies can also set up “virtual-experiments” to test the effect of changing one model variable (e.g. the presence of trees) on downstream river flows. Such modelling experiments can relatively easily provide multi-year simulations and thus provide the “robust” statistics required to test the effect of tree cover on extreme flood events. However, models are created by model developers who are required to numerically reproduce the “real world” effect of (say) tree-cover in their “model world” representations of evaporation, runoff, infiltration or other hydrological variables. While models draw on robust “real world” data from process studies at the plot/site level, model developers have to upscale tree effects and interactions to catchments and landscapes based on best evidence/understanding available at the time, which becomes increasingly complex and difficult with increasing catchment size. For example, if a model developer designs a hydrological model in which evaporation is 10% higher in areas of tree cover, then it follows that soil-

moisture and flow downstream will also be lower (because water is evaporated from the land to the atmosphere, and in most hydrological models, will then be thought of as “lost” from the earth’s surface). However, this result only shows the effect of trees in the “model world”, it does not prove that the presence of trees leads to a reduction in river flows in the “real world”.

5.3.3 Application of Systematic Review methods

Finally we must make some comment on the very application of systematic review methods and the overall comprehension of what such methods infer. Through the process of conducting this review it has become clear that the lack of consistent reporting on details such as effect modifiers or size of flood has severely limited its scope. Thus the review has focused in upon a few key areas of comparison in order to objectively assess the evidence base and provide some overall synthesis that allows the primary question to be addressed qualitatively. The difficulties in synthesising information from disparate studies in a systematic review is not unique to this study, and is a considerable problem in the area of environmental sciences due to a lack of overall guidance or agreement on methods and reporting of scientific research. Additionally there are also different views on what such a review should look like and how it can be reported on, that need to be voiced and reconciled. Central to this is the need to consider that only the evidence reviewed and reported in the review can be objectively discussed, and that any discussion to evidence or opinion outside of the evidence base assessed, even where relatively accepted, is inference. This objectivity and open discussion is both the strength of such a review as it provides the objective form on which to base further analysis or set research objectives, but can also be its weakness when the available literature is either limited or difficult to synthesise and interpret and the overall focus is not fully understood. Thus any interpretation of results in relation to wider literature or policy, while important, must be considered inference and outside the primary scope and question of the review as it is not based on the evidence in the review.

5.4 Knowledge gaps and recommendations for further research

The process of conducting a systematic review objectively reveals the strengths and weaknesses in the evidence base in providing suitable and high quality research to answer a focused question. The difficulties identified in retrieving and synthesising evidence, while a hindrance to the review process, in fact provide an objective and detailed means of defining future research requirements and defining the types of methods and reporting that should be undertaken to best meet the research need and provide robust comparable evidence. From this review we have identified a number of knowledge gaps and set out a number of recommendations for future research that, if followed, would better facilitate such a review in the future and best answer the question at hand:

- A priority for further synthesis is to extract the contextual information (e.g. tree type, amount of cover, age, forest management, antecedent conditions, soil properties, pre-afforestation drainage, location of tree cover within the catchment etc.) that can be crucial to explaining the detailed response of different situations. Future work should focus upon defining clear reporting guidance for contextual information from such studies, in the form of systematic meta-data, to facilitate clear and objective comparison between studies, and further detailed comparative analysis. We recommend developing a table identifying what variables and confounding factors should routinely be measured and clearly reported in future research (e.g. Stand size, catchment size, soil type, season, ground works, drainage etc).
- There is a clear lack of consistent reporting on hydrological impacts across the available literature and need for more consistent reporting on the impacts to facilitate clear and objective comparison. We would recommend all papers provide data with publication and provide a more routine number of hydrological variables in their data analysis.
- We recognise the role of models in understanding and separating effects, exploring scenarios and extrapolating findings, however it is very important that where possible observed data are used to calibrate and validate models. It is also crucial that uncertainty is considered and reported in both observational and modelled studies. We believe there is an ongoing need for more properly designed and resourced catchment-scale experiments to provide these data.
- Hydrological models bring together process knowledge but model results include inferences that make them different to observed data. Differences between the results of observational and modelled studies should be investigated further. A likely outcome being that analysis needs to be integrated by applying models to understand and explore the more mixed results in observed studies. It is possible that an examination of the role of effect modifiers in these studies would help to explain differences and the results improve our ability to parameterise and scale processes that link trees to floods.
- This review has focused upon the effects of tree cover on peak flows, but future work should attempt to review the impacts of tree cover on flood

characteristics in general, to determine if tree cover has an observable effect upon the volume of runoff generated and the response times of catchments – both of which are important hydrological changes that affect downstream flooding.

- Measurements of hydrological response should be carried out over the full range of conditions likely to occur (e.g. dry landscape to saturated landscape). In practice this is difficult to ensure but is likely to mean monitoring over at least several hydrological years.
- There is a need to consider how to objectively compare and consider studies undertaken at a particular site, but over a number of years and through subsequent development of forest cover (e.g. Coalburn).
- The role of existing observational studies in continuing to provide useful data should be considered particularly in cases where modifications to the tree cover are ongoing.
- Future work should focus on trees as one part of the flood mitigation solution and through working with other sectors (e.g. engineering) should develop understanding of how different measures interact and best combine to reduce flood risk.
- Future effort should endeavour to uncover any relevant unpublished studies. As well as adding to the overall knowledge base, these may address any potential bias in publications resulting from a tendency for publication to be more likely in the instance of finding a positive result. Researchers and journals should be encouraged to publish null results.
- There is a need to consider the wider context and implications of this work to inform future policy development on flood risk management.

6 Appendices

Appendix A - Review Question

Arriving at the final agreed review question took considerable time and involved many iterations. A brief summary of the evolution of the question is included here as it may be of use and relevance to others. The question initially proposed was ‘Does planting trees in catchments change flood characteristics?’. Concerns were raised that the focus on planting rather than more generally on trees would greatly limit the number of references returned i.e. it would likely return those studies in which monitoring of flood characteristics had taken place during and after the planting of trees, and would omit paired catchment studies with presence and absence of trees, or studies on the effects of removal or management of trees. The question was therefore changed to ‘Are UK river floods reduced by the presence of trees in the catchment?’ however the presumption that floods might be reduced caused concern as the proposed question should not make any pre-judgement of the systematic review outcome.

A third version of the question was then proposed: ‘Do trees in UK-relevant catchments influence the flood characteristics of rivers?’. This version successfully removed any pre-judgement of the outcome and kept the description of trees very broad so that afforestation, deforestation and many other forms of study could be considered. It also introduced the term ‘UK-relevant catchments’ to broaden the search scope out from just UK, to include areas with similar characteristics to the UK. This question made good sense initially however when fitting the question to the Population, Intervention, Comparison and Outcome (PICO) elements a problem arose that the population term was ‘UK-relevant catchments’ and the outcome was ‘flood characteristics of rivers’. Examination of the literature found that quite often the term river (or similar e.g. stream, channel) was used in conjunction a population term (e.g. river catchment). To clarify this issue the terms ‘river catchments’ and ‘fluvial flood characteristics’ were inserted. The inclusion of the term ‘fluvial flood characteristics’ ensures that the systematic review only includes only those studies relevant to rivers. As the review proceeded and it became clear that not all flood characteristics could be considered, it was decided that priority should be given to flood peak (m^3/s). Following these changes, the agreed question to take forward is:

‘Do trees in UK-relevant river catchments influence fluvial flood peaks?’

Appendix B – Papers included in the final analysis

Author(s)	Title	Publication Name	Year Published
Acreman, M.C.	The effects of afforestation on the flood hydrology of the Upper Ettrick Valley	Scottish Forestry	1985
Adelana, SM; Dresel, PE; Hekmeijer, P; Zydor, H; Webb, JA; Reynolds, M; Ryan, M	A comparison of streamflow, salt and water balances in adjacent farmland and forest catchments in south-western Victoria, Australia	HYDROLOGICAL PROCESSES	2015
Badoux, A; Jeisy, M; Kienholz, H; Luscher, P; Weingartner, R; Witzig, J; Hegg, C	Influence of storm damage on the runoff generation in two sub-catchments of the Sperbelgraben, Swiss Emmental	EUROPEAN JOURNAL OF FOREST RESEARCH	2006
Bathurst, JC; Birkinshaw, SJ; Cisneros, F; Fallas, J; Iroume, A; Iturraspe, R; Novillo, MG; Urciuolo, A; Alvarado, A; Coello, C; Huber, A; Miranda, M; Ramirez, M; Sarandon, R	Forest impact on floods due to extreme rainfall and snowmelt in four Latin American environments 2: Model analysis	JOURNAL OF HYDROLOGY	2011
Bernsteinova, J; Bassler, C; Zimmermann, L; Langhammer, J; Beudert, B	Changes in runoff in two neighbouring catchments in the Bohemian Forest related to climate and land cover changes	JOURNAL OF HYDROLOGY AND HYDROMECHANICS	2015
Birkinshaw, SJ; Bathurst, JC; Iroume, A; Palacios, H	The effect of forest cover on peak flow and sediment discharge-an integrated field and modelling study in central-southern Chile	HYDROLOGICAL PROCESSES	2011
Birkinshaw, SJ; Bathurst, JC; Robinson, M	45 years of non-stationary hydrology over a forest plantation growth cycle, Coalburn catchment, Northern England	JOURNAL OF HYDROLOGY	2014

Bren, LJ; Papworth, M	Early water yield effects of conversion of slopes of a eucalypt forest catchment to Radiata pine plantation	WATER RESOURCES RESEARCH	1991
Brown, LE; Cooper, L; Holden, J; Ramchunder, SJ	A comparison of stream water temperature regimes from open and afforested moorland, Yorkshire Dales, northern England	HYDROLOGICAL PROCESSES	2010
Bulygina, N; Ballard, C; McIntyre, N; O'Donnell, G; Wheater, H	Integrating different types of information into hydrological model parameter estimation: Application to ungauged catchments and land use scenario analysis	WATER RESOURCES RESEARCH	2012
Bulygina, N; McIntyre, N; Wheater, H	Bayesian conditioning of a rainfall-runoff model for predicting flows in ungauged catchments and under land use changes	WATER RESOURCES RESEARCH	2011
Bulygina, N; McIntyre, N; Wheater, H	Conditioning rainfall-runoff model parameters for ungauged catchments and land management impacts analysis	HYDROLOGY AND EARTH SYSTEM SCIENCES	2009
Burch, GJ; Bath, RK; Moore, ID; Oloughlin, EM	Comparative hydrological behaviour of forested and cleared catchments in South Eastern Australia	JOURNAL OF HYDROLOGY	1987
Burguete, J; Garcia-Navarro, P; Aliod, R	Numerical simulation of runoff from extreme rainfall events in a mountain water catchment	NATURAL HAZARDS AND EARTH SYSTEM SCIENCES	2002
Clark, C	Deforestation and floods	ENVIRONMENTAL CONSERVATION	1987
Conedera, M; Peter, L; Marxer, P; Forster, F; Rickenmann, D; Re, L	Consequences of forest fires on the hydrogeological response of mountain catchments: A case study of the Riale Buffaga, Ticino, Switzerland	EARTH SURFACE PROCESSES AND LANDFORMS	2003
Cosandey, C; Andreassian, V; Martin, C; Didon-Lescot, JF; Lavabre, J; Folton, N; Mathys, N; Richard, D	The hydrological impact of the Mediterranean forest: a review of French research	JOURNAL OF HYDROLOGY	2005

De Smedt, FH; Liu, YB; Gebremeskel, S; Hoffmann, L; Pfister, L	Application of GIS and remote sensing in flood modelling for complex terrain	GIS and Remote Sensing in Hydrology, Water Resources and Environment	2004
Dixon, SJ; Sear, DA; Odoni, NA; Sykes, T; Lane, SN	The effects of river restoration on catchment scale flood risk and flood hydrology	EARTH SURFACE PROCESSES AND LANDFORMS	2016
Fahey, B; Jackson, R	Hydrological impacts of converting native forests and grasslands to pine plantations, South Island, New Zealand	AGRICULTURAL AND FOREST METEOROLOGY	1997
Fohrer, N; Haverkamp, S; Eckhardt, K; Frede, HG	Hydrologic response to land use changes on the catchment scale	PHYSICS AND CHEMISTRY OF THE EARTH PART B-HYDROLOGY OCEANS AND ATMOSPHERE	2001
Fohrer, N; Haverkamp, S; Frede, HG	Assessment of the effects of land use patterns on hydrologic landscape functions: development of sustainable land use concepts for low mountain range areas	HYDROLOGICAL PROCESSES	2005
Foster, GC; Dearing, JA; Jones, RT; Crook, DS; Siddle, DJ; Harvey, AM; James, PA; Appleby, PG; Thompson, R; Nicholson, J; Loizeau, JL	Meteorological and land use controls on past and present hydro-geomorphic processes in the pre-alpine environment: an integrated lake-catchment study at the Petit Lac d ‘Annecy, France	HYDROLOGICAL PROCESSES	2003
Garcia-Ruiz, JM; Lana-Renault, N; Begueria, S; Lasanta, T; Regues, D; Nadal-Romero, E; Serrano-Muela, P; Lopez-Moreno, JI; Alvera, B; Marti-Bono, C; Alatorre, LC	From plot to regional scales: Interactions of slope and catchment hydrological and geomorphic processes in the Spanish Pyrenees	GEOMORPHOLOGY	2010

Garcia-Ruiz, JM; Regues, D; Alvera, B; Lana-Renault, N; Serrano-Muela, P; Nadal-Romero, E; Navas, A; Latron, J; Marti-Bono, C; Arnaez, J	Flood generation and sediment transport in experimental catchments affected by land use changes in the central Pyrenees	JOURNAL OF HYDROLOGY	2008
Gaume, E; Livet, M; Desbordes, M; Villeneuve, JP	Hydrological analysis of the river Aude, France, flash flood on 12 and 13 November 1999	JOURNAL OF HYDROLOGY	2004
Geris, J; Tetzlaff, D; McDonnell, J; Soulsby, C	The relative role of soil type and tree cover on water storage and transmission in northern headwater catchments	HYDROLOGICAL PROCESSES	2015
Gurnell, AM; Gregory, KJ	Vegetation characteristics and the prediction of runoff – analysis of an experiment in the New Forest, Hampshire.	HYDROLOGICAL PROCESSES	1987
Hall, G; Cratchley, R	Mechanisms of flooding in the Mawddach catchment	Water in Celtic Countries: Quantity, Quality and Climate Variability	2007
Hundecha, Y; Bardossy, A	Modeling of the effect of land use changes on the runoff generation of a river basin through parameter regionalization of a watershed model	JOURNAL OF HYDROLOGY	2004
Hurkmans, RTWL; Terink, W; Uijlenhoet, R; Moors, EJ; Troch, PA; Verburg, PH	Effects of land use changes on streamflow generation in the Rhine basin	WATER RESOURCES RESEARCH	2009
Iritz, L; Johansson, B; Lundin, L	Impacts of forest drainage on floods	HYDROLOGICAL SCIENCES JOURNAL-JOURNAL DES SCIENCES HYDROLOGIQUES	1994
Jackson, BM; Wheater, HS; Mcintyre, NR; Chell, J; Francis, OJ; Frogbrook, Z; Marshall, M; Reynolds, B; Solloway, I	The impact of upland land management on flooding: insights from a multiscale experimental and modelling programme	JOURNAL OF FLOOD RISK MANAGEMENT	2008

Jayasuriya, MDA; Dunn, G; Benyon, R; Oshaughnessy, PJ	Some factors affecting water yield from mountain ash (*Eucalyptus Regnans)* dominated forests in south-east Australia	JOURNAL OF HYDROLOGY	1993
Kalantari, Z; Lyon, SW; Folkeson, L; French, HK; Stolte, J; Jansson, PE; Sassner, M	Quantifying the hydrological impact of simulated changes in land use on peak discharge in a small catchment	SCIENCE OF THE TOTAL ENVIRONMENT	2014
Klocking, B; Haberlandt, U	Impact of land use changes on water dynamics-a case study in temperate meso and macroscale river basins	PHYSICS AND CHEMISTRY OF THE EARTH	2002
Krause, P	Quantifying the impact of land use changes on the water balance of large catchments using the J2000 model	PHYSICS AND CHEMISTRY OF THE EARTH	2002
Kuras, PK; Alila, Y; Weiler, M	Forest harvesting effects on the magnitude and frequency of peak flows can increase with return period	WATER RESOURCES RESEARCH	2012
Lana-Renault, N; Latron, J; Karssenberg, D; Serrano-Muela, P; Regues, D; Bierkens, MFP	Differences in stream flow in relation to changes in land cover: A comparative study in two sub-Mediterranean mountain catchments	JOURNAL OF HYDROLOGY	2011
Lane, PNJ; Sheridan, GJ; Noske, PJ	Changes in sediment loads and discharge from small mountain-catchments following wild-fire in south eastern Australia	JOURNAL OF HYDROLOGY	2006
Langhammer, J; Su, Y; Bernsteinova, J	Runoff Response to Climate Warming and Forest Disturbance in a Mid-Mountain Basin	WATER	2015
Linde, AHT; Aerts, JCJH; Kwadijk, JCJ	Effectiveness of flood management measures on peak discharges in the Rhine basin under climate change	JOURNAL OF FLOOD RISK MANAGEMENT	2010
Liu, YB; De Smedt, F; Hoffmann, L; Pfister, L	Assessing land use impacts on flood processes in complex terrain by using GIS and modeling approach	ENVIRONMENTAL MODELING & ASSESSMENT	2004

Lopez-Moreno, JI; Begueria, S; Garcia-Ruiz, JM	Trends in high flows in the central Spanish Pyrenees: response to climatic factors or to land-use change?	HYDROLOGICAL SCIENCES JOURNAL-JOURNAL DES SCIENCES HYDROLOGIQUES	2006
Meuser, A	Effects of afforestation on run-off characteristics	AGRICULTURAL AND FOREST METEOROLOGY	1990
Moran-Tejeda, E; Lopez-Moreno, JI; Vicente-Serrano, SM; Lorenzo-Lacruz, J; Ceballos-Barbancho, A	The contrasted evolution of high and low flows and precipitation indices in the Duero basin (Spain)	HYDROLOGICAL SCIENCES JOURNAL-JOURNAL DES SCIENCES HYDROLOGIQUES	2012
Mudelsee, M; Borngen, M; Tetzlaff, G; Grunewald, U	No upward trends in the occurrence of extreme floods in central Europe	NATURE	2003
Ott, B; Uhlenbrook, S	Quantifying the impact of land-use changes at the event and seasonal time scale using a process-oriented catchment model	HYDROLOGY AND EARTH SYSTEM SCIENCES	2004
Piegay, H	Interactions between floodplain forests and overbank flows: data from three piedmont rivers of southeastern France	GLOBAL ECOLOGY AND BIOGEOGRAPHY LETTERS	1997
Reinhardt, C; Bolscher, J; Ramelow, M; Wenzel, R; Schulte, A	Alternatives in flood protection: the effect of decentralized measures in the Upper Floha watershed (Southeastern Germany)	RIVER BASIN MANAGEMENT V	2009
Reinhardt, C; Bolscher, J; Schulte, A; Wenzel, R	Decentralised water retention along the river channels in a mesoscale catchment in south-eastern Germany	PHYSICS AND CHEMISTRY OF THE EARTH	2011
Robinson, M	30 years of forest hydrology changes at Coalburn: water balance and extreme flows.	HYDROLOGY AND EARTH SYSTEM SCIENCES	1998
Robinson, M	Changes in catchment runoff following drainage and afforestation	JOURNAL OF HYDROLOGY	1986

Robinson, M; Cognard-Plancq, AL; Cosandey, C; David, J; Durand, P; Fuhrer, HW; Hall, R; Hendriques, MO; Marc, V; McCarthy, R; McDonnell, M; Martin, C; Nisbet, T; O'Dea, P; Rodgers, M; Zollner, A	Studies of the impact of forests on peak flows and baseflows: a European perspective	FOREST ECOLOGY AND MANAGEMENT	2003
Robinson, M; Dupeyrat, A	Effects of commercial timber harvesting on streamflow regimes in the Plynlimon catchments, mid-Wales	HYDROLOGICAL PROCESSES	2005
Salazar, S; Frances, F; Komma, J; Blume, T; Francke, T; Bronstert, A; Bloschl, G	A comparative analysis of the effectiveness of flood management measures based on the concept of "retaining water in the landscape" in different European hydro-climatic regions	NATURAL HAZARDS AND EARTH SYSTEM SCIENCES	2012
Savill, P.S. and Weatherup, S.T.C.	The effect of afforestation on water runoff in the Woodburn Catchment area	Forestry	1974
Serrano-Muela, MP; Lana-Renault, N; Nadal-Romero, E; Regues, D; Latron, J; Marti-Bono, C; Garcia-Ruiz, JM	Forests and Their Hydrological Effects in Mediterranean Mountains The Case of the Central Spanish Pyrenees	MOUNTAIN RESEARCH AND DEVELOPMENT	2008
Smith, CM	Riparian afforestation effects on water yields and water-quality in pasture catchments	JOURNAL OF ENVIRONMENTAL QUALITY	1992
Tu, M; Hall, MJ; de Laat, PJM; de Wit, MJM	Extreme floods in the Meuse river over the past century: aggravated by land-use changes?	PHYSICS AND CHEMISTRY OF THE EARTH	2005
Vanova, V; Langhammer, J	MODELLING THE IMPACT OF LAND COVER CHANGES ON FLOOD MITIGATION IN THE UPPER LUZNICE BASIN	JOURNAL OF HYDROLOGY AND HYDROMECHANICS	2011
Versini, PA; Velasco, M; Cabello, A; Sempere-Torres, D	Hydrological impact of forest fires and climate change in a Mediterranean basin	NATURAL HAZARDS	2013

Wahren, A; Schwarzel, K; Feger, KH	Potentials and limitations of natural flood retention by forested land in headwater catchments: evidence from experimental and model studies	JOURNAL OF FLOOD RISK MANAGEMENT	2012
Ward, PJ; Renssen, H; Aerts, JCJH; van Balen, RT; Vandenberghe, J	Strong increases in flood frequency and discharge of the River Meuse over the late Holocene: impacts of long-term anthropogenic land use change and climate variability	HYDROLOGY AND EARTH SYSTEM SCIENCES	2008
Ward, PJ; Renssen, H; Aerts, JCJH; Verburg, PH	Sensitivity of discharge and flood frequency to twenty-first century and late Holocene changes in climate and land use (River Meuse, northwest Europe)	CLIMATIC CHANGE	2011
Webb, AA	Streamflow response to Pinus plantation harvesting: Canobolas State forest, southeastern Australia	HYDROLOGICAL PROCESSES	2009
Webb, AA; Jarrett, BW	Hydrological response to wildfire, integrated logging and dry mixed species eucalypt forest regeneration: The Yambulla experiment	FOREST ECOLOGY AND MANAGEMENT	2013
Wegehenkel, M	Longterm evaluation of land use changes on catchment water balance - a case study from North-East Germany	PHYSICS AND CHEMISTRY OF THE EARTH	2003
Wheater, H.S., McIntyre, N., Jackson, B., Marshall, M., Ballard, C., Bulygina, N., Reynolds, B., Frogbrook, Z.	Multiscale impacts of land management on flooding	Flood Risk Science and Management	2011
Yu, X; Lamacova, A; Duffy, C; Kram, P; Hruska, J; White, T; Bhatt, G	Modelling long-term water yield effects of forest management in a Norway spruce forest	HYDROLOGICAL SCIENCES JOURNAL-JOURNAL DES SCIENCES HYDROLOGIQUES	2015
Zhang, L; Zhao, FF; Brown, AE	Predicting effects of plantation expansion on streamflow regime for catchments in Australia	HYDROLOGY AND EARTH SYSTEM SCIENCES	2012

Zhao, FF; Xu, ZX; Zhang, L	Changes in streamflow regime following vegetation changes from paired catchments	HYDROLOGICAL PROCESSES	2012

Appendix C – Combined analysis papers not included in the final analysis

Author(s)	Title	Publication Name	Year Published
Birkinshaw, SJ; Bathurst, JC; Iroume, A; Palacios, H	The effect of forest cover on peak flow and sediment discharge-an integrated field and modelling study in central-southern Chile	HYDROLOGICAL PROCESSES	2011
Bren, LJ; Papworth, M	Early water yield effects of conversion of slopes of a eucalypt forest catchment to Radiata pine plantation	WATER RESOURCES RESEARCH	1991
Conedera, M; Peter, L; Marxer, P; Forster, F; Rickenmann, D; Re, L	Consequences of forest fires on the hydrogeological response of mountain catchments: A case study of the Riale Buffaga, Ticino, Switzerland	EARTH SURFACE PROCESSES AND LANDFORMS	2003
Gaume, E; Livet, M; Desbordes, M; Villeneuve, JP	Hydrological analysis of the river Aude, France, flash flood on 12 and 13 November 1999	JOURNAL OF HYDROLOGY	2004
Geris, J; Tetzlaff, D; McDonnell, J; Soulsby, C	The relative role of soil type and tree cover on water storage and transmission in northern headwater catchments	HYDROLOGICAL PROCESSES	2015
Iritz, L; Johansson, B; Lundin, L	Impacts of forest drainage on floods	HYDROLOGICAL SCIENCES JOURNAL-JOURNAL DES SCIENCES HYDROLOGIQUES	1994
Moran-Tejeda, E; Lopez-Moreno, JI; Vicente-Serrano, SM; Lorenzo-Lacruz, J; Ceballos-Barbancho, A	The contrasted evolution of high and low flows and precipitation indices in the Duero basin (Spain)	HYDROLOGICAL SCIENCES JOURNAL-JOURNAL DES SCIENCES HYDROLOGIQUES	2012

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