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Dixon, Simon

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The effects of river restoration on catchment scale flood risk and flood hydrology.

Dixon, S.J.; Sear, D.A.; Odoni, N.A.; Sykes, T. and Lane, S.N.

Abstract

A rising exposure to flood risk is a predicted consequence of increased development in vulnerable areas and an increase in the frequency of extreme weather events due to climate change. In the face of this challenge, a continued reliance on engineered at-a-point flood defences is seen as both unrealistic and undesirable. The contribution of "soft engineering" solutions (e.g. riparian forests, wood in rivers) to integrated, catchment scale flood risk management has been demonstrated at small scales but not larger ones. In this study we use reduced complexity hydrological modelling to analyse the effects of land use and channel changes resulting from river restoration upon flood flows at the catchment scale. Results show short sections of river-floodplain restoration using engineered logjams, typical of many current restoration schemes, have highly variable impacts on catchment-scale flood peak magnitude and so need to be used with caution as a flood management solution. Forested floodplains have a more general impact upon flood hydrology, with areas in the middle and upper catchment tending to show reductions in peak magnitude at the catchment outflow. The most promising restoration scenarios for flood risk management are for riparian forest restoration at the sub-catchment scale, representing 20-40% of the total catchment area, where reductions in peak magnitude of up to 19% are observed through de-synchronisation of the timings of sub-catchment flood waves. Sub-catchment floodplain forest restoration over 10-15% of total catchment area can lead to reductions in peak magnitude of 6% at 25 years post-restoration.

Introduction

In the face of increased exposure to flood risk resulting from encroachment of properties and infrastructure on floodplains, and the forecast increases in flood magnitude and frequency, continual reliance on conventional structural flood defences has been recognised as unsustainable (Broadmeadow and Nisbet, 2004; Johnson et al., 2007; Johnson and Priest, 2008). As a result, there is an increasing recognition that non-structural flood mitigation strategies may form an important part of future planning (Werritty, 2006; Johnson and Priest, 2008; Nisbet et al., 2011b). These include catchment-based interventions, based on manipulation of land use. Similarly, since channel geometry and floodplain topography are the principal variables that affect flood wave propagation (Wong et al., 2015), river managers are also exploring options for restoring river channel and floodplain morphology in order to modify the flood hydrograph for the benefit of downstream communities. Such approaches have the added advantage of benefitting aquatic ecology and delivering additional ecosystem services (Nisbet et al., 2011a).

The basic principle behind such approaches is that the geomorphological configuration of a drainage basin determines the time that it takes for a parcel of water (a runoff unit) to travel to a point where there is a flood risk. This time of travel is controlled by the drainage basin structure, that is the spatial organisation of runoff units as defined by catchment topography, and this has been shown to dominate hydrograph form (Rinaldo et al., 1991); geomorphologically-driven flow dispersion tends to be dominant over hydrodynamically-driven dispersion (Rigon et al., In Press). Such a conclusion holds if it is assumed that flood wave celerity is constant in space and time. In practice, it is relatively easy to relax these assumptions, to allow celerity to vary in space (e.g. as a function of channel slope, or to reflect differences in hillslope and channel velocities. e.g. van der Tak and Bras, 1990). In theory, it is possible to allow celerities to vary as a function of time, such as to reflect the effects of changing flow depth on the proportion of flow momentum lost to turbulence, and hence celerity. If such spatio-temporal variability can be properly represented, in theory, it ought to be possible to work with the geomorphological configuration of a drainage basin so as to change the level of geomorphological dispersion in the system.

There are objections to this approach, notably for large basins where the spatio-temporal evolution of precipitation fields during an event, which can't be generalised between events, may drive hydrograph response (e.g. Pattison and Lane, 2012; Pattison *et al.*, 2014). For smaller drainage basins, typically less than 100 km^2, there is evidence that restoration of river channel morphology (Acreman et al., 2003) and floodplain woodland with associated large wood logjams (Thomas and Nisbet, 2012)

may be the basis of flood risk reduction. However, even then, care is required (Lane and Milledge, 2013) as the impact on flood risk reduction is always relative to the point of intervention. For example, a reduction in flood wave celerity downstream of an intervention may desynchronise the flood response of that sub-catchment from a neighbouring sub-catchment. But, it may re-synchronise itself with a third sub-catchment further downstream. Thus, making use of geomorphological dispersion in flood risk management requires a spatially explicit evaluation of where each intervention is added, in combination with other interventions. The aim of this paper is to demonstrate an heuristic numerical modelling approach that is able to do this. In the next section, we review the two basic interventions (floodplain reforestation and logjams) that we consider, and show why their adoption needs a catchment-scale approach. We then introduce the numerical model that we have adopted for this purpose (a fuller description is provided in a Supplementary Online Only section), describe its application, and use it to evaluate the catchment-scale impacts of floodplain forest and logjam interventions.

Floodplain forest, logjams and catchment-scale impacts on downstream flood risk

Floodplain forest

Land cover has a large effect on flow paths and temporary storage capacity within a catchment. Afforestation can potentially mitigate flood risk through increases in interception (Robinson et al., 2003), infiltration (Bracken and Croke, 2007), temporary storage (Ghavasieh et al., 2006), slowing conveyance (Lane et al., 2007; Thomas and Nisbet, 2007), and attenuating runoff (Hundecha and Bárdossy, 2004; Broadmeadow and Nisbet, 2010). These effects are particularly effective under forest cover, which increase as the forest ages (Harr, 1986). In this paper, the particular interest is in the impacts of afforestation on flood wave celerity, that is conveyance.

Mature forests are a complex patchwork of upright stems and fallen deadwood; the complex floodplain surface slows the velocity of floodwater passing over it. Thomas and Nisbet (2007) showed a 50ha block of floodplain woodland in an 84km^2 catchment during a 1% recurrence interval flood can slow flood wave travel time by 30 minutes and increased temporary flood storage through backwatering effects by 15%. In modelling studies, Ghavasieh et al., (2006) showed that vegetated

strips could reduce peak discharge by 3.8% over a 20km reach and Anderson et al., (2006) showed tall vegetation could reduce peak discharge by 12% over a 50km reach respectively.

However, there remains a lack of consensus as to the general efficacy of forests in mitigating flooding risk (Robinson et al., 1998; Andréassian, 2004; Van Dijk et al., 2009; Archer et al., 2010) due in part to the variability in climatic factors being the same order of magnitude as variations in land use change (Andréassian, 2004) and due to a lack of evidence from catchments over 10km^2 (Archer et al., 2010). Flood mitigation effects have also been shown to be greatest for moderate floods and have less impact in extreme rainfall events (Anderson et al., 2006; Hess et al., 2010; Sholtes and Doyle, 2011).

This research aside, there are few projects that have tried to assess how different extents and locations of floodplain forest contribute to flood risk changes at different spatial scales.

Engineered Logjams

The use of Engineered Logjams (ELJs) is widespread (Bernhardt et al., 2005; River Restoration Centre, 2013) and has been shown to have local effects upon flood hydrology (Thomas and Nisbet, 2007; Thomas and Nisbet, 2012). Logjams alter local hydraulics by increasing hydraulic roughness (Shields Jr and Gippel, 1995; Curran and Wohl, 2003; Sear et al., 2006; Kitts, 2010), increasing water levels and slowing flow velocities (Shields Jr and Gippel, 1995), this reduces channel conveyance and increases flood wave travel time (Gregory et al., 1985; Thomas and Nisbet, 2007; Thomas and Nisbet, 2012). Increases in water level may also increase the connectivity between a river and its floodplain (Sear et al., 2010), such that the effects of floodplain forest may also depend upon use of ELJs.

Sholtes and Doyle (2011) conducted numerical modelling on the effects of short lengths of channel restoration including simulating higher channel hydraulic resistance. There were only minimal effects of flood attenuation (<1%) with restoration in ~0.9km reaches, and it is suggested that restoration at scales of 5-10km would be needed to see catchment level effects . Thomas and Nisbet (2012) modelled 0.7km reaches with the addition of ELJs and found that although flood peaks were delayed they were not substantially reduced.

Empirical evidence for the effects of both clearance and restoration of logjams has been derived from the longterm monitoring of flood hydrographs and logjam frequency in a 12.5 km^2 headwater stream (Figure 1a) in the New Forest, UK (Gregory et al., 1985; Sear et al., 2006; Kitts, 2010). In 2004 , 1.4 km (21%) of main channel were restored within the study reach, involving re-occupation of the former meandering channel, reduction in channel capacity and reconnection to the floodplain. Logjam

frequency was increased through toppling of riparian trees into the remaining channelised reach (Sear et al., 2006) and allowing wood to naturally accumlate around the larger pieces of wood.

Locally, the effectiveness of logjams was found to depend on their type and spatial frequency (Kitts, 2010). The most hydraulically effective logjam, at a frequency of 2.7/100m (the average logjam density for the catchment), increased the frequency of floodplain inundation by a 1-in-2 year return interval (RI) flow by up to 175%, and the inundation duration by up to 156% when compared to scenarios without any logjams.

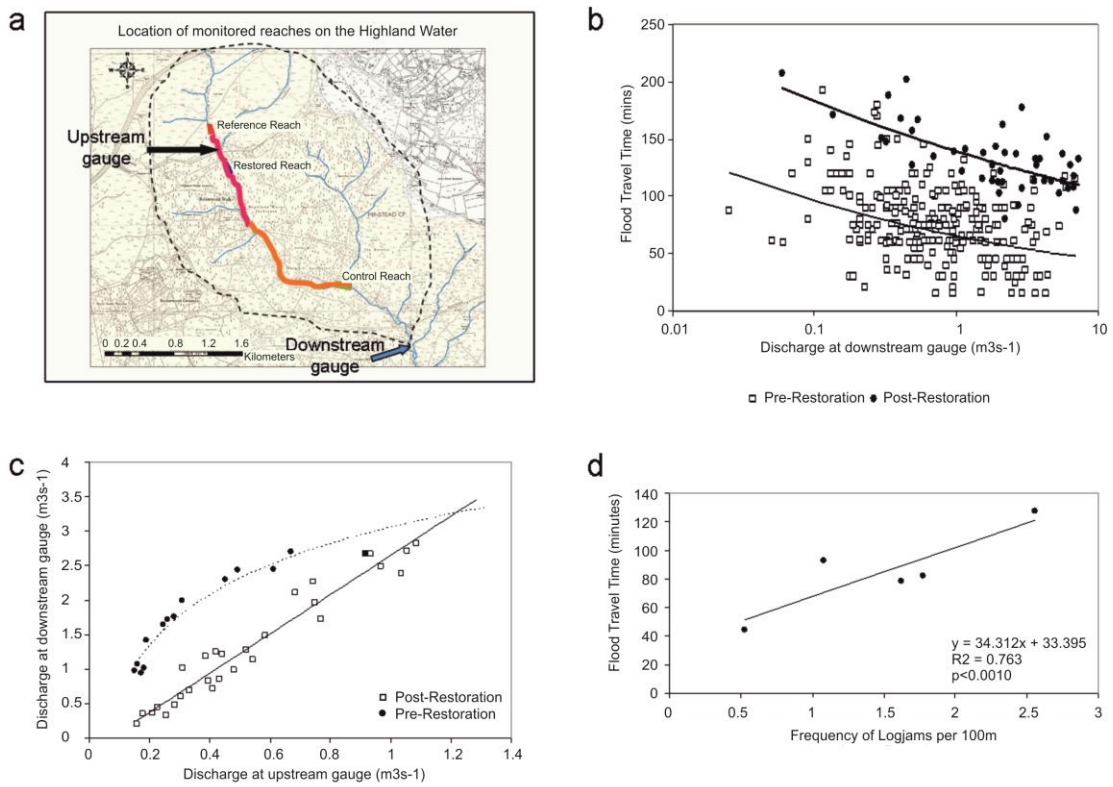

Figure 1 Empirical evidence for the effectiveness of channel and logjam restoration in headwater streams, New Forest, UK. a) Catchment, showing logjam and channel restoration (pink), logjam only restoration (orange) and position of the gauging stations; b) Increase in flood travel time as a result of the restoration actions shown in (a); c) Flood attentuation independent of antecedent catchment wetness following restoration actions in (a) in which the effect of the attenuation due to logjams decreases once the flows go overbank; d) Increase in flood travel time with increasing logjam density within the intervening river network. After Kitts (2010).

An increase in channel length of 21%, together with a 142% increase in the frequency of large wood accumulations resulted (on average) in a 21% reduction in flood peak magnitude and a 33% increase

in flood peak travel time (Figure 1) which was independent of antecedent conditions. This is a similar magnitude to that found by Acreman *et al.* (2003) on the River Cherwell in south-east England, where modelled restoration of the channel to pre-engineered dimensions led to a reduction in peak flow of 10-15%. However, although increasing logjam density increases flood travel time (Figure 1d), the data in Figure 1c illustrates that the effectiveness of the restoration appears to be limited to flows $<1 m^3 s^{-1}$, equivalent to a 1-in-2 year RI. We hypothesize that up to this threshold, flood wave travel time is predominantly influenced by in channel flow resistance. Larger overbank floods drown out the floodplain roughness elements resulting in progressive attainment of flood travel times similar to the unrestored channel state.

Catchment-scale impacts

These observations aside, there have been fewer attempts to identify catchment-scale impacts. Both the restoration of floodplain forest and river channels, including ELJs, may have some impact upon downstream flow peaks. For example, Sear et al., (2000) report a modelling study in which re-meandering and reducing the capacity of headwater streams resulted in up to a 20% reduction in flood height at an urban centre 30km downstream. Similarly, Liu et al., (2004) used a distributed hydrological model to simulate the restoration through increased channel hydraulic resistance and sinuosity of all first to third order streams in a $408 km^2$ catchment (76% of catchment area) finding on average a 14% reduction in peak discharge. However, not all studies show that interventions that have a local impact scale up to entire catchments; a report by Jacobs Babtie (2006) on the River Enrick in Scotland, modelling large scale land use changes to floodplain woodlands, found a negligible effect on downstream flood peaks.

There are a number of reasons for such contrasting results. One of the most important elements in reducing runoff contributions to flood peaks is the spatial configuration of land cover use, not just total area (Fitzjohn et al., 1998; Cammeraat and Imeson, 1999; Ludwig et al., 2005). It is possible that effects that are apparent at the local scale do not translate to the larger scale (e.g. Lane and Milledge, 2013). Statistical analysis and hydraulic modelling of the River Eden in the north of England (Pattison et al., 2014) showed that the relative timing of sub-catchment response could significantly impact downstream peak flow magnitudes. An isolated intervention may attenuate flood wave propagation, and reduce downstream peak flow magnitude, in the given sub-catchment; but its impact further downstream depends upon the relative timing of the contributions from all sub-catchments comprising the main flood hydrograph (Lane, 2003; Pattison et al., 2008; Lane and Milledge, 2013; Pattison et al., 2014). Modelling in small urban watersheds has also shown the overall downstream effects of storm water management can be complex and depend heavily on relative timings of sub-

catchment contributions (McCuen, 1979; Hess and Inman, 1994; Ferguson, 1995; Emerson et al., 2005). Positive effects in one sub-catchment, with respect to reducing flood risk, may actually be negative at the catchment-scale, potentially increasing flood peak magnitude and/or duration. The effects of local attenuation and catchment scale floodwave synchronisation are not well understood, particularly in terms of the effects of catchment scale restoration upon catchment scale floodwave attenuation.

Numerical Modelling approaches

Given uncertainties in empirical studies of the the effects of ELJ insertion (Nisbet et al., 2011b) and land use management (Parrott et al., 2009; Pattison and Lane, 2012) upon flood hydrology at the catchment scale, coupled with the logistical challenges in setting up study catchments, numerical modelling offers a useful route to explore the broader effects of catchment scale restoration on flood hydrology. Thus, the remaining paper focusses on a modelling study in which empirical data are integrated into a spatially distributed flood model (OVERFLOW) to explore the effects of different restoration scenarios on flood hydrology. The specific aim of the work is to evaluate the impacts of various restoration scenarios in multiple spatial configurations impact on downstream peak flood flows. By testing multiple spatial arrangements of restoration throughout the catchment we advance upon on the work of Liu et al., (2003) who only modelled restoration to all headwater streams in a catchment. We expect that the reforestation of floodplain forest and construction of ELJs will reduce downstream flood risk, but that their effectiveness will depend on their location within a catchment.

Methods

The OVERFLOW model

Although conventional hydrological models can be used to test land use scenarios there are technical challenges related to: the need for a spatially-explicit model repsonse; the challenges of calibrating a basin-scale hydrological model; and the objective of assessing possible multiple combinations of individual and combined interventions, meaning that many scenarios may be necessary. Numerical modelling was therefore conducted using the reduced complexity model OVERFLOW (Dixon, 2013) which simplifies many of the physical processes involved in flood wave propagation.

OVERFLOW is based upon the well-established principle of a geomorphological unit hydrograph, here considered as a spatio-temporally means of determining flood flow attenuation or dispersion. It recognises the demonstrated importance of geomorphological dispersion in attenuating runoff response (Rinaldo et al, 1991) by using a spatially distributed unit hydrograph approach (Maidment, 1993; Maidment et al., 1996; Olivera and Maidment, 1999; Saghafian et al., 2002; Liu et al., 2003; Du et

al., 2009) and the Saghafian and Julien (1995) time to equilibrium concept. Model complexity is reduced by focusing on floods generated by rainfall events of duration approaching time to equilibrim and within catchments approaching saturation such that standard runoff coefficients exceed 70%. Thus OVERFLOW focuses on the contribution to peak flow of rapid runoff pathways. The model is designed as a initial exploratory tool to test multiple combinations of land use and channel changes in a computationally efficient manner. It explores general relationships between flood hydrology and the extent, location and magnitude of land use change at the catchment scale but, given the model simplifications, does not aim to deliver explicit, quantitative, site specific predictions of flood reponse. Rather, the latter should be based upon more detailed testing of the smaller number of possible flood peak reducing strategies that OVERFLOW identifies.

An overview of the OVERFLOW model is provided in supplemental material and detailed descriptions of the model architecture can be found in Dixon (2013).

Calibrating the model to the reference event

Although this modelling study is primarily heuristic, the model needs an input rainfall event and baseline flood hydrograph and therefore needs to be set up and calibrated to a recorded event in a specific catchment. Data were used for the 98km^2 Lymington River catchment in Southern UK. A rainfall and subsequent moderate flood event of 3% exceedance from 30th-31st March 2006 was used for calibration. Rainfall data were collected using a tipping bucket raingauge at Oknell Plain, the highest elevation in the catchment (112m), and was assumed to be spatially uniform for the model, which is acceptable for a relatively low relief catchment. River flow data was obtained from the Environment Agency gauging station at Brockenhurst on the Lymington River.

A 20m resolution DEM was resampled from a 5m resolution DEM provided by Environment Agency Geomatics Group, which was pit-filled using the Planchon and Darboux (2002) method. Resampling to a coarser resolution is necessary to ensure the channel is a sub-grid feature throughout the DEM.

The model requires data on channel capacity, effectively as defined by width and depth. This was obtained using downstream hydraulic geometry equations (after Leopold & Maddock, 1953) and field survey data of hydraulic geometry collected throughout the catchment, including channel heads. Field data were used to fit empirical constants in Leopold & Maddock (1953) equations for width and depth, these derived constants were then used to generate hydraulic geometry on a cell-by-cell basis for the channel network.

Effective rainfall rate was calculated using a mass balance approach and the measured rainfall and hydrograph, giving an estimated runoff percentage of 87.7% for the 30th-31st March 2006 event used in this study. The high runoff percentage reflects the underlying Eocene Barton clay geology of the catchment (Piégay and Gurnell, 1997; Gurnell and Sweet, 1998) and high antecedent soil moisture prior to the event.

Values for the channel Manning's n were calculated using a variable power equation based on catchment average grainsize (Ferguson, 2007; Ferguson, 2010) using field data. In the Lymington Basin catchment average values are; channel depth = 1.19m, channel width=4.98m, D_{84}=19mm (Sear et al., 2006; Millington, 2007; Kitts, 2010). Using values of a_1=6.5, a_2=2.5 (Ferguson, 2010) an estimated Manning's n=0.048 ±0.003 is calculated.

The model calibration curve (Figure 2) shows the calibrated OVERFLOW predicts the observed hydrograph well with a Nash-Sutcliffe index of ≥0.98. The 200 calibration hydrographs are used as the basis for modelling investigations and the mean outputs of these are compared to the mean of the original calibration hydrographs (red line in Figure 2).

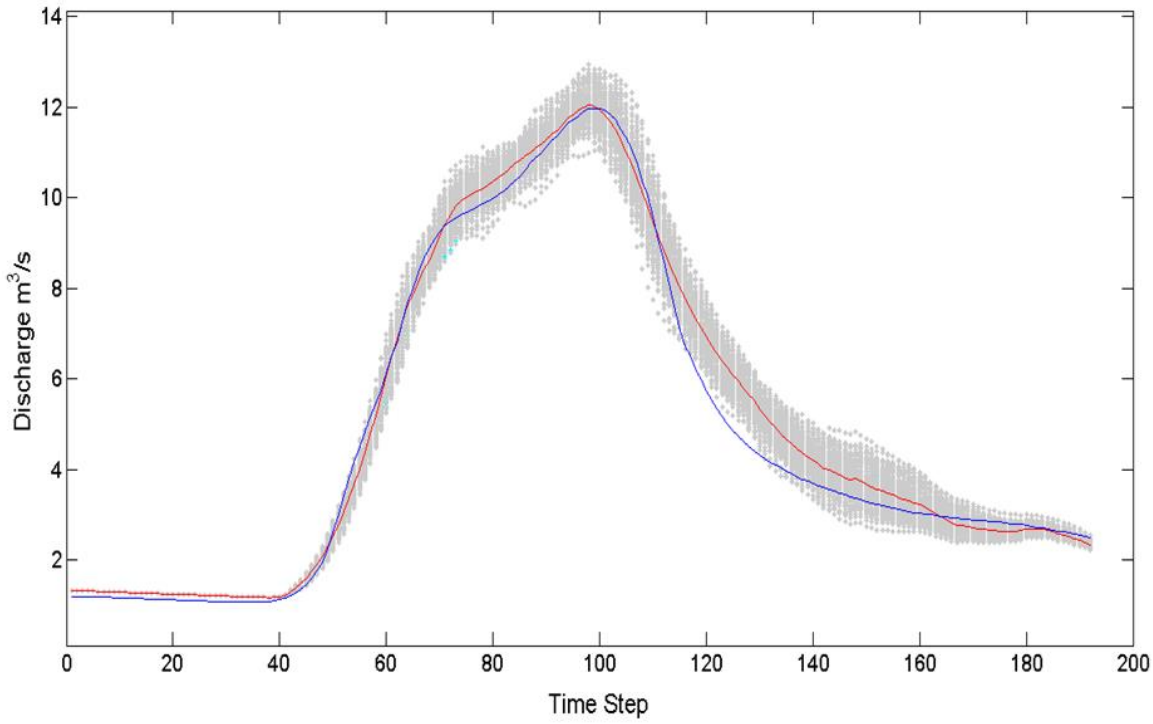

Figure 2 - Calibration curve for March 30th 2006 flood event. Blue line shows the observed discharge at Brockenhurst, Red line is the mean modelled hydrographs, light grey points shows the spread of 200 best simulations from the Monte-Carlo calibration with Nash-Sutcliffe ≥0.98.

Model Scenarios

Restoration projects at the reach or segment scale are frequently the norm, often reflecting restoration that is undertaken on an opportunistic basis (Bernhardt et al., 2005; River Restoration Centre, 2013). More extensive sub-catchment or catchment-scale processed based restoration is increasingly advocated as being more sustainable and effective at meeting restoration aims (Beechie et al., 2010; Nisbet et al., 2011b). In order to represent both types of restoration project, for each scenario, 435 model runs were conducted on scales ranging from the segment to the entire catchment. Model runs were conducted for a series of spatial arrangements, these were based on: each segment individually, sets of five sequential segments, each individual sub-catchment and finally combinations of sub-catchments up to an including the entire catchment. Sub-catchments were defined as the stream network and catchment area draining to a given nodal point in the catchment network. Sub-catchments therefore represent descrite, geographically contiguous areas of stream network within the catchment. Model runs were also conducted in which all segments of a given Shreve reach order had restoration scenarios applied to them, up to and including all segments of reach order 1-10 (after Liu et al., 2003). Modelling scenarios and associated Manning's n hydraulic resistance values are summarised in Table 1.

Implementation of ELJs is variable with few specific design guidelines in the academic or grey literature (Dixon, 2013). We base our modelling on the advocation for channel spanning logjams (e.g. Abbe and Montgomery, 1996; Thomas and Nisbet, 2012) installed at downstream spacings of 7-10 channel widths (Linstead and Gurnell, 1998; Thomas and Nisbet, 2012). Given the lack of standardisation in ELJ implemention this study uses an average of calculated logjam hydraulic resistance values from field studies within study catchment during near bankfull flood events (Kitts, 2010; Dixon, 2013). This gives a Manning's n = 0.196±0.08 for model cells for which an ELJ is being applied. Although ELJs are represented just by an elevated hydraulic roughness within a 20m grid cell the evolution of ephemeral floodplain flowpaths for overbank flow and an empirical backwatering functionality within OVERFLOW serve to represent the additional major hydraulic impacts of logjams.

With floodplain forest restoration the land cover and in channel wood loadings will vary over time as the new forest matures and moves through successional phases. As the forest matures deadwood volumes and thus deadwood inputs to the channel increase. These will form natural logjams over time and so the in channel hydraulic resistance, as well as the overbank resistance will increase. In order to predict the floodplain and in channel hydraulic resistance for a restored forest a conceptual model of beech forest succession was used based on forest growth modelling (Nislow, 2010; Dixon,

2013), coupled with literature values for dead wood biomass in forest stands of different ages (Christensen et al., 2005). From these data three restoration scenarios for 25 years, 50 years and 100 years post restoration were derived. In the 25 year scenario there is abundant polewood, but very low volumes of dead wood, thus in channel hydraulic resistance will show little change from pre-restoration baselines (Bretz Guby and Dobbertin, 1996; Laser et al., 2009; Dixon, 2013). At 100 years post-restoration the forest is approaching a state of dynamic equilibrium where the abundance of tree specimens in all age classes is approximately constant and the quantity of large dead wood has reached a maximum value where input is roughly equal to decay rate. Thus the 25 year and 100 year scenarios constrain the minimum and maximum change to hydraulic resistance following forest restoration. A 50 year scenario gives a mid-point in the complexity of forest development.

In addition to these scenarios a further set were run to examine the effects of forest restoration in which new inputs of large wood are cleared from the channel through management to maintain low large wood loadings. These scenarios represent cases where managers have to remove large wood through stakeholder pressure (Piegay et al., 2005) and where the project has been designed to have minimal or only engineered wood (Brooks et al., 2006; Lewis, 2010).

Scenario Number	Scenario	Channel Hydraulic Resistance	Floodplain Hydraulic Resistance
1	Engineered Logjams	n=0.20 (in individual grid cells)	n=0.07 (calibration value)
2	25 year forest growth (forest only)	n=0.05 (calibration value)	n=0.10
3	50 year forest growth(forest only)	n=0.05 (calibration value)	n=0.12
4	100 year forest growth (forest only)	n=0.05 (calibration value)	n=0.15
5	25 year forest growth	n=0.06	n=0.10
6	50 year forest growth	n=0.075	n=0.12
7	100 year forest growth	n=0.10	n=0.15

Table 1 – Channel and land use modelling scenarios and associated values for Manning's n.

Uncertainty Analysis

The modelling conducted in this study is a primarily heuristic exercise to investigate the effects of spatially diffuse land use change at the catchment level. In such an exercise the individual model runs are not treated as providing explicit, quantitative prediction of flood hydrology, rather the modelling exercise is treated as a whole and attempts to define and constrain the plausible in terms of the magnitude and directionality of changes to flood hydrology (Bankes, 1993). With an exploratory modelling approach, concepts of model validation and sensitivity analysis can be seen as nonsequiters, as the quality of the modelling analysis rests rather with the validity of the analytic strategy and the accuracy of the input data, or 'prior knowledge' used by the model to generate new insights and knowledge (Bankes, 1993). The modelling results, or 'new information' are implicit in the 'prior knowledge' used to generate them (Bankes, 1993) and may influence the results in a meaningful way. The empirical values for Manning's n used in the scenarios are therefore the greatest source of uncertainty in the modelling approach as they are not directly measured from field data.

A two stage, four level uncertainty analysis was conducted to vary the input values for Manning's n. Manning's n values for floodplain and channel hydraulic resistance are selected as part of defining the model scenarios. They therefore represent uncertainty in the "prior knowledge" used in the modelling. In order to explore the effects of uncertainty in hydraulic resistance upon model results it is necessary to understand the sensitivity of the calibrated model to these input parameters. For all the Manning's n values used in the model scenarios (for modified floodplain, channel and logjam resistance) two higher and two lower values were used (<±20%) and a sample of model runs were re-run using each of these alternative resistance values. Model runs were divided into three groups, those which showed an increase, a decrease and no change (<0.1%) in peak discharge and a random sample of six of these were used as model runs for the uncertainty analysis. This analysis shows the uncertainty in change to peak discharge magnitude for segment scale scenarios for ELJs is ±0.23% and for forest restoration is ±0.50%. Furthermore the analysis shows for model runs predicting a change of ≥±0.1% in flood peak magnitude there is no uncertainty in directionality of response, only in magnitude. The uncertainty analysis results give confidence that modelled high magnitude changes in flood peak magnitude are real effects.

Results

Peak Magnitude Changes

For all results we compare the output hydrograph(s) generated by the model to the calibration hydrograph generated during the model set up, focusing on percentage changes to the peak discharge. Scenarios using only engineered logjam insertion (Table 1, scenario 1) show fairly modest changes to flood peak magnitude, ranging from a 6% reduction to a 6% increase (Figure 3A). The proportion of the network restored in Figure 3 refers to the total proportion of the network to which the given restoration scenario is applied; for engineered logjam scenarios therefore this is the total reach length with logjams spaced at 7-10 channel widths. The magnitude of potential change in peak discharge increases with proportion of the channel network restored. However, there is strongly variable directions of change, with both discharge increases and decreases. For small sections of <10% of the catchment network restored using ELJs, model results show the overwhelming majority of scenarios result in a change of less than ±2% in peak dischange.

With model runs for both forest restoration alone (Figure 3C, Table 1, scenarios 2-4), and for forest and channel restoration (Figure 3E, Table 1, scenarios 5-7) there is a three stage relationship between the proportion of the channel network restored and the change in peak discharge; for between 0-22% of the network restored the response is highly variable in both magnitude and directionality, with the majority of model runs showing only small changes. For model runs in which 22-50% of the network is restored, on an entire sub-catchment basis, for scenarios 2-7; all model runs lead to a decrease in peak discharge with the magnitude of change for a given scenario increasing as the forest becomes more complex from 25 year through to 100 year scenarios. For scenarios in which over 50% of the network is restored, all model runs lead to a decrease in peak discharge, however these decreases are typically of a lower magnitude than the 22-50% model scenarios.

Shape of hydrograph

A quadrant analysis was used to asses the changes in hydrograph in terms of the peak magnitude and time exceeding bankfull discharge at the catchment outflow compared to the calibration hydrograph (Figures 3B, 3D and 3F). For ELJ model runs (scenario 1), Figure 3B shows changes in both the size and shape of the hydrograph peak; demonstrating that ELJ model runs do not always result in a simple scaling of the hydrograph peak, but can often broaden the peak even with little change in

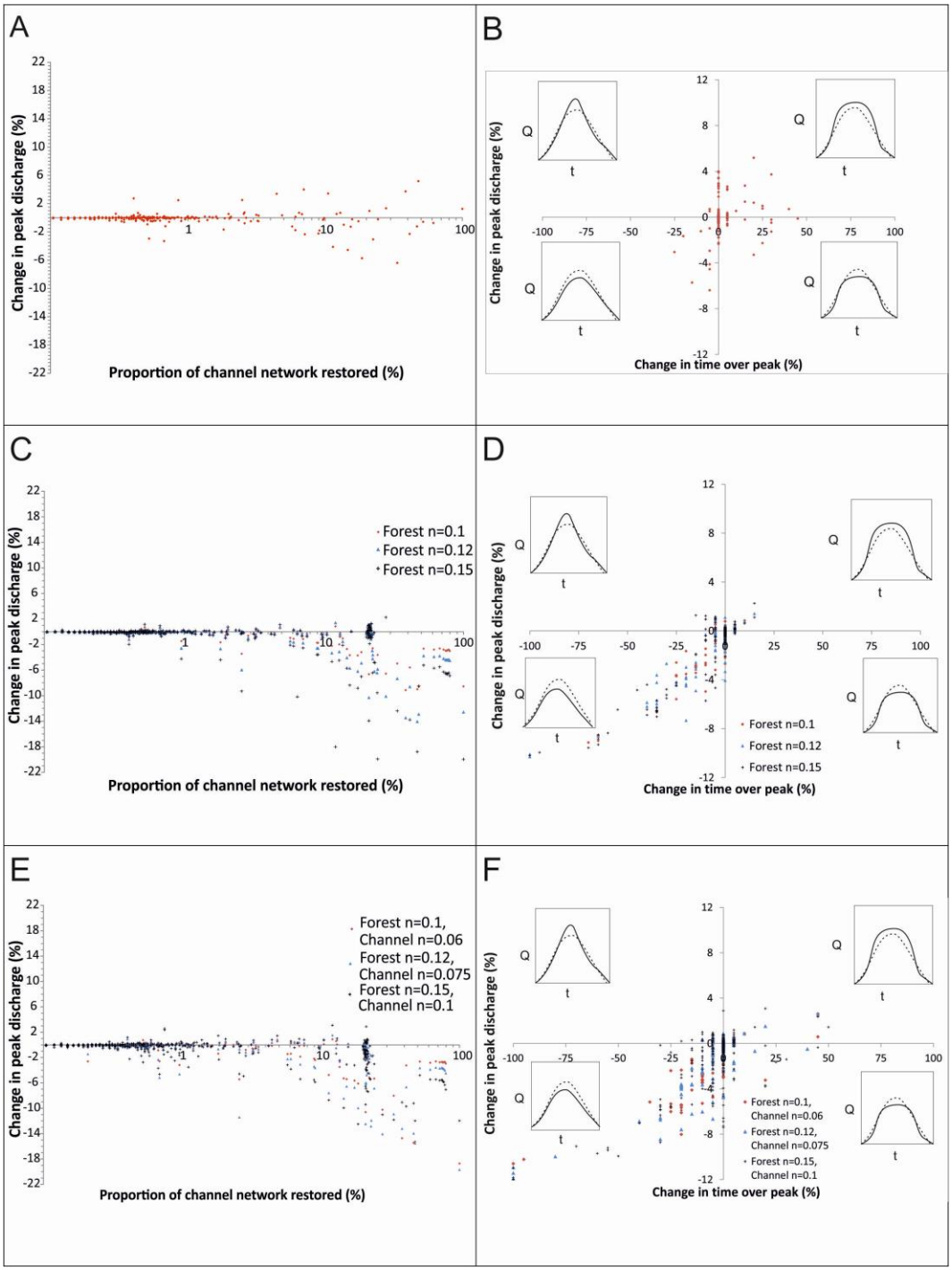

Figure 3 - Change in peak discharge for all model runs compared to baseline calibration hydrograph, for three restoration scenarios. Change in peak discharge is plotted against the percentage of the catchment altered (left hand column; A, C, E) and as a quadrant analysis against change in time over peak (right hand column; B, D, F). A & B, – Engineered logjams (Scenario 1), C & D – Forest restoration alone (Scenarios 2-4), E & F – Forest Restoration and associated increases to in channel large wood, and thus natural logjams (Scenarios 5-7). These plots show there is a greater predictability in response for forest restoration scenarios with the hydrograph broadly scaling with original shape (D & F), and a relationship between greater extent of restoration and a decrease in peak magnitude (C & E). Whereas, for logjams alone changes to hydrograph shape are less predictable (B), as is the directionality and magnitude of change to peak discharge (A).

overall peak discharge, representing longer duration flood events. For forest model runs (Figures 3D, scenarios 2-4 and 3F, scenarios 5-7), model runs are either located in the bottom left quadrant (both magnitude and time over peak reduced) or upper right (both magnitude and time of peak increased). This demonstrates that forest scenarios lead to a broadening of the flood hydrograph with very few model runs resulting in more flashy (shorter duration, higher peak) or more moderate but persistent flood events.

Spatial patterns of response

The spatial distribution of response to scenarios 4-7 for short sections (≤2.5% of catchment network) of forest restoration with no channel management, and thus increasing in channel large wood over time (Figure 4) shows segments close to the catchment outflow tend to increase peak magnitude (orange/red), whereas more distant segments tend to decrease the peak discharge (blue). When older, more complex forests are modelled (Figure 4B, scenario 6 and Figure 4C, scenario 7), the spatial pattern is reinforced with many more distal segments showing the greatest decreases in peak magnitude (dark blue) and with the number of neutral segments (yellow) reducing. Restoration of trunk channels (Shreve stream order ~40-150) broadly reduces peak discharge; this is the opposite of scenarios using ELJs (Figure 5) and for forest restoration alone where these reaches tend to increase peak discharge or have no effect.

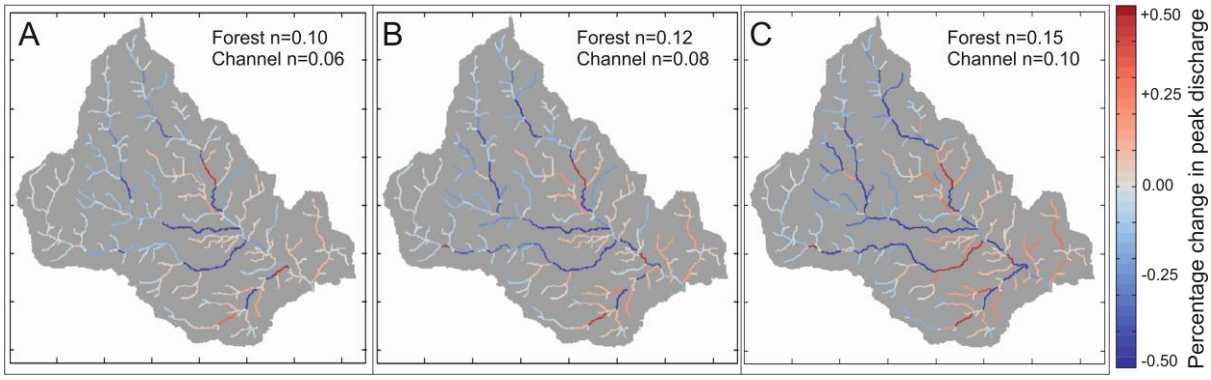

Figure 4 - Maps showing response in change to peak discharge at catchment outflow in response to applying forest restoration and changes to in channel wood loads to individual reaches. A – 25 years post-restoration, B – 50 years post-restoration, C – 100 years post-restoration. Note pattern of hydrologically distal reaches generally showing relatively large reductions in peak discharge following reach-scale restoration, whereas hydrologically proximal reaches tend to increase peak discharge (custom colour map after Moreland, 2009).

The pattern for more hydrologically distal areas of restoration to decrease peak magnitude is also found for larger areas of restoration for scenarios 2-7. For model runs with more extensive restoration

there is a trend for restoration at 1-22% of the catchment area, applied in the more hydrologically distal parts of the catchment, to tend to show reductions in peak magnitude, in comparison to similar model runs with restoration near to the catchment outflow.

Results from OVERFLOW modelling show scenarios related to river and floodplain forest restoration can lead to changes in flood peak magnitude ranging from a 6% increase to a 20% decrease relative to the original flood hydrograph (Figure 3). For all restoration scenarios changes in peak discharge at the catchment outflow could be detected with segment scale model runs.

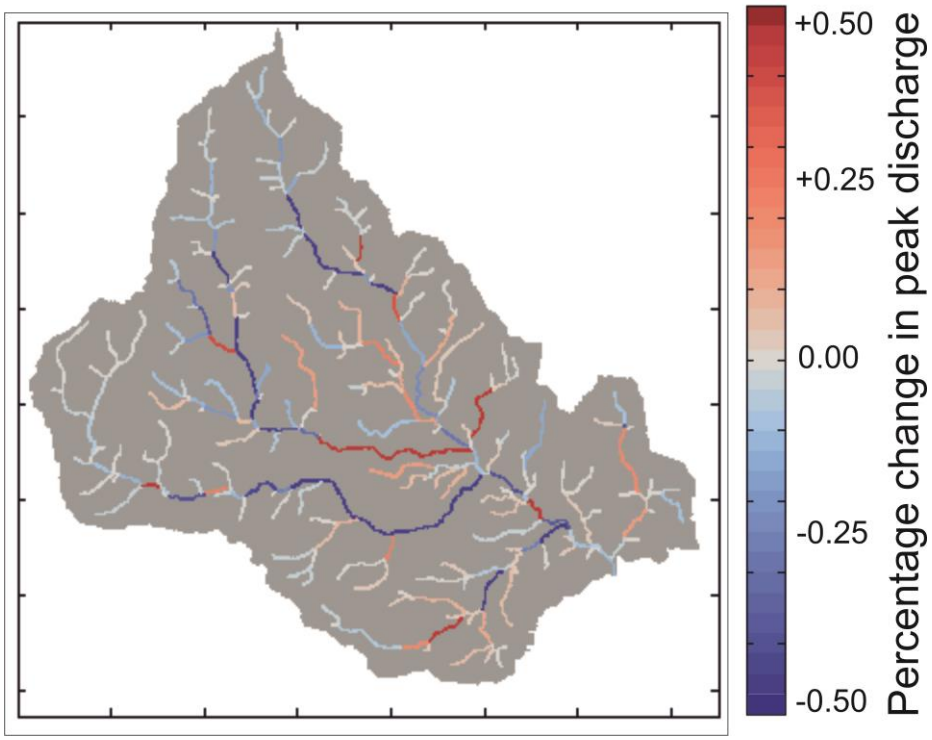

Figure 5 - Map showing change to peak discharge at catchment outflow in response to applying engineered logjams to individual reaches. Note, although main trunk channels generally show reduction in peak discharge following insertion of logjams, the overall spatial pattern of response is highly variable (custom colour map after Moreland, 2009) .

Discussion

Results from this modelling study suggest that river restoration, and specifically coupled in channel logjam and floodplain forest restoration, does have the potential to be part of an integrated programme of flood risk management through its effects on catchment scale flood wave dispersion. However, restoration needs to occur over a large spatial extent in order to have appreciable impacts.

Restoration scenarios applied at the segment/reach scale are observable in the response of the catchment outflow hydrograph and there is a general pattern of more extensive restoration, both in scale and complexity, leading to larger reductions in flood peak magnitude. The largest reductions in peak discharge occur for model runs of entire sub-catchments with forest restoration scenarios from 25 years post restoration onwards for between 20-50% of the catchment network/area (scenarios 2-7). There is a high degree of variability in hydrograph response to ELJ insertion both in terms of the relationships between restoration extent and response, and location and response, making it difficult to derive any general relationships between location or degree of ELJ placement and hydrograph response. Sub-catchment patterns are also highly variable; individual small headwater sub-catchments (up to and including Shreve stream order ~15) and distal from the outflow can show reductions in peak magnitude of 3-5%. More extensive sub-catchments (up to and including Shreve stream order ~35) tend to show <±1% change in peak discharge, however combining one or more of these sub-catchments in the same model can lead to increases in peak discharge of 5%. This confirms that at larger scales, different ELJs impacts may be cancelling.

Local Attenuation Effects

With small sections of restoration changes in the outflow hydrograph can be attributed to the effects of increasing the flood wave travel time through short, isolated sections of the channel network, which results in a variable catchment level response. The general spatial picture for individual reaches from Figure 5 is for greatest reductions in peak discharge in response to ELJs in main channel reaches (Shreve stream order >10) in the lower and mid catchment. Distal headwater streams are likely to be neutral or slightly reduce peak discharge compared to headwater streams near the catchment outflow. However, within this general pattern there is a great deal of variability. The magnitude of change to peak discharge with ELJ insertion at the reach scale is proportional to neither reach length nor catchment area restored, suggesting that location within the catchment and the characteristics of the reach are more important than the number or extent of dams: the signal associated with geomorpological dispersion is dominant. For both types of forest restoration scenario with up to 22% of the channel network restored there is a small, and variable response in the hydrograph with the majority of model runs showing <±2% change in peak discharge.

There is a weak realtionship between slope and peak discharge response for short sections of restoration, with reaches with higher slopes tending to show little change to peak discharge (Figure 6). This is because higher slopes tend towards a kinematic type flood wave which is less susceptible to attenuation by hydraulic resistance (Sholtes and Doyle, 2011). Sturm (2001) suggests a slope

threshold of 0.001m/m represents the transition to a kinematic wave, in this study a slightly higher threshold of 0.005m/m represents the steepest slope where a measureable change in catchment scale flood peak magnitude is found with the use of ELJ and 0.008m/m in the case of forest restoration (Figure 6).

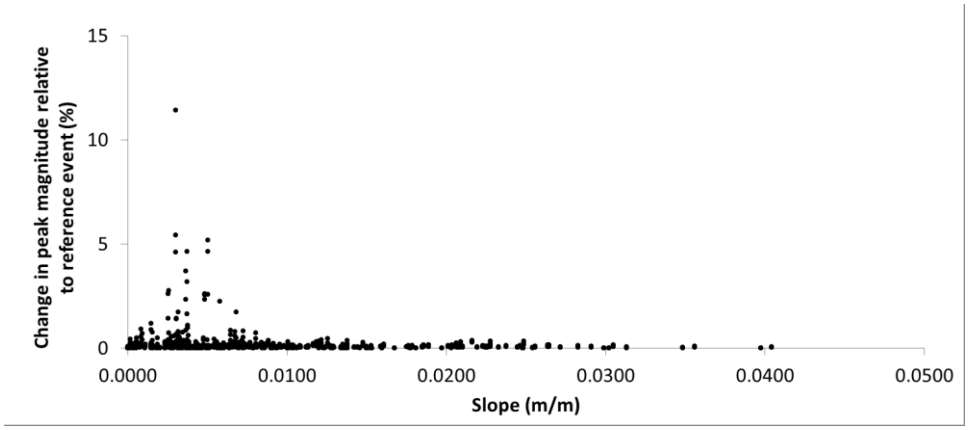

Figure 6 – Segment scale data for scenarios 2-4 (forest & channel hydraulic resistance changed) showing measurable change to flood peak discharge is only detected at shallower slopes of <0.008m/m

For scenarios of forest regeneration, those scenarios which show a decrease in peak magnitude also tend to show a larger decrease with older modelled forest age. As a riparian forest grows and moves through successional phases it progressively becomes more complex, this is expected to increase the hydraulic resistance to water flowing across the floodplain (Dixon, 2013). In addition, as trees age and die, they contribute increasing volumes of deadwood to the channel, which in turn becomes less mobile with more complex riparian forest (Dixon and Sear, 2014). The increasing hydraulic resistance of the channel and floodplain as the forest ages will increase overbank flow and flood wave travel time through the reaches, resulting in greater extension and translation of the sub-catchment hydrograph (Wolff and Burges, 1994). In the case of scenarios where forest restoration is paired with continued channel management of large wood, keeping in-stream large wood to pre-restoration levels, the attenuation affects are much less pronounced. Effectively without increases to in channel hydraulic resistance the restoration does not promote additional overbank flow, thus any attenuation effects will only occur in those locations which already experience overbank flow in the reference event

De-synchronising sub-catchment flood waves

For forest restoration applied on a sub-catchment basis and for 22-50% of the channel network there are large decreases in peak discharge up to 19% and these decreases scale with the proportion of network restored. In these cases the restoration is of sufficient extent to desynchronise the sub-catchment runoff contribution from the main catchment flood wave. Desynchronisation results in substantial decreases to peak discharge, particularly where sub-catchments are in the mid and upper part of the catchment. In these cases, the runoff contribution from the respective sub-catchments has been completely decoupled from the main hydrograph peak, resulting in the substantial reductions observed. These model findings are consistent with previous studies that suggest that up to 20% of the variability in peak flood discharge could be due to synchronisation of sub-catchment waves (Lane, 2003; Pattison et al., 2014). This is the first time forest growth effects have been included in the hydrological modelling of river restoration, and highlights one of the key benefits of modelling approaches over empirical studies.

For more extensive restoration scenarios (>50% of the network) there is a predictable decrease in flood peak magnitude, however this is less than for the sub-catchment scale scenarios. This may partly be a function of the catchment channel network and experimental design. There are four major sub-catchments of the Lymington River each around 25% of the channel network, thus when agglomerating smaller subcatchments into larger ones for our scenarios there are few options above 50% catchment area and so a relatively small sample size. In these cases the small magnitude decrease in peak discharge compared to single sub-catchment scenarios can be attributed to the effects of individual sub-catchment decoupling being complicated by the restoration of multiple sub-catchments. The remaining scenarios over 50% catchment extent are for restoration to all reaches of given stream orders. We hypothesise relative timing effects are a key control on changing flood magnitude, and with catchment wide restoration these are less important. For all larger extent scenarios hydrograph response is primarily due to attenuation effects upon the main flood wave traveling through the restored sections, rather than relative timing effects, hence the lower magnitude decreases in peak discharge.

The direction and magnitude of change to peak discharge for reach scale restoration depends on the location and extent of the restoration and the slope of the reach. The spatial pattern in hydrograph response can be explained conceptually by considering each reach segment as contributing a proportion of water to the main hydrograph. Reaches near to the catchment outflow will contribute water to the early part of the overall catchment outflow hydrograph. Conversely, given a rainfall

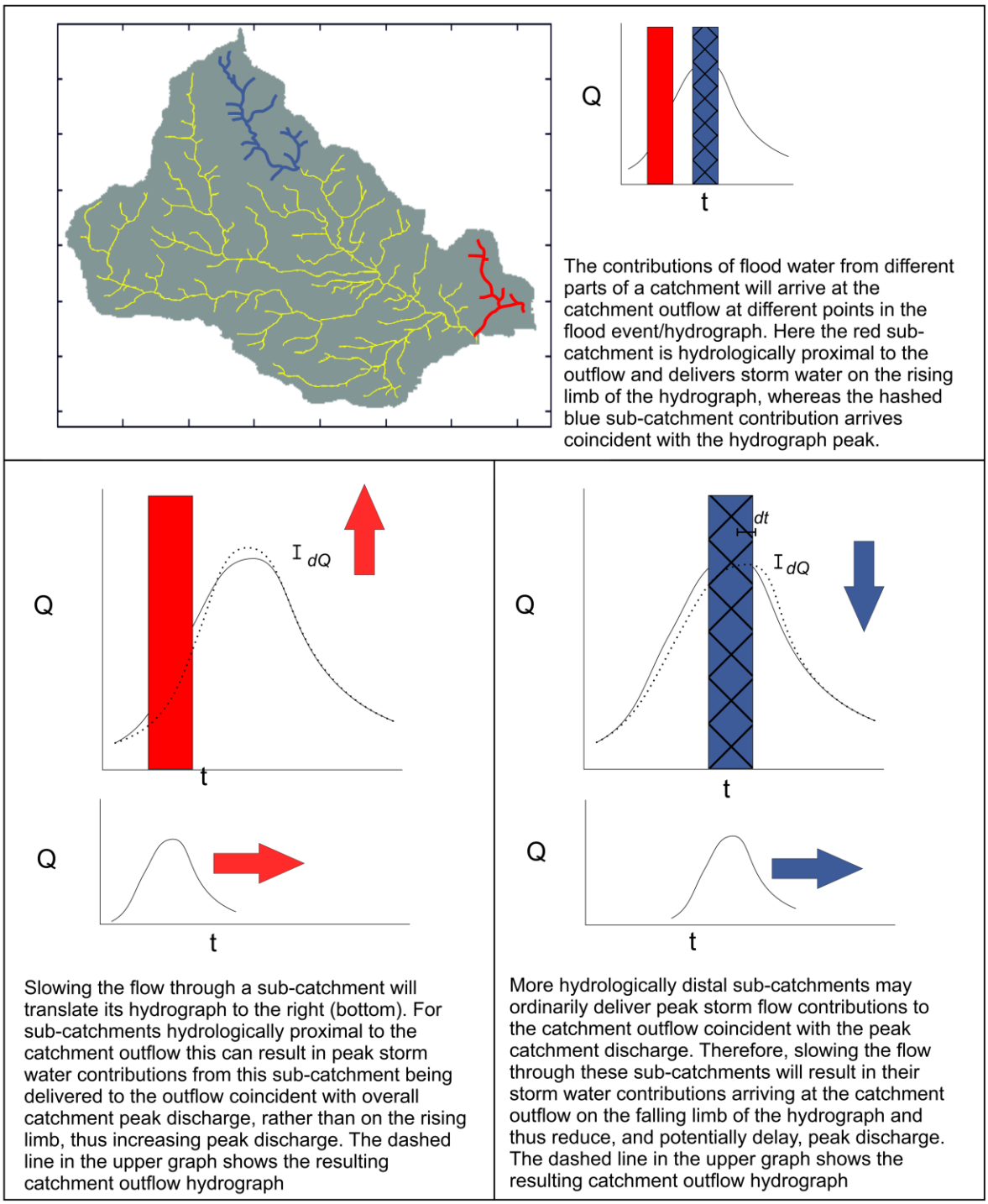

Figure 7 - Conceptual model illustrating the mechanisms behind the spatial variability in peak discharge response at the catchment outflow following restoration treatments applied to small areas of the catchment in different locations. In the simplified hydrographs Q is discharge and t is time.

event of sufficiently long duration the most distal reaches in the catchment will contribute water to the catchment outflow at, or near to the peak discharge (Saghafian and Julien, 1995). When a restoration scenario is applied to a reach the attenuation of the flood wave through increased

hydraulic resistance may either result in the extension of the contribution hydrograph, spreading the runoff over a longer timeframe, translation of the contributing hydrograph where the peak is shifted later in time, or a combination of the two.

The effect of extending or translating a contributing hydrograph from a reach or sub-catchment will vary depending upon where in the catchment network it is located (Figure 7). For hydrologically proximal locations the contributing flood wave will arrive at the catchment outflow quicker than the majority of the catchment runoff and thus will form part of the rising limb of the main hydrograph, and its contribution will have largely passed before the main peak discharge. If the contribution from one of these proximal location is sufficiently delayed it may become synchronised with the timing of the main flood wave and instead arrive at the catchment outflow coincident with the peak discharge, thus increasing peak discharge. This mechanism explains many of the model runs in which the restoration treatment was found to increase peak discharge. Conversely in the case of hydrologically distal reaches and sub-catchments, in sufficiently long rainfall events they will be delivering their peak contribution to the catchment hydrograph at equilibruim runoff (Saghafian and Julien, 1995), thus forming part of the main flood peak discharge. Extending, or delaying the contributing hydrograph will result in this runoff arriving during the falling limb of the main hydrograph, rather than at the peak, and will thus lower peak discharge. Although the hydrograph shapes in Figure 7 are conceptual, modelling restoration of the sub-catchment highlighted in dark blue resulted in up to a 5.90% reduction in peak discharge, whereas the red subcatchment resulted in up to a 1.42% increase in peak discharge. Note that these observations will be complicated by catchment scale: as catchment area increases, it is likely that the spatial extent and movement through time of individual rain events will complicate these findings because they will also influence the relative synchroneity of individual sub-catchments (Pattison and Lane, 2012).

Implications for river and catchment restoration

The findings of these empirical and modelling studies are important to help begin to unravel the complex interconnections between geomorphology, river restoration and land cover management at the catchment scale. Although the empirical work has demonstrated the efficicacy of logjams in localling slowing flood wave travel times and reducing flood peaks in small catchments (e.g. Gregory et al., 1985; Thomas and Nisbet, 2007; Thomas and Nisbet, 2012) the effects of forests on flooding remain a strongly debated issue (Van Dijk et al., 2009).

The most promising river restoration scenarios for mitigating flood risk are applying forest restoration at the sub-catchment scale (22-47% of channel network restored) in distal headwater

locations, this was found to result in a mean reduction to peak discharge of 10% after 25 years of forest growth and no in stream large wood management/removal. Conversely, ELJs were not found to be a predictable flood mitigation measure, particularly at the 1-5km reach based scale which represents the most popular form of river restoration. ELJs should not be used uncritically as a flood mitigation measure and would need detailed hydrological modelling during planning stages to assess the site specific hydrological response to restoration, particularly as they may exacerbate downstream flood peak magnitude.

Conclusions

Contributions from both field and modelling research support the potential for flood risk management based on restoration of channel morphology, large wood loadings (especially hydraulically effective logjams), and the management of riparian woodlands towards older growth stands. Behind these principles is the notion of geomorphological dispersion and that this can be manipulated through interventions that desynchronise the response of individual sub-catchments. We argue that because of the complex number and position of such interventions, a numerical modelling approach is needed if the potential of geomorphological dispersion in flood risk reduction is to be realised. Indeed, the results caution against wholesale uptake of the restoration measures that we test, suggesting instead the need for a more careful analysis of the spatial and temporal implications of such activity; in effect advocating more planned strategic approaches.

A key finding is that although both increases to in channel large wood loads and floodplain complexity at the reach scale is capable of attenuating local flood waves, the effect of this local attenuation at the catchment scale is highly variable. Generally, the implementation of river restoration using either engineered logjams or floodplain forest restoration in areas hydrological proximal to the main catchment outflow tends to increase flood peak discharge. Floodplain forest restoration in the upper and middle parts of the catchment tend to either decrease peak discharge at the catchment outflow, or have no effect. The spatial variability in response is due to changes in the timings of runoff contributions reaching the main catchment outflow relative to the timing of the main flood peak.

Engineered logjams inserted at the reach scale remain one of the most widespread forms of river restoration. Modelling results from this study indicate that engineered logjams applied to reaches of 1-5km will result in changes to flood peak magnitude of up to ±4%. In cases where floodplain vegetation is non-woody and the floodplain surface is not complex engineered logjams should not be expected to produce substantial flood attention effects as overbank flow is unlikely to be substantially

slower than that confined to the channel. This finding has important implications as the insertion of engineered logjams alone cannot be counted on to reduce flood risk at the catchment scale, despite documented local attenuation effects. Where engineered logjams are planned in a flood sensitive area, particularly in the lower portion of the catchment, detailed hydrological modelling should be conducted to determine the potential effects as they may actually make the situation worse not better.

Retoring floodplain forests and allowing these to naturally increase the quantity of large wood in the channel over time represent the most promising catchment restoration scenarios for balancing substantial reductions in flood risk and a relative ease of implementation. Where floodplain forest restoration is modelled at the sub-catchment scale with 10-15% of the catchment restored, reductions of up to 6% in peak discharge can be seen at the catchment outflow after 25 years of forest growth, with larger reductions in peak discharge as the forest ages up to 100 years. The largest overall reductions are seen for mature forest growth in sub-catchments representing 20-35% of the total catchment area where sub-catchment desynchronisation leads to reductions in peak discharge up to 20%.

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