

Natural Flood Risk Management

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<https://doi.org/10.1093/acrefore/9780199389407.013.320>

Published online: 25 January 2019

Summary

Flooding is a natural hazard with the potential to cause damage at the local, national, and global scale. Flooding is a natural product of heavy precipitation and increased runoff. It may also arise from elevated groundwater tables, coastal inundation, or failed drainage systems. Flooded areas can be identified as land beyond the channel network covered by water. Although flooding can cause significant damage to urban developments and infrastructure, it may be beneficial to the natural environment. Preemptive actions may be taken to protect communities at risk of inundation that are not able to relocate to an area not at risk of flooding. Adaptation measures include flood defenses, river channel modification, relocation, and active warning systems. Natural flood management (NFM) interventions are designed to restore, emulate, or enhance catchment processes. Such interventions are common in upper reaches of the river and in areas previously transformed by agriculture and urban development. Natural techniques can be categorized into three groups: water retention through management of infiltration and overland flow, managing channel connectivity and conveyance, and floodplain conveyance and storage. NFM may alter land use, improve land management, repair river channel morphology, enhance the riparian habitat, enrich floodplain vegetation, or alter land drainage. The range of natural flood management options allows a diverse range of flood hazards to be considered. As a consequence, there is an abundance of NFM case studies from contrasting environments around the globe, each addressing a particular set of flood risks. Much of the research supporting the use of NFM highlights both the benefits and costs of working with natural processes to reduce flood hazards in the landscape. However, there is a lack of quantitative evidence of the effectiveness of measures, both individually and in combination, especially at the largest scales and for extreme floods. Most evidence is based on modeling studies and observations often relate to a specific set of upstream measures that are challenging to apply elsewhere.

Keywords: natural flood management, catchment-based flood management, flood risk, hazard, hydrology

Subjects: Floods

Natural Flood Management

Flooding affects communities around the globe, damaging valuable assets built on floodplains and endangering life. Research indicates that flood risk is worsening globally as the value of floodplain assets grows and flood discharges increase (Hall et al., 2014). Risk is a product of a hazard with potential to cause destruction, exposure to the hazard, and vulnerability to the hazard. Here, the hazard is the type of flooding and its distinguishing features. The hazard may be characterized by flood magnitude, floodwater velocity and depth, flood duration, or water quality (Dadson et al., 2017). The nature of this flooding, however, is dynamic in both space and time. Land use changes, economic development, and climate change all affect the degree of flood risk

and scale of impact. That is not to say that the impacts of flooding are solely negative; as a natural process flooding brings ecological benefits that are essential to maintaining functional habitats. Balancing flood risks and benefits pose a great challenge for water resource managers, river managers, insurance companies, and conservationists.

This article will focus on the natural approaches (restoration and/or modification of non-anthropogenic features in the landscape) available to reduce flood hazards in a wide range of hydrological systems. The analysis will focus on fluvial, pluvial, groundwater, and coastal flooding (Table 1). “Coincident flooding” is a term used to describe when more than one type of flooding takes place simultaneously (Thorne, 2014).

Table 1. Types of Flooding

Flooding Type	Definition
Fluvial	Fluvial flooding occurs when the volume of water in the river channel exceeds the channel capacity. This may be caused by sustained or intense rainfall, increased runoff, or decreased channel capacity. It may also occur in response to rapid snow melt. Most research concerning reduced flood risk focuses on fluvial flooding.
Pluvial	Pluvial flooding (surface water flooding) affects areas where rainfall cannot be absorbed by the ground and so sits in large volumes on the impermeable surface.
Groundwater	Groundwater flooding is triggered by prolonged rainfall, which causes the groundwater table (the boundary between permanently saturated ground deep below the surface and shallow drier ground) to rise toward the surface. Groundwater flooding often emerges concurrently with fluvial and pluvial flooding.
Coastal	Coastal flooding is driven by storms and storm surges, sea level rise, or tsunamis. Human interventions to reduce coastal flooding differ widely from those in river systems.

Flood-generating mechanisms occur on different scales. In large catchments (1,000–30,000 km² and greater), flooding is generally caused by prolonged rainfall and snow melting over multiple days or weeks. The floods are long-lasting and are exacerbated by antecedent soil saturation. In comparison, flash floods occur in small catchments (100–1,000 km²) after short periods of intense, often localized precipitation. This flooding is intensified by steep slopes and shallow soils, both of which encourage low infiltration rates and fast hillslope runoff (Bronstert, Niehoff, & Burger, 2002). Owing to the heterogeneity of flood-generating mechanisms, flood-prevention methods must be carefully tailored to specific catchment properties.

There are two main approaches used to assess flood risk. Data-based, statistical methods are used to quantify and detect changes in the flood regime, whereas numerical or theoretical models seek to represent the hydrological system in order to produce forward estimates of flood risk based on

simulations. Observational data can be used together with hydrological and hydraulic models to simulate scenarios of flood inundation in different parts of the catchment (Bates & De Roo, 2000; Horritt & Bates, 2002). Gridded models permit examination of how flood characteristics are sensitive to changes in land use (O'Donnell, Ewen, & O'Connell, 2011), and Monte Carlo methods can be used to simulate extreme rainfall and to estimate the probability of flood events of different magnitudes. Successful investigations using these models rely on both accurate data and robust model parameters. Spatial dependencies between different river reaches within a catchment can also be explored using numerical models (Neal, Keef, Bates, Beven, & Leedal, 2013), and flood inundation models can be run with climate projections to estimate potential future flood hazards (Hall et al., 2003; Ramsbottom, Sayers, & Panzeri, 2012; Samuels, 2001). Such tools help flood managers identify the appropriate flood-management interventions to be implemented in the future to reduce flood risk.

Traditional flood risk-management methods seek to reduce the probability of flood inundation by structurally altering the natural environment. Examples include channel straightening and dredging, river damming, construction of levees and embankments, diversion spillways, and dykes built within the channel perpendicular to the river bank. However, such interventions can have high social, economic, and environmental costs. Modern flood risk management “involves responding sustainably to flood risk with portfolios of structural and non-structural measures” (Hall & Solomatine, 2008, p. 85). Consequently, recent research has included catchment-based flood management (CBFM) and natural flood management (NFM) among the approaches taken to reducing flood risk.

CBFM aims to manipulate how river flows move through the river basin, reducing flows in specific locations during periods of high flood risk. This can be achieved through structural and non-structural interventions that focus on optimizing “the balance between attenuation and tributary inputs” (Lane, 2017, p. 2). NFM is a subset of CBFM, which aims to reduce flood hazards using techniques that restore, emulate, or enhance catchment processes. NFM techniques are often beneficial to many stakeholders within the catchment, seeking to develop the river's riparian habitat, enrich floodplain vegetation, restore land drainage, alter land use, and improve land management. Much like CBFM, NFM aims to alter the movement of water within the river catchment. It does this by reducing runoff generation, storing floodwater, and slowing flow. By the coast, NFM seeks to reduce and dissipate wave and tidal energy, protect land adjacent to beaches, and lower water levels near hard-engineered defenses. Nature-based solutions (NBS) (European Commission, 2015) and working with natural processes (WWNP) (Cooper & McKenna, 2008; Everard, 2014) are similar schemes to NFM, promoting sustainable management that focuses on the environmental benefits of natural approaches to flood risk management. These techniques often work in harmony with structurally engineered flood defense mechanisms (UK Environment Agency, 2017b).

The premise of NFM is that the natural landscape has been altered to such an extent by human activities that attenuation has decreased, thus increasing the risk of flooding. NFM strives to restore the catchment so that it operates more as it might have done in its unmodified state, which in some cases may result in increased flood-wave attenuation and decreased flood risk.

Debate between scientists has emerged over the effectiveness of NFM at larger spatial scales (Lane, 2017). As the United Kingdom's Environment Agency point out in their Working with Natural Processes Study, it is very difficult to understand the effectiveness of natural flood measures at different spatial and temporal scales, and there is a widely noted need for more observational and modeled data to advance flood-management knowledge (Dadson et al., 2017; UK Environment Agency, 2017b). Numerous studies exploring the relationship between land management and downstream flood risk have shown that landscape heterogeneity plays an important role in determining which parts of the catchment are vulnerable to flooding and which generate flooding. This suggests that careful thought should be given to individual flood-management measures and their role in reducing flood risk at specific locations in the catchment. Pattison and Lane (2012) test the effect of the location and timing of land-management measures on flood risk, showing that flood risk response will vary depending on where the measure is located and when it is implemented. Caution is also urged (see, e.g., O'Connell, Ewen, O'Donnell, & Quinn, 2007) in the extrapolation of small field scale studies to infer changes in flood regime in larger catchments.

The aim of this article is to evaluate natural flood-management strategies, examine their relevance to different catchments and river basins, and identify the potential of NFM interventions on reducing flood risk while simultaneously producing social, environmental, and economic co-benefits. It draws on evidence from case studies located in the United Kingdom and overseas.

Water Retention Through Management of Infiltration and Overland Flow

Influence of Land Cover on Flooding

Global land cover has been evolving since prehistoric times as a result of climate change and anthropogenic activity. Human influence in particular contributes greatly to the changes in the landscape observed in the early 21st century. Intensified agricultural practices, upland and forestry management, and urbanization have caused changes to hydrological systems (Ferrier & Jenkins, 2009). For this reason, many hydrological studies have explored the impact of land use change and management on runoff generation, river discharges, and flood risk (Hess, Holman, Rose, Rsolova, & Parrott, 2010).

Runoff occurs either when the rate of precipitation exceeds the infiltration capacity of the soil surface or when the soil becomes saturated at the surface and produces runoff. Several hydrological texts cover runoff-generating processes in detail (Beven, 1987, 2012). Bronstert et al. (2002) present a comprehensive review of the relationship between flood runoff, rainfall, infiltration, and subsurface flow. It had been widely hypothesized that land use changes that increase surface runoff will increase flood risk. This is because changes to the land surface that reduce the lag time between water falling on the ground and reaching the river channel result in "flashier" flood hydrographs with higher flow peaks and short times to peak flow. Such changes to the land surface may include expansion of impermeable surfaces, introduction of bare and sparsely vegetated surfaces, or poor drainage of saturated soils. Several studies have explored the

role of land use change on flood frequency and magnitude. Crooks and Davies (2001) look into the effect of land use changes over a 30-year period on flood frequency in the Thames catchment, revealing minor changes in flood frequency with land use change. Wheeler et al. (2010) explore future drivers of flood risk, suggesting that land use change on a large scale has a bigger impact on flooding than small-scale changes. Solín, Feranec, and Nováček (2011) present a statistical approach to analyzing the relationship between flood frequency and land cover in Slovakia, testing the hypotheses that flood frequency increases with areas of greater land cover change and areas where land cover change accelerates direct runoff. The study's results indicate that as the area undergoing land cover change increases, the frequency of flood events also increases. This is particularly true for catchments with high flood potential. By using a conceptual rainfall-runoff model, Hundedcha and Bárdossy (2004) show that urbanization and afforestation alter peak catchment runoff under different land use and population scenarios, revealing a relationship between widespread urbanization and increasing peak flow in response to different rainfall events.

The effect of land cover on flood events varies considerably at different scales and is unique to each catchment (Pattison & Lane, 2012). Numerous studies have shown that at the local and small catchment scale, land use and land-management practices are capable of controlling runoff generation and moderating smaller magnitude floods (O'Connell, Beven, Clements, & Harris, 2004). However, success at this scale varies for extreme flooding events. Niehoff, Fritsch, and Bronstert (2002) show that the influence of land use conditions on storm runoff vary considerably across different spatial scales, with the type of rainfall event having more of an influence than land cover. For example, an intense convective storm will have a greater effect on small catchments, whereas a low-intensity, long-lasting advective storm will stimulate floods in larger catchments.

Orr and Carling (2006) also emphasize the need to distinguish between the effect of changes in land use and changes in the observed climate on the magnitude and frequency of flood events. Their study of the change in frequency of medium-sized floods throughout the 20th century indicates that land drainage was to blame for increased frequency before the 1970s, whereas rainfall variability had a greater influence after 1970. A similar study by Sullivan, Ternan, and Williams (2004) shows that for a predominantly agricultural catchment in southwest England, no single factor is responsible for increases in flood frequency, rather changes in climate, farming activity, and urban expansion have all played a role in transforming the catchment flood response.

Although it is difficult to quantify the impact of land use change on the water cycle, the knowledge gained from studies exploring this relationship allows regulators and planners to explore the capability of rural land use in mitigating flood risk (Mcintyre et al., 2013). The rest of this section will outline the natural flood-management measures that focus on reducing flood risk by managing water infiltration and overland flow and by retaining floodwater in the landscape.

Forest Type, Cover, and Management

The impact of forest type and tree cover on flooding has been explored widely in the United Kingdom, Europe, and North America, with several experimental studies at the catchment scale providing observational data for long time periods. Numerical models have also been used to simulate the effect of tree cover on flood events. Stratford et al. (2017) review 71 case studies that use observation data, model output, or both, to explore this relationship. In many cases, increased tree cover results in a decreased flood peak (23 of 36 studies), while decreased tree cover increases the flood peak (14 of 21 studies). This is attributed to improved interception and storage of water and decelerated movement of water. However, care needs to be taken when comparing different types of studies, as some observation-based studies (22 studies) suggested the opposite effect or no relationship between flood peaks and tree cover. This was especially true for observational studies that looked at the peak flows of large flood events in large catchments. Most studies that provided support for trees reducing floods were model based. Disparities in results between different studies may be due to lack of observed data to test models, inaccuracies in measurements of large peak flows, or external influences such as variability in rainfall, urbanization, or changes in agricultural practices (Stratford et al., 2017).

Forest type also plays a part in determining the characteristics of flood events. A European study by Robinson et al. (2003) focused on the influence of forestry on stream flows in 28 basins, seeking to identify critical situations most likely to cause flooding. Results indicate that the act of coppicing in eucalyptus plantations caused increases in peak flow and enhanced baseflow. This is caused by changes to soil structure and release of natural water-repellent chemicals from the eucalyptus plants. In contrast, European mixed broadleaf and Mediterranean open forests produce very few changes in flow dynamics. Much like other studies presented here, forest type has a smaller role to play in managing peak flow for larger catchments.

The Plynlimon and Coalburn experimental catchments in the United Kingdom have provided insights into the long-term role of upland plantations on hydrological systems. In the Plynlimon catchments, dense instrumentation of coniferous forest and grassland have allowed researchers to compare the role of each land use type on managing flood risk (Marc & Robinson, 2007). In contrast, the Coalburn experimental catchment has monitored hydrological responses to a change in land use from rough grazing to coniferous forest. The results from both studies suggest that forested areas reduce water yields compared to upland pastures (O'Connell et al., 2004) but only affect peak flows of small-scale floods. As Robinson and Newson (1986) report, peak flows during small and medium flood events may be lower in forested areas, but peak flows during larger floods show no difference between forested and grassland areas in Plynlimon. Similarly, moorland in Plynlimon demonstrates greater flow variability and flood pulses, especially in the summer, than nearby forested areas (Archer, 2007). Moreover, both the Plynlimon and Coalburn studies indicate that newly planted forests affect the hydrological cycle in very different ways than mature forests. This difference may affect the perceived value of trees in flood risk management. Robinson (1998) suggests that staged plantings that create tree stands of different ages would result in a forest structure that benefits both catchment hydrology and the wider

environment. Other co-benefits of woodland include carbon sequestration, improved ecology and wildlife, and improved water quality. Conversion of land from arable or pasture to woodland reduces the introduction of fertilizers and pesticides into riparian habitats.

Forest thinning, coppicing, and wildfire damage has also been shown to affect runoff generation. Forest thinning (removal of stems) in a Japanese cypress (*Chamaecyparis obtusa*) forest was shown to increase base flows and annual catchment runoff as a result of decreased interception and evapotranspiration (Dung et al., 2012). Likewise, clear-felling in a *Eucalyptus globulus* Labill watershed in North West Spain also resulted in increases to annual streamflow in the three subsequent years after the trees were removed (Fernández, Vega, Gras, & Fonturbel, 2006).

Forest roads can also intensify mean annual floods by increasing connectivity and decreasing surface roughness (Marche & Lettenmaier, 2001). This is because use of forest roads by heavy machinery can lead to soil compaction, reducing infiltration rates and increasing surface runoff. The literature in this field suggests that forestry operations and management decisions should be made with careful consideration of their effects on catchment hydrology.

Agricultural Practices and Soil Compaction

Poor agricultural management can lead to degraded soils and thus higher rates of runoff during periods of increased rainfall. Similarly, agricultural intensification is often accompanied by loss of hedgerows and increased slope lengths, thus affecting hydrological connectivity between farmland and downstream receptor areas (Posthumus, Hewett, Morris, & Quinn, 2008). In northwestern Europe, increases in flooding events have been attributed to the use of chemical fertilizers, decline in aggregate stability, and increase in field sizes. Agricultural land management can therefore play a role in flood risk management (McIntyre & Ballard, 2012).

One of the main approaches to reducing flood risk through agricultural management is to improve soil condition, improve soil storage capacity, and increase infiltration rates to maintaining high-quality, permeable soils (Hess, Holman, Rose, Rosolova, & Parrott, 2010). Large-scale modeling approaches can be used to assess the effect of agricultural soil management on the base flow index of catchments, testing different scenarios of soil structural degradation in river catchments. Results from a simulation model have shown that improved soil management may help to mitigate some of the adverse effects of projected warmer summers and cooler winters on local flood risk, with additional benefits like improved crop yields and reduced pollutant movement (Holman, Hess, & Rose, 2011). Some studies campaign for locally controlled soil management in an attempt to reduce soil degradation and surface runoff during flood events (Holman, Hollis, Bramley, & Thompson, 2003), but few studies have successfully demonstrated evidence for significant flood risk management benefits at larger catchment scales (Dadson et al., 2017; O'Connell et al., 2007). In fact, O'Donnell go as far as to suggest that local decisions on land management can be made without considering interactions outside of the immediate area because the impact of such actions will not be far reaching (O'Donnell et al., 2011).

Strategic management of vegetation type and the way in which it is harvested has also been explored as a strategy for managing flood risk, with the added benefit that it increases diversity in the agricultural landscape and improves soil quality through nutrient replenishment. A study into the effect of changes in land use on the Raccoon River, Iowa, on the likelihood of flood events revealed that converting some cropland to perennial vegetation such as switchgrass (*Panicum virgatum*) and extending crop rotations reduces the likelihood, number, and frequency of severe floods. These techniques have the additional benefit of ensuring crop production throughout the year (Schilling et al., 2014). The pattern of crop planting has also been attributed to reducing soil degradation; avoiding row crops may result in less soil erosion and therefore reduced surface runoff (Biielders, Ramelot, & Persoons, 2003). Flood risk can be further reduced through careful consideration of when crops should be planted and harvested. As Holman, Hollis, and Thompson (2000) found in their analysis of the 2000 UK floods, severe soil degradation occurred on 55% of all inspected sites where maize and sugar beet crops were harvested late. In contrast, only 25% of sites with grass, autumn-sown crops, and field vegetables showed signs of extensive degradation. This suggests that soil erosion can be mitigated by farmers carefully choosing when to harvest their crops based on the current and predicted weather conditions. Maintaining vegetative cover on soil during periods of intense, heavy, and sustained rainfall may also help to buffer surface runoff (Harris, Clements, Rose, Parkin, & Shepherd, 2004).

At the field scale, artificial open ditches and tramlines accelerate surface runoff and result in higher peak flows than subsurface drains. Farmers can mitigate this by introducing natural obstacles to the water pathway and excavating retention ponds at the base of fields to store overland flow. Grass strips, hedges, and vegetative buffers may also decelerate surface runoff (FRMRC, 2008; Posthumus et al., 2008).

Numerous catchment-scale investigations have explored the role of agriculture in reducing flood risk management. For example, the Pontbren Catchment Study monitored hydrological change in an agricultural catchment of the River Severn at plot ($\sim 100 \text{ m}^2$), field ($\sim 10,000 \text{ m}^2$), and catchment ($<12 \text{ km}^2$) scale. Observations indicated that grassland used for sheep grazing had much greater surface runoff volumes than adjacent sites without grazing, while the introduction of tree shelterbelts to the farmed land decreased overland flow by 60% and flood peaks by 10–40% due to increased interception and infiltration. The variability observed in the results was caused by orientation of the tree strips relative to the field slope and the narrow time frame of observations. The authors therefore acknowledged the need for longer-term monitoring in order to understand the impact of antecedent conditions (Jackson et al., 2008). Flow gauges were also used to determine streamflow response to different land-management regimes. Results indicate that the flashiness of rainfall-runoff response is closely linked to the proportion of improved grassland and area of land covered by lakes and ponds. Likewise, research in the Parrett and Tone catchments in South West England have exposed the extensive degradation caused by animal farming in the lowlands and crop farming in the upper parts of the catchment. Better drainage and improved soil quality may contribute to sustainable management in the uplands, so that infiltration can occur during times of heavy rainfall. In lower areas, flood retention ponds have a small potential to improve flood risk. The success of this, however, depends on the space available to retain water during periods of peak flow (McIntyre & Ballard, 2012).

Like all types of flood risk management, natural flood management requires engagement with local stakeholders to ensure that the measures put into place are maintained effectively and that they positively contribute to the local environment and ecosystem. This is particularly important for agricultural approaches, as land owners and farmers play a key role in NFM success. The Pontbren case study demonstrates the value of incorporating local knowledge into scientific research, helping to produce informative maps that expose areas of the catchment with the potential to mitigate floods and those that are at most risk to flooding. The maps can also be used to focus on co-benefits such as carbon and sediment management. The value of accessible education for farmers on flood management has been promoted globally, through the dissemination of advice on agricultural techniques to improve infiltration, maintain existing storage capacity, and reduce conveyance. Panel discussions with farmers, policymakers, environmentalists, and scientists have also proved useful in communicating messages of flood risk (Kenyon, Hill, & Shannon, 2008).

Upland and Peatland Management

Most studies investigating the impact of upland and peatland management are based in the United Kingdom using data from research catchments including Coalburn, Pontbren, and Plynlimon. This research, however, provides evidence that upland and peatland management is effective only at small catchment scales ($<20 \text{ km}^2$). It has not been possible, in the light of current evidence, to identify systematic effects on flood risk at larger catchment scales ($>100 \text{ km}^2$; Dadson et al., 2017).

The impact of upland drains has attracted attention among hydrologists and ecologists due to their transformation of upland hydrological systems and negative impact on biodiversity. Drains (referred to locally as grips) are used to remove excess water from heath and blanket bog in moorland and peatland areas. The drains improve connectivity through the flow network (Lane & Milledge, 2013; Marshall et al., 2009). Several studies have highlighted the impact of land drainage on headwater runoff in upland areas. A study in the Coalburn catchment revealed that threshold flow pulses increase significantly during and immediately after moorland drainage but subsequently decrease as the drained area is converted to forest. Both changes disturbed the instream habitat regime (Archer & Newson, 2002). In northern Europe artificial drainage of uplands pre-forest planting has also resulted in increased annual runoff and baseflows (Robinson, 1986).

The impact of surface roughness and vegetation cover on peatland flood runoff has also been explored, using both models (Gao, Holden, & Kirkby, 2014) and observational data (Grayson, Holden, & Rose, 2010). Results indicate that vegetation cover does influence river flow response to rainfall, with removal of vegetation creating exposed areas of bare peat that cause flashy, narrow-shaped hydrographs with higher peaks. A similar response is observed after heather burning, but only for the highest 20% of rainfall events; slower rainfall runoff was observed after light and moderate rainfall (Gao, Holden, & Kirkby, 2017). Drainage (grip) blocking is another method to reduce the risk of soil erosion and flash flooding in steep upland areas. In one study, blocking led to high and stable water tables, which were more resilient to drought conditions

(Wilson et al., 2011). Evidence suggests that the success of blocking is largely scale dependent, varying with different local conditions (drain smoothness, level of vegetation, slope gradient). In some instances drain blocking increased peak flows (Ballard, McIntyre, & Wheeler, 2012).

Blocking does, however, have significant co-benefits. It restores natural drainage patterns (to pre-1960s in upland Britain), encourages revegetation, and minimizes hydrological change downstream (RSPB, 2003). The water level in the land adjacent to the drains rises after blocking, encouraging the growth of peatland and moorland vegetation such as *Sphagnum*, *Narthecium ossifragum*, and *Drosera*. Biodiversity is also enriched as a result of increased invertebrate numbers. Dense groundcover of *Sphagnum* moss has since been identified as an effective measure to reduce flood peaks if located on gentle gradient slopes, providing out-of-channel storage during flood events (Gilman, 2002).

Urbanization and SuDs

Urbanization increases total surface area of impermeable surfaces, decreasing infiltration and causing rapid surface flow (Aronica & Lanza, 2005). A summary of the effect of urbanization on fluvial systems is provided by Chin, O'Dowd, and Gregory (2013). Flow along channelized streams and through drains is also heightened in urban areas, especially during intense convective storms. Flood risk in urbanized areas can be reduced by increasing conveyance of floodwaters in surrounding floodplains (MacDonald, Dixon, Newell, & Hallaways, 2012) and optimizing urban drainage systems (Aronica & Lanza, 2005). Green infrastructure has also proven successful in reducing flood risk, providing green spaces and environmental features that increase water-storage capacity of urban landscapes. Examples include parks and gardens, amenity greenspace, allotments, and green corridors (Natural England, 2009). It is important to note that the benefits of green infrastructure are context-dependent and often develop over time (Chu & Fenner, n.d.).

Sustainable drainage systems (SuDs) can be used to alleviate the problems caused by urbanization. SuDs work to (1) control water entering the urban area by intercepting rainfall to be used for irrigation (green roofs, water butts, vegetation corridors), (2) retain excess surface water by storing it in ponds and retention basins, and (3) encourage natural recharge through infiltration trenches and soakaways. An outline of how SuDs can be implemented is covered by the Construction Industry Research and Information Association (Woods Ballard et al., 2007).

Catchment Scale Management

Various projects have investigated the impact of local changes in land cover and land management on flood risk downstream (FRMRC, 2008; Mayes et al., 2006). Ferrier and Jenkins (2009), for example, provide a comprehensive synthesis of catchment-based approaches to managing and protecting water resources, addressing the interactions between land use change in coastal, lowland, and upland areas. However, several issues are apparent in the quest to understand the relationship between small-scale land management and catchment-scale effects. As Pattison and Lane (2012) discuss, the link between land management and flood risk is location dependent. Complexities emerge as a result of landscape heterogeneity and can therefore make

the conclusions drawn from individual case studies highly specific. That being said, certain modeling techniques can be used to gain a broad understanding of the casual links between land management, river catchments, and flood hydrographs. As Ewen, O'Donnell, Bulygina, Ballard, and O'Connell (2013) demonstrate, changes in land management can be modeled to investigate their impact on peak flow for different rainfall events throughout the year. Considerable efforts have also been made in the private sector to track back locations that are particularly important in shaping the flood hydrograph. This is especially important in identifying where in the catchment NFM interventions should be located (JBA Consulting, n.d.). Nevertheless, more information is needed at the small scale to improve representation of NFM interventions at the larger scale.

Managing Channel Connectivity and Conveyance

Geomorphic Processes, River Channel Form, and the Effects of Channel Modification

Fluvial flooding occurs when the amount of water entering a river exceeds the bankfull channel capacity. The net balance between erosion, transport, and deposition of sediment in the river channel can greatly influence the channel's capacity to convey flow. These properties combine to influence channel morphology, which is defined by cross-sectional size and shape, planform attributes, in-channel bar characteristic and length, and the presence and nature of bedforms. The interplay between channel morphology and flooding is the subject of many introductory texts on fluvial geomorphology, including classic works by Leopold, Wolman, and Miller (1965) and more recent introductory texts like Knighton (1984). Changes to this balance will modify channel morphology and as a result affect the pattern of water flow, riparian habitat structure and availability, floodplain processes, bank stability, and sediment motion (Arthington & Zalucki, 1998). Such changes may occur independently of or alongside climate-related changes in flood risk, and in some cases the two drivers of change may interact and exacerbate each other (Lane, Tayefi, Reid, Yu, & Hardy, 2007). An example of how to model channel geometry and simulate channel bankfull capacity is presented by Fewtrell, Neal, Bates, and Harrison (2011), who explore the impact of channel characteristics on floodplain inundation. Results indicate that channel long profile is more important than cross-sectional variability for model calibration.

It is widely accepted that if geomorphic processes like sediment delivery, flow frequency, and vegetation growth cause river channel capacity to decrease, flood hazards both locally and downstream will increase. Several studies have attempted to quantify the relationship between channel morphology and flood frequency. For example, Slater (2016) use data from 41 stream gauging stations in the United Kingdom to measure trends in flood stage frequency, comparing the trends to observations of geomorphic components. Results indicate that a 10% decrease (increase) in channel capacity would increase (decrease) flood frequency by ~1.5 days per year. Processes that encourage infilling of river channels or increase sediment delivery from agriculture also contribute to increases in decadal flooding. Likewise, Stover and Montgomery's (2001) analysis of river cross-section change in the Skokomish River in Washington State suggests that a gradual reduction in channel conveyance caused by aggradation of sediments

resulted in increased flooding over a 45-year period. A study of a river in upland Yorkshire also investigated the impact of increased sedimentation of flood flow. Over a period of 16 months, in-channel measurements identified an increase in flood inundation during the highest observed flows, which was closely linked to intensified deposition of coarse-grained sediment (Lane et al., 2007).

Flood-management measures can also focus on reducing sediment yield in subcatchments with high levels of agriculture. These measures can be important in areas where land cultivation has caused accumulation of sediments in drainage channels and rivers, reducing channel capacity and increasing flood risk. Henshaw (2009) recommend reducing the movement of sediment from farmland to river channels during peak flows by restoring woodland and hedgerows bordering fields. Ockenden, Deasy, Quinton, Surridge, and Stoate (2014) suggest constructing small field wetlands to slow and store runoff, which encourages sedimentation away from river channels.

For small flood events, channel morphology plays an important role in conveyance of floodwaters downstream. However, channel geometry affects conveyance differently during larger floods, because the floodplain and channel behave as a single unit. During the largest floods, bed and bank material can become mobile and channel morphology can change dramatically over short periods of time (Wong, Freer, Bates, Sear, & Stephens, 2014).

Historically, flood-control measures sought to increase the hydraulic gradient of rivers through widening, deepening, and straightening of the river channel. This “river training” resulted in increased conveyance of water; caused channel instabilities, erosion, and sedimentation problems; and amplified flood hazard downstream (Hall et al., 2014). Moreover, channel modification through channel regrading (removal of sediment to offset in-channel sedimentation) has been observed to have a negative impact on river habitat quality and aquatic biodiversity (Downs & Thorne, 2000; Janes et al., 2017). Natural flood measures can be designed to mitigate the consequences of overwidening and overdeepening the natural watercourse, seeking to reproduce some properties of the natural floodplain and restore the river to its pre-developed form (Darby & Thorne, 1996).

Channel adjustment and modification can have important effects on the hydraulic properties of the river and sedimentation. Thorne and Osman (1988) demonstrate how by lowering the river bed bank instability is increased, causing rapid bank retreat and increased sediment delivery downstream. The importance of setting sediment targets for modified river channels is discussed by Collins et al. (2011), who emphasize the pivotal role of sediment delivery to watercourses in maintaining the physical, chemical, and biological integrity of riverine ecosystems. Prevention of accelerated erosion and sediment delivery is often a stated target of flood-management measures that seek to reduce artificial disturbances in the natural flood regime. The role of sediment in fluvial environments and the tools that can be used to assess sediment-related problems in sustainable flood risk management are explored comprehensively by Thorne et al. (2010).

The NFM measures available to moderate the effects of channel modification are discussed here. Each measure focuses on retaining water in the landscape by managing connectivity and conveyance within the river channel and slowing the propagation of sediment and water downstream. Some measures work by increasing river–floodplain interaction to increase water

storage outside the channel, whereas other measures modify the channel to ensure flows remain within the river banks. These methods will be diminished in their impact during the highest-magnitude flows, when river discharge exceeds bankfull capacity (Hall et al., 2014).

Bank Stabilization

Bank erosion can be enhanced by human activity such as livestock management and vegetation control. Deposition of eroded bank material both locally and downstream can cause considerable problems to structures, human assets, and the riverine environment (Arthington & Zalucki, 1998). That is not to say that bank erosion should be stopped—it is a natural process that renews ecological habitats and dissipates river energy. Traditional river engineering measures focus on slowing or stopping bank erosion completely, but this can have detrimental consequences for river reaches downstream and riparian habitats. As Raven, Lane, and Bracken (2010) explain, in-channel feedbacks and ecological concerns are often important when directly altering channel conveyance and sedimentation, while bank erosion is in many circumstances accepted as a natural process that is necessary to restore watercourse pathways. Flood-management measures have recently sought a balance between controlling enhanced bank erosion (in areas of unnatural river widening) and encouraging natural bank erosion (in areas where river capacity has been reduced) (SEPA, 2008).

Developing an advanced understanding of the relationship between bank erosion rates, reach mean shear stress, sedimentation, and specific flow episodes is invaluable when managing bank erosion problems. As Lawler, Couperthwaite, Bull, and Harris (1997) demonstrate, understanding the natural controls of river bank erosion is vital in order to identify the best erosion-control measures for specific river sections. Methods to stabilize channel banks and moderate erosion have been reviewed comprehensively by the Scottish Environment Protection Agency (SEPA, 2008, 2012). Brushwood bundles, layering, and mattresses can all be used to stabilize banks, lining the river to slow the flow of water, trap silt and sediment, and stop shallow sliding. Woven stems can also provide bank protection from flowing water. Biodegradable geotextiles, such as coir, can be used to protect and stabilize bank sides by preventing soil outwash. The textiles are also designed to encourage plant growth by acting as a rooting base. Green toe protection (untreated timber and green materials) can be used to guard the foot of the bank from toe scour. For river reaches susceptible to high levels of sedimentation, NFM measures can be implemented to manage channel narrowing. These include removal of in-stream obstructions and re-establishment of morphological features within the channel. These nature-based bank-protection measures can often be cheaper than engineered alternatives and provide greater environmental benefits. They do, however, need to be installed with consideration of local river geomorphology and often need maintenance after high-energy events (SEPA, 2008).

River Restoration

River restoration strives to restore natural watercourses and physical processes that have been altered in the past. Restoration measures increase the sinuosity of the river, increase the ability for a river to flow onto the floodplain, and enhance the storage available for floodwater during periods of high flow. By doing this, water velocities during peak flow are reduced and downstream flood risk is lessened (UK Environment Agency, 2017b). Beechie et al. (2010) outline several process-based principles of river restoration that will help a river manager ensure the restoration project is sustainable and effective: the project must address the main causes of degradation; the project must be consistent with physical and biological characteristics of the section of river being restored; the restoration actions should be equal to the environmental problems caused by flooding; and the benefits of the restoration on ecosystem dynamics should be clearly outlined. This approach ensures that the stakeholders involved in the restoration can fully evaluate the trade-offs between ecological benefits, flood risk, and competing demands for use of the river.

Geomorphological models can be used to hypothetically predict river channel response to restoration. A study of a 5-km stretch of the River Cherwell in England revealed that peak flow could be reduced by 10 to 15% if the river and surrounding floodplains are restored to their pre-engineered dimensions. The restoration would increase inundation of the floodplain, consequently enhancing floodplain biodiversity (Acreman, Riddington, & Booker, 2003). Sear, Briggs, and Brookes (1998) suggest that river adjustment to pre-engineered dimensions largely relies on sediment availability, power to transport sediment within the flow of water, and the nature of the channel's morphology. Much like the studies described previously, this work emphasizes the need for site evaluation before implementing river-restoration measures due to the complexity and heterogeneity of river environments. More observational data at both local and catchment scales is needed to verify model findings and ensure that river restoration is suited for a specific stretch of river. Likewise, Downs and Thorne (2000) stress the importance of post-project monitoring to determine the success of restoration measures and if they satisfy the flood defense requirements of the surrounding area.

In the Czech Republic, river restoration has become an integral part of governmental attempts to rectify ecological damage caused by river degradation. Surveying of the Morava River Basin has helped to identify river sections to be restored and natural habitats to be enriched (Sterba et al., 1997). Similarly, research in the New Forest in England demonstrated the value of river restoration in small and medium-sized drainage basins, with a 21% reduction in flood peak being observed over a three-year monitoring period. An increase in pool habitat was also observed, as was an increase in the retention of floodwater within the catchment. No negative effects of the restoration were observed downstream (Sear, Kitts, & Millington, 2006).

Channel and Bank Vegetation

A large part of river bank and bed stabilization involves improving the volume and diversity of vegetation growing within the river channel and along the exposed banks. This can increase in-stream channel roughness, reducing flow velocity and encouraging sediment deposition. It also

binds soil together, thus reducing erosion of bank material. Seasonality can also have a significant impact on flow velocity, with a study based on the River Stour in England revealing that reduced vegetation cover instream and on the banks in colder, winter months can account for higher seasonal flows by up to 50% (Bates et al., 1998).

The importance of vegetation in controlling bank and bed erosion is presented by Solari et al. (2016). Their review evaluates a selection of models that assess the different ways that riparian vegetation can affect hydromorphology. The study demonstrates the value of morphological models and emphasizes the need to develop bank accretion and erosion models in order to fully understand riparian vegetation dynamics. Old et al. (2014) investigate the role of vegetation on flow in the River Lambourn, England, using a multidisciplinary approach to quantify instream and riparian responses to three weed cutting activities. Measurements suggest that weed cutting increased conveyance capacity of the river (by 89 to 141%) and river velocities in addition to mobilizing suspended sediment and reducing sediment retention within the channel.

Darby and Thorne (1996) express the need for a wider range of physically based methods that explore the relationship between vegetation growth on channel flow and flood capacity, presenting their own numerical hydraulic model that can be used to simulate stage-discharge curves of rivers with different vegetation and channel features. Likewise, Masterman and Thorne (1992) describe a theoretically based method to evaluate how changes in bank vegetation affect the discharge capacity of a channel. This is especially important when deciding if the benefits of stabilizing a river bank outweigh the negative impacts of reducing channel capacity. Results indicate that reductions in channel capacity only occur when the channel width-to-depth ratio is less than 16. An alternative approach to representing vegetation effects on channel surface roughness is proposed by Marjoribanks, Hardy, Lane, and Parsons (2014), with their three-dimensional model successfully replicating the key features of canopy flows in vegetated channels.

Riparian Buffer Strips

Riparian buffer strips can be introduced to the land bordering rivers as a measure to limit catchment sediment inputs into the channel and protect the freshwater environment from agricultural pollutants. Riparian buffer strips also work in similar ways to bank vegetation, protecting the river bank from erosion and sediment removal.

Broadmeadow and Nisbet (2004) explain how the structure of a riparian buffer strip (notably its width, vegetation type, and species) can be designed to effectively manage flood risk and improve habitat diversity in the riparian zone. A narrow riparian buffer protects physical and chemical properties of the stream, whereas wider strips also maintain ecological integrity. Replicating the structure and species of the riparian vegetation of surrounding land will ensure the strip does not disturb established plant communities already existing in the area. Plants and trees with deep roots should be introduced to stabilize the river bank and regulate the flow of nutrients to the aquatic environment, while falling leaf litter will feed the mulch under the canopy. Limited

observations also suggest that no more than half of the river's surface should be covered by the buffer's shade to maintain a good distribution of aquatic and marginal vegetation reliant on sunlight (e.g., benthic invertebrate populations; Broadmeadow & Nisbet, 2004).

In upland areas, the buffer strip should line both sides of the river and be as continuous as is feasible (Correll, 2005). Moreover, several zones (layers) of buffer vegetation will be most effective at filtering basin drainage. For example, a narrow strip of grass can trap small suspended particles, while a wide strip of woodland with deep roots will trap nitrate dissolved in water flowing through the surrounding soil. Owens et al. (2007) argue that the location of buffer strips is also important for trapping sediment and stopping contaminants entering the river channel. Linear buffers are not effective at trapping sediment in areas where erosion and overland flow are channelized. Instead, a reinforced buffer would provide more protection, especially during periods of high precipitation.

Riparian forest restoration has been shown to positively impact flood hydrology by de-synchronizing subcatchment flood waves and reducing the peak magnitude of flood outflow in both the middle and upper parts of the catchment. The largest reductions in peak discharge have been observed in riparian areas with mature forest growth and well-established floodplain complexity (Dixon, Sear, Odoni, Sykes, & Lane, 2016).

Large Wood and Beavers

Large wood (LW; leaky barriers) and beaver dams can reduce flood risk downstream by storing water and sediment in upper parts of the catchment. Both measures can increase local risk of flooding, requiring careful management.

LW can be used as barriers within the river channel or on floodplains. In channels it increases the frequency and extent of overbank flows, but it interferes with the flow of water, slowing water velocities and storing excess water on the floodplain (UK Environment Agency, 2017b). One co-benefit of LW is that sediment accretion on floodplains increases, dispersing nutrient-dense sediments from the channel to surrounding land (Jeffries, Darby, & Sear, 2003). However, habitats with low nutrient densities may not see a benefit from this intervention. On the Nisqually River in Washington State, wood jams play a key role in maintaining dynamic river morphology. Restoration of wood-depleted areas has shown that LW promotes channel migration and avulsion, but only when instream log jams are continually monitored and managed (Collins & Montgomery, 2002). Benefits of LW as a flood-management mechanism are observed by Abbe and Montgomery (1996) in the alluvial Queets River channel in Washington State, by Sear, Millington, Kitts, and Jeffries (2010) in tributaries of the Lymington River in southern England, and by Piégay and Gurnell (1997) in semi-natural river reaches in southeast France and southern England.

Beaver activity has been proposed by some as an effective, sustainable way to reduce flood risk downstream. Beavers can alter the distribution of large wood within the river system, developing complex flow pathways and networks (Gurnell, 1998). The construction of beaver dams has been shown to increase stream inflow to riparian areas, consequently increasing surface flooding

locally and raising the riparian water table (Hill & Duval, 2009). Downstream of beaver dams, reduced flows and sedimentation are common. This is because dam structures trap sediments and reduce stream velocity and discharge (Meentemeyer & Butler, 1999). Puttock, Graham, Cunliffe, Elliott, and Brazier (2017) investigate the impact of Eurasian beaver activity in a wooded site in Devon, South West England. Over a short period of time the beavers transformed the landscape, creating more storage for water flowing into the study site. Lateral redistribution of water also encouraged infiltration and evapotranspiration. Connectivity was reduced downstream of the dams and an increase in flood attenuation observed. Further work in the Devon area indicates that during dry periods baseflow is enhanced as a result of beaver activity, whereas storm flow is attenuated. Enhanced baseflow and increased attenuation could potentially reduce the risk of flooding downstream (Brazier et al., 2016).

In the event of beaver dam failure, river reaches can experience minor flood waves that may damage infrastructure in the flood's path (Butler & Malanson, 2005).

Co-benefits of Managing Connectivity and Conveyance

Water managers are often urged to consider the co-benefits of natural flood-management measures and how they will transform the river channel and adjacent riparian areas. For example, modifications to the flow regime will have a considerable effect on the structure and function of aquatic and riparian ecosystems. Before implementing NFM measures, the ecological limits of the hydrological alteration and the dynamic relationships between different features of the riparian habitat must be understood. Several methods have been proposed to do this, including the ELOHA framework of Poff et al. (2010), which assesses individual environmental flow needs to set sustainable environmental standards for different river types. This should be used to guide hydroecology and manage environmental flows sustainably at different spatial scales but can also aid water managers by ensuring that the co-benefits of NFM are realized.

Floodplain Conveyance and Storage

Floodwater Storage

As has been described in the previous sections, excess floodwater can be stored and slowed in upland areas using measures such as river restoration, afforestation, and revegetation. In lower parts of the catchment, engineered flood-management actions are commonly used to retain water, with detention reservoirs, embankments, and flood gates all working to slow the flow of water downstream. More natural flood measures can also work effectively to store water outside the river channel, in wetlands, floodplains, soils, and aquifer rocks. In order for an engineered management action to work successfully, the release of stored water should be timed so that it does not exacerbate the flood peak and so that the floodwater itself can be stored. NFM measures will do this naturally.

Offline storage measures store and release floodwaters in a controlled manner. Measures include ponds, wetlands, and soils. Decentralized storage and infiltration measures have been shown to counterbalance the effect of urbanization in meso-scale catchments, reducing the flood peak in areas where it would otherwise have increased due to changing land use (Bronstert et al., 2007). Salazar et al. (2012) demonstrate the effectiveness of decentralized micro-ponds and small reservoirs in reducing flood hazard for small to medium-sized events, with substantial ecological benefits emerging in farming areas with micro-ponds that help to moderate water quality.

The value of storage schemes has been closely examined by Lane et al. (2011) and Nisbet et al. (2015) in the long-term Pickering Scheme, which aims to “slow the flow” of floodwaters through the Pickering Beck catchment in North Yorkshire. The project is unique as it only uses management measures that benefit local communities. The measures are designed to carefully route rainfall across the hillslopes upstream of the town and increase storage areas in the surrounding floodplains through the use of small bunds that can retain water. The project demonstrated the importance of integrated land-management interventions that work to reduce flood risk at multiple scales. However, more observational data is needed to fully assess the long-term performance of the measures and their resilience to large-scale events.

Wetlands play an important role in the conveyance of floodwater, influencing the timing of peak flows, volume, and duration of floods (Acreman & Holden, 2013). They have been shown to lessen floods, recharge groundwater, and improve low flows, but they can also increase floods, block recharge, and enhance low flows. A meta-analysis of published evidence relating to the role of wetlands in the hydrological cycle indicates that for most studies from Europe, West Africa, and southern Africa, floodplain wetlands reduce or delay floods, while headwater wetlands increase flood peaks (Bullock & Acreman, 2003). Effective management of wetlands can enhance their ability to retain water during high-flow events, offering water managers an opportunity to maintain low water levels during flood periods and increase vegetation cover to decrease floodplain attenuation of flood waves. Wetlands offer considerable benefits to people and ecosystems, providing grazing for cattle, sequestering carbon, and providing space for recreational activities. Consequently, many world-wide policies have emerged to conserve wetland areas (Acreman et al., 2011).

Floodplain Cross Section and Capacity

Floodplains play a large role in flood management, with modification to the floodplain cross section transforming the propagation of flood waves downstream (Valentova, Valenta, & Weyskrabova, 2010). Flood defenses (embankments, levees) are often built on floodplains to protect encroaching urban development adjacent to the river channel. While these measures may adequately manage flood hazard locally, they can increase flood risk downstream, reduce the natural floodplain storage capacity, and increase water depth in the floodplain. Several studies have documented the effect of floodplain modification on flood risk. Vorogushyn and Merz (2013) investigate the role of river training in changes to daily flows in the Rhine River, revealing an acceleration of flood waves downstream as a result of a weir cascade, channelization, and dike heightening. Likewise, infrastructural adaptations designed to mitigate flood damage have been

used in the Mekong River Delta, with changes such as dredging, embankment raising, and upgrading roads extending inundation time by 5 to 10 days and propagating flood waves downstream. The effect of recent modification also had negative effects on other regions, increasing peak flood height and duration (Hoa, Shigeko, Nhan, & Cong, 2008).

Floodplain restoration reverts the floodplain to its natural state before any dredging works or embankment building was undertaken. Its aim is to restore the hydrological connectivity between the river and the floodplain, encouraging more natural inundation and enhancing storage (UK Environment Agency, 2017a). Restoration should be approached carefully, taking into consideration the hydrological and hydro-chemical regimes of the floodplain (Duranel, Acreman, Stratford, Thompson, & Mould, 2007) and anticipating the changes to river channel geometry after the floodplain morphology has been altered (Acreman et al., 2003). Acreman et al. (2000) demonstrate the effect of floodplain restoration on a stretch of the River Cherwell using hydrological and hydrodynamic models. Before restoration, river embankments caused an increase of flood flows downstream by 50–150%. After restoration, flood flows were reduced by 10–15%, and water levels within the floodplain increased by 0.5 m. Re-inundation of the floodplain is expected to bring ecological benefits to the land adjacent to the river.

Another approach to increase the capacity of floodplain storage is the “Room for the River,” which emerged from flood-management research in the Netherlands. The project aimed to make more space for floodwaters during peak flows by relocating dykes, lowering the floodplain, removing floodplain obstacles, and reducing the height of river groynes. The project successfully enhanced and lowered natural water levels during peak discharges, thus reducing flood risk (Haasnoot, Kwakkel, Walker, & ter Maat, 2013; Warner & van Buuren, 2011). The 2.2 billion euro program enabled a more integrated river basin management across the Rhine, Meuse, Waal, and IJssel catchments, combining multi-level governance and strategic policy planning (Rijke, van Herk, Zevenbergen, & Ashley, 2012). The “Room for the River” approach has since been included as an NFM measure in Lavers and Charlesworth’s (2017) opportunity mapping of the Warwickshire–Avon catchment.

Floodplain Roughness

In addition to increasing the volume of floodwater stored in floodplains, water managers can also slow floodwaters and dissipate flood energy by increasing the surface roughness of floodplains. The sensitivity of peak attenuation to surface roughness has been investigated by Hall, Tarantola, Bates, and Horritt (2005) and the use of different roughness analyses measures by Thomas and Nisbet (2016), Helmio (2002), Aronica, Bates, and Horritt (2002) and Werner, Hunter, and Bates (2005).

Increasing the surface roughness of a floodplain can be achieved through afforestation and by planting obstructive vegetation. Floodplain woodland (and associated large woody debris; Jeffries et al., 2003) has been shown to increase hydraulic roughness during periods of floodplain inundation, decrease water velocity, and slow downstream passage of a flood peak. As a result, the presence of floodplain woodland will extend the duration of a flood event but lower the impact of the event. Thomas and Nisbet (2007) found that vegetation type plays a key role on

frictional effect, with trees providing more resistance than smaller bushes that can flatten during high flow. Moreover, trees with lower-lying branches and dense undergrowth cover will have a greater effect on reducing flow than tall, smooth trees with few branches. Using one- and two-dimensional hydraulic models to represent a 2.2-km stretch of the River Cray in Somerset, Thomas and Nisbet (2007) showed that flood storage can be increased by up to 71% through woodland planting, while water levels can increase by 270 mm. The study also revealed that riparian and floodplain woodland will only be effective at reducing flood risk downstream if location and composition is chosen strategically.

Coastal Flooding

The duration and intensity of coastal flooding may worsen in the future with sea level rise, intensification of storms, and changes to the wave climate (Dawson et al., 2009; Richards, Mokrech, Berry, & Nicholls, 2008). It is imperative that coastal zones are protected against the increasing hazard of coastal flooding, with settlements lining cliff edges and low-lying hinterland becoming more at risk of erosion and inundation. As with flood-management measures further upstream in the catchment, land use and land management in coastal zones will play a key role in managing flood risk (Parrott, Brooks, Harmar, & Pygott, 2009).

Several hard engineering techniques have been used to mitigate the effects of coastal flooding. These include concrete sea walls, groynes, revetments, gabions, rock armor, and breakwater barriers. Although effective, the techniques have high capital and operating costs and are visually intrusive. NFM measures have become more popular in coastal regions in recent years as they offer a more natural, sustainable, visually subtle, and environmentally responsible solution.

Salt Marshes and Mudflats

Salt marshes and mudflats are found in many coastal areas, providing a natural barrier for land in the coastal zone by dissipating wave energy and storing excess floodwaters after stormy periods (Van Den Belt & Constanza, 2011). Intertidal mudflats are also distinct wetland habitats for coastal birds, while the marshes offer grazing area for livestock. Richards et al. (2008) have explored the value of salt marsh and coastal grazing marsh in two regions of the United Kingdom, highlighting the importance of coastal management in maintaining and protecting the natural coastal defense measures. The study recommends converting abandoned agricultural land to coastal and fluvial grazing marsh and allowing low-density urban areas to be inundated periodically through removal or abandonment of current defense systems. This would preserve older intertidal habitats and create new habitats that are at lower risk of climate change impacts. Areas with existing hard engineered flood defenses, such as sea walls, can also use salt marshes and mudflats as natural barriers that reduce the force of waves breaking onto the defense structure. As Vuik, Jonkman, Borsje, and Suzuki's (2016) study using the numerical wave model SWAN shows, vegetated salt marshes reduce the wave loads on coastal defenses and decrease inundation

depths within the intertidal zone during storms. Furthermore, maintaining salt marsh vegetation has been shown to reduce wave heights and energy (Bird, Hansom, & May, 2000), with as much as 60% of wave reduction caused by marsh vegetation (Möller et al., 2014).

Restoration of intertidal mudflats and salt marshes is encouraged in coastal areas with high levels of erosion. Methods should focus on enhancing the natural accretion of sediment in the intertidal zone, recharging sediment stores, and raising mudflat levels. For example, oyster reefs have been shown to increase silt levels behind reef barriers and dissipate wave energy along the Dutch coastline (Deltares, 2013).

Sand Dunes and Beach Management

Much like salt marshes and mudflats, sand dunes provide a natural barrier to tidal inundation, protecting existing flood defenses from wave damage and cliffs from erosion. The dunes also act as a sediment supply for beaches. Beaches can also be classed as a natural flood-management measure, as they too absorb wave and tidal energy before it reaches areas in land. To work effectively, beaches must be sufficiently wide and contain enough sediment to withstand impacts from storms and the sea. Beaches that are not sufficiently deep can be replenished with sediment brought in from another location, although this is a high-cost option (UK Environment Agency, 2017a). A more natural approach was adopted at Fylde Sand Dunes in Lancashire, England, positioning brush wood and old Christmas trees on dunes to encourage mobile sand accretion (Skelcher, 2008). Pioneering plants, such as couchgrass (*Elytrigia juncea*) and lyme grass (*Leymus arenarius*), can also be planted on dunes to bind surface grains and increase vegetation cover (Pye, Saye, & Blot, 2007). Adjacent to beaches, trees can be planted to further protect against coastal flooding, as seen along the coast near Delft in the Netherlands.

Advantages of NFM

The positive effects of natural flood management measures extend beyond the protection they provide against flood risks. The benefits can be seen throughout the catchment at multiple scales, encouraging water managers to consider NFM alongside traditional hard-engineering projects. A systematic meta-analysis of the co-benefits of NFM is presented by Iacob, Rowan, Brown, and Ellis (2014), revealing more co-benefits associated with wetland and floodplain restoration compared to increased woodland coverage and reversing historical drainage operations. The results also suggest that NFM proposals should be assessed on a case-by-case basis that carefully explores the location specific trade-offs between co- and dis-benefits of the NFM measure. This is particularly important when assessing the advantages of afforestation, with different types of forests yielding benefits in contrasting social and economic spheres (commercial woodland vs. natural woodland).

Moorland, river, wetland, and floodplain restoration yield many ecological benefits, enhancing terrestrial and aquatic biodiversity and sequestering carbon. In some cases, sustainable flood management policies led by natural and ecosystem performance have proved successful in minimizing flood risk and maximizing the co-benefits (Huq & Stubbings, 2015). River restoration

also modifies in-channel sedimentation, reducing sediment and pollutant delivery to the channel. Pollutant removal is particularly important for improving habitat quality, with more natural river reaches displaying more ecological benefits than unrestored water courses (Janes et al., 2017). Reduced soil erosion through restoration projects also has positive effects on instream and lake ecology.

Many NFM schemes are designed to enhance recreational value of the surrounding area, improving access to natural spaces for the general public. For example, tourism in recently restored woodland, beaches, and moorland has been shown to increase after restoration efforts (UK Environment Agency, 2017b), while retention ponds in upland areas can be maintained for recreational activities (Chen, Tsai, & Tsai, 2007). River restoration is also beneficial for anglers and walkers using the river banks (Downs & Thorne, 1998). A further advantage of NFM, if managed correctly, is the close cooperation established between communities, land owners, water managers, and policymakers during an NFM project. Because NFM has well-established principles of public participation and often has low initial and maintenance costs, it is often supported by a wide range of community members (Howgate & Kenyon, 2009). It is imperative that NFM measures be developed and implemented with the support of stakeholders, as the knowledge they can provide may reach far beyond that of an academic (McIntyre & Ballard, 2012). As Lane et al. (2011) demonstrate, the value of listening to the community at risk of flooding is key when developing a successful and accepted flood-management strategy.

The Current State of NFM and Moving Forward

This article has examined the value of natural flood-management measures at different spatial and temporal scales. Many NFM measures have been shown to effectively reduce flood risk at the local level during low to medium-scale flooding events. However, there is limited evidence to demonstrate the effectiveness of these measures at the catchment scale and during extreme flood events. A lack of up-to-date data at the catchment and national scale makes quantifying the success of flood-management strategies during flood events difficult, and a mismatch as to where measures are put in and where benefits are received occurs in several of the studies discussed here. An absence of sufficient research on the impact of NFM actions working together within the same area also limits current understanding (Dadson et al., 2017). Progress in this field can be made through maintenance and enhancement of monitoring systems at local, catchment, and national scales and building up data bases that capture flood events of different magnitudes. This is especially important for large flood events that occur less frequently.

The use of numerical models in flood risk research has progressed significantly in the last couple of decades, providing valuable tools to analyze flood events of the past and potential events in the future. Models that have previously represented small catchments should be developed to represent flood events in larger catchments, allowing practitioners to examine the effect of NFM measures on catchment hydrology under different climatological and socioeconomic scenarios. Improvements to NFM parameters will also improve functionality for use in other models. Model representations should be used to compare the impact of natural flood measures to their hard-engineered counterparts; analysis may prove invaluable for policymakers and water managers.

Long-term monitoring of NFM measures should be maintained well after the intervention is completed. Most studies presented here only observe the effect of NFM measures over short to medium timescales, and as a result the longevity and durability of NFM over time is relatively unknown. Uncertainties associated with intervention resilience and reliability are cause for concern among policymakers, particularly in environments vulnerable to climate change. More must be done to fully understand these uncertainties and the potential shortcomings of NFM measures beyond near-future timescales.

There is a need to establish effective communication between policymakers, water managers, academics, communities, and land owners. One way to improve this is for research groups to communicate and collaborate with other stakeholders to produce interdisciplinary work relevant to the many aspects of flood risk management. This will also contribute to understanding the complex relationships between terrestrial and aquatic systems throughout the catchment.

Conclusions

The discussion presented here should be used as an introduction to the potential contributions of natural flood management in mitigating flood risk. The reader should remember that, much like other approaches to flood management, NFM is highly scale- and time-dependent and should be implemented on a case-by-case basis.

NFM measures are unlikely to provide significant protection during large flood events and at large catchment scales because such measures seeking to store floodwater become less effective during periods of high rainfall when soils and other storage units are already saturated. A current research question concerns the extent to which NFM measures seeking to slow the water in one part of a catchment may exacerbate flooding in other parts of the catchment. Nevertheless, there are several advantages of NFM that emerge from the literature, particularly for small to medium-scale catchments. NFM interventions offer considerable local benefits for the environment and nearby communities. They are more sustainable than hard-engineered alternatives and are resilient to urbanization and future changes to the climate. NFM measures can have significant social benefits (e.g., boosting tourism) while also working effectively to reduce flood risk. This is achieved by providing extra space for floodwater, reducing peak flows, and lowering floodwater levels.

Further Reading

Dadson, S., Hall, J. W., Murgatroyd, A., Acreman, M., Bates, P., Beven, K., . . . Wilby, R. (2017). A restatement of the natural science evidence concerning catchment-based “natural” flood management in the UK <https://dx.doi.org/10.1098/rspa.2016.0706>. *Proceedings of the Royal Society*, 473, 1–34.

Lane, S. N. (2017). Natural flood management <https://dx.doi.org/10.1002/wat2.1211>. *Wiley Interdisciplinary Reviews: Water*, 4(3), 1–14.

UK Environment Agency. (2017a). *Working with natural processes—The evidence base* https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/654429/Working_with_natural_processes_summary.pdf.

UK Environment Agency. (2017b). *Working with natural processes to reduce flood risk—The evidence behind natural flood management*. <https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/654440/Working_with_natural_processes_one_page_summaries.pdf>.

References

Abbe, T. B., & Montgomery, D. R. (1996). Large woody debris jams, channel hydraulics and habitat formation in large rivers <[https://dx.doi.org/10.1002/\(SICI\)1099-1646\(199603\)12:2/3%3C201::AID-RRR390%3E3.0.CO;2-A](https://dx.doi.org/10.1002/(SICI)1099-1646(199603)12:2/3%3C201::AID-RRR390%3E3.0.CO;2-A)>. *Regulated Rivers Research Management*, 12, 201–221.

Acreman, M. C., Harding, R. J., Lloyd, C., McNamara, N. P., Mountford, J. O., Mould, D. J., . . . Dury, S. J. (2011). Trade-off in ecosystem services of the Somerset Levels and Moors wetlands <<https://dx.doi.org/10.1080/02626667.2011.629783>>. *Hydrological Sciences Journal*, 56(8), 1543–1565.

Acreman, M. C., Riddington, R., & Booker, D. J. (2003). Hydrological impacts of floodplain restoration: A case study of the River Cherwell, UK <<https://dx.doi.org/10.5194/hess-7-75-2003>>. *Hydrology and Earth System Sciences*, 7(1), 75–85.

Acreman, M., Crook, S., Glenney, C., Hewitt, N., Lucas, F., Packman, J., . . . Scholey, G. (2000). *Hydrological impact assessment: Modelling the impacts of floodplain restoration* <http://www.floodplains.org/pdf/technical_reports/Hydrological%20Impact%20Assessment%20draft1.pdf>. The Royal Society for the Protection of Birds.

Acreman, M., & Holden, J. (2013). How wetlands affect floods <<https://dx.doi.org/10.1007/s13157-013-0473-2>>. *Wetlands*, 33, 773–786.

Archer, D., & Newson, M. (2002). The use of indices of flow variability in assessing the hydrological and instream habitat impacts of upland afforestation and drainage <[https://dx.doi.org/10.1016/S0022-1694\(02\)00171-3](https://dx.doi.org/10.1016/S0022-1694(02)00171-3)>. *Journal of Hydrology*, 268, 244–258.

Archer, D. R. (2007). The use of flow variability analysis to assess the impact of land use change on the paired Plynlimon catchments, mid-Wales <<https://dx.doi.org/10.1016/j.jhydrol.2007.09.036>>. *Journal of Hydrology*, 347(3–4), 487–496.

Aronica, G. T., Bates, P. D., & Horritt, M. S. (2002). Assessing the uncertainty in distributed model predictions using observed binary pattern information within GLUE <<https://dx.doi.org/10.1002/hyp.398>>. *Hydrological Processes*, 16(10), 2001–2016.

Aronica, G. T., & Lanza, L. G. (2005). Drainage efficiency in urban areas: A case study <<https://dx.doi.org/10.1002/hyp.5648>>. *Hydrological Processes*, 19, 1105–1119.

Arthington, A. H., & Zalucki, J. M. (1998). *Comparative evaluation of environmental flow assessment techniques: Review of methods*. LWRDRC Occasional Paper 25/98. ISBN 0 642 26746 4.

Ballard, C. E., McIntyre, N., & Wheeler, H. S. (2012). Effects of peatland drainage management on peak flows <<https://dx.doi.org/10.5194/hess-16-2299-2012>>. *Hydrology and Earth System Sciences*, 16, 2299–2310.

Bates, P. D., & De Roo, A. P. J. (2000). A simple raster-based model for flood inundation simulation <[https://dx.doi.org/10.1016/S0022-1694\(00\)00278-X](https://dx.doi.org/10.1016/S0022-1694(00)00278-X)>. *Journal of Hydrology*, 236, 54–77.

- Bates, P. D., Stewart, M. D., Siggers, G. B., Smith, C. N., Hervouet, J. M., & Sellin, R. H. J. (1998). Internal and external validation of a two-dimensional finite element code for river flood simulations. *Proceedings of the Institution of Civil Engineers-Water and Maritime Engineering*, 130(3), 127–141.
- Beechie, T. J., Sear, D. a., Olden, J. D., Pess, G. R., Buffington, J. M., Moir, H., . . . Pollock, M. M. (2010). Process-based principles for restoring river ecosystems <https://dx.doi.org/10.1525/bio.2010.60.3.7>. *BioScience*, 60(3), 209–222.
- Beven, K. (1987). Towards the use of catchment geomorphology in flood frequency predictions <https://dx.doi.org/10.1002/esp.3290120109>. *Earth Surface Processes and Landforms*, 12, 69–82.
- Beven, K. (2012). *Rainfall-runoff modelling: The primer* <https://dx.doi.org/10.1002/9781119951001> (2nd ed.). Chichester, UK: John Wiley & Sons.
- Bielders, C. L., Ramelot, C., & Persoons, E. (2003). Farmer perception of runoff and erosion and extent of flooding in the silt-loam belt of the Belgian Walloon Region [https://dx.doi.org/10.1016/S1462-9011\(02\)00117-X](https://dx.doi.org/10.1016/S1462-9011(02)00117-X). *Environmental Science and Policy*, 6, 85–93.
- Bird, E. C. F., Hansom, J. D., & May, V. J. (2000). Saltmarshes. In J. D. Hansom & V. J. May (Eds.), *Coastal geomorphology of Great Britain* (754p). Geological Conservation Review Series, No. 28, Joint Nature Conservation Committee. Peterborough.
- Brazier, R. E., Puttock, A., Graham, H., Anderson, K., Cunliffe, A. M., & Elliott, M. (2016). Quantifying the multiple, environmental benefits of reintroducing the Eurasian Beaver <https://meetingorganizer.copernicus.org/EGU2016/EGU2016-7243.pdf>. *EGU General Assembly*, 18(1), EGU2016-7243.
- Broadmeadow, S. B., & Nisbet, T. R. (2004). The effects of riparian forest management on the freshwater environment: A literature review of best management practice <https://dx.doi.org/10.5194/hess-8-286-2004>. *Hydrology and Earth System Sciences*, 8(3), 286–305.
- Bronstert, A., Bárdossy, A., Bismuth, C., Buiteveld, H., Disse, M., Engel, H., . . . Ritter, N. (2007). Multi-scale modelling of land-use change and river training effects on floods in the Rhine basin <https://dx.doi.org/10.1002/rra.1036>. *River Research and Applications*, 23(10), 1102–1125.
- Bronstert, A., Niehoff, D., & Burger, G. (2002). Effects of climate and land-use change on storm runoff generation: Present knowledge and modelling capabilities <https://dx.doi.org/10.1002/hyp.326>. *Hydrological Processes*, 16, 509–529.
- Bullock, A., & Acreman, M. (2003). The role of wetlands in the hydrological cycle <https://dx.doi.org/10.5194/hess-7-358-2003>. *Hydrology and Earth System Sciences*, 7(3), 358–389.
- Butler, D. R., & Malanson, G. P. (2005). The geomorphic influences of beaver dams and failures of beaver dams <https://dx.doi.org/10.1016/j.geomorph.2004.08.016>. *Geomorphology*, 71(1–2), 48–60.
- Chen, C.-N., Tsai, C.-H., & Tsai, C.-T. (2007). Reduction of discharge hydrograph and flood stage resulted from upstream detention ponds <https://dx.doi.org/10.1002/hyp.6546>. *Hydrological Sciences Journal*, 21, 3492–3506.
- Chin, A., O'Dowd, A. P., & Gregory, K. J. (2013). Urbanization and river channels. In John F. Shroder (Eds.), *Treatise on geomorphology* (pp. 809–827). Elsevier/Academic Press.

- Chu, H. L., & Fenner, R. (n.d.). Green infrastructure evaluation <http://www.bluegreencities.ac.uk>. Delivering and Evaluating Multiple Flood Risk Benefits in Blue-Green Cities.
- Collins, A. L., Naden, P. S., Sear, D. A., Jones, J. I., Foster, I. D. L., & Morrow, K. (2011). Sediment targets for informing river catchment management: International experience and prospects <https://dx.doi.org/10.1002/hyp.7965>. *Hydrological Processes*, 25, 2112–2129.
- Collins, B. D., & Montgomery, D. R. (2002). Forest development wood jams, and restoration of floodplain rivers in the Puget Lowland, Washington <https://dx.doi.org/10.1046/j.1526-100X.2002.01023.x>. *Restoration Ecology*, 10(2), 237–247.
- Cooper, J. A. G., & McKenna, J. (2008). Working with natural processes: The challenge for coastal protection strategies <https://dx.doi.org/10.1111/j.1475-4959.2008.00302.x>. *Geographical Journal*, 174(4), 315–331.
- Correll, D. L. (2005). Principles of planning and establishment of buffer zones <https://dx.doi.org/10.1016/j.ecoleng.2005.01.007>. *Ecological Engineering*, 24(5), 433–439.
- Crooks, S., & Davies, H. (2001). Assessment of land use change in the Thames catchment and its effect on the flood regime of the river [https://dx.doi.org/10.1016/S1464-1909\(01\)00053-3](https://dx.doi.org/10.1016/S1464-1909(01)00053-3). *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere*, 26(7–8), 583–591.
- Dadson, S., Hall, J., Murgatroyd, A., Acreman, M., Bates, P., Beven, K., . . . Wilby, R. (2017). A restatement of the natural science evidence concerning catchment-based “natural” flood management in the UK <https://dx.doi.org/10.1098/rspa.2016.0706>. *Proceedings of the Royal Society*, 473, 1–34.
- Darby, S. E., & Thorne, C. R. (1996). Predicting stage-discharge curves in channels with bank vegetation [https://dx.doi.org/10.1061/\(ASCE\)0733-9429\(1996\)122:10\(583\)](https://dx.doi.org/10.1061/(ASCE)0733-9429(1996)122:10(583)). *Journal of Hydraulic Engineering*, 122, 583–586.
- Dawson, R. J., Dickson, M. E., Nicholls, R. J., Hall, J. W., Walkden, M. J. a, Stansby, P. K., . . . Watkinson, a. R. (2009). Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change <https://dx.doi.org/10.1007/s10584-008-9532-8>. *Climatic Change*, 95, 249–288.
- Deltares. (2013). *Eco-engineering in the Netherlands. Soft interventions with a solid impact*. The Hague: Ministry of Infrastructure and the Environment.
- Dixon, S. J., Sear, D. A., Odoni, N. A., Sykes, T., & Lane, S. N. (2016). The effects of river restoration on catchment scale flood risk and flood hydrology <https://dx.doi.org/10.1002/esp.3919>. *Earth Surface Processes and Landforms*, 41(7), 997–1008.
- Downs, P. W., & Thorne, C. R. (1998). Design principles and suitability testing for rehabilitation in a flood defence channel: The River Idle, Nottinghamshire, UK. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 8, 17–38.
- Downs, P. W., & Thorne, C. R. (2000). Rehabilitation of a lowland river: Reconciling flood defence with habitat diversity and geomorphological sustainability <https://dx.doi.org/10.1006/jema.2000.0327>. *Journal of Environmental Management*, 58, 249–268.
- Dung, B. X., Gomi, T., Miyata, S., Sidle, R. C., Kosugi, K., & Onda, Y. (2012). Runoff responses to forest thinning at plot and catchment scales in a headwater catchment draining Japanese cypress forest <https://dx.doi.org/10.1016/j.jhydrol.2012.03.040>. *Journal of Hydrology*, 444–445, 51–62.

- Duranel, A. J., Acreman, M. C., Stratford, C. J., Thompson, J. R., & Mould, D. J. (2007). Assessing the hydrological suitability of floodplains for species-rich meadow restoration: A case study of the Thames floodplain, UK <https://dx.doi.org/10.5194/hess-11-170-2007>. *Hydrology and Earth System Sciences*, 11(1), 170–179.
- European Commission. (2015). *Towards an EU research and innovation policy agenda for nature-based solutions and re-naturing cities: Final report of the Horizon 2020 Expert Group on Nature-based Solutions and Re-naturing Cities*. Brussels: Directorate-General for Research and Innovation.
- Everard, M. (2014). Integrating integrated water management <https://dx.doi.org/10.1680/wama.12.00125>. *Proceedings of the Institution of Civil Engineers-Water Management*, 167(9), 512–522.
- Ewen, J., O'Donnell, G., Bulygina, N., Ballard, C., & O'Connell, E. (2013). Towards understanding links between rural land management and the catchment flood hydrograph <https://dx.doi.org/10.1002/qj.2026>. *Quarterly Journal of the Royal Meteorological Society*, 139, 350–357.
- Fernández, C., Vega, J. A., Gras, J. M., & Fonturbel, T. (2006). Changes in water yield after a sequence of perturbations and forest management practices in an Eucalyptus globulus Labill. watershed in northern Spain <https://dx.doi.org/10.1016/j.foreco.2006.07.008>. *Forest Ecology and Management*, 234, 275–281.
- Ferrier, R. C., & Jenkins, A. (2009). *Handbook of catchment management* <https://dx.doi.org/10.1002/9781444307672> (560p). Wiley-Blackwell.
- Fewtrell, T. J., Neal, J. C., Bates, P. D., & Harrison, P. J. (2011). Geometric and structural river channel complexity and the prediction of urban inundation <https://dx.doi.org/10.1002/hyp.8035>. *Hydrological Processes*, 25, 3173–3186.
- FRMRC. (2008). *Impacts of upland land management on flood risk: Multi-scale Modelling methodology and results from the Pontbren experiment* (126p). Manchester. Flood Risk Management Research Consortium (FRMRC Research Report UR16, CEH Project number: C02699).
- Gao, J., Holden, J., & Kirkby, M. (2014). A distributed TOPMODEL for modelling impacts of land-cover change on river flow in upland peatland catchments <https://dx.doi.org/10.1002/hyp.10408>. *Hydrological Processes*, 29, 2867–2879.
- Gao, J., Holden, J., & Kirkby, M. (2017). Modelling impacts of agricultural practice on flood peaks in upland catchments: An application of the distributed TOPMODEL <https://dx.doi.org/10.1002/hyp.11355>. *Hydrological Processes*, 31(23), 4206–4216.
- Gilman, K. (2002). *Modelling the effect of land use change in the upper Severn catchment on flood levels downstream* (104p). English Nature. Peterborough.
- Grayson, R., Holden, J., & Rose, R. (2010). Long-term change in storm hydrographs in response to peatland vegetation change <https://dx.doi.org/10.1016/j.jhydrol.2010.06.012>. *Journal of Hydrology*, 389, 336–343.
- Gurnell, A. M. (1998). The hydrogeomorphological effects of beaver dam-building activity <https://dx.doi.org/10.1191/030913398673990613>. *Progress in Physical Geography*, 22(2), 167–189.
- Haasnoot, M., Kwakkel, J. H., Walker, W. E., & ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world <https://dx.doi.org/10.1016/j.gloenvcha.2012.12.006>. *Global Environmental Change*, 23, 485–498.

- Hall, J., Arheimer, B., Borga, M., Brázdil, R., Claps, P., Kiss, A., . . . Blöschl, G. (2014). Understanding flood regime changes in Europe: a state-of-the-art assessment <https://dx.doi.org/10.5194/hess-18-2735-2014>. *Hydrology and Earth System Sciences*, 18, 2735–2772.
- Hall, J. W., Evans, E. P., Penning-Rowsell, E. C., Sayers, P. B., Thorne, C. R., & Saul, A. J. (2003). Quantified scenarios analysis of drivers and impacts of changing flood risk in England and Wales: 2030–2100 <https://dx.doi.org/10.1016/j.hazards.2004.04.002>. *Environmental Hazards*, 5(2), 51–65.
- Hall, J. W., & Solomatine, D. (2008). A framework for uncertainty analysis in flood risk management decisions <https://dx.doi.org/10.1080/15715124.2008.9635339>. *International Journal of River Basin Management*, 6(2), 85–98.
- Hall, J. W., Tarantola, S., Bates, P. D., & Horritt, M. S. (2005). Distributed sensitivity analysis of flood inundation model calibration [https://dx.doi.org/10.1061/\(ASCE\)0733-9429\(2005\)131:2\(117\)](https://dx.doi.org/10.1061/(ASCE)0733-9429(2005)131:2(117)). *Journal of Hydraulic Engineering*, 131, 117–126.
- Harris, G. L., Clements, R. O., Rose, S. C., Parkin, A., & Shepherd, M. (2004). *Review of impacts of rural land use and management on flood generation. Impact study report. Appendix C: Current state of managed rural land and mitigation measures* (142p). Joint DEFRA/ EA Flood and Coastal Erosion Risk Management R&D Programme. R&D Technical Report FD2114/TR.
- Helmio, T. (2002). Unsteady 1D flow model of compound channel with vegetated floodplains [https://dx.doi.org/10.1016/S0022-1694\(02\)00197-X](https://dx.doi.org/10.1016/S0022-1694(02)00197-X). *Journal of Hydrology*, 269, 89–99.
- Henshaw, A. J. (2009). *Impacts of land use changes and land management practices on upland catchment sediment dynamics: Pontbren, Mid-Wales*. PhD Thesis. University of Nottingham.
- Hess, T. M., Holman, I. P., Rose, S. C., Rosolova, Z., & Parrott, A. (2010). Estimating the impact of rural land management changes on catchment runoff generation in England and Wales <https://dx.doi.org/10.1002/hyp.7598>. *Hydrological Processes*, 24, 1357–1368.
- Hill, A. R., & Duval, T. P. (2009). Beaver dams along an agricultural stream in southern Ontario, Canada: their impact on riparian zone hydrology and nitrogen chemistry <https://dx.doi.org/10.1002/hyp.7249>. *Hydrological Processes*, 23, 1324–1336.
- Hoa, L. T. V., Shigeko, H., Nhan, N. H., & Cong, T. T. (2008). Infrastructure effects on floods in the Mekong River Delta in Vietnam <https://dx.doi.org/10.1002/hyp.6945>. *Hydrological Processes*, 22, 1359–1372.
- Holman, I. P., Hess, T. M., & Rose, S. C. (2011). A broad-scale assessment of the effect of improved soil management on catchment baseflow index <https://dx.doi.org/10.1002/hyp.8131>. *Hydrological Processes*, 25, 2563–2572.
- Holman, I. P., Hollis, J. M., Bramley, M. E., & Thompson, T. R. E. (2003). The contribution of soil structural degradation to catchment flooding: A preliminary investigation of the 2000 floods in England and Wales <https://dx.doi.org/10.5194/hess-7-755-2003>. *Hydrology and Earth System Sciences*, 7(5), 754–765.
- Holman, I. P., Hollis, J. M., & Thompson, T. R. E. (2000). *Impact of agricultural soil conditions on floods—Autumn 2000* (36p). Joint DEFRA/ EA Flood and Coastal Erosion Risk Management R&D Programme. R&D Technical Report W5B-026/TR.

- Horritt, M. S., & Bates, P. D. (2002). Evaluation of 1D and 2D numerical models for predicting river flood inundation [https://dx.doi.org/10.1016/S0022-1694\(02\)00121-X](https://dx.doi.org/10.1016/S0022-1694(02)00121-X). *Journal of Hydrology*, 268, 87–99.
- Howgate, O. R., & Kenyon, W. (2009). Community cooperation with natural flood management: A case study in the Scottish Borders <https://dx.doi.org/10.1111/j.1475-4762.2008.00869.x>. *Area*, 41(3), 329–340.
- Hundecha, Y., & Bárdossy, A. (2004). Modeling of the effect of land use changes on the runoff generation of a river basin through parameter regionalization of a watershed model <https://dx.doi.org/10.1016/j.jhydrol.2004.01.002>. *Journal of Hydrology*, 292, 281–295.
- Huq, N., & Stubbings, A. (2015). How is the role of ecosystem services considered in local level flood management policies: Case study in Cumbria, England <https://dx.doi.org/10.1142/S1464333215500325>. *Journal of Environmental Assessment Policy and Management*, 17(04), 1–29.
- Iacob, O., Rowan, J. S., Brown, I., & Ellis, C. (2014). Evaluating wider benefits of natural flood management strategies: An ecosystem-based adaptation perspective <https://dx.doi.org/10.2166/nh.2014.184>. *Hydrology Research*, 45(6), 774–787.
- Jackson, B. M., Wheeler, H. S., McIntyre, N. R., Chell, J., Francis, O. J., Frogbrook, Z., . . . Solloway, I. (2008). The impact of upland land management on flooding: insights from a multiscale experimental and modelling programme <https://dx.doi.org/10.1111/j.1753-318X.2008.00009.x>. *Journal of Flood Risk Management*, 1, 71–80.
- Janes, V. J., Grabowski, R. C., Mant, J., Allen, D., Morse, J. L., & Haynes, H. (2017). The impacts of natural flood management approaches on in-channel sediment quality <https://dx.doi.org/10.1002/rra.3068>. *River Research and Applications*, 33, 89–101.
- JBA Consulting. (n.d.). *Natural flood management* <https://www.jbaconsulting.com>.
- Jeffries, R., Darby, S. E., & Sear, D. A. (2003). The influence of vegetation and organic debris on flood-plain sediment dynamics: Case study of a low-order stream in the New Forest, England [https://dx.doi.org/10.1016/S0169-555X\(02\)00325-2](https://dx.doi.org/10.1016/S0169-555X(02)00325-2). *Geomorphology*, 51, 61–80.
- Kenyon, W., Hill, G., & Shannon, P. (2008). Scoping the role of agriculture in sustainable flood management <https://dx.doi.org/10.1016/j.landusepol.2007.09.003>. *Land Use Policy*, 25, 351–360.
- Knighton, D. (1984). *Fluvial forms and processes* (E. Arnold, Ed.) (218p). Baltimore.
- Lane, S. (2017). Natural flood management <https://dx.doi.org/10.1002/wat2.1211>. *Wiley Interdisciplinary Reviews: Water*, 4(3), 1–14.
- Lane, S., Tayefi, V., Reid, S. C., Yu, D., & Hardy, R. (2007). Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment <https://dx.doi.org/10.1002/esp.1404>. *Earth Surface Processes and Landforms*, 32, 429–446.
- Lane, S. N., & Milledge, D. G. (2013). Impacts of upland open drains upon runoff generation: A numerical assessment of catchment-scale impacts <https://dx.doi.org/10.1002/hyp.9285>. *Hydrological Processes*, 27, 1701–1726.

- Lane, S. N., Odoni, N., Landström, C., Whatmore, S. J., Ward, N., & Bradley, S. (2011). Doing flood risk science differently: An experiment in radical scientific method <http://dx.doi.org/10.1111/j.1475-5661.2010.00410.x>. *Transactions of the Institute of British Geographers*, 36, 15–36.
- Lavers, T., & Charlesworth, S. (2017). Opportunity mapping of natural flood management measures: A case study from the headwaters of the Warwickshire-Avon <https://dx.doi.org/10.1007/s11356-017-0418-z>. *Environmental Science and Pollution Research*, 25(20), 19313–19322.
- Lawler, D. M., Couperthwaite, J., Bull, L. J., & Harris, N. M. (1997). Bank erosion events and processes in the Upper Severn basin <https://dx.doi.org/10.5194/hess-1-523-1997>. *Hydrology and Earth System Sciences*, 1(3), 523–534.
- Leopold, L. B., Wolman, M. G., & Miller, J. P. (1965). *Fluvial processes in geomorphology* (542p). San Francisco: W. H. Freeman & Co.
- MacDonald, D., Dixon, A., Newell, A., & Hallaways, A. (2012). Groundwater flooding within an urbanised flood plain <https://dx.doi.org/10.1111/j.1753-318X.2011.01127.x>. *Journal of Flood Risk Management*, 5, 68–80.
- Marc, V., & Robinson, M. (2007). The long-term water balance (1972–2004) of upland forestry and grassland at Plynlimon, Mid-Wales <https://dx.doi.org/10.5194/hess-11-44-2007>. *Hydrological Sciences Journal*, 11(1), 44–60.
- Marche, J., & Lettenmaier, D. (2001). Effects of forest roads on flood flows in the Deschutes River Basin, Washington. *Earth Surface Processes and Landforms*, 26, 115–134.
- Marjoribanks, T. I., Hardy, R. J., Lane, S. N., & Parsons, D. R. (2014). High-resolution numerical modelling of flow–vegetation interactions <https://dx.doi.org/10.1080/00221686.2014.948502>. *Journal of Hydraulic Research*, 52(6), 775–793.
- Marshall M. R., Francis, O. J., Frogbrook, Z. L., Jackson, B. M., McIntyre, N., Reynolds, B., . . . Chell, J. (2009). The impact of upland land management on flooding: Results from an improved pasture hillslope <https://dx.doi.org/10.1002/hyp>. *Hydrological Processes*, 23, 464–475.
- Masterman, R., & Thorne, C. R. (1992). Predicting influence of bank vegetation on channel capacity [https://dx.doi.org/10.1061/\(ASCE\)0733-9429\(1992\)118:7\(1052\)](https://dx.doi.org/10.1061/(ASCE)0733-9429(1992)118:7(1052)). *Journal of Hydraulic Engineering*, 118, 1052–1058.
- Mayes, W. M., Walsh, C. L., Bathurst, J. C., Kilsby, C. G., Quinn, P. F., Wilkinson, M. E., . . . Connell, P. E. (2006). Monitoring a flood event in a densely instrumented catchment, the Upper Eden, Cumbria, UK <https://dx.doi.org/10.1111/j.1747-6593.2005.00006.x>. *Water and Environment Journal*, 20, 217–226.
- McIntyre, N., & Ballard, C. (2012). *The potential for reducing flood risk through changes to rural land management: Outcomes from the Flood Risk Management Research Consortium*. In BHS Eleventh National Symposium, Hydrology for a changing world.
- McIntyre, N., Ballard, C., Bruen, M., Bulygina, N., Buytaert, W., Cluckie, I., . . . Wheeler, H. (2013). Modelling the hydrological impacts of rural land use change: Current state of the science and future challenges <https://dx.doi.org/10.2166/nh.2013.145>. *Hydrology Research*, 45(6), 737–754.
- Meentemeyer, R. K., & Butler, D. R. (1999). Hydrogeomorphic effects of beaver dams in Glacier National Park, Montana <https://dx.doi.org/10.1080/02723646.1999.10642688>. *Physical Geography*, 20(5), 436–446.

- Möller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., Van Wesenbeeck, B. K., . . . Schimmels, S. (2014). Wave attenuation over coastal salt marshes under storm surge conditions <<https://dx.doi.org/10.1038/NGEO2251>>. *Nature Geoscience*, 7(10), 727–731.
- Natural England. (2009). *Green infrastructure guidance. Report NE176* <<http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Green+Infrastructure+Guidance#0>>.
- Neal, J., Keef, C., Bates, P., Beven, K., & Leedal, D. (2013). Probabilistic flood risk mapping including spatial dependence <<https://dx.doi.org/10.1002/hyp.9572>>. *Hydrological Processes*, 27, 1349–1363.
- Niehoff, D., Fritsch, U., & Bronstert, A. (2002). Land-use impacts on storm-runoff generation: Scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany <[https://dx.doi.org/10.1016/S0022-1694\(02\)00142-7](https://dx.doi.org/10.1016/S0022-1694(02)00142-7)>. *Journal of Hydrology*, 267, 80–93.
- Nisbet, T., Roe, P., Marrington, S., Thomas, H., Broadmeadow, S., & Valatin, G. (2015). *Defra FCERM Multi-objective Flood Management Demonstration project; PROJECT RMP5455: Slowing the flow at Pickering; Final Report: Phase II* (p. 32). DEFRA.
- O’Connell, P. E., Beven, K. J., Clements, R. O., & Harris, G. L. (2004). *Review of impacts of rural land use and management on flood generation. Impact Study Report. Appendix A: Review of UK data sources relating to the impacts of land use and management on flood generation* (34p). Joint DEFRA/ EA Flood and Coastal Erosion Risk Management R&D Document. R&D Technical Report FD2114/TR.
- O’Connell, P. E., Ewen, J., O’Donnell, G., & Quinn, P. (2007). Is there a link between agricultural land-use management and flooding? <<https://dx.doi.org/10.5194/hess-11-96-2007>> *Hydrology and Earth System Sciences*, 11(1), 96–107.
- O’Donnell, G., Ewen, J., & O’Connell, P. E. (2011). Sensitivity maps for impacts of land management on an extreme flood in the Hodder catchment, UK <<https://dx.doi.org/10.1016/j.pce.2011.06.005>>. *Physics and Chemistry of the Earth*, 36, 630–637.
- Ockenden, M. C., Deasy, C., Quinton, J. N., Surridge, B., & Stoate, C. (2014). Keeping agricultural soil out of rivers: Evidence of sediment and nutrient accumulation within field wetlands in the UK <<https://dx.doi.org/10.1016/j.jenvman.2014.01.015>>. *Journal of Environmental Management*, 135, 54–62.
- Old, G. H., Naden, P. S., Rameshwaran, P., Acreman, M. C., Baker, S., Edwards, F. K., . . . Neal, M. (2014). Instream and riparian implications of weed cutting in a chalk river <<https://dx.doi.org/10.1016/j.ecoleng.2014.07.006>>. *Ecological Engineering*, 71, 290–300.
- Orr, H. G., & Carling, P. a. (2006). Hydro-climatic and land use changes in the river lune catchment, North West England, implications for catchment management <<https://dx.doi.org/10.1002/rra.908>>. *River Research and Applications*, 22, 239–255.
- Owens, P. N., Duzant, J. H., Deeks, L. K., Wood, G. A., Morgan, R. P. C., & Collins, A. J. (2007). Evaluation of contrasting buffer features within an agricultural landscape for reducing sediment and sediment-associated phosphorus delivery to surface waters <<https://dx.doi.org/10.1111/j.1475-2743.2007.00121.x>>. *Soil Use and Management*, 23(Suppl. 1), 165–175.

- Parrott, A., Brooks, W., Harmar, O., & Pygott, K. (2009). Role of rural land use management in flood and coastal risk management <<https://dx.doi.org/10.1111/j.1753-318X.2009.01044.x>>. *Journal of Flood Risk Management*, 2, 272–284.
- Pattison, I., & Lane, S. N. (2012). The link between land-use management and fluvial flood risk: A chaotic conception? <<https://dx.doi.org/10.1177/0309133311425398>> *Progress in Physical Geography*, 36(1), 72–92.
- Piégay, H., & Gurnell, A. M. (1997). Large woody debris and river geomorphological pattern: Examples from S. E. France and S. England <[https://dx.doi.org/10.1016/S0169-555X\(96\)00045-1](https://dx.doi.org/10.1016/S0169-555X(96)00045-1)>. *Geomorphology*, 19, 99–116.
- Poff, N. L., Richter, B. D., Arthington, A. H., Bunn, S. E., Naiman, R. J., Kendy, E., . . . Warner, A. (2010). The ecological limits of hydrologic alteration (ELOHA): A new framework for developing regional environmental flow standards <<https://dx.doi.org/10.1111/j.1365-2427.2009.02204.x>>. *Freshwater Biology*, 55, 147–170.
- Posthumus, H., Hewett, C. J. M., Morris, J., & Quinn, P. F. (2008). Agricultural land use and flood risk management: Engaging with stakeholders in North Yorkshire <<https://dx.doi.org/10.1016/j.agwat.2008.02.001>>. *Agricultural Water Management*, 95, 787–798.
- Puttock, A., Graham, H. A., Cunliffe, A. M., Elliott, M., & Brazier, R. E. (2017). Eurasian beaver activity increases water storage, attenuates flow and mitigates diffuse pollution from intensively-managed grasslands <<https://dx.doi.org/10.1016/j.scitotenv.2016.10.122>>. *Science of the Total Environment*, 576, 430–443.
- Pye, K., Saye, S., & Blott, S. (2007). *Management for flood and coastal defence, Part 4: Techniques for sand dune management*. Defra/Environment Agency R&D Technical Report FD1392/TR. London: Department for Environment, Food and Rural Affairs.
- Ramsbottom, D., Sayers, P., & Panzeri, M. (2012). *Climate change risk assessment for the floods and coastal erosion sector (244p)*. UK Climate Change Risk Assessment. Defra Project Code GA0204.
- Raven, E. K., Lane, S. N., & Bracken, L. J. (2010). Understanding sediment transfer and morphological change for managing upland gravel-bed rivers <<https://dx.doi.org/10.1177/0309133309355631>>. *Progress in Physical Geography*, 34(1), 23–45.
- Richards, J. A., Mokrech, M., Berry, P. M., & Nicholls, R. J. (2008). Regional assessment of climate change impacts on coastal and fluvial ecosystems and the scope for adaptation <<https://dx.doi.org/10.1007/s10584-008-9451-8>>. *Climatic Change*, 90(1–2), 141–167.
- Rijke, J., van Herk, S., Zevenbergen, C., & Ashley, R. (2012). Room for the river: Delivering integrated river basin management in the Netherlands <<https://dx.doi.org/10.1080/15715124.2012.739173>>. *International Journal of River Basin Management*, 10(4), 369–382.
- Robinson, M. (1986). Changes in catchment runoff following drainage and afforestation. *Journal of Hydrology*, 86, 71–84.
- Robinson, M. (1998). 30 years of forest hydrology changes at Coalburn: Water balance and extreme flows <<https://dx.doi.org/10.5194/hess-2-233-1998>>. *Hydrology and Earth System Sciences*, 2(2/3), 233–238.
- Robinson, M., Cognard-Plancq, a. L., Cosandey, C., David, J., Durand, P., Führer, H. W., . . . Zollner, a. (2003). Studies of the impact of forests on peak flows and baseflows: A European perspective <[https://dx.doi.org/10.1016/S0378-1127\(03\)00238-X](https://dx.doi.org/10.1016/S0378-1127(03)00238-X)>. *Forest Ecology and Management*, 186(1–3), 85–97.

- Robinson, M., & Newson, M. (1986). Comparison of forest and moorland hydrology in an upland area with peat soil. *International Peat Journal*, 1, 49–68.
- RSPB. (2003). *Farming for wildlife—GRIP blocking* (2p). Joint RSPB/ DEFRA publication.
- Salazar, S., Frances, F., Komma, J., Blume, T., Francke, T., Bronstert, A., & Blöschl, G. (2012). 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 <https://dx.doi.org/10.5194/nhess-12-3287-2012>. *Natural Hazards and Earth System Science*, 12(11), 3287–3306.
- Samuels, P. G. (2001). The European River Flood Occurrence and Total Risk Assessment System (EUROTAS <https://dx.doi.org/10.13140/2.1.2002.7682>). HR Wallingford. 60pp.
- Schilling, K. E., Gassman, P. W., Kling, C. L., Campbell, T., Jha, M. K., Wolter, C. F., & Arnold, J. G. (2014). The potential for agricultural land use change to reduce flood risk in a large watershed <https://dx.doi.org/10.1002/hyp.9865>. *Hydrological Processes*, 28(8), 3314–3325.
- Sear, D. A., Briggs, A., & Brookes, A. (1998). A preliminary analysis of the morphological adjustment within and downstream of a lowland river subject to river. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 8, 167–183.
- Sear, D. A., Kitts, D., & Millington, C. (2006). *New Forest LIFE-III Monitoring Report. The geomorphic and hydrological response of new forest streams to river restoration*. <http://www.newforestlife.org.uk/life3/pdfs/pdfs/9.16geomorphologicalmonitoringreport.pdf>. (185p). New Forest Life. School of Geography, University of Southampton.
- Sear, D. A., Millington, C. E., Kitts, D. R., & Jeffries, R. (2010). Logjam controls on channel: Floodplain interactions in wooded catchments and their role in the formation of multi-channel patterns <https://dx.doi.org/10.1016/j.geomorph.2009.11.022>. *Geomorphology*, 116, 305–319.
- SEPA. (2008). *Bank protection: Rivers and lochs*. Stirling, Scotland: Scottish Environment Protection Agency.
- SEPA. (2012). *SEPA position statement to support the implementation of the Water Environment (Controlled Activities) (Scotland) Regulations 2011*. Stirling, Scotland: Scottish Environment Protection Agency.
- Skelcher, G. (2008). *Fylde sand dunes management action plan*. Lytham St Annes, Lancashire, UK: Fylde Borough Council.
- Slater, L. J. (2016). To what extent have changes in channel capacity contributed to flood hazard trends in England and Wales? <https://dx.doi.org/10.1002/esp.3927> *Earth Surface Processes and Landforms*, 41(8), 1115–1128.
- Solari, L., Van Oorschot, M., Belletti, B., Hendriks, D., Rinaldi, M., & Vargas-Luna, A. (2016). Advances on modelling riparian vegetation–hydromorphology interactions <https://dx.doi.org/10.1002/rra.2910>. *River Research and Applications*, 32, 164–178.
- Solín, Ľ., Feranec, J., & Nováček, J. (2011). Land cover changes in small catchments in Slovakia during 1990–2006 and their effects on frequency of flood events <https://dx.doi.org/10.1007/s11069-010-9562-1>. *Natural Hazards*, 56, 195–214.

- Sterba, O., Mekotova, J., Krskova, M., Samsonova, P., Harper, D., Ecology, S. G., ... Forests, F. (1997). Floodplain forests and river restoration [<https://dx.doi.org/10.2307/2997747>](https://dx.doi.org/10.2307/2997747). *Global Ecology and Biogeography Letters*, 6(3/4), 331–337.
- Stover, S. C., & Montgomery, D. R. (2001). Channel change and flooding, Skokomish River, Washington [<https://dx.doi.org/10.1016/S0022-1694\(00\)00421-2>](https://dx.doi.org/10.1016/S0022-1694(00)00421-2). *Journal of Hydrology*, 243(3–4), 272–286.
- Stratford, C., Miller, J., House, A., Old, G., Acreman, M., Dueñas-Lopez, M. A., ... Tickner, D. (2017). Do trees in the UK-relevant river catchments influence fluvial flood peaks? [<http://nora.nerc.ac.uk/517804/7/N517804CR.pdf>](http://nora.nerc.ac.uk/517804/7/N517804CR.pdf). (46p). NERC Open Research Archive. Wallingford, UK: NERC/ Centre for Ecology & Hydrology.
- Sullivan, A., Ternan, J. L., & Williams, A. G. (2004). Land use change and hydrological response in the Camel catchment, Cornwall [<https://dx.doi.org/10.1016/j.apgeog.2003.11.002>](https://dx.doi.org/10.1016/j.apgeog.2003.11.002). *Applied Geography*, 24, 119–137.
- Thomas, H., & Nisbet, T. R. (2007). An assessment of the impact of floodplain woodland on flood flows [<https://dx.doi.org/10.1111/j.1747-6593.2006.00056.x>](https://dx.doi.org/10.1111/j.1747-6593.2006.00056.x). *Water and Environment Journal*, 21, 114–126.
- Thomas, H., & Nisbet, T. R. (2016). Slowing the flow in Pickering: Quantifying the effect of catchment woodland planting on flooding using the soil conservation service curve number method [<https://dx.doi.org/10.2495/SAFE-V6-N3-466-474>](https://dx.doi.org/10.2495/SAFE-V6-N3-466-474). In D. Proverbs (Eds.), *Flood Risk Management and Response*. WitPress (pp. 12–20). Birmingham City University, UK; C. A. Brebbia, Wessex Institute.
- Thorne, C. (2014). Geographies of UK flooding in 2013/4 [<https://dx.doi.org/10.1111/geoj.12122>](https://dx.doi.org/10.1111/geoj.12122). *Geographical Journal*, 180(4), 297–309.
- Thorne, C., & Osman, A. M. (1988). Riverbank stability analysis. II: Applications [<https://dx.doi.org/10.1061/\(ASCE\)0733-9429\(1988\)114:2\(151\)>](https://dx.doi.org/10.1061/(ASCE)0733-9429(1988)114:2(151)). *Journal of Hydraulic Engineering*, 14(2), 151–172.
- Thorne, C., Wallerstein, N., Soar, P., Brookes, A., Wishart, D., Biedenharn, D., ... Coulthard, T. (2010). Accounting for sediment in flood risk management [<https://dx.doi.org/10.1002/9781444324846.ch5>](https://dx.doi.org/10.1002/9781444324846.ch5). In G. Pender & H. Faulkner (Eds.), *Flood risk science and management* (pp. 87–113). Wiley-Blackwell.
- UK Environment Agency. (2017a). *Working with natural processes—the evidence base*. [<https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/654429/Working_with_natural_processes_summary.pdf>](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/654429/Working_with_natural_processes_summary.pdf).
- UK Environment Agency. (2017b). *Working with natural processes to reduce flood risk—The evidence behind natural flood management*. [<https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/654440/Working_with_natural_processes_one_page_summaries.pdf>](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/654440/Working_with_natural_processes_one_page_summaries.pdf).
- Valentova, J., Valenta, P., & Weyskrabova, L. (2010). Assessing the retention capacity of a floodplain using a 2D numerical model [<https://dx.doi.org/10.2478/v10098-010-0021-1>](https://dx.doi.org/10.2478/v10098-010-0021-1). *Journal of Hydrology and Hydromechanics*, 58(4), 221–232.
- Van Den Belt, M., & Constanza, R. (2011). Ecological economics of estuaries and coasts. In D. McLusky & E. Wolanski (Eds.), *Treatise on Estuarine and Coastal Science* (Vol. 12, pp. 1–14). Academic Press.
- Vorogushyn, S., & Merz, B. (2013). Flood trends along the Rhine: The role of river training [<https://dx.doi.org/10.5194/hess-17-3871-2013>](https://dx.doi.org/10.5194/hess-17-3871-2013). *Hydrology and Earth System Sciences*, 17(10), 3871–3884.

Vuik, V., Jonkman, S. N., Borsje, B. W., & Suzuki, T. (2016). Nature-based flood protection: The efficiency of vegetated foreshores for reducing wave loads on coastal dikes <<https://dx.doi.org/10.1016/j.coastaleng.2016.06.001>>. *Coastal Engineering*, 116, 42–56.

Warner, J., & van Buuren, A. (2011). Implementing room for the river: Narratives of success and failure in Kampen, the Netherlands <<https://dx.doi.org/10.1177/0020852311419387>>. *International Review of Administrative Sciences*, 77(4), 779–801.

Werner, M. G. F., Hunter, N. M., & Bates, P. D. (2005). Identifiability of distributed floodplain roughness values in flood extent estimation <<https://dx.doi.org/10.1016/j.jhydrol.2005.03.012>>. *Journal of Hydrology*, 314, 139–157.

Wheater, H. S., McIntyre, N., Jackson, B. M., Marshall, M. R., Ballard, C., Bulygina, N. S., . . . Frogbrook, Z. (2010). Multiscale impacts of land management on flooding <<https://dx.doi.org/10.1002/9781444324846.ch3>>. In G. Pender & H. Faulkner (Eds.), *Flood Risk Science and Management* (pp. 39–59). Wiley-Blackwell.

Wilson, L., Wilson, J., Holden, J., Johnstone, I., Armstrong, A., & Morris, M. (2011). The impact of drain blocking on an upland blanket bog during storm and drought events, and the importance of sampling-scale <<https://dx.doi.org/10.1016/j.jhydrol.2011.04.030>>. *Journal of Hydrology*, 404, 198–208.

Wong, J. S., Freer, J. E., Bates, P. D., Sear, D. A., & Stephens, E. M. (2014). Sensitivity of a hydraulic model to channel erosion uncertainty during extreme flooding <<https://dx.doi.org/10.1002/hyp.10148>>. *Hydrological Processes*, 29, 261–279.

Woods Ballard, B., Kellagher, R., Martin, P., Jefferies, C., Bray, R., & Shaffer, P. (2007). *The SuDS manual*. London: CIRIA.

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