

Annotated bibliography to accompany:

A restatement of the natural science evidence concerning catchment-based 'natural' flood management in the United Kingdom

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Paragraph numbers correspond to those in the main document: full references are given at the end. Website URLs were accessed on 16th September 2016.

(a) Introduction and aims

- (1) *Background* The complexity of flooding and flood risk management in a UK context is discussed by Sayers et al. (2002), Pattison and Lane (2012) and Thorne (2014) and, in a broader European context, by Hall et al. (2014). The process of Integrated Flood Management is introduced by WMO (2009), and a recent review of strategic flood management is given by Sayers et al. (2015a). The SEPA Natural Flood Management Handbook gives a recent, comprehensive introduction to the principles and application of NFM (SEPA, 2016). Examples of studies that have sought to draw together evidence from multiple investigations include the Foresight Project on Flood and Coastal Defence, described in Evans et al. (2004), Thorne et al. (2007), and Evans et al. (2008). The Flood Risk Management Consortium FRMRC (2004-2011) conducted research on multiple aspects of flooding, including field and model studies of land use and sediment impacts. FRMRC Fact Sheets, academic papers and technical reports may be downloaded from the FRMRC legacy website: <https://web.sbe.hw.ac.uk/frmrc/>.

The role of extreme events in shaping policy on flood management is scrutinized by Lane et al. (2013) and the use of risk-based decision-making to prioritize investments in reducing exposure to flooding is discussed in detail by Hall et al. (2005a) and Hall (2010). For some UK examples of groundwater flooding (in an urban context), see MacDonald et al. (2012). The effect of urbanization on flood risk in urban areas is covered by Miller et al. (2014) in a UK context. Coastal flooding and the effects of sea level changes are analysed by Dawson et al. (2005), Dawson et al. (2009), Dawson et al. (2011), and Hall et al. (2005b).

- (2) *Principles* Relevant hydrological principles are covered in introductory texts (Ward and Robinson, 1999; Shaw et al., 2011; Beven, 2012). The importance of scale in hydrology is articulated well by Dooge (1986), Blöschl and Sivapalan (1995) and, in relation to the effects of land cover on flooding, Blöschl et al. (2007). The relative importance of hillslope and channel network routing in hydrograph formation has been studied extensively as a function of catchment scale (e.g., Kirkby, 1976; Beven and Wood, 1993; Robinson et al., 1995; Botter and Rinaldo, 2003; D'Odorico and Rigon, 2003). Theoretical consideration of how hydrodynamic and geomorphic dispersion affect flood wave propagation can be found in Saco and Kumar (2002), Viglione et al. (2010), and Zoccatelli et al. (2015). An example of how this translates into flood hazard is provided for the UK by Pattison et al. (2014).
- (3) *Evidence* Multi-scale analyses of the effectiveness of interventions from plot to catchment scale are given by O'Connell et al. (2007) and McIntyre et al. (2013). Theoretical work on the decomposition of risk into its components: hazard, exposure and vulnerability is

summarized by Rougier et al. (2013), and discussed in detail in relation to flooding by Beven and Hall (2014).

- (4) *Aim* Further examples of studies in other fields in which the strength of scientific evidence is judged in order to inform policy are given by Godfray et al. (2013); Godfray et al. (2014).

(b) Meteorological drivers of flooding

- (5) *Meteorological data and trends* The UK hydrometric network is described in Dixon et al. (2013). Historical trends in rainfall since 1961 are described by Jones and Conway (1997) and Osborn et al. (2000). Analysis of upland and lowland precipitation is based on Burt and Holden (2010).
- (6) *River flow variability and trends* Several writers have sought to identify trends in river flow data (Mudelsee et al., 2003; Kundzewicz et al., 2005; Svensson et al., 2006). In the UK, there are several recent accounts of historical changes in runoff and river flows (Wilby et al., 2008; Hannaford and Marsh, 2008; Hannaford, 2015; Watts et al., 2015). Trends in daily maxima and 30-day maxima between 1960 and the early 2000s have been identified in some parts of the UK, notably the north and west (Hannaford and Marsh, 2008), who also comment on the continuity of these trends in earlier periods.
- (7) *Flood magnitude and frequency* The review by Hannaford (2015) is particularly comprehensive. The long-term study for the Thames is by Marsh and Harvey (2012).
- (8) *Flood-rich and flood-poor periods* Flood-rich and flood-poor periods during the twentieth century are identified by Wilby and Quinn (2013), Burt et al. (2015), and Foulds and Macklin (2015), in the context of prevailing weather types. The North Atlantic Oscillation (NAO) influences the pattern of wet winters and dry summers experienced in parts of the British Isles. The NAO is controlled partly by sea surface temperatures in the Atlantic Ocean, via the Atlantic Multi-decadal Oscillation (AMO). There is much recent work on the link between NAO and hydro-climatic regime in the UK (Hannaford and Marsh, 2008; Burt and Howden, 2013; Burt et al., 2015). The role of the North Atlantic Ocean in driving the pattern of anomalously wet summers in northern Europe since the 1990s is explained by Sutton and Dong (2012). Emerging evidence suggests that the North Atlantic may be affected by climate variability in the tropical Pacific (e.g., El Niño; Hoerling et al., 2001) and the stratosphere (explained by Scaife et al., 2005).

The role of atmospheric rivers in bringing anomalously wet winters is introduced by Lavers et al. (2011) who subsequently rule out any effect on summer precipitation (Champion et al., 2015). The effect of arctic sea ice on Northern Hemisphere circulation is documented by Cohen et al. (2014). The frequency of cyclonic conditions is analysed by Matthews et al. (2015). Slingo and

Palmer (2011) summarize the state of the art with respect to seasonal predictability in a UK context.

Evidence from the sedimentary record – in the form of boulder berm and debris flow deposits dated by using lichenometry – is catalogued by Macklin and Rumsby (2007) and interpreted in the context of recent UK flooding by Foulds and Macklin (2015).

- (9) *Climate change projections* Several recent reviews of the hydrological impacts of climate change are global in scope (Bates et al., 2008; Trenberth, 2011). The theoretical link between warming and precipitation is discussed by Allen and Ingram (2002). The most accessible review of the current state of the art is given by Watts et al. (2015), from which estimates of future precipitation changes quoted in this paragraph are taken. Several model-based results showing the projected effects of climate change on river flows are available (Prudhomme et al., 2012; Christerson et al., 2012; Kay et al., 2014; Kundzewicz et al., 2014) along with projections of future impacts on flood risk (Sayers et al., 2015b). Changes in the intensity of summer precipitation are investigated by Kendon et al. (2014) and reviewed in their broader context by Westra et al. (2014).

(c) The effects of land cover and land management on flooding

- (10) *Historical changes in land cover* The history of British forest is covered by Hoskins (1955) and Rackham (1976), and the palaeo-ecological basis for reconstructing land cover during pre-historic times is summarized by Roberts (1998). Modern data on land cover in Great Britain are from Fuller et al. (1994) and Morton et al. (2011). Land management practices are widely known to affect the magnitude and timing of runoff generation in the local vicinity (Ferrier and Jenkins, 2009).
- (11) *The influence of land cover on flooding* International studies indicate a link between land cover and hydrological response (De Roo et al., 2003; Oudin et al., 2008). Nonetheless, in large UK catchments the influence of land-cover on flood peaks is hard to discern (e.g., in the Thames, Crooks and Davies, 2001). Extensive analysis of the impact of catchment properties on flooding is contained within the Flood Studies Report and the Flood Estimation Handbook (Natural Environment Research Council, 1975; Institute of Hydrology, 1999). More recent studies include the EPSRC-funded FRMRC projects and NERC-funded Flooding from Intense Rainfall projects, which are summarized in (1).
- (12) *Effects of forest cover* Houghton-Carr et al. (2013a) and Houghton-Carr et al. (2013b) provide a rapid evidence assessment for the effects of forest cover on water balance. See Marc and Robinson (2007) for a comprehensive review of the Plynlimon catchment experiments. Further information is also given in Hudson and Crane (1997) and Howe et al. (1967).
- (13) *Timber harvesting; forestry operations* Findings relating to timber harvesting and its effects on flood peaks are documented by Robinson and Dupeyrat (2005). Time-dependent effects of plantation forestry have been noted in many settings (e.g., Hudson and Crane, 1997; Scott and Prinsloo, 2008). Robinson et al. (2003) review the effects of forestry in several European settings. Effects of timber harvesting on stream flows through soil compaction, construction and use of forest roads, and changes in vegetation are documented by Jones and Grant (1996), while scale dependence is shown by Dung et al. (2012). Results from the Balquhiddy and Coalburn experiments are described by Johnson (1995) and Robinson (1998), respectively. The effects of mature forest and simulations of peak flows at Coalburn are reported in Birkinshaw et al. (2014).

- (14) *Impact of agricultural practices* Modern trends in agricultural practices are reviewed by Wheeler and Evans (2009) and Burgess and Morris (2009). For comprehensive reviews of the impacts of land management on flood generation see O'Connell et al. (2004), Beven et al. (2006), O'Connell et al. (2007) and Lane et al. (2007a). The total number of sheep and lambs in England peaked in 1990 at 20.8 million and has since declined by approximately 27%; over the same period the number of cattle and calves has declined by approximately 20% to 5.4 million (DEFRA, 2016). The effects of pasture and arable management practices on soil structural degradation in local cases are documented by Holman et al. (2003). Several studies have examined the impacts of agriculture on local-scale runoff production (Heathwaite et al., 1989; Heathwaite et al., 1990; O'Connell et al., 2004) and specifically in flood generation (Boardman et al., 1994; Boardman et al., 2003).
- (15) *Impact of land drainage* Comprehensive data on the effects of land drainage on river flows are compiled by Robinson (1990) and reviewed by Robinson and Rycroft (1999). A summary of the state-of-the-art and a list of studies into the effects of drainage is given by CREW (2012). The impact of agricultural drainage on historical channel network extent is documented by Ovenden and Gregory (1980). The key practitioner reference work is Buisson et al. (2008).
- (16) *Soil compaction* O'Donnell (2007) used modelling to explore the possible effect of soil compaction in the Scandal Beck sub-catchment of the River Eden on downstream flood flows. The survey of soil compaction in arable and grassland plots in south-west England by Palmer and Smith (2013) shows that the effects of intensive farming depend on soil and crop type. The studies on soil compaction at Pontbren are by Marshall et al. (2009) and Marshall et al. (2014).
- (17) *Upland and peatland impacts* The complexities of managing peat in uplands are reviewed by Holden et al. (2004), Holden (2005), Acreman and Holden (2013), and O'Connell et al. (2007). Specific details of runoff production mechanisms in upland areas are outlined in Evans et al. (1999), Holden and Burt (2003), and Holden (2008). The study on overland flow velocities across peat surfaces was conducted by Holden et al. (2008) and the 11.4 km² catchment study at Trout Beck in the North Pennines was by Grayson et al. (2010). Modelling studies highlighting the importance of surface roughness in upland peatlands include Ballard et al. (2011), Lane and Milledge (2013), and Gao et al. (2015) while experiments on spatial sensitivity to surface roughness within headwater catchments were conducted by Gao et al. (2016). The study of heather burning by Holden et al. (2015) compared five catchments with and five without patch burning, examining differences in peat properties, water tables and streamflow response to rainfall. The Exmoor Mires Project has demonstrated the benefits for ecosystem services (e.g., water and carbon storage and improvements to water quality) that can arise from the restoration of peatlands (Grand-Clement et al., 2013).
- (18) *Upland ditch blocking* Ramchunder et al. (2009) investigated the effectiveness of drain blocking. Lane and Milledge (2013) quantify the effects of upland drains on downstream flood risk. The simulation study by Ballard et al. (2012) looked in detail at when drain blocking can be effective in upland peat catchments while the other modelling studies indicate the importance of surrounding peat surface roughness (Ballard et al., 2011). The Peak District peatland revegetation and gully blocking study was documented in detail by Pilkington et al. (2015).
- (19) *Impacts of urbanization and Sustainable Drainage Systems (SuDS)* Urban surfaces are often assumed to be highly impervious thus converting large proportions of rainfall into surface runoff. However, empirical studies have demonstrated that the hydrological properties of urban surfaces depend on the type of surfacing and its condition with potentially complex, seasonally variable hydrological behaviour shown for some surfaces. The

hydrological properties of different urban surfaces are covered by Mansell and Rollet (2006). Kjeldsen (2009) gives some examples of current approaches to flood frequency estimation in urban areas. Urban flooding during extreme summer convective storms was typified by the Summer 2007 floods in England and Wales (Marsh and Hannaford, 2007). Several studies have evaluated the role and effectiveness of Sustainable Drainage Systems (Smith et al., 2002; Nelson et al., 2006). The definitive technical work is The SuDS Manual (Woods Ballard et al., 2015) published by the Construction Industry Research and Information Association (CIRIA; ciria.org). The multiple-benefits of restoring natural functions in urban drainage systems and watercourses as part of 'Blue-Green' approaches to urban flood risk and water management have received attention in research and practice-led consortia (<http://www.bluegreencities.ac.uk/>; <http://bgd.org.uk/>).

- (20) *Catchment-scale effects of land management practices* McIntyre and Thorne (2013) give a comprehensive review of the effects of land management on flooding. The conceptual difficulties associated with the extrapolation of results from one site and scale to another are discussed by several scholars (Blöschl et al., 2007; Viglione et al., 2010; Pattison and Lane, 2012), and results from numerical simulations reinforce this apparent complexity (Dunn and Mackay, 1995; Ewen et al., 2013). O'Connell et al. (2007) reviews how local-scale changes propagate downstream, both individually and collectively, and several catchment-scale demonstrations have been documented in the literature (Marshall et al., 2009; McIntyre et al., 2012; McIntyre et al., 2013). O'Donnell (2007) has developed a modelling method for tracking impacts through the river channel network while O'Donnell et al. (2011) have used modelling to provide catchment sensitivity maps for the impacts of land management changes. There have been several recent advances in modelling methods to investigate land management impacts on flood flows at larger scales (Bulygina et al., 2011; Bulygina et al., 2012; McIntyre et al., 2013; Bulygina et al., 2013; Ewen et al., 2013).

The Hodder study is described in O'Donnell et al. (2011) and Ewen et al. (2015). Source area risk attribution is pioneered by Ewen et al. (2013). The SCaMP programme is described by McGrath and Smith (2006) and the results concerning the impacts of changes on the flood hydrograph are given by Ewen et al. (2015).

The Pontbren study is documented in Wheeler et al. (2008), Marshall et al. (2009), and Marshall et al. (2014). Modelled impacts on flood peaks at the 6 km² catchment scale are reported by Wheeler et al. (2008), Jackson et al. (2008), and McIntyre and Marshall (2010).

Results from the River Axe are reported by Climent-Soler et al. (2009) and Archer et al. (2010).

Parrott et al. (2009) discuss the way in which the effectiveness of NFM diminishes with catchment size. The role of tributary timing on flood risk is explored in a modelling study by Pattison et al. (2014). Runoff and sediment transfer are scale-dependent processes, and hence cannot be transferred directly between scales (Deasy et al., 2011; Deasy et al., 2014).

- (21) *Summary* Peer-reviewed evaluations of the effectiveness of NFM and CBFM interventions are listed in Table 2. Further practitioner-led implementations of NFM and CBFM can be found in databases compiled by the Environment Agency (Barlow et al., 2014), James Hutton Institute, and the JBA Trust. (<https://www.gov.uk/government/publications/working-with-natural-processes-to-reduce-flood-risk-a-research-and-development-framework>; <http://www.crew.ac.uk/content/natural-flood-management-database>; <http://naturalprocesses.jbahosting.com/>).

An evidence directory compiled by the Environment Agency (SC15005 – Working with Natural Processes – evidence base & catchment/coastal laboratories), gives a synthesis of best practice drawn from twenty projects that have implemented CBFM/NFM measures in England and Wales (<http://evidence.environment-agency.gov.uk/FCERM/en/Default/FCRM/Project.aspx?ProjectID=d17370c6-135f-4ceb-8ed7-23867eaa2efd&PageID=4c167c62-3bba-475d-8965-d6528b5d5f61>).

Details of the Environment Agency's Catchment Flood Management Plans can be found here:

<https://www.gov.uk/government/collections/catchment-flood-management-plans>, and the associated legislative and policy drivers are discussed by Parrott et al. (2009).

(d) Channel flow

- (22) *Geomorphic processes and river channel form* Channel morphology and stability reflect the net sediment budget, which in turn reflects: (i) the net erosion and deposition observed; and (ii) the supply and connectivity of sediment from the hillslopes and upstream reaches. Effects on floodplain and channel morphology are widely discussed in the geomorphological literature (e.g., Hey, 1979; Kleinhans et al., 2013). For sediment budgets see Hooke (2003). The simulation by Lane et al. (2007b) shows the effects of flood related sedimentation on river channel form. Slater et al. (2015); Slater (2016) detect the effects of channel capacity changes by quantifying the non-stationarity in stage-discharge records. The role of fine sediments in nutrient transport is summarized by Owens and Walling (2002). The implications of UK farming intensification for sediment-related flood risks in upland and lowland basins are investigated in doctoral theses by Henshaw (2009) and Dangerfield (2013), respectively. Results of field experiments with on-farm wetlands in Cumbria and Leicestershire are reported by Ockenden et al. (2014). The comparison of sediment yields in basins dominated by improved grassland with those from traditionally-managed¹ moorland at Pontbren is by Henshaw (2009) and Thorne et al. (2011a).

- (23) *Hydraulic effects of channel modification* The hydraulic effects of modifications to the geometry of channels are governed by known physical laws of steady and unsteady flow (Jain, 2001). Hall et al. (2014) review these principles in the context of changes to the flood regime in Europe.

- (24) *Sedimentary effects of channel modification* Tracking and predicting river channel adjustment and the complex interrelationships between flood conveyance, sediment transport, channel morphology and adjustment to natural and artificial disturbance is a mainstay of fluvial geomorphology (Gilbert, 1880; Mackin, 1948; Hack, 1957; Schumm, 1979). Work on the effects of channel modification on channel stability is summarized by Darby and Thorne (1996). The effect of bed lowering on bank stability is considered in detail in several studies (Schumm, 1979; Thorne and Osman, 1988; Sear et al., 1995; Harvey, 2001; Hooke, 2003). A modern set of tools provided to assess the problem of dealing with sediment in flood risk management is given by Thorne et al. (2011b).

- (25) *Bank stabilization* Advances in understanding river bank erosion, its natural controls and its management are covered by Lawler et al. (1997) and Midgley et al. (2012). The impacts of artificially restricting lateral channel movement on sedimentation and in-channel conveyance are explained by Raven et al. (2010). A good

¹ Moorland managed through lower stocking densities of local breeds of sheep (Welsh Mountain instead of Merino), conservation of native vegetation and no underdrainage.

practice guide to using bank stabilization as part of sustainable river and flood risk management is provided by the Scottish Environmental Protection Agency (SEPA, 2008; SEPA, 2012). The importance of vegetation in controlling bank erosion is reviewed by Solari et al. (2016).

- (26) *River restoration* The type and scale of river restoration in the UK is summarized by Sear et al. (2000) and Newson et al. (2002), with updates available via the River Restoration Centre website (<http://www.therrc.co.uk>). Examples of the hydrological effects of river restoration are given in modelling studies (Acreman et al., 2003) and field and modelling data (Dixon et al., 2016). Local hydraulic impacts of restoration can be found in Sear et al. (2004) with reviews in Brookes and Shields (1996). The role of large wood in headwater streams in the New Forest is investigated by Dixon and Sear (2014) and the reduction in flood risk that might be achieved with floodplain forest restoration is quantified by Dixon et al. (2016).
- (27) *Channel and bank vegetation* In-channel vegetation can reduce water velocity and elevate water levels significantly thus enhancing the flood hazard at that site and upstream. Early flow-resistance guides such as those of Chow (1959) and Barnes (1967) assist with the estimation of channel roughness parameters but do not properly account for composite roughness nor the time-varying roughness of vegetation subject to different depths and flow velocities (Masterman and Thorne, 1992). HR Wallingford's more advanced Conveyance Estimation System, which partitions hydrodynamic roughness between its various components, is described in McGahey et al. (2006) and reviewed comprehensively by Knight et al. (2010). Alternatives for representing vegetation effects on roughness are reviewed by Marjoribanks et al. (2014). The study in the River Stour is documented by Bates et al. (1998); the effect of vegetation on conveyance in summer floods is widely noted (Marsh and Hannaford, 2007).
- (28) *Riparian buffer strips* The effects of interventions in riparian vegetation on flood conveyance are covered by Downs and Thorne (2000). The broader range of benefits conferred by riparian buffer strips is the subject of many papers in the hydrological and freshwater biological literatures, which are reviewed by Broadmeadow and Nisbet (2004). The co-benefits for sediment management are illustrated by Owens et al. (2007) and the co-benefits for biodiversity are articulated by Correll (2005).
- (29) *Large wood* The general effects of wood in rivers are documented by Abbe and Montgomery (1996) and more recently by USBR (2016). As the size of wood approaches the order of the channel width, its role alters from simply providing additional resistance to fluid flow in the channel, to a role in which the debris can exert a strong structural control on channel morphology and stability. In a UK context, the reach-scale hydraulic effects are considered by Jeffries et al. (2003) and Sear et al. (2010).
- (30) *Beavers* The role of beavers is reviewed by Gurnell (1998). International evidence concerning the effectiveness of beaver dams at trapping sediment is presented by Meentemeyer and Butler (1999) and Butler and Malanson (2005). Pollock et al. (2015) give practical information on the role of beavers in river restoration. Scottish Natural Heritage has published results from the Scottish Beaver Trial in a series of reports, including Perfect et al. (2015). Several additional studies of the reintroduction of beaver are underway (e.g., the Mid-Devon Beaver Trial and the River Otter Beaver Trial) but results were not available at the time of writing.
- (31) *Summary* No references cited.

(e) Flood storage and floodplain conveyance

- (32) *Storage* A series of European studies consider the issues associated with managing offline storage (Hooijer et al., 2004; Bronstert et al., 2007; Salazar et al., 2012). Work at Belford is described by Wilkinson et al. (2010). Similar storage features are in use at other locations, e.g., Lustrum Beck, Stockton-on-Tees, although full evaluations of their performance have not been published at the time of writing. The Pickering scheme is documented by Lane et al. (2011) and Nisbet et al. (2015). A briefing note on post-event analysis following heavy rain in December 2015 is available here: Slowing the Flow Partnership Briefing: Boxing Day 2015 Flood Event [http://www.forestry.gov.uk/pdf/160329_PBeck_Boxing_Day_2015_Final.pdf/\\$FILE/160329_PBeck_Boxing_Day_2015_Final.pdf](http://www.forestry.gov.uk/pdf/160329_PBeck_Boxing_Day_2015_Final.pdf/$FILE/160329_PBeck_Boxing_Day_2015_Final.pdf)
- (33) *Floodplain cross-section* International studies have examined floodplain modification on the Mekong (Hoa et al., 2008), Po (Di Baldassarre et al., 2009), Rhine (Vorogushyn and Merz, 2013), and Danube (Blöschl et al., 2013). Work on flood risk in the Cherwell associated with disconnection from the flood plain and the potential effects of floodplain and channel restoration is presented by Acreman et al. (2003). The effect of wetlands on flood risk is discussed by Bullock and Acreman (2003).
- (34) *Floodplain roughness* The effects of riparian forest on resistance to flow are documented widely in the international literature (Everitt, 1968; Swanson and Sparks, 1990; Hupp and Osterkamp, 1996; Stromberg et al., 1993). Controls on flood peak attenuation are investigated by Valentová et al. (2010) and sensitivity to floodplain roughness is presented by Hall et al. (2005b). A study that documents a case where floodplain friction has only a limited impact on flooding is reported by Aronica et al. (2002).
- (35) No references cited.

(f) Co-benefits

- (36) The need for further quantitative evaluation of the co-benefits associated with nature-based solutions like CBFM/NFM is articulated by Jones et al. (2012). An analysis of net benefits associated with 25 NFM schemes by Iacob et al. (2014) highlights the need to consider ecosystem co-benefits and tradeoffs on a case-by-case basis. Co-benefits associated with the influence of riparian shade on water temperature are reviewed by Orr et al. (2015).

(g) Conclusions

- (37)–(38) No references cited.

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