Natural flood management (NFM) knowledge system: Part 3 - The effect of land drainage on flood risk and farming practice

Final Report

01/07/2012

Published by CREW – Scotland's Centre of Expertise for Waters. CREW connects research and policy, delivering objective and robust research and professional opinion to support the development and implementation of water policy in Scotland. CREW is a partnership between the James Hutton Institute and all Scottish Higher Education Institutes funded by the Scottish Government.

This document was produced by:

Janice Blanc, Scott Arthur, Grant Wright & Lindsay Beevers.
Institute for Infrastructure and Environment,
School of the Built Environment,
Heriot-Watt University, Edinburgh EH14 4AS, Scotland, UK

http://www.sbe.hw.ac.uk/research/institute-infrastructure-environment.htm

Contents

Executive summary

Land drainage is typically classified as either surface or subsurface and is widespread throughout developed countries. Substantial drainage has been undertaken during various periods in history and it is estimated that within the United Kingdom 60.9% of agricultural land is drained. In Scotland there was a dramatic increase in drainage after the Second World War, mostly due to the need to increase food production aided by a rapid development in mechanised installation; increased drainage was also evident during a period of agricultural intensification in the 1960s and 1970s. In Scotland the aim has often been to lower the water table to encourage vegetation cover more suitable for livestock grazing. Whilst drainage was common for grazing land, extensive land drainage was also undertaken in upland regions for commercial forestry operations. It should not be doubted that land drainage has shaped the way society has grown and developed.

While offering benefits that may improve yield, agricultural and forestry drainage have altered the rate of water runoff and increased peak flows during heavy rainfall and can result in diffuse pollution. It can therefore have a significant impact on the landscape, biodiversity and downstream hydrological processes.

Land Drainage is now recognised as having an impact on peak flows however, the extent of any potential changes is uncertain and likely to be site specific. Reviews of drained sites indicate a variety of responses. A number of studies found that field drainage could increase or decrease peak drain flows by as much as two to three times; the behaviour appeared to depend on soil type, antecedent conditions and rainfall event. Fundamentally, the key factor is the relative importance given to two processes; increasing flood flows due to the ability of drains to carry water faster than subsurface flow through the soil and reduced flood flows due to an increase in soil storage capacity created by lowering the water table. Which of these processes exerts the greatest influence will depend on various factors including: drainage density and geometry, hydraulic conductivity, drain and surface roughness, topography, event size, and antecedent conditions. Although not conclusive, authoritative studies have linked land drainage derived increased flood risk to dry catchments and arterial network geometry.

Drain blocking, commonly undertaken by installing a series of permanent dams in a drain, can be used to help restore a site to its pre-drained condition. However, a number of studies report that while drain blocking of peatland has benefits for the ecosystem, the impact on peak flows and flood volumes is not clear. Controlling the volume of flow through an existing drainage network in a manner which allows peak flow control while also maintaining water table levels appropriate for agriculture offers an alternative to permanent blocking. This review has found that there may be an opportunity to meet the needs of agriculture whilst managing diffuse pollution and flood risk by deploying real-time control as a method of dynamically controlling land drainage.

1.0 Introduction

The first Scottish National Flood Risk Assessment, produced by the Scottish Environmental Protection Agency (SEPA, 2011), reports that approximately one in 22 of all residential properties and one in 13 of all non-residential properties in Scotland are at risk from flooding, and notes that the average annual damage to homes, businesses and agriculture from all sources of flooding is estimated to be between £720 million and £850 million. In addition, climate change trends suggest that Scotland will experience more frequent extreme weather events, including intense summer rainfall (SEPA, 2012). Given these predictions, there is a clear need to ensure appropriate flood management processes are in place. Over time, the approach to flood management has changed: an initial focus on land drainage and flood defence throughout the 1950s, 60s and 70s moved towards a flood control and then a flood management approach in the 1980s and 90s. Whilst, these approaches had a strong focus on engineering measures, a more integrated and sustainable flood management (SFM) approach is currently being adopted. In Scotland, SFM was established in legislation as part of the Water Environment and Water Services (Scotland) Act in 2003, which also transposed the European Water Framework Directive (WFD) (EU, 2000) into Scots law. The WFD requires the development of river basin management plans which promote sustainable water use in a way which protects and improves the water environment. Described as "the most substantial piece of EC water legislation to date" (Potter *et al*., 2011), the river-basin management approach stresses the interrelationship between water management and land use. Scotland's first comprehensive river basin management plan was produced in 2009 (SEPA, 2009).

It is increasingly becoming understood that effective management of river basins in terms of water resources (floods, droughts, recreation and biodiversity) requires the integrated management of both land and water practices (O'Donnell *et al*., 2011). This integrated approach is also recognised as a requirement at smaller scales. For example, Abdel-Dayem (2006) notes that in most countries drainage systems are "...not designed to address simultaneously water management, disease control, drainage water reuse and flood management" and suggests that an approach to managing drainage from an integrated water and land perspective is essential.

Within this context, this report is one of three produced for CREW to verify the current state of knowledge on NFM. It briefly reviews the historical development of land drainage and looks at the impacts on flood risk from land drains and the recent move towards drain blocking.

2.0 Land Drainage

Drainage types

"Drainage is typically classified as either surface or subsurface drainage"

Land drainage is typically classified as either surface or sub-surface drainage. Surface drainage is gravity driven and generally involves the use of shallow trenches or ditches (often referred to as grips). A simple example of this approach to drainage are 'lazy beds' where a series of trenches are constructed with the removed soil piled up between to create a ridge and furrow effect.

Sub-surface drainage can be either gravity driven or directly pumped. This type of drainage can be created using deep open/covered ditches, trenches or by installing perforated pipe systems. This is commonly referred to as tile drainage.

Agriculture and forestry practices

"While offering benefits that may improve yield, agricultural and forestry drainage have altered the rate of water runoff and increased peak flow during heavy rainfall"

Land drainage offers a number of benefits for agriculture and forestry including: reclamation of land, intensification of current practice, land use change and reduced production costs (Morris, 1992). Drainage can influence the scale of cultivation, crop selection, irrigation and fertilization practices, and field structure (Herzon & Helenius, 2008). In a review of the role of agriculture in sustainable flood management, Kenyon *et al*. (2008) report that it is generally acknowledged that incentives provided to farmers to drain agricultural land have altered the rate of water runoff and increased the peak flow during heavy rainfall. The same study noted that certain agricultural practices including bog, pond and wetland drainage were recognised as being significantly responsible for increasing downstream flood risk since they reduced natural flood storage capacity and increased runoff.

In terms of forestry management, in recent decades the use of once common practices such as aggressive drainage ditching to prepare wet soils and direct connection of drainage ditches to natural watercourses have been proscribed (Jacobs Engineering, 2011).

Environmental Impacts of Drainage

''Drainage has a significant impact on the landscape, biodiversity and downstream hydrological processes''

Land drainage is recognised as playing a key role in agricultural and environmental sustainability. A review by The World Bank in 1993 identified inadequate or inappropriate drainage as perhaps the most severe long term problem reducing the benefits of irrigation, encouraging adverse river morphology and leading to noxious environmental effects (Abbot & Leeds-Harrison, 1998).

Blann *et al*., (2009) note that in the US, the most prominent effect of artificial drainage has been the direct elimination of wetland and riparian habitats. They report that less than half of the 221 million acres of wetland estimated to have been present in the United States at the end of the nineteenth century currently remain and suggest that most of these historic losses of wetlands are attributable to drainage for agriculture. Similar impacts were also noted for Canada where agricultural drainage has accounted for between 81 and 85% of wetland losses in southern Ontario (Walters & Shrubsole, 2003) and for Austria and Denmark where land drainage was cited as ''probably the single most important measure which has adversely affected the landscape (loss of wetlands, small scale structures in the landscape), the biodiversity and the hydrological cycle'' (Scheidleder *et al*., 1996).

Several impacts of peatland drainage have been noted including changes in the peat structure, erosion of the ditches, increased aerobic decomposition due to the lowering of the water table and increased leaching of nutrients (including dissolved organic carbon - DOC) and an associated increase in water colour (Armstrong *et al*., 2010). Land drainage affects the water budget of the whole catchment by altering soil water storage, groundwater storage, the proportion of rainfall subject to evapotranspiration, and rates and volumes of water export. Artificial drainage of peatlands lowers the water table in areas directly adjacent to the drain, with the strongest influence downslope of the drain (Holden *et al.*, 2006). In addition to lowering the water table, drained blanket peat shows greater volumes of sub-surface through-flow than overland flow (Holden *et al.*, 2006). As well as these local impacts, there are acknowledged adverse effects on downstream hydrological processes including increases and decreases in flood peaks (Holden *et al*., 2004; Holden *et al*., 2006) and increases in baseflows (Robinson, 1985).

3.0 Historical Development of Land Drainage

Historical Impact

"Land drainage has shaped the way society has grown and developed"

The potential of drainage to transform landscapes and agriculture and its importance in shaping history is well recognised. For example, a review of drainage in West Lancashire argues that "...drainage of this land, resulting in its transformation from some of the worst land in the country to some of the best, was a major contributor not only to the agricultural success of the region, but also to Lancashire's industrial success." (Gritt, 2008). Another study notes that within the United States, by 1920, the amount of agricultural land made available through drainage was far greater than the amount of land opened by irrigation and suggests that the development of societies around the now intensely managed and highly productive 'Corn Belt' of the Grand Prairie of East Central Illinois was the result of growth due to "... the energetic drainage enterprises of the Midwestern US and the Canadian Great Plains in the late-nineteenth and early twentieth centuries." (Imlay & Carter, 2012).

Geographical extent

"Land drainage is widespread throughout developed countries"

Within Europe, significant areas of land have been modified by drainage to increase agricultural production. In 1998 it was estimated that around 34% of farmland in Northwest Europe was drained with much higher drainage concentrations in some countries (Blann *et al*., 2009). For example, in 2000 it was estimated that within the United Kingdom 60.9% of agricultural land was drained, while 51.4% of agricultural land was drained in Denmark and 91% in Finland (Wiskow & van der Ploeg, 2003). Areas outside of Europe are also extensively drained. For example, by 1987 more than 17% of U.S. cropland (up to 30% in the Upper Midwest) had been altered by artificial surface or subsurface drainage (Pavelis, 1987). Within the UK, whilst drainage was common for grazing land, extensive land drainage was also undertaken in upland regions for commercial forestry operations (Dunn & Mackay, 1996). Open ditch drainage, sometimes referred to as gripping, has historically been a common land management practice in UK upland blanket peats (Ballard *et al*., 2011a). For example, in the twentieth century more than 9,000 km of drains were dug in the moorlands of the North Pennines (Natural England, 2011).

The development of drainage in the UK

"Substantial drainage has been undertaken during various periods in history driven by agricultural demands"

Within Scotland, numerous methods have been used historically to lower the water table and improve the soil, one of the earliest reported methods being the *lazy-beds* of the Highlands and Islands (Green, 1979). Government funding of public loans for large-scale drainage were available from the 1840s onwards (Gritt, 2008). In the UK, about £12M was loaned in the period 1850-78 by government and private drainage companies. This was a period of agricultural prosperity and expansion and drainage played an important role being termed “the great improvement of the age” (Chambers & Mingay, 1966). Although a period of agricultural depression towards the end of the nineteenth century led to very little drainage being carried out (Robinson, 1990), substantial land drainage was undertaken in the early part of the nineteenth century although this cannot now be accurately quantified. However, the introduction of a grant system in the 1940’s to support drainage resulted in accurate records of work undertaken. From these records it is possible to gain a general impression of the extent of drainage prior to the introduction of the grant system. For example, in 1976/77 nearly fifty per cent of the grant applications in the southern half of Scotland were recorded as being to deal with failure of existing drains (Green, 1979).

In Scotland and the rest of the UK there was a dramatic increase in drainage after the Second World War, mostly due to the need to increase food production by improving the land for sheep and grouse farming (Armstrong *et al.*, 2010, Ballard *et al*., 2011a, Holden *et al*., 2007; Stewart & Lance, 1983) aided by a rapid development in mechanised installation (Ritzema *et al*., 2006); increased drainage was also evident during a period of agricultural intensification in the 1960s and 1970s (Posthumus *et al*,. 2008, Ballard *et al*., 2011a). Although it is now recognised that drainage generally only results in local drawdown of the water table (Robinson, 1986; Stewart and Lance, 1983), the aim was to lower it to encourage vegetation cover more suitable for livestock grazing. Since the 1980’s, when government subsidies ceased, little new land has been drained (Wheater & Evans, 2009). At the same time public support for agricultural/drainage development became greatly affected by emerging environmental awareness, as these land management activities were perceived to harm or compete with a number of environmental values (Smedema, 2011). However, maintenance of land drains has continued, although to varying degrees with many becoming blocked (O’Connell *et al*., 2007).

4.0 Land Drainage and Flood Risk

Historical association with flooding

“Historically a number of claims have been made stating upstream land drainage had increased damages resulting from floods.”

As noted by Nicholson (1953), “The connection between field drainage and flooding in rivers has been a subject of debate for centuries”. While land drainage and associated management practices have been identified as having a significant impact on upland hydrological processes (Reed *et al*., 2009), as well as on biological and chemical processes (Wheater & Evans, 2009), there is still limited knowledge available regarding the links between land drainage and management in upland rural catchments and hydrological and flooding mechanisms downstream.

Historically a number of claims have been made stating upstream land drainage had increased damages resulting from floods. For example, after severe flooding occurred as a result of exceptionally heavy rainfall over south-east Scotland and north-east England in 1948, a study by Learmonth (1950) concluded that the runoff generated by the rainfall was “as high in proportion to the size of catchment area as any recorded in Britain” and suggested that it had been increased and the flood peak reached earlier in areas that had been artificially drained. The report noted that “The 1948 flood apart, it may be a matter of national importance that recent hill drainage schemes are causing violent and flashy spates in many and widespread areas.”

Drainage today

"While drainage is now recognised as having an impact on peak flow, the extent of any potential changes is uncertain and likely to be site specific."

While the potentially detrimental impacts of drainage, at both local and global scales are now recognised (Holden *et al*., 2004), opinion regarding the downstream effects of drainage remains divided: some supporting the fact that drainage speeds up the movement of water towards the stream channels (e.g. Robinson, 1986; Nicholson *et al*., 1989; Ballard *et al*., 2010, Ballard *et al*., 2011a), whilst others consider drainage reduces maximum flows (e.g. Newson & Robinson, 1983; Iritz *et al*., 1994). As reported by O'Connell *et al.* (2007) evidence suggests that both situations can occur. In a review of a number of studies they found that field drainage could increase or decrease peak drain flows by as much as two to three times; the behaviour appeared to depend on soil type, antecedent conditions and rainfall event. Fundamentally, the key factor is the relative importance given to two processes: increasing flood flows due to the ability of drains to carry water faster than subsurface flow through the soil and reduced flood flows due to an increase in soil storage capacity created by lowering the water table. Which of these processes exerts the greatest influence will depend on various factors including: drainage density and geometry, hydraulic conductivity, drain and surface roughness, topography, event size, and antecedent conditions (Ballard *et al*., 2011b).

Downstream impacts of drainage

"Reviews of drained sites indicate a variety of responses to drainage. These variations may be due to the characteristics of the individual sites, seasonal changes, variations in climate patterns and antecedent conditions, or changes in drainage efficiency over time."

A comprehensive report detailing field and catchment studies relating to land drainage was produced by the Institute of Hydrology in 1990 (Robinson, 1990). Although now dated, this key report reviewed data from numerous published and unpublished field drainage experiments where flows were measured from both drained and undrained land and covers aspects of drainage density, soil water storage, the impacts of different drainage systems and the extent and location of drainage within a catchment. In general it was found that at wetter sites (high rainfall and/or high clay content) peak flows are reduced, whilst at drier sites (lower rain, more permeable soils) peaks are increased. The author suggests that the likely effect of artificial drainage (to worsen or reduce flood risk) at the field scale may be assessed from measurable site characteristics including the soil water regime and the physical properties of the soil profile. In addition, baseflow was found to be higher from drained than undrained land at both field and catchment scales. The review also looked at catchment scale arterial channel improvements and found that they lead to larger flow peaks downstream, due to higher channel velocities and a reduction in overbank flooding and storage. The combined effect of field drainage and arterial works was found to increase stream flow peaks independent of whether maximum flows were increased or decreased at the field scale. The influence of drainage on response times was also found to be significant at regional scales.

While a smaller review of 22 agricultural land drainage schemes in England found that flooding was reduced after installation of drainage in 80% of the areas which had previously flooded (Morris, 1992), its focus was on the condition of the drained areas not on the downstream impact.

A more recent review by Jacobs Engineering (2011) includes an analysis of studies of three experimental catchments (Blacklaw Moss, Llanbrynmair and Coalburn). In Blacklaw Moss (Lanark, Scotland), a 7 ha experimental site was instrumented for 5 years from 1959-1964. After a 3-year calibration period the land was drained by cutting open ditches about 40cm wide and 36cm deep at 9 metre spacings. Although there was little difference in storm characteristics between the two periods, there was a large increase in the observed flood peaks mainly due to an increase in the flashiness of the site thought to be due to the channel network speeding up flows by shortening the slower flow paths through the soil to the channels (Robinson, 1990). Despite the drainage, there was very little compensating increase in the available storage capacity of the soil. The time taken to peak was reduced by more than a factor of ten, the percentage runoff increased from 46% to 58%, and the peak of the unit hydrograph increased by a factor of 2.6.

In Llanbrynmair (central Wales), a peat moorland catchment was progressively drained over a 4-year period until 70% of the area was affected. Unit hydrographs from before and after the drainage showed similar hydrological effects to those at Blacklaw; open drainage resulted in a much peakier storm flow response. The location of the drainage was found to be significant. Drainage of the higher land resulted in a much peakier runoff response at the outlet. However, subsequent drainage of the valley bottom led to no further increase in peaks, although the catchment response time shortened. This was interpreted as the result of earlier flows from the areas near the gauge becoming desynchronised from the arrival of flows from the more distant parts of the catchment. The effect of location of drainage was also reported by Acreman (1985) for the extensive pre-planting upland drainage that occurred in the Ettrick catchment in southern Scotland and by Wisler & Brater (1949) who noted that in addition to the extent of drainage in a catchment, its location was important for influencing flood flows: “In the lower portions of a drainage basin, speeding up the runoff process is likely to decrease flood flow, whereas slowing down the process may increase the flood peak. In the upper reaches, the effects may be just the opposite”.

Hydrological data from the third catchment, Coalburn (northern England), was collected for 5 years before the whole catchment was subject to the ploughing of open drains about 5 m apart and aligned with the ground slope. Water from these drains was either intercepted by deeper drains or allowed to connect directly to the natural water course. In the 5-year period after the drainage the time to peak reduced on average by 22%, although the effect diminished over the following 20 years (Robinson *et al*., 1998). However the authors note the apparent effectiveness of the drainage may be influenced by the establishment of forest cover. They suggest that the increase in catchment flashiness is a result of a greater density of drainage channels which speeds up the removal of surface waters while the reduction in efficiency over time is the result of reduced hydraulic efficiency of the drains as the furrows become colonised by vegetation and filled with leaf litter. Vegetation has become re-established in the bases of many peatland drains. This vegetation and litter will influence the rate of water transport through the drains and into downstream channels (Holden *et al*., 2008a). In a study looking at the hydrological impacts of drainage ditch cleaning on two pairs of artificially delineated catchments in drained peatland forests in Finland, ditch cleaning was found to lower the level of the water table in sites where a shallow peat layer was underlain by mineral soil. In sites with deep peat formation, the water table showed no detectable response to ditch cleaning. Runoff data suggested that annual runoff clearly increased after ditch cleaning (Koivusalo *et al*., 2008). However, the authors note that a model simulation was unable to reproduce the pattern of results and suggest that the catchments assessed were perhaps not hydrologically isolated and therefore the validity of the results is questionable – a point which highlights the difficulty in using field studies to assess hydrological impacts.

The speed of water delivery may also be influenced by the presence of natural pathways such as pipes within the soil. In a review of 160 blanket peat catchments, Holden (2005, 2006) notes that moorland gripping is the most important control on hillslope pipe frequency in blanket peats; more pipes are found where land drainage has occurred.

While the general consensus from these studies suggests that drainage leads to increased downstream flashiness, the degree of response was found to vary. The variations may be due to the characteristics of the study sites, differing drainage patterns and locations within the catchment, differing study seasons or durations, or variations in climate patterns and antecedent conditions. For example, the underlying moisture content of the site (Robinson, 1990) and the design of the arterial channel network (Robinson, 1990 & Jacobs Engineering) may be factors which underlie any increase in flood risk. In addition, Holden *et al*. (2006) indicate that the long-term response of peatlands to drainage differs from short-term responses. A point emphasised by Worrell *et al*. (2007b) who conclude that “care should be taken when making inferences from studies of peatland response to management change when the studies describe responses over different time periods”.

5.0 Drain Blocking

Overview

“Drain blocking, commonly undertaken by installing a series of permanent dams in a drain, can be used to help restore a site to its pre-drained condition.”

The objective of drain blocking is to reduce the connectivity of the artificial drains, slowing down the movement of water across and from the drained area and allowing water to remain in the soil for longer, resulting in raised water tables and increased residency times. Whilst a number of studies have reported these effects (e.g. Armstrong *et al*., 2010; Worrall *et al*., 2007a), the scale of the responses has varied. Drains are generally not completely refilled but are blocked by a series of dams. Numerous blocking techniques have been applied with varying degrees of success including: peat dams, straw and heather bales, plastic piling or sheeting, plywood or wooden planks, stone dams, or a combination of approaches. A report by Jacobs Engineering (2011), looking at Natural Approaches to Flood Management under the Flood Risk Management (Scotland) Act 2009 includes a comprehensive review of upland drain blocking.

In the UK, the oldest drain blocks were installed in the late 1980s (Armstrong *et al*., 2010) and there has been a significant increase in the practice of drain-blocking over recent years. In a move towards reaching ‘favourable’ or ‘unfavourable recovering’ condition for 95% of the SSSIs in England by 2010, large scale drain-blocking initiatives were implemented by the UK government (English Nature, 2003). One example of an ongoing restoration project is the North Pennines Area of Outstanding Natural Beauty’s ‘Peatscapes’ project which is enabling the blocking of thousands of kilometres of drainage channels (Natural England, 2011). One site benefiting from this is the Bowes Moor SSSI, an extensive tract of moorland in south-west Durham. The ‘peatscapes’ project along with other moorland management initiatives led to the establishment of an Environmental Stewardship Agreement in 2007 which is helping to fund a programme of land management including drain blocking. By 2010 all the drains on Bowes Moor had been blocked and this along with the last remaining management changes led to an assessment of 100 per cent of the land in recovering condition (Natural England, 2011). While this and similar recent projects have the potential to provide some valuable catchment scale evidence, Ramchunder *et al*. (2009) reported that approximately £500M had been spent on drain-blocking in northern England in the previous five years despite limited understanding of the full environmental effects of the practice.

Peatland drain blocking

"While a number of studies report that drain blocking of peatland has benefits for the ecosystem, the impact on peak flows and flood volumes is not clear."

Despite significant resources being invested in drain-blocking on blanket bog, there are few published studies on its effectiveness in restoring hydrological or ecological function (Bellamy *et al*., 2012) and the processes involved are not well understood. In addition Holden *et al*., (2011) note that "Even if full hydrological function is eventually restored at blocked sites the timescales involved appear to be greater than may have been anticipated by most restoration agency-funded monitoring programmes".

While a number of studies report that peat drain blocking has benefits for the ecosystem such as increased biodiversity, habitat restoration and carbon sequestration (Bellamy *et al*., 2012, Wallage *et al*., 2006; Worrall *et al*., 2007b) the impact on peak flows and flood volumes is not clear.

The runoff response from drained blanket peatlands is generally found to have reduced times to peak, increased peak flows and a quicker recession (e.g. Ballard *et al*., 2011b; Holden *et al*., 2006; Robinson, 1986; Stewart & Lance, 1991). Blanket peat bogs are now classed as both EU and UK Biodiversity Action Plan priority habitats (JNCC, 2008) and there is a significant focus on actions to restore these environments. In a review of 56 peatland restoration projects, Holden *et al*. (2008b) found that most projects were focussed on restoring both ecological and hydrological function. However, despite hydrological function being reported as the second most important justification factor for the projects, after biodiversity, the largest area of uncertainty expressed by the peat restoration project personnel was in understanding peatland hydrology. Additionally, it was noted that in general there is a lack of pre-restoration monitoring which is required to allow the establishment of baseline hydrological conditions.

Downstream impacts of drain blocking

"Drain blocking has been found to decrease or increase peak flows depending on local conditions"

Drain blocking is generally acknowledged to alter hydrological routing, resulting in non-continuous flow, and reducing or preventing the delivery of water through artificial networks. However, only a few studies have directly investigated the impact of drain blocking on peak flow hydrographs. In addition, there is currently little evidence available demonstrating large scale impacts (Ramchunder *et al.,* 2009). A similar point was made by Grayson *et al.* (2010) who noted that despite a lack of reliable evidence of the impact on the flood peak downstream of grip blocking, flood mitigation is increasingly used to justify the expenditure on peatland restoration.

Drain blocking has been found to decrease or increase peak flows depending on local conditions (Rose & Rosolova, 2007; Wilson *et al*., 2010; Wilson *et al*., 2011). Holden *et al*. (2008a) report that drain-blocking significantly reduces the velocity of flows across the bog surface, as well as reducing the rate and volume of water flowing out through drains at peak times. Other studies have shown an increase in overland flow after blocking (e.g. Shantz & Price, 2006), which may be the result of raised water table levels. The impact of drainage on water tables was noted by Price (2003) who reported that after drain-blocking water-table levels increased to similar heights as intact peatland and Armstrong *et al*. (2010) who found shallower and less variable water table levels on sites with blocked drains compared to control sites. The areal extent to which drainage influences water table level is quite limited in blanket peats, due to very low hydraulic conductivities. As a result, drain spacing has a significant impact on both the short and long term effects of drainage (Ballard *et al*., 2011b). A study by Kladivko *et al*. (2004) also noted the importance of drain spacing - in a study of nitrate leaching to subsurface drains they reported that annual drain flow increased from 12 to 15 to 21% of annual precipitation as the drain spacing decreased from 20 to 10 to 5 m. In addition to spacing, the location of the drains has a significant influence on their efficacy. For example, a few ditches running across a steep slope may have a greater influence on peat saturation and decomposition across the catchment than a much denser ditch network on relatively flat terrain (Holden *et al*., 2006). By considering topographic location, ditches with the greatest impact could be identified leading to efficient targeting of resources for ditch blocking (Lane *et al*., 2003; Lane *et al*., 2004);

Modelling studies

"Simulations from a number of modelling studies suggest drain blocking will reduce peak flow."

A number of modelling studies have been undertaken to try to predict how effective peatland drain blocking will be. The SCIMAP (Sensitive Catchment Integrated Modelling and Analysis Platform) study (Lane *et al*., 2003) investigated drain blocking using a model that linked a hydrological model to a detailed digital elevation model. They concluded that a catchment scale model that represents the spatial arrangement of drains and their connectivity to the drainage network is needed to

a) determine the catchment scale impact of drainage or drainage blocking on downstream runoff; and,

b) to identify which channels would be most effective to block.

Ballard *et al*. (2010) used a simplified physics based model to simulate the flood response of a 200m x 200m plot of upland peat. The simulations suggested that on average drain blocking leads to the greatest reduction in flooding for sites with larger drain spacing, steeper drain angle, steeper slope, rougher plant cover, smoother drains and a thin acrotelm (The upper layer of a peat bog, in which organic matter decomposes aerobically). However the results showed substantial variability, with both increases and decreases in peak flow predicted depending on the event and parameter set used.

A study by Johnson (2007), used a hydraulic model to estimate predicted impacts on floods due to the blocking of artificial drains at Glendey, a catchment located within the headwaters of the River Devon in the Ochills, Scotland. The results suggested a 4% to 6% reduction in peak outflow and a 72% to 75% reduction in peak flow velocity with the lower outflow reduction being estimated for the biggest event that was believed to represent a 0.04 annual probability event (25-year event). However, the drained area also had an artificial watercourse running through it that was realigned into a meandering channel. The results are therefore likely to reflect both the effects of drain blocking and the effect of re-arranging the watercourse flow path.

In a case study looking at land management practices in the Ripon catchment (Rose & Rosolova, 2007), sensitivity testing was used as a means of indicating potential catchment scale impacts on flood generation resulting from changes in runoff characteristics from farms and sub-catchment areas. Individual sub-catchment rainfall-runoff models, in the form of Probability Distributed Moisture (PDM) models were linked together via an ISIS flood routing model in order to simulate flows at the catchment outlet. The impact of the proposed land management changes were represented in the PDM models by alterations to specific PDM model parameters affecting the rapid runoff component, the condition of soil moisture store and the hydrograph timing. The impact of moorland drainage blocking in controlling the generation and rate of runoff was also investigated. Results indicated that the worst case land change scenario (combining soil degradation across the whole catchment with moorland drain maintenance) resulted in peak flow increases in Ripon, compared to the baseline case, of between 20% for smaller scale floods and 10% for more extreme floods. In contrast, the best case land improvement scenario (drain blocking) resulted in flood peak magnitude reductions in Ripon by up to about 8% when compared to the baseline case. The timing of the flood peak in Ripon was altered by up to 75 minutes as a result of the scenarios, though changes to the timing of the hydrographs generated in the moorland areas were attenuated by the time they had reached Ripon partly as a result of being channelled through areas of flood plain storage.

6.0 Drainage Management

"Controlling the volume of flow through an existing drainage network offers an alternative to permanent blocking that may allow peak flow control while maintaining water table levels appropriate for agriculture"

While drain blocking offers a method by which land can potentially be restored to its pre-drainage condition, this approach may not be appropriate where there remains a need for land drainage to meet agricultural requirements. In these situations, some form of managed drainage may offer a solution. As an alternative to permanently blocking drains, a number of practices can be used to control the flow volume within an existing drainage network. These generally use a water control structure (e.g. a gate or weir) to temporarily block or reduce the volume of flow within the drain. Flow volume can be reduced by raising the level of the outflow of the drain so that varying depths of water are allowed to be transported within the drainage system.

Drainage Water Management

"Controlled drainage is shown to both reduce drained water volumes and increase crop yield"

Singh *et al.* (2007) report that several studies have shown reductions in subsurface drainage through shallow or controlled drainage practices with values ranging from 25 to 44%. A number of studies were undertaken looking at drainage water management (DWM) in Midwestern USA (Ale *et al*., 2009, 2010, 2012). The DWM practice reviewed involves the use of a water control structure which controls the height above the drainage ditch base at which outflow occurs. The structure is raised after harvest, reducing outflow volume and the delivery of nitrate to ditches and streams during the off-season and lowered in early spring and autumn so there is free flow from the drain before field operations such as planting or harvest. It may also be raised again after planting if there is a need to store water for midsummer crop use.

In model simulations for a variety of drain spacings and operational strategies, Ale *et al*. (2010) found DWM showed great potential for reducing annual drain flow. The long-term average (1915–2006) annual drain flow reduction due to DWM varied between 52 and 55% for all drain spacings and operational strategies considered.

In a modelling study undertaken to determine the optimal DWM operational strategy (Ale *et al*., 2009), simulations suggested dates of raising and lowering the outlet which minimised winter drain flow and maximized yield of 0–20 days after planting and about 4–6 weeks before crop maturity respectively. However, the date depended on the antecedent moisture condition. The preferred height of control above the drain was found to be 50 cm. They found that implementation of DWM 10–85 days after planting during the crop season, and in the non-growing season resulted in a statistically significant reduction of the average annual drain flow by 60% (38–96% reduction in individual years). The predicted increase in surface runoff was not found to be significant. Subsequent to their previous studies, Ale *et al*. (2012) noted that while numerous field and modelling studies had reported significant reductions in annual drain flow with DWM, of the order of 20–58%, in order to assess the impacts of large-scale adoption of these practices, the effects at watershed scale would need to be quantified. In an expansion of their previous modelling to watershed scales, results indicated that DWM decreased the average annual (1985–2009) predicted drain flow from 11.0 to 5.9 cm.

In a different study of similar control mechanisms (Woli *et al*., 2010), the outlet level for a free drainage system was constantly set at the drainage ditch base, while the outlet level of the controlled system was raised to within 15cm of the soil surface at approximately November 1st of each year, and lowered back down to the base level at approximately March 15th of the following year. The controlled drainage was found to be effective in reducing ditch flow with a three-year average depth of 10.7cm of flow compared to 41cm from the free drainage. In addition the controlled drainage greatly reduced nitrate export.

An experimental facility representing a hypothetical 6-ha agricultural basin was used in another study to assess four different land drainage systems (1. open ditches with free drainage and no irrigation, 2. open ditches with controlled drainage and subirrigation, 3. subsurface corrugated drains with free drainage and no irrigation, 4. subsurface corrugated drains with controlled drainage and subirrigation) (Bonaiti & Borin, 2010). Results showed a variation in the percentage of rainfall drained depending on the system applied (Average rainfall percentage drained: 1: 18%; 2: 10%, 3: 50%, 4: 10%). The authors suggest that the reduced volumes resulted from the combined effects of reduced peak flow and reduced number of days with drainage and proposed that controlled drainage along with subirrigation could be applied at farm scale with advantages for water conservation.

Similar results for reduced flow were reported in a number of other studies investigating drainage management options (Konyha *et al*., 1992, Ma *et al*., 2007; Luo *et al*., 2008;, Luo *et al*., 2010).

7.0 Conclusion

Drainage involves many different processes and produces different responses depending on environment and conditions. Therefore any generalisation of whether drainage causes or reduces flooding is by necessity an over-simplification of the complex processes involved. Additional complexity is added when trying to identify the effects of drainage independently from the cumulative effects of other changes that may have altered the hydrological processes including land use change, surface and groundwater withdrawals, and river channel alterations.

While field drainage has been shown to both increase and decrease peak flows, general opinion suggests that drainage leads to increased downstream flashiness with higher peak flows and a reduced time to peak. However any associated increased flood risk is highly site specific and is dependent on factors such as drainage pattern and location within the catchment, characteristics of the soil and underlying hydrological pathways. Some evidence suggests that the restoration of water table levels through drain blocking will also increase flashiness through increased overland flow although in general the limited number of studies currently available show a decline in both peak discharge volume and velocity after restoration. While these apparent conflicts in the effects of both drainage and drain blocking may be due to the variation between different study sites and durations, or variations in climate patterns and antecedent conditions the uncertainty which lies beneath these conclusions demonstrates the uncertainty still surrounding the hydrological impacts of drainage and drain blocking and highlights the need for further study if a fuller understanding of the impact of drainage and drain blocking on peak flow events is to be achieved.

While drain blocking remains a preferred practice, despite the uncertainty regarding impacts on downstream flood risk, it is recognised that land drainage may still be a requirement in some areas. Whilst the amount of flood damage that currently effects the agricultural sector is limited (less than 1 percent) (Evans *et al*., 2004a, Evans *et al*., 2004b), Wheater & Evans (2009) note that a significant proportion of the most agriculturally productive land in England and Wales is dependent on flood protection and land drainage and suggest that with increased importance currently being placed on future food security, land management options may need to be re-evaluated "…to reduce flood risk and to maintain standards of land drainage in areas of national agricultural importance".

Given the need to ensure sufficient land is drained to meet growing food production needs, drainage water management practices that alter the volume of drainage through the use of control structures may offer a solution that both reduces downstream flood risk and provides workable agricultural land. While current studies of drainage water management have looked at seasonal control of drainage volumes, real-time control based on soil moisture levels or downstream flow volumes may offer an alternative approach. While no current studies were found assessing the potential for real-time control (of weirs etc) in agricultural drainage, a number of studies report the potential for its use for managing other hydrological processes including urban wastewater systems (Vanrolleghem *et al*., 2005); combined sewer systems (Darsono & Labadie , 2007), storm sampling techniques (Gall *et al*., 2010), soil salinity control (Park & Harmon, 2011) and urban groundwater works (Bauser *et al*., 2012). There may be an opportunity to meet the needs of agriculture whilst managing diffuse pollution and flood risk by deploying real-time control technology.

8.0 Appendix 1 – NFM knowledge database

The publications summarised in this Appendix formed the evidence base for this report. As it was not possible to undertake a comprehensive review of the very substantial body of NFM literature relating to agricultural drainage, source selection was based on studies where the main focus was on impacts on runoff volume rather than on water quality or improved agricultural production. In addition, an emphasis was put on post 2009 publications, which may have been missed by earlier literature reviews (O'Connell *et al*., 2007; Blann *et al.,* 2009; Jacobs Engineering, 2011).

The data is presented using the following format:

Source	Author and date of publication (refer to **References** for full details)
Location	Location of study site
Methodology	Field data, modelling or review.
Key Points	Summary of relevant information

Source	Ale *et al*. (2009)
Location	Purdue University Water Quality Field Station, USA.
Methodology	The hypothetical effects of drainage water management operational strategy on hydrology and crop yield were simulated using DRAINMOD, a field-scale hydrologic model.
Key Points	This study looked at different drainage water management systems. Preferred timetables for raising and lowering the outlet during the crop period were identified as 0–20 days after planting and about 4–6 weeks before crop maturity with the timing depending on the antecedent moisture condition. Under dry soil conditions, the outlet may be raised soon after planting while wet soil allowed raising of the outlet to be delayed by a week. It was found that by controlling the volume of water drained both during crop growing (10–85 days after planting), and for a period during the non-growing season a statistically significant reduction of the average annual drain flow (60%, 38–96% reduction in individual years) could be achieved. The predicted increase in runoff by 85% (0% to 493% in individual years) was not found to be significant.

Source	Ale *et al*. (2010)
Location	Purdue University Water Quality Field Station, USA.
Methodology	The hypothetical effects of drainage water management operational strategy on hydrology and crop yield were simulated using DRAINMOD, a field-scale hydrologic model.

Key Points	This study looked at different drainage water management systems. Modelled results suggest drainage water management showed great potential for reducing annual drain flow. The long-term average (1915–2006) annual drain flow reduction due to drainage water management varied between 52 and 55% for all drain spacings and operational strategies considered. Depending on the growing season and operational strategy, about 81 to 99% of the annual drain flow reduction occurred during the non-growing season.

Source	Ale *et al*. (2012)
Location	Purdue University Water Quality Field Station, USA.
Methodology	A distributed modelling approach was developed to apply the field-scale DRAINMOD model at the watershed scale.
Key Points	This study looked at drainage water management systems. Numerous field and modeling studies conducted in North Carolina and the Midwest of the United States and Canada have reported significant reductions (20 – 58%) in annual drain flow and nitrate load as a result of drainage water management. Results from watershed scale modelling indicated that drainage water management: • decreased the average annual (1985–2009) predicted drain flow from 11.0 to 5.9 cm • decreased the total nitrate load through subsurface drainage from 236 to 126 ton

Source	Armstrong *et al*. (2010)
Location	-
Methodology	Review
Key Points	This study combined an extensive UK-wide survey of blocked and unblocked drains across 32 study sites and intensive monitoring of a peat drain system that has been blocked for 7 years. Dissolved organic carbon concentrations were found to be significantly lower (28% lower) in blocked drains with a resulting decrease in colouration. This pattern was not consistent at all sites. The authors note that while blocking may be a useful tool for reducing dissolved organic carbon concentrations and colour there will be a number of sites where no significant change will occur.

Source	Ballard *et al*. (2011a)
Location	-
Methodology	A physics-based model that couples four one-dimensional models to represent a three-dimensional hillslope, allowing for the exploration of flow and water table response throughout the model domain for a range of drainage configurations and peat

	properties.
Key Points	Drainage of peatlands will increase peak flows. Drain blocking will not necessarily always reduce peak flows: some cases show negligible changes in runoff while other cases indicate an increase in peak flows.

Source	Ballard *et al*. (2011b)
Location	Oughtershaw Beck, UK,
Methodology	A physics-based model that couples four one-dimensional models to represent a three-dimensional hillslope, allowing for the exploration of flow and water table response throughout the model domain for a range of drainage configurations and peat properties.
Key Points	Drained peatlands typically have a shorter time to peak, higher peak flow and a quicker recession than undrained areas. Drained peatlands typically are associated with increased water table fluctuations. The areal extent of influence of the water table drawdown due to the drains is quite limited, due to very low hydraulic conductivities; therefore drain spacing plays a significant role in both short and long term effects. The effect is not uniformly distributed, the most significant impact being immediately downslope of a drain.

Source	Bellamy *et al*. (2012)
Location	Forsinard Flows National Nature Reserve, Sutherland, UK.
Methodology	Field study
Key Points	Drain-blocking has a negative effect on vegetation indicative of drier conditions and bog degradation. In some cases drain-blocking can improve the ecological functioning of blanket bogs by increasing cover of healthy bog vegetation. Cover of species indicative of bog recovery was greater where the drains had been blocked for the longest time.

Source	Blann *et al*. (2009)
Location	North America
Methodology	Comprehensive review of agricultural drainage in the US
Key Points	This is a comprehensive review of the impact of land drainage on ecosystems in the US. By 1987 more than 17% of U.S. cropland (up to 30% in the Upper Midwest) had been altered by artificial surface or subsurface drainage. The addition of subsurface drainage to lands already drained by surface drainage may result in field and catchment-scale changes in hydrology and water quality. Subsurface drainage typically alters the total water yield from a field or small watershed, not just the timing and shape of the hydrograph. The increase in total runoff tends to be relatively minor (~10%) but occurs because subsurface drainage may increase the proportion of total annual precipitation that is discharged to surface waters via subsurface flow relative to the amount that is stored semi-permanently, evaporated, or transpired.

Source	Bonaiti & Borin (2010).
Location	N E Italy
Methodology	Field experiment on an experimental facility representing a hypothetical 6-ha agricultural basin with four different land drainage systems (1. open ditches with free drainage and no irrigation (O), 2. open ditches with controlled drainage and subirrigation (O-CI), 3. subsurface corrugated drains with free drainage and no irrigation (S), 4. subsurface corrugated drains with controlled drainage and subirrigation(S-CI)).
Key Points	Measured drainage volumes (% of annual rainfall) showed reductions of average volumes for controlled drainage with irrigation when compared to free drainage of 8% in open drains and 40% for subsurface drains. Reduced drained volumes resulted from the combined effects of reduced peak flow and reduced number of days with drainage. The authors suggest that controlled drainage and subirrigation can be applied at farm scale in northeast Italy, with advantages for water conservation.

Source	Bullock *et al*. (2012)
Location	-
Methodology	-
Key Points	The 2011 Durban Climate Summit agreed that developed countries could voluntarily include emissions from drained peatlands in their carbon accounting, but also allows inclusion of reductions due to re-wetting. This leaves open the possibility that peatland restoration could be acknowledged in future emissions trading and that rights holders could be rewarded for preserving peat in situ through tradable permits for carbon storage.

Source	Dunn & Mackay (1996)
Location	River South Tyne at Alston
Methodology	Physically based distributed modelling (SHETRAN), with a fine grid resolution on a very simple hill-slope model
Key Points	Little difference was found in the total runoff volume between the undrained and drained model simulations but drainage accelerated surface runoff and the simulations for the drained model show both a higher and earlier peak discharge The mechanism of water transport varied: • Undrained model: 81% of the total runoff from direct surface runoff, 19% subsurface flow • Drained model: 53% of the total runoff from direct surface runoff, 47% subsurface flow Water levels varied • Undrained model: level of sub-surface runoff remained fairly constant throughout the year • Drained model: slight lowering in water level that varied throughout the year

Source	Gritt (2008)
Location	West Lancashire
Methodology	Historical review
Key Points	This study reviews the impact drainage has had on Lancashire. The authors suggest that drainage of the land, resulting in its transformation from some of the worst land in the country to some of the best, was a major contributor not only to the agricultural success of the region, but also to Lancashire's industrial success.

Source	Herzon & Helenius (2008)
Location	Temperate and boreal zones of the Northern Hemisphere
Review	Review
Key Points	The major regulating functions of the drainage network within cultivated catchments include: • transfer of water and soluble nutrients from the fields • water retention and nutrient recycling • processing of phosphorus and nitrogen by vegetation • mitigation of herbicides in vegetation and sediment • modifying erosion rate and transfer of soil-bound nutrients • supporting pollination and pest control functions. The relative values of ditches in draining land, control of water flow and chemical transfer, and as a wildlife habitat are likely to vary greatly regionally and even locally.

Source	Holden (2005)
Location	UK
Methodology	Field survey using consistent application of ground-penetrating radar
Key Points	A survey of 160 British blanket peat catchments showed soil pipes in all catchments. Gripping (open land drains) is the most important control on hillslope pipe frequency in blanket peats; there are more pipes where land drainage has occurred.

Source	Holden (2006)
Location	UK
Methodology	Remote mapping using GPR and historical records of drainage installation
Key Points	Drainage induced desiccation is followed by rapid pipe network expansion through erosion of material along flow paths. Desaturation causes peat to shrink and crack. Summer surface peat desiccation and winter freeze-thaw activity alter peat . Water flow enlarges the pipes and allows pipe networks to expand. No evidence that pipe network development reaches a threshold beyond which its growth slows (although data were only available for artificial drainage systems up to 80 years old). Streamflow response to peat drainage may continue to change over long time periods as pipe networks expand.

Source	Holden *et al*. (2006)
Location	Moor House National Nature Reserve, north Pennines, UK,
Methodology	Field study of two catchments drained with open-cut ditches in the 1950s
Key Points	Ditching originally resulted in shorter lag times and flashier storm hydrographs but no change in the annual catchment runoff efficiency. During 2002 and 2004, the hydrographs in the drained catchments, while still flashy, were less sensitive to rainfall than in the 1950s. Gradual changes to peat structure could explain the long-term changes in river flow, which are in addition to those occurring in the immediate aftermath of peatland drainage.

Source	Holden *et al*. (2007)
Location	-
Methodology	-
Key Points	Drainage has played a fundamental role in the history of British farming. Until the 20th century most land drainage was focussed on 'improving' lowlands for agriculture by lowering the water table. The drainage resulted in changes in water flow paths through and over moorland soils. The benefits of upland drainage in terms of reduced runoff due to increased soil storage capacity are countered by the resulting higher flow velocities in the ditches speeding up the discharge of the water into the river. Current practices of drain blocking are occurring in a similar manner to that of drain creation in the 20th Century; with limited consideration of natural processes and no real understanding of the role of each site in terms of its local setting and within the catchment as a whole.

Source	Holden at al. (2008a)
Location	Upper Wharfe catchment, UK
Methodology	Experimental field study
Key Points	Even if a peatland surface remains fully vegetated, if the vegetation type is altered then flow velocities could change leading to alterations in the timing of runoff delivery from slopes to streams. Reestablishment of Sphagnum on degraded (especially bare) peatlands may therefore be important for reducing the potential for sheet erosion and downstream flood peaks more than Eriophorum or Eriophorum-Sphagnum mixes.

Source	Holden *et al*. (2011)
Location	Oughtershaw Moss, a blanket peat catchment located in the headwaters of the River Wharfe, northern England
Methodology	Field study using transects of automated water table recorders
Key Points	Hydrological changes induced by 40 years of drainage were not reversed over the 6–7 year period since drain blocking occurred. Many of the components of water table dynamics at the blocked site were intermediate between those found at the drained and intact sites. While blocked drains showed shallower water table levels than drained sites, several components of the water table record (e.g. depth exceedance probability curves, seasonality of water table variability, and water table responses to individual rainfall events) were symptomatic of slow recovery of hydrological function. Even if full hydrological function is eventually restored at blocked sites the timescales involved appear to be greater than may have been anticipated by most restoration agency-funded monitoring programmes.

Source	Imlay & Carter (2012)
Location	East central Illinois
Methodology	Historical review
Key Points	The amount of agricultural land reclaimed by drainage by 1920, mainly in the Midwest, far exceeded that opened by irrigation in the West. A distinctive social order in east central Illinois emerged from, and was shaped by, an agrarian structure that had developed in response to marshy, unpredictable conditions before drainage began in the late 1800s. The beneficiaries of the old order capitalized on the new opportunities presented by drainage enterprises, to create a ‘hydraulic society’ on the prairie.

Source	Kenyon *et al*. (2008)
Location	Scotland
Methodology	Policy review using Delphi study
Key Points	A number of factors were identified as having potentially led to an increased risk of surface water flooding in Scotland over the past 50 years. Panellists agreed that incentives provided to farmers to drain agricultural land have altered the rate of water runoff and increased the peak flow during heavy rainfall. Most panellists thought certain agricultural practices (drainage of ponds and natural wetlands, upland areas and lowland raised bogs) had been highly responsible for increasing downstream flood risk since they resulted in the loss of natural flood storage capacity and increased runoff.

Source	Kladivko *et al*. (2004)
Location	Field study
Methodology	Southeast Indiana
Key Points	In drier years, drain flow volume is lower and also tends to be a lower percentage of total precipitation. The horizontal spacing between parallel drains exerts a fundamental control on the drainage volume. Drain flow losses are greater per unit area for narrower drain spacings: annual drain flow increased from 12 to 15 to 21% of annual precipitation as the drain spacing decreased from 20 to 10 to 5 m.

Source	Koivusalo *et al*. (2008)
Location	-
Methodology	Field study of two pairs of artificially delineated catchments in drained peatland forests in Finland
Key Points	The response to ditch cleaning differend depending on peat depth: water table levels were lowered in sites with shallow peat layers while in sites with deep peat formation, the water table showed no detectable response. Annual runoff increased after ditch cleaning. The authors note that a model simulation was unable to reproduce the pattern of results and suggest that the catchments assessed were not hydrologically isolated and therefore question the validity of the results.

Source	Konyha *et al*. (1992)
Location	North Carolina
Methodology	A field-scale hydrologic model (DRAINMOD) was used to simulate the hydrology of two North Carolina muck soils under four water-management methods over 33 years: conventional drainage using open field ditches (CNVL), improved subsurface drainage using pipes (IMPP), Controlled drainage where water level control structures used during the growing season (CTR1) and Controlled drainage where water level control structures used all year except during planting and harvest (CTR2).
Key Points	With CVNL the soil differences had considerable influence on the hydrology. The soil with high hydraulic conductivity resulted in better subsurface drainage. Both soils were well drained using IMPP and the hydrologic differences between the two soils were less noticable. CTR1 increased surface runoff and decreased subsurface drainage, compared to IMPP. For CTR2, subsurface drainage was further reduced while surface runoff increased. The impact of a water-management system was found to be soil specific, but in general improved subsurface drainage decreased surface runoff and reduced the volume of runoff that leaves at high flow rates while controlled-drainage systems

	tended to increase the volume leaving at high flow rates. Impacts of drainage practice were less noticeable for larger events.

Source	Luo *et al*. (2008)
Location	YinNan Irrigation District
Methodology	A controlled drainage experiment was conducted during the growing seasons of 2004 and 2005
Key Points	Controlled drainage reduced drainage discharge by 50–60%.

Source	Luo *et al*. (2010)
Location	Data from South Central Minnesota
Methodology	Long-term simulations using DRAINMOD-NII
Key Points	Both shallow drainage and controlled drainage may reduce annual drainage discharge by 20–30%, while impacting crop yields from 3% (yield decrease) to 2%, depending on lateral drain spacing. Controlled drainage showed the greatest potential to reduce annual drainage volumes.

Source	Ma *et al*. (2007)
Location	Nashua, Iowa
Methodology	The Root Zone Water Quality Model (RZWQM) was applied to evaluate various management effects in several previous studies
Key Points	Analysis of simulated results from an experimental study initiated in 1978 at Nashua, Iowa for management effects (tillage, crop rotation, and controlled drainage) on crop production and N loss in drain flow showed a 30% reduction in average annual drain flow with controlled drainage compared with free drainage when the drain depth was 1.20 m. Controlled drainage also promoted lateral subsurface flow, simulations showed an increase of 17%.

Source	Meijles & Williams (2012)
Location	A regional scale case study of the Drentsche Aa catchment in the province of Drenthe, The Netherlands
Methodology	Policy review
Key Points	Land management policies and the resulting land use change resulted in the watershed of the river Drentsche suffering from desiccation, low base flow levels and a short response time to rainfall, including high runoff peaks. One of the largest changes was demonstrated to have been brought about by extensive field drainage.

Source	Newson &Robinson (1983)
Location	-
Methodology	-
Key Points	Artificial drainage reduced the peak rates of outflow into the river network due to a general lowering of the water table, providing an increase in the storage capacity of the soil, and encouraging the movement of water in deeper soil horizons. The authors warn that this result cannot necessarily be extrapolated to other situations.

Source	Posthumus & Morris (2010)
Location	The Laver and Skell catchments in North Yorkshire; the Parrett catchment in Somerset; the Eden catchment in Cumbria; the Upper Severn catchment in Montgomeryshire, Wales; and the Hampshire Avon catchment in Wiltshire
Methodology	Fieldwork
Key Points	While most of the interviewed farmers recognised the need to reduce soil erosion and diffuse pollution, they were less willing to accept responsibiliy for controlling storm-water runoff from farmland that might contribute to flooding downstream unless it would be organised and compensated for by the government. One farmers thought: "... We had a government that was paying farmers 60% to drain all the wetlands, ..., all this sort of thing. And now they turn around paying that sort of money to reinstate it...farmers are government-oriented, it always has been like, you know. And we're led by them." Extensive land drainage in North Yorkshire is thought that to have contributed to an increased frequency of flooding downstream. In Somerset, flood risk was thought to be aggravated by more frequent heavy rainfall events, runoff from hard surfaces and development in floodplains. Land drainage was acknowledged as a contributing factor to flooding, but this reduces flood risk in the floodplains and is thus a good practice according to the farmers. Targeting high-risk areas of runoff with professional advice and locally appropriate control measures is likely to be the most effective approach to reducing runoff .

Source	Posthumus *et al*. (2008)
Location	North Yorkshire
Methodology	
Key Points	Runoff and subsurface drainage from farmland acts as a pathway, causing flooding in downstream receptor areas. This is influenced by several factors including the extent of soil compaction, the efficiency of land drains and the connectivity of flow paths. During a stakeholder workshop, most participants thought that land drainage had increased flood generation as rainfall water is

	discharged quicker into the watercourses.

Source	Potter *et al*. (2011)
Location	UK
Methodology	Policy
Key Points	Events in the 1990s and turn of the century at Boscastle and Carlisle highlighted the cumulative impact of land drainage, urbanisation and river regulation over the previous decades

Source	Ramchunder *et al*. (2009)
Location	UK
Methodology	Review
Key Points	While approximately £500M has been spent on drain-blocking in northern England in the last five years the full environmental effects of drain-blocking remain uncertain. Drainage and burning of peat often lead to altered runoff regimes. Peatland drainage lowers the water table directly adjacent to the drain, and more specifically downslope of the drain. In addition to lowering the water table, drained blanket peats exhibit more deep throughflow than saturation-excess overland flow. The magnitude of the response to drainage is complicated by variations in plant species/peat type, drain patterns and spacing/density and the section of the catchment in which drainage takes place. There are long-term differences in the hydrological response of drained catchments over time. While drain blocking has been noted to reduce discharge by over 70% there is little evidence as yet at a larger scale than that of the hillslope to indicate any hydrological impacts related to drain-blocking.

Source	Ritzema *et al*. (2006)
Location	The Netherlands
Methodology	Review
Key Points	Subsurface drainage was widely introduced in many parts of the world in the late 20th century as the theoretical understanding of drainage and salinity control gained became established This was further accelerated by rapid developments in mechanized installation from the 1940s onwards. New drainage materials (plastic drain pipes and synthetic envelopes) resulted in lower transportation and installation costs.

Source	Rose & Rosolova (2007)
Location	120km^2 catchment draining through Ripon in North Yorkshire, which includes the rivers Skell and Laver, and Kex Beck.
Methodology	Individual sub-catchment rainfall-runoff models, in the form of Probability Distributed Moisture (PDM) models were linked together via an ISIS flood routing model in order to simulate flows at the catchment outlet.
Key Points	Sensitivity testing was used to indicate the potential impact of changes in runoff characteristics from farms and sub-catchments on catchment scale flood generation. The impact of moorland grip drainage blocking in controlling the generation and rate of runoff was also investigated. Results indicated that the worst case degradation scenario (combining soil structural degradation across the whole catchment and additional moorland grip maintenance) led to increased peak flows in Ripon compared to the baseline case of between 20% for smaller scale floods and 10% for more extreme floods. The best case improvement scenario (moorland grip blocking) led to a reduction of flood peak magnitudes in Ripon by up to about 8% when compared to the baseline case. The timing of the flood peak in Ripon was altered by up to ±1.5 hours as a result of the scenarios, though changes to the timing of the hydrographs generated in the moorland areas were attenuated by the time they had reached Ripon.

Source	Scheidleder *et al*. (1996)
Location	-
Methodology	Review
Key Points	In Austria and Denmark land drainage was cited as ‘‘probably the single most important measure which has adversely affected the landscape (loss of wetlands, small scale structures in the landscape), the biodiversity and the hydrological cycle’’

Source	Singh *et al*. (2007)
Location	Iowa
Methodology	Deterministic hydrologic model (DRAINMOD) using long-term (1945-2004) hydrologic simulations to predict the effects of drainage water management on subsurface drainage, surface runoff and crop production
Key Points	Simulation results indicate the potential of a trade-off between subsurface drainage and surface runoff as a pathway to remove excess water from the system. Controlled drainage reduced subsurface drainage (9-18% compared to conventional (free) drainage) while surface runoff increased (31-54%). The water table remains shallower in the case of controlled drainage as compared to free drainage. Controlled drainage might increase the excess water stress on crop production, and thereby result in slightly lower relative yields. The authors suggest field experiments are needed to examine the pathways of water movement and assess the total water balance.

Source	Smedema (1993)
Location	-
Methodology	-
Key Points	The performance of installed subsurface drainage systems is considerably influenced by soil management practices. These influences can be both positive and negative. For example, rootzone drainage is severely limited when the upper soil layers are subjected to compaction practices while the effects of drainage on early workability are enhanced by practices that increase the proportion of organic matter in the soil.

Source	Smedema (2011)
Location	-
Methodology	Policy
Key Points	Drainage development rain fed agricultural land is driven by a combination of forces and conducive conditions: mainly the state of agricultural development and the economics of improved drainage. In the 1980's public support for agricultural drainage was greatly affected by emerging environmental awareness. Some adverse drainage development conditions can be overcome by appropriate government policies and interventions.

Source	Sutherland (2010)
Location	Upper Deeside, Scotland
Methodology	Policy & farming
Key Points	Farmers were found to actively consider environmental regulations and grant opportunities as part of processes for farm development or securing additional land. While according to a Farming and Wildlife Advisory Group (FWAG) Advisor "A lot of the older farmers will see putting agricultural land into sort of wildlife management as alien, because they've spent all of their lives draining them and improving them", farmer engagement in environmental schemes is becoming a widely accepted practice. There is some evidence that the social practice of observing other farmers' innovations is beginning to include environmental actions: one farmer after attending an open day on an organic farm in a nearby region favourably reviewed the other farmer's wetland drainage system, which created a habitat for wildlife for part of the summer, but drained the water to provide additional grazing for the remainder of the year.

Source	Wallage *et al*. (2006)
Location	Oughtershaw Beck, a headwater tributary of the River Wharfe, northern England
Methodology	Field/ Experimental study
Key Points	Dissolved organic carbon and water colour production from a site where the drains had been blocked three years prior to measurement was significantly lower than the adjacent drained site, but also significantly lower than that from undrained moorland: a process of store exhaustion and flushing may have been operating. Drain blocking alters the composition of DOC making darker-coloured humic substances more dominant compared to the intact site. The dominance of water flow paths in peat varies depending on water table depth in conjunction with antecedent conditions and topographic position.

Source	Walters & Shrubsole (2003)
Location	Zorra Township, located within the Thames River valley, Ontario.
Methodology	Review of processes for approval for drainage
Key Points	Agricultural drainage has accounted for between 81 and 85% of wetland losses in southern Ontario. Wetland management and agricultural drainage illustrate the conflict between economic development and natural values.

Source	Wheater & Evans (2009)
Location	-
Methodology	Review
Key Points	Sheep numbers in Great Britain doubled between 1950 and 1990 as a result of farm support payments based on stock numbers and at the same time the amount of improved pasture in upland areas increased as a result of draining, ploughing, and reseeding, financially supported by government and EU incentives. Runoff response from drained fields varies seasonally, depending on antecedent moisture conditions. Runoff from drained land may be faster or slower than from undrained land depending on the nature of the soil and its management, as well as the timing and intensity of rainfall. As a result of the increased importance being placed on future food security drainage and blocking practices may need to be re-evaluated to both reduce flood risk and maintain standards of land drainage in areas of national agricultural importance.

Source	Wilson *et al*. (2010)
Location	A degraded Welsh upland blanket bog, Lake Vyrnwy catchment (mid-Wales)
Methodology	-
Key Points	Results show a reduction in peak flows and increases in water residency after rainfall. Average flow rates from both drains and streams declined after drain-blocking, largely due to a reduction in the time spent at peak flows. After drain blocking, the rate of water table level recovery varied and was influenced strongly by slope, aspect and peat depth. The water table was also more stable. There was a strong overall increase in surface water in response to blocking, ranging up to approximately 40% more after blocking. The study demonstrated the importance of small and large scale topography in determining the degree of any response. This study showed strong catchment scale differences in response, and a very gradual recovery of water tables.

Source	Wilson *et al*. (2011)
Location	Wales
Methodology	A landscape scale experimental study on an upland peatland in Wales that has been restored through drain-blocking.
Key Points	The water table response to storm events changes after drain blocking, with levels rising higher and taking longer to recede to antecedent levels. Peak flow hydrographs from drains show considerable change after restoration, with lower peak flow rates, less runoff and less rainwater being released during the event. The results suggest • drain blocking leads to higher and more stable water tables that are able to better resist drought periods • even with a reduced potential storage, restored peatlands can exhibit less flashy flood responses and provide better retention of rainfall even during peak events. • Peak flow responses in both drains and upland streams were less severe, with more rainfall being retained within the bog While the authors suggest that restoration leads to a more buffered system and more moderate responses to extreme events they note that the most severe events covered in the study had return periods of 2 years therefore it was not possible to conclude if extreme events would show similar or different flood responses.

Source	Wiskow & van der Ploeg (2003).
Location	Leine river in Northern Germany
Methodology	A two-dimensional drainage model
Key Points	Drain discharge was found to be inversely and nonlinearly related to drain spacing across a range of spacings from 5 to 50 m. • Narrow spacing prevents the water table from rising into the rooting zone of a growing crop and allows it to fall quickly after a storm. Water storage is limited therefore drainage systems may add to river floods in periods with excess precipitation, especially if drainage is employed at a large scale • Larger spacing, that allows soil saturation, may increase soil water retention. While the drainage performance will be reduced, restricted drainage efficiency may help to reduce the risk of winter floods.

Source	Woli *et al*. (2010)
Location	A private farm Near DeLand in Piatt County, east-central Illinois
Methodology	Field study
Key Points	Controlled drainage was extremely effective in reducing tile flow with a three-year average of 10.7cm of flow compared to 41cm from free drainage. The outlet level for the free drainage system was set at the tile depth for the duration of the study, while the outlet level of the controlled system was raised to within 15cm of the soil surface on or close to November 1st of each year, and lowered back down to the level of the tile on or close to March 15th of the following year.

Source	Worrall *et al*. (2007a)
Location	Whitendale catchment, UK
Methodology	Field study: 54 stream and drain sites were sampled on an approximately weekly basis
Key Points	There is a significantly higher water table in peat adjacent to blocked drains. Whenever runoff occurred from a blocked drain it was always more discoloured than prior to blocking. During the 10 months following drain-blocking no catchment scale change in river water colour could be determined. No drain-blocking technique was demonstrably better or worse than any other with respect to time for which there was flow in the drain. No evidence that drain-blocking was an effective technique for reducing water discolouration and DOC at the catchment scale in the short-term; however the short-term response of a peatland to drain-blocking may not be the same as the long-term response.

Source	Worrall *et al*. (2007b)
Location	Trout Beck catchment, UK
Methodology	Modelling using a combination of empirical equations
Key Points	The model predicted that drained catchments export more dissolved organic carbon (DOC), increases are of the order of 15–33% over a 10-year period depending upon the drain-spacing. When drainage is blocked, improvements in DOC export are predicted but the magnitude of the decrease is critically dependent upon the drain-spacing and for the larger drain-spacings no decrease may be observed. Improvements in DOC export after blocking are shown to lessen over time.

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CREW Facilitation Team

James Hutton Institute
Craigiebuckler
Aberdeen AB15 8QH
Scotland UK
Tel: +44 (0) 844 928 5428

Email: enquiries@crew.ac.uk

www.crew.ac.uk

This study is co-financed by SAWA, an EU-Interreg IVb North Sea Programme project.

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