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A framework for managing runoff and pollution in the rural landscape using a Catchment Systems Engineering approach

M.E. Wilkinson [a,b,*], P.F. Quinn [b], N.J. Barber [b], J. Jonczyk [b]

[a] The James Hutton Institute, Craigiebuckler, Aberdeen, AB15 8QH, UK
[b] School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK

HIGHLIGHTS

- A framework to achieve multiple-benefit catchment management plans is presented.
- Catchment Systems Engineering is an approach that seeks to manage flow pathways.
- Mitigation measures have been created that slow, store and filter catchment runoff.
- Several measures have been optimised for reducing diffuse pollution from agriculture.
- Results suggest that optimised features are reducing pollutant concentrations during storms.

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ABSTRACT

Intense farming plays a key role in increasing local scale runoff and erosion rates, resulting in water quality issues and flooding problems. There is potential for agricultural management to become a major part of improved strategies for controlling runoff. Here, a Catchment Systems Engineering (CSE) approach has been explored to solve the above problem. CSE is an interventionist approach to altering the catchment scale runoff regime through the manipulation of hydrological flow pathways throughout the catchment. By targeting hydrological flow pathways at source, such as overland flow, field drain and ditch function, a significant component of the runoff generation can be managed in turn reducing soil nutrient losses.

The Belford catchment (5.7 km^2) is a catchment scale study for which a CSE approach has been used to tackle a number of environmental issues. A variety of Runoff Attenuation Features (RAFs) have been implemented throughout the catchment to address diffuse pollution and flooding issues. The RAFs include bunds disconnecting flow pathways, diversion structures in ditches to spill and store high flows, large wood debris structure within the channel, and riparian zone management.

Here a framework for applying a CSE approach to the catchment is shown in a step by step guide to implementing mitigation measures in the Belford Burn catchment. The framework is based around engagement with catchment stakeholders and uses evidence arising from field science. Using the framework, the flooding issue has been addressed at the catchment scale by altering the runoff regime. Initial findings suggest that RAFs have functioned as designed to reduce/attenuate runoff locally. However, evidence suggested that some RAFs needed modification and new RAFs be created to address diffuse pollution issues during storm events. Initial findings from these modified RAFs are showing improvements in sediment trapping capacities and reductions in phosphorus, nitrate and suspended sediment losses during storm events.

1. Introduction

Intensive farming practices have the potential to increase local runoff rates, resulting in various water quality issues and local flooding problems (e.g. O'Connell et al., 2004, 2007; Parrott et al., 2009). Reducing diffuse pollution caused by agricultural activities is a major challenge in many European catchments where the sustainability of the ecosystems and water uses is compromised by intensive agriculture (Laurent and Ruelland, 2011). The European Community Water Framework Directive (WFD: 2000/60/EC) has highlighted the issues of diffuse pollution and is intended to foster the improvement of the ecology and amenity value of the UK surface waters. A central issue is excess nutrient inputs from agriculture and households to surface waters, leading to eutrophication (Hilton et al., 2006; Neal et al., 2008), which is still the most significant reason for water bodies failing to achieve good ecological

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* Corresponding author at: The James Hutton Institute, Craigiebuckler, Aberdeen, AB15 8QH, UK. Tel.: +44 1224 395158.
E-mail address: mark.wilkinson@hutton.ac.uk (M.E. Wilkinson).

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status (GES) in 2015 and beyond (Scheuer and Naus, 2010). Agriculture in the EU contributes circa 70% of the suspended sediment (SS), 40–80% of the nitrate (NO_3) and 20–40% of the phosphorus (P) entering surface waters (OECD, 2001). Despite the 2009 deadline for the adoption of river basin management plans (RBMPs) and programmes of measures (PoMs) to meet GES by 2015, it is estimated by the European Environment Agency (2012) that only 52% of European water bodies will meet GES by 2015, with diffuse pollution from agriculture being the significant pressure for 40% of European water bodies. River basin management plans and PoMs, as key tools of WFD, take into consideration the variability in ecosystem characteristics and as such a catchment-specific approach for implementation of mitigation measures is required (Johnes et al., 2007; Doody et al., 2012). The latest review of the RBMP by the European Commission in 2012, recommended that member states should "*step up ambition in taking measures to achieve good status*" and "*in case of uncertainties in effectiveness, take no-regret measures*" (European Commission, 2012b). It is thus becoming more expedient in agricultural catchments to implement the type of management necessary to reduce sediment and nutrient losses to standing water bodies (Jordan et al., 2007).

The Floods Directive (2007/60/EC) has created a platform for the management of flood risk with aims to reduce the adverse consequences to human health, economic activity, the environment and cultural heritage associated with floods. Flooding is a significant hazard in England and Wales with approximately 1.85 million homes, 185,000 commercial properties, circa 5 million people, and half of the most productive agricultural land at some risk from flooding (Parker, 2000; Environment Agency, 2001; Penning-Rowsell et al., 2006). There is widespread concern that shifts in extreme weather events associated with climate change could exacerbate damages globally or even reverse development gains in some regions (UNDP, 2007; Wilby and Keenan, 2012). Sustainable flood risk management measures need to have a prominent role in the implementation of the directive. In the UK, sustainable flood risk management embodies a shift from a traditional, predominantly piecemeal and reactive method towards a catchment-based approach that takes account of long-term social and economic factors, which uses natural processes and natural systems to slow down and store water (Scottish Environment LINK, 2007).

Methodologies for mitigating water quantity and quality share many commonalities and these aspects should be considered together in order to maximise benefits and persuade local actions. This idea is embraced in policy within the *Blueprint to safeguard Europe's waters* document (European Commission, 2012a); however, it is rarely applied in practice. Achieving water quality targets at minimum economic cost is one of the underlying principles driving the selection of mitigation measures (Balana et al., 2012). However, there is an urgent need to tackle multiple issues in a holistic way, whilst delivering more for less and demonstrating the impact at the catchment scale. The current financial constraints throughout Europe means that multi-objective measures to meet the targets of the above directives are critical and action needs to be taken. The commonality between many western European catchments is in the intensity of the farming, the wide range of recognised environmental concerns, a highly regulated governance regime and a vulnerability to climate and demographic changes. Hence, there is potential for agricultural management to become a major part of improved strategies for controlling runoff for better water quantity and quality.

This paper presents a case study for which a framework has been developed for implementing multi-purpose measures in the Belford Burn catchment, Northumberland, UK. It provides a guide to implementing measures in the catchment, which could be easily applied to other catchments of a similar scale. The key to this uptake is to have a demonstration catchment that has soft engineering features imposed on it and to show stakeholders and regulators how the benefits were achieved and at what cost. The paper presents the framework methodology and a description of these steps. In the final two steps provisional assessment and discussion of the data are performed.

2. Study area and catchment issues

The Belford Burn catchment (5.7 km^2) lies in Northumberland in the northeast of England and drains through the village of Belford (OS Grid Reference NU-339107). The stream flows into Elswick Burn, which then drains into Budle Bay (~30 km^2). Over recent decades, increasing summer blooms of macrophytic algae (mainly *Enteromorpha*/*Ulva intestinalis*) have occurred in Budle Bay (Palmer, 2012). This is a concern as it forms part of the Lindisfarne Special Protection Area protected under the Birds Directive (79/409/EEC), and is also designated a Natura 2000 site and Ramsar wetland. The River Water Body WFD Ecological Status in 2009 classed the Belford Burn as poor; without appropriate mitigation it is predicted to remain so in 2015 (Environment Agency, 2009) and therefore fail the WFD targets. Table 1 indicates that average annual (2006–2009) reactive P (RP) concentrations consistently exceeded levels prescribed under the WFD, whilst other water quality determinands were below recommended thresholds. The main sources of water pollution were identified by the Environment Agency for England and Wales (EA) as agricultural diffuse pollution and domestic septic tanks.

The headwaters of the Belford catchment are predominately pasture and cultivated grasslands. Grasslands and arable land dominate the lowlands. The topography is relatively steep (elevation change of 150 m over 4 km river length), which is a contributing factor to the flashy response to heavy rainfall. Belford has a long history of flooding; the 2002 flood caused damage to a number of properties and businesses, which culminated in the EA commissioned flood defence pre-feasibility study (see Halcrow, 2007). The analyses concluded that traditional flood defences were not suitable for Belford because of the high-cost, lack of space for flood walls and banks, and the small number of properties at risk; therefore the town did not meet the criteria for Grant-in Aid funding. This situation is typical for many small rural villages that are at risk of flooding. Five months after the pre-feasibility study was published, the July 2007 storm occurred and caused flooding to more than 10 properties. The feeling in the village community was highlighted by the local press headline "Sick of sandbags and sympathy" (12th July 2007, Northumbrian Gazette). Owing to the high costs of traditional flood defences, there was a desire by the local EA Flood Levy Team and the Northumbria Regional Flood Defence Committee at the EA to deliver an alternative catchment-based solution to the problem (Wilkinson et al., 2010b). The original work for this study was carried out at the farm-scale (Nafferton Farm ~1 km^2) where mitigation measures were installed for water quality management purposes (Quinn et al., 2007; Jonczyk et al., 2008; Shaw et al., 2011).

3. Methodology: A runoff management framework

Applying upstream multi-purpose mitigation measures in Belford was a new approach to flood risk management for the local EA Flood Levy Team, whilst the primary goal was to reduce the risk of flooding in Belford secondary objectives which included: to work with the community to design, locate and construct measures; to gain evidence from the measures to investigate their effectiveness in reducing flood risk; and to assess the multiple environmental benefits (e.g., modifying flood measures to be better adapted to reduce diffuse pollution).

Table 1
Average (from 36 samples) yearly ammonia, dissolved oxygen, nitrate (N) and phosphate (P) levels in Belford Burn at Ross Law, 2 km downstream of the village of Belford. (Source: Environment Agency http://maps.environment-agency.gov.uk/wiyby/ accessed December 2010.)

Average	2009	2008	2007	2006
Ammonia (mg $l-^{1}$)	0.125	0.116	0.101	0.094
Dissolved oxygen (%)	95.58	95.75	95.78	97.47
Nitrates (mg l^{-1})	22.43	22.89	23.05	23.68
Phosphates (mg l^{-1})	0.13	0.12	0.1	0.16

However, the framework methodology could be used in a catchment where diffuse pollution is the primary issue and these features could be adapted to offer flood reduction benefits. Evidence is vital for influencing and informing policy and creating a local catchment plan. In order for the lessons learned in the Belford catchment to be transferable to other catchments, a runoff management framework has been developed. The framework is based around implementing mitigation measures that target crucial pathways, engaging with catchment stakeholders and using evidence from field science and effective management protocols. Stakeholder engagement is the foundation of the framework (Fig. 1). Ensuring that all stakeholders are well informed and can all actively contribute to solving the problems will lead to greater stakeholder confidence and better outcomes being reached (Collins et al., 2012). Only through engagement with stakeholders' concerns can research output lead to improvements in farming practice and realistic policy (Hewett et al., 2009). The framework aims to facilitate cross-issue communication in order to find the most holistic solution.

Fig. 1 shows the runoff management framework that was developed in the Belford case study; it is a modification of the Hewett et al. (2009) model for a multi-scale framework for the strategic management of diffuse pollution. The framework begins by identifying catchment environmental issues; these issues are subject related and are usually poorly connected in terms of communicating and achieving multiple benefits (Fig. 1; top catchment). Within catchments there are many issues that need to be resolved, but rarely is a project funded to deliver numerous benefits. The steps of the framework as shown in Fig. 1 will be described in the following sections. Finally, the loop commences again (via modification) and the long-term catchment plan evolves further; especially if the future issues are made more ambitious, for example tackling water quality and ecological issues downstream.

3.1. Step 1: The concept for catchment change — Catchment Systems Engineering approach

The objective of the *concept for catchment change* step is to come to a consensus, through engagement, on a vision for a local catchment management plan. In Belford a Catchment Systems Engineering (CSE) approach was used. CSE follows the principles of Earth Systems Engineering and management (see Allenby, 2000, 2007; Schneider, 2001; Hall and O'Connell, 2007). CSE is an interventionist approach to altering the catchment scale runoff regime and nutrient dynamics through the manipulation of hydrological flow pathways to manage water quality and quantity sustainably (Quinn et al., 2010). It seeks first to describe catchment function (or role) as the principal driver for evaluating how it should be managed in the future. The term '*systems*' in CSE relates to both the natural and human functioning of a catchment as ultimately the stakeholders must agree with the interventions proposed. The success of CSE depends upon long-term commitment, which can only be sustained by building a consensus (Hall and O'Connell, 2007).

Runoff Attenuation Features (RAFs) are a practical component of CSE. On-farm impacts can be mitigated through good land use management practices that delay or attenuate runoff (O'Connell et al., 2004; O'Donnell et al., 2011). RAFs are based on the concept of the storage, slowing, filtering and infiltration of runoff on farms, at source, by targeting surface flow pathways in fields and farm ditches (Quinn et al., 2007; Wilkinson et al., 2010a, 2010b; Barber and Quinn, 2012b; Nicholson et al., 2012; Wilby and Keenan, 2012). RAFs have the potential to create a simple multi-purpose solution, which aims to cover all the issues highlighted in Fig. 1. RAFs include bunds, drain barriers, runoff storage features (both *online* — located within the main channel; and *offline* — located adjacent to the channel), large woody debris dams, buffer strip management, and willow barriers.

3.2. Step 2: Catchment characterisation

The objective of *catchment characterisation* is to set up a monitoring platform in order to characterise the hydrological functioning of the catchment and gather evidence on the effectiveness of mitigation strategies. Moreover, evidence is required to determine the impact of the CSE approach and to underpin future management plans. Evidence is usually available in two forms: qualitative and quantitative. However, policy makers have tended to favour quantitative forms of evidence and systematic reviews of hydrological data often ignore the benefits of soft evidence (e.g. Seibert and McDonnell, 2002). It is important to characterise the catchment pre-, during and post-change. Ideally, it would be useful to have a long period of pre-change data allowing the catchment to be understood before any mitigation strategies are put in place. In many cases this is not a feasible option, especially where flood defence schemes require urgent execution. However, it is vital to

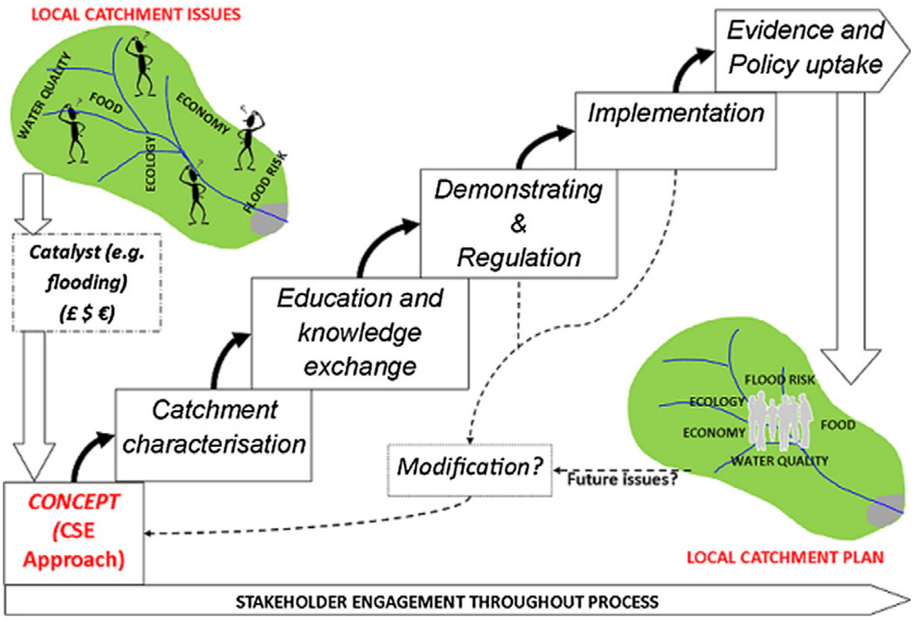

Fig. 1. The runoff management framework developed in the Belford Burn catchment.

characterise the catchment at the earliest stage possible to allow for some pre-change data to be collected; this can be achieved whilst mitigation measures are being considered. Stakeholders have a large role to play in providing expert opinion concerning the design of monitoring networks; for example, in identifying which water bodies are at risk of failing to achieve the WFD objectives and assessing the most appropriate water quality elements to monitor at suitable surveillance monitoring points (Collins et al., 2012).

A multi-scale, nested hydrometric experiment was deployed in the Belford Burn catchment in November 2007 (Fig. 2). This consisted of a rain gauge, five stream level stations and six water level recorders within RAFs. There was a desire from the EA and Newcastle University to show the multi-purpose potential of the approach. Thus, four automatic water pump samplers (ISCO 3700 and 6700) were deployed in 2009 to take samples from the stream during storm events. These were followed by a further two samplers in 2011, to monitor a ditch management RAF.

3.3. Step 3: Education and knowledge exchange

The objective of the *education and knowledge exchange* step is to share knowledge and use tools that help stakeholders understand informative concepts therefore helping to facilitate links between several issues (Fig. 1). A decision support tool was used to help accelerate the knowledge exchange process during stakeholder meetings. In academia, as well as in professional consultancy, a number of decision support systems (DSS) for river basin management have been proposed to comply with WFD, but have rarely been used by the competent authorities (de Kok et al., 2009; Klauer et al., 2012). It is important that all stakeholders are able to use and have an understanding of the DSS tool. Initially a combination of different conceptual runoff scenarios provided end users with a number of ways to visualise the effects of different land management practices. The Floods and Agriculture Risk Matrix (FARM) tool is an example of an education tool that focuses on runoff risk from farms (Wilkinson et al., 2013). The FARM tool was built around the findings of the FD2114 Defra research project (O'Connell et al., 2004) and was further refined during consultation with stakeholders in the Ripon Multi-Objective Pilot project (Posthumus et al., 2008). Primarily used at farmer meetings, with regulators in attendance, the tool reflects what stakeholders consider to be ‘slow and low’ and ‘fast and high’ runoff rates, respectively. Earlier forms of the same tool exist for pollution management including the Nutrient Export Risk Matrix (NERM) for NO_3 losses (see Quinn, 2004), and the Phosphorus Export Risk Matrix (PERM) for P losses (Hewett et al., 2004). These tools allow non-expert stakeholders to understand conceptually the underlying issues behind the problems and empower them with adequate knowledge to participate in formulating a solution.

3.4. Step 4: Demonstration and regulation

The objective at the *demonstration and regulation* step is to exhibit to catchment stakeholders and regulators how catchment intervention using RAFs will work. In Belford, a pilot/demonstration RAF site and design were agreed and constructed for this purpose (for more details refer to Wilkinson et al. (2008, 2010b)). This proved to be a long process with many regulators raising different issues about the design and location of features as well as the environmental, ecological (for example, in stream RAFs need to consider fish habitats and riparian zone features needed to consider vole habitats), and archaeological impacts of the interventions. At first, it was difficult to manage the plethora of EA advice, regulation and administration; however, the engagement with all the EA parties proved very useful and a robust solution was developed. The pilot RAF is an offline intervention (capacity ~1000 m^3), which consists of a 1 m high wooden bund, crossing a hollow in the landscape collecting both surface runoff and high flows spilled from the nearby stream. If the RAF is full it is allowed to overflow via a controlled spillway slot at the end of the wooden bund, reducing the risk of soil erosion from overspilling. The pilot RAF has performed well during the storms presented in Table 3. During the September 2008 event (a storm with a 24 h return period of 20 years) the pond was full at around the same time as the main peak indicating that RAF was functioning well (Wilkinson et al., 2010b). However, it is likely for a storm with a higher return period that this pond may have overtopped earlier. Information on the functioning of the pilot RAF during this event can be found in Wilkinson et al. (2010b).

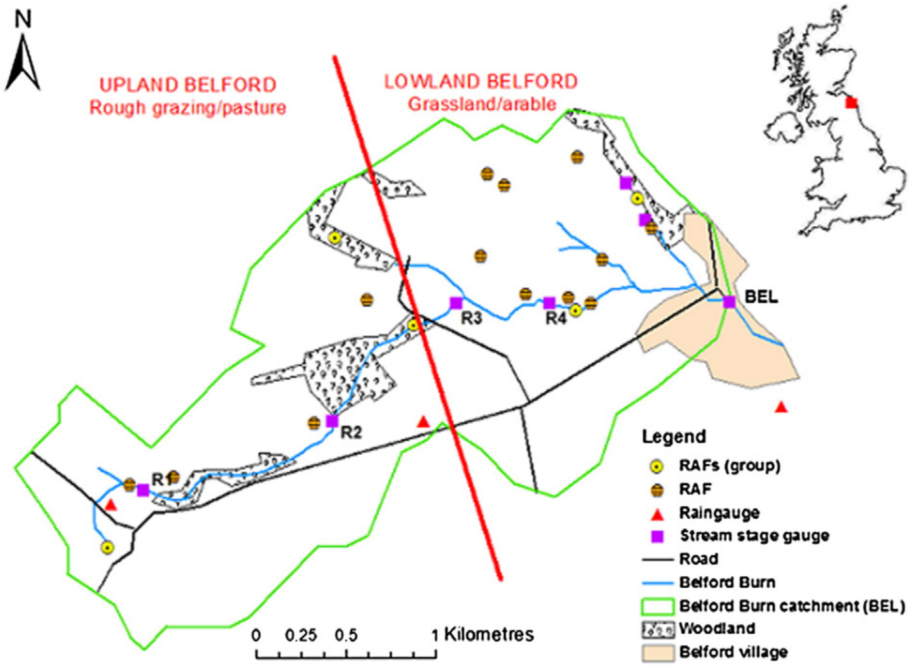

Fig. 2. The Belford Burn catchment showing the hydrometric network and Runoff Attenuation Feature (RAF) sites.

Table 2
A construction and operational summary of six instrumented RAFs in the Belford Burn catchment.

RAF number	Type	Construction and operation	Capacity (approx.) m^3
0	Offline flow storage/incepting fast overland flow pathway	Timber permeable barrier; disconnects major overland flow pathway and diverts high flows from stream	800
1	Offline flow storage	Soil bund; high flows diverted from stream	310
2	Online flow storage/wetland area	Earth dam; wetland pond with extra storage during high flows	700
3	Offline flow storage	Soil bund; high flows diverted from stream	360
4	Incepting fast overland flow pathway	Soil bund with wooden sluice; disconnects major overland flow pathway	3000
12	Online flow storage/wetland area	Soil bund around wetland pond; wetland pond with extra storage during high flows	250

3.5. Step 5: Implementation

The *implementation* step involves the construction of RAFs across the entire catchment in order to address the identified issues (Fig. 1). In a three-year period (2008–2011) over 30 RAFs were constructed in the Belford catchment (Fig. 2). A detailed summary of these features can be found in Wilkinson et al. (2010a) and Nicholson et al. (2012) (also see http://research.ncl.ac.uk/proactive/belford: accessed May 2012). Six instrumented RAFs are selected for analysis with differing construction and operation regimes. These are summarised in Table 2 and cover the broad range of features in the catchment.

Farmer participation was fundamental to the effective implementation of RAFs. Often farmers would suggest suitable sites and modify/optimise the initial design in order to gain the most advantageous environmental and agri-economic benefits. Thus, the agreed final design was based on local knowledge on current details such as land use; for example, woody debris was placed only in wooded channel sections, ponds were placed within existing riparian area buffer zones, and a range of ditch barriers were created using wood within upland ditches and willow within the lowland arable ditches. Usually, an attempt was made to solve more than one environmental problem; for example, bunds were placed across hollows in fields prone to overland flow. One bund was constructed as a farm track thus removing the problem of trafficking through a frequently saturated zone whilst also allowing the feature to be much larger. Several of the features were instrumented and assessed so that the RAF functioning could be understood. This allowed a provisional assessment of the data to take place using the methodology framework so far to understand whether the evidence was sufficient for policy uptake.

4. Results and discussion

4.1. Provisional assessment of collected data

The provisional assessment of data feeds into the evidence and policy uptake step. If the provisional evidence suggests that the RAFs could be optimised then appropriate changes could take place. Over a four year period (2008–2012) that the Belford mitigation measures have been in place, the catchment has witnessed an unusual high number of flood level storm events (Table 3).

Initially, qualitative evidence (such as photographic evidence, videos and two farmers visited some of the RAFs during the September 2008 flood) showed the stakeholders that the RAFs were clearly holding water upstream of the village despite the lack of quantitative evidence. However, the numerous storms have subsequently provided a large dataset of the RAF hydrological functioning; this is highlighted for the largest recorded flood during the project, the March 2010 event (Fig. 3; Table 3).

Table 3
A summary of the top 3 extreme storm events in the Belford Burn catchment (during 2008–2011); storm return periods calculated using the Flood Estimation Handbook.

Rank	Dates	Storm duration (hrs)	Rainfall (mm)	% of yearly average rainfall	24 h rainfall return period
1st	29–30th Mar 2010	30	62.4	9	12.5 years (58.8 mm)
2nd	17th July 2009	43	102.6	15	12.5 years (58.2 mm)
3rd	5–7th Sept 2008	45	99.6	14	20 years (65.8 mm)

Fig. 3 shows the performance of six RAFs during the March 2010 event (the largest recorded during the catchment characterisation period). Fig. 3 shows that RAFs 1, 3, 4 and 12 have a peak (in water level) after the observed peak in the stream at R3 (Fig. 2). These RAFs are located nearby stream monitoring point R3. RAF 4 is one of the last features to peak and this occurs 2 h after the stream peaks (Fig. 3). This is owing to its relatively large capacity and its ability to capture a major overland flow pathway, which continues to produce runoff after the peak of the flood (as seen in Fig. 4). The pilot feature (RAF 0) peaks before the observed peak at R3, however, this site is located in the headwaters near R1 and it is likely that the peak has passed this site. Wilkinson et al. (2010b) found this feature to be functioning as intended during the September 2008 event; data indicated that the time of travel of a peak increased by 15 min over a 1 km stretch of the stream by comparing data from several storm events before and after the installation. Fig. 3 demonstrates that most RAFs are performing as specified: storing runoff at and after the peak, and then emptying within half a day of the last peak (Fig. 3). However, it is evident that RAF 2, an in-stream dam/online pond feature, reaches storage capacity some time before peak stream level, meaning that it has little-to-no effect on flow storage/attenuation during this critical part of the storm. Despite this, visual evidence suggested that RAF 2, along with other online features, was accumulating sediment. RAF 2 was surveyed in May 2010 and again 19 months later in December 2011, which revealed a reduction in storage capacity of approximately 190 m^3 (Barber et al., 2011). This could be translated into a long-term estimate of trapped sediment.

Fig. 4 shows cumulative runoff and rainfall recorded during the March 2010 event. The photograph in Fig. 4 shows that overland flow taking place before peak stage is observed in the main channel. The rainfall runoff ratio for this event was estimated at 91% (based on a runoff calculation using an extrapolation of the rating curve at R3 [Fig. 2] to estimate runoff), which could be attributed to the land drain network becoming surcharged, leading to a rapid increase in overland flow. Significant proportions of the catchment exhibit overland flow during large events, which have the potential to cause significant soil erosion and sediment (and associated nutrient) losses.

4.2. Modification and optimisation

All RAFs are under continuous review and a number of them are undergoing varying degrees of modification and optimisation (Fig. 1). A number of offline ponds have required the inlet level to be raised in order to target the peak of storms in a more timely fashion (Nicholson et al., 2012), thus ensuring a more efficient use of storage capacity. In terms of optimisation, a number of new features will be built differently based on the experience gained throughout the project; for example, despite the relative high cost of using treated timber (as an alternative to earth bunds) its versatility makes it easy to work with, its inherent strength provides resistance to the attention of livestock (particularly cattle), and it requires little in the way of space — thus having a lesser

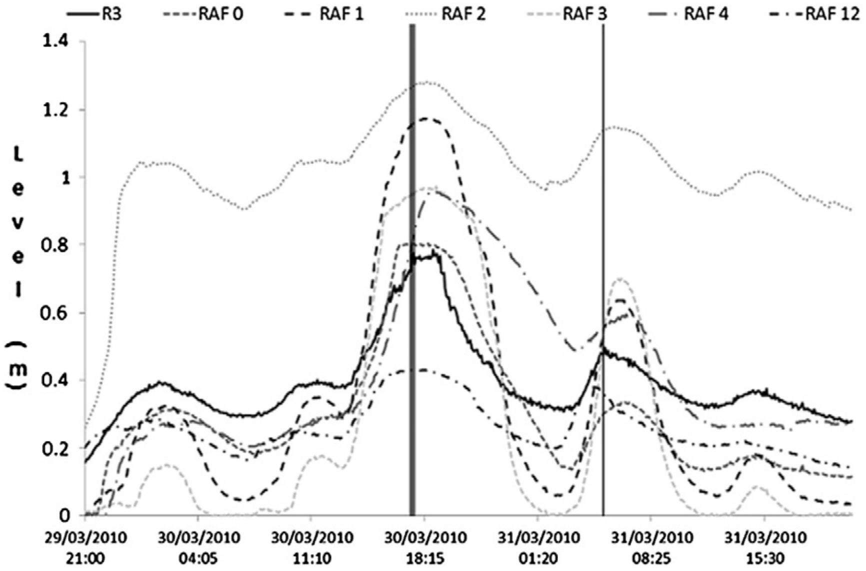

Fig. 3. The performance of six RAFs (see Table 2) during the March 2010 flood (observed at R3). RAF 0 collects runoff and stream spill, RAFs 1 and 3 collect stream spill, RAF 2 is in the stream and RAF 12 is a combination of an in-stream feature with spill overflow. Solid vertical lines indicate the peak observed in the stream at R3.

impact on agricultural activities. Soil bunds also have their merits; they can be low-cost and relatively simple to construct but suit locations with fewer livestock and where space is available to build a wider bund. Using other locally sourced materials, such as stone, from local quarries or construction sites can build much stronger RAFs that can carry the weight of vehicles. Visits from ecologists, RSPB officers and wildlife groups, inter alia have provided insight into ways the features can be further optimised to create niche habitats for valuable species. For example, ensuring that a small amount of water remains permanently in ponds can improve habitat diversity. There have been some unverified local reports of Great Crested Newts in several of the online ponds; if present this is positive in terms of biodiversity, but sediment removal from those features would be more difficult to justify and maintenance of these features will, in future, need to consider the lifecycle stage of any valuable inhabitants. Not all RAFs need to be multi-functional; for example, there may be a need to sacrifice flood storage capacity in order to enhance water quality amelioration potential.

The process of RAF modification and optimisation in order to provide multiple benefits in the Belford catchment has raised an important management issue that is summarised by the following questions:

1 Could a RAF designed for flood attenuation purposes be optimised for water quality amelioration?or
2 Would new bespoke RAFs designed specifically for diffuse water pollution management be required?

These questions will be addressed in the following section.

4.2.1. Collected evidence on the impact to water quality (based on RAF modification)

As described previously, Belford Burn (along with other streams) eventually discharges into Budle Bay, a sensitive downstream receptor. The consensus view by the EA and Natural England was that eutrophication from freshwater tributaries was causing thick mats of marine macroalgae to develop, which were a threat to benthic ecology and the large populations of wading birds (Palmer, 2012). In response, an

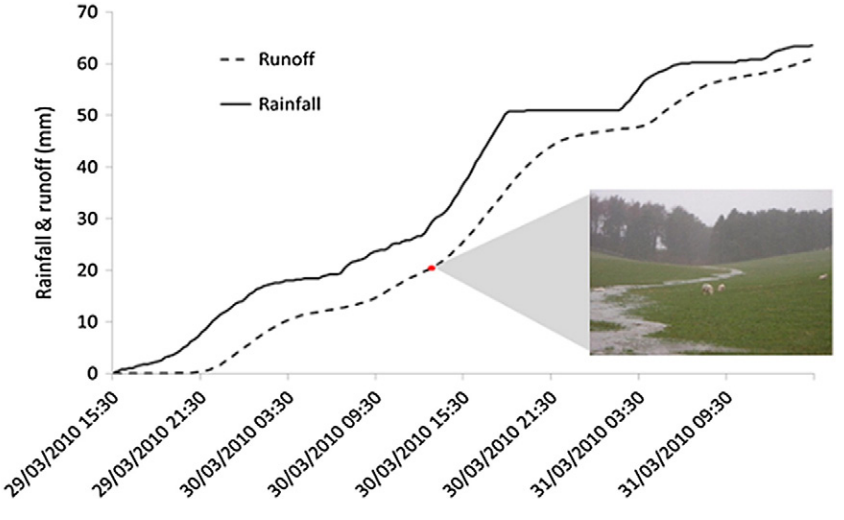

Fig. 4. Cumulative rainfall and runoff during the March 2010 flood event. The image shows overland flow occurring over the field before the main peak of the flood (red spot indicates the time that the photograph was taken in relation to the data).

investigation was begun in 2009 to establish the effectiveness of existing RAFs to reduce losses of sediment and nutrients. The investigation included a catchment-wide grab sampling campaign to characterise the sediment and nutrient regime and to identify locations that were contributing elevated levels of agricultural diffuse pollution. Four auto-samplers were also deployed at two online ponds (RAFs 2 and 12 — two samplers per feature: one directly upstream and one directly downstream). The online features were chosen for monitoring as a result of visual evidence that suggested that sedimentation was occurring. It was therefore desirable to find out whether they were retaining sediment and nutrients during storm events (please refer to Barber and Quinn (2012b) for details of the methodology used for the determination of SS, P and NO_3 concentrations).

Data from the grab sampling campaign indicated that background sediment and nutrient concentrations in the main burn, during baseflow conditions were of no ecological concern (under WFD guidelines). However, it also highlighted that certain parts of the catchment were characterised by significantly higher concentrations of SS, P and NO_3. At the outfall of one 17.5 ha sub-catchment TP concentrations exceeded the EA recommended maximum concentration of 0.1 mg l^{-1} on every sampling occasion, and SS concentrations as high as 400 mg l^{-1} were recorded that significantly surpass the 25 mg l^{-1} average annual threshold prescribed under the Freshwater Fish Directive (2006/44/EC). An average NO_3 concentration of 16.7 mg l^{-1} was recorded, with a maximum of 44.6 mg l^{-1} (Barber and Quinn, 2012b). Although below the 50 mg l^{-1} maximum concentration prescribed by the Drinking Water Directive (98/83/EC), Skinner et al. (2003) and Hickey and Martin (2009) argue that such concentrations are potentially of ecological significance. As this part of the catchment was fed principally by field drains, the data highlighted the importance of subsurface drainage as a significant conveyor of sediment and nutrients (also reported by Deasy et al., 2009), particularly during residual flow conditions when the majority of flow is being transferred by the drains.

Data collected by the auto-samplers during storm events drew attention to two important characteristics: firstly, that P and SS concentrations increased significantly above background levels; and secondly, that online ponds were not retaining pollutants during the rising limb and peak of events. Maximum TP and SS concentrations of 1.24 mg l^{-1} and 530 mg l^{-1}, respectively, were recorded during an 'average' sized event in February 2010. The paired inflow and outflow concentration data suggested that no sediment or nutrient retention occurred, particularly during the early high-flow component of the event. Based on this single event, net losses of SS, TP and NO_3 of 9%, 14.5% and 0.7%, respectively, were recorded at RAF 2 (Barber and Quinn, 2012a). Results from RAF 12 (recorded during the same event) showed that there were also net losses of SS and NO_3, 2.3 and 2.5%, respectively, but a small 1.6% net retention of TP (based on concentrations) (Barber and Quinn, 2012b). These results clearly contradict the observation that the online ponds were filling with sediment in the long term. Thus, online features appear to be functioning to reduce chronic losses of SS (and sediment-phase nutrients), but are far less effective in (acute) storm events. It is strongly suspected that remobilisation of previously deposited material is the principle problem.

Another RAF that is considered to be multi-functional is the within-field retention bund. Fig. 5 shows one example built across the main valley thalweg (the line following the lowest part of the valley) of an arable field (4.1 ha) designed to intercept and temporarily store overland flow. The field has a gradient of approximately 4° and its land cover (predominantly winter wheat during the study period) makes it highly susceptible to soil erosion. The RAF is located at the top of the 17.5 ha sub-catchment draining into RAF 12 and also doubles as a raised track. Construction was carried out by the farmer using locally-sourced materials, thus incurred relatively low cost. Whilst its ability to retain overland flow is obvious (the feature can store approximately 500 m^3 of flood water) its sediment trapping capabilities were more difficult to quantify. However, following a large runoff event in January 2011, Palmer (2012), by surveying the rills and gullys (erosion) and sediment fan left behind the retention bund (deposition), and by determining the particle size distribution and bulk density of the material, was able to calculate the mass of sediment retained by the RAF. It was estimated that 0.99 tonnes of sediment (consisting mainly of silt/clay and fine-sand) was captured but that a proportion of fine sediment was lost via the feature's outlet pipe and bypassed by sub-surface drains. Trapped sediment becomes re-incorporated back into the topsoil during annual ploughing.

In response to question 1, which asked if flood RAFs could be modified to ameliorate water quality, it has become evident that different features operate to retain pollutants under contrasting flow conditions. The flood RAFs were designed and constructed to intercept strategic pathways, either surface or subsurface and as sediment/nutrient transfer is driven chiefly by hydrology, it stands to reason that there is potential to intercept contaminants moving along the intercepted pathway. The in-field retention bund has shown the potential to reduce diffuse pollution but only functions to do so during overland flow events; although this is arguably the case when the largest pollutant loads are exported from a catchment (Haygarth et al., 2005). However, in this particular location it is apparent (according to evidence presented by Palmer (2012) and the grab sampling data described by Barber and Quinn (2012b)) that a significant proportion of the pollution is lost via the sub-surface field drains, therefore by-passing the feature. The sub-surface drains could be broken and allowed to spill into the RAF, but this would impact on the workability of the land, and could negatively impact farm operations.

Intercepting the sub-surface pathway, in the existing ditch network provides an alternative location that is more favourable to the farm. The online pond RAFs were constructed to target and 'slow and store' the subsurface pathway. They appear to retain sediment (and associated nutrients) during residual flow conditions but not during flood peaks. To improve pollutant retention, the residence time in the features could be increased by adding baffles, or introducing vegetation (as reported by Braskerud (2002)), to increase settlement time whilst not having to increase the overall RAF size. Also, in order to maximise the lifespan and water storage capacity of the online pond RAFs it would be favourable to construct upstream sediment traps to attenuate the sedimentation rate in the main ponds. Although these modifications have not been made to existing RAFs, alterations will be made to future designs based on the experience gained to further improve performance.

Concerning question 2, it was felt that a new, optimised RAF was required to meet some of the shortcomings highlighted above. A bespoke multi-stage RAF was constructed in February 2011 in a 150 m length of ditch, directly upstream of RAF 12 and approximately 500 m down the catchment from the in-field retention bund (Fig. 5). The design represents the culmination of experience gained from the Nafferton Farm and Belford projects and has the following objectives:

- mitigate polluted drain flow, *which will help to*
- reduce pollutant concentrations during residual flow conditions
- reduce remobilisation of previously settled sediment (and associated nutrients) in ponds during storm events.

The RAF consists of an upstream sediment trap, followed by a filtering system consisting of leaky willow barriers and brash screens, and a wood chip barrier/filter (Fig. 6). The feature has been instrumented with water level recorders and upstream/downstream auto-samplers to determine its performance. Initial findings in Belford suggested that it was important to create more sediment traps, especially upstream of on-line ponds to help reduce their sedimentation, thus prolonging maximum flood storage capacity. Sediment traps help to determine where in the system material is stored; therefore it is vital to ensure easy access to allow periodic emptying. Barber et al. (2011) reported that six months after construction, the sediment trap (with an area of 12 m^2) had an average sediment depth of 10 cm, giving a wet volume

Fig. 5. A field bund RAF storing water during a storm.

of circa 1.2 m^3; sediment mass and P concentration are still to be determined. The willow dams and brash screens are designed to slow the flow, reduce channel erosion, and provide a coarse level of filtration, possibly aided by flocculation (as reported by Braskerud (2002)). The wood chip filter is designed to remove fine sediment — particles less than 106 μm (fine sand, silt and clay), and associated nutrients. The use of a wood chip bioreactor is a method for removing NO_3 from drainage water by denitrification (in which NO_3 is converted to nitrous oxide and nitrogen gas). Bioreactors have been studied in Illinois and have been shown to effectively reduce NO_3 levels by 33% on average, but up to 100% during certain conditions (Woli et al., 2010). Greenan et al. (2009) also reported positive results from trials carried out in the United States, as did Saliling et al. (2007) who conducted a series of laboratory experiments using wood chips as a media for denitrification. The bioreactor is designed to 'treat' the persistent low levels of NO_3 that can have subtle but important effects on aquatic species (Earl and Whiteman, 2009).

Fig. 7 shows sediment and nutrient data taken simultaneously upstream and downstream of the multi-stage RAF during a May 2012 storm event. The average reduction in pollutant concentrations over the duration of the storm (24 h) is as follows: 40% SS, 26% TP, 25% soluble RP, and 15% NO_3. Over the course of 2012, which included several storm events of varying magnitudes and durations, inflow and outflow sampling has revealed reductions of 30–45% SS, 14–25% TP, 25–30% soluble RP and 8–38% NO_3 concentrations. Thus, although based on concentration only, these preliminary results suggest that the feature is working to reduce sediment and nutrient losses from this part of the catchment during storms. Ockenden et al. (2012) reported a 60% reduction in SS concentration during an event at a paired-pond sediment trap, which formed part of the Mitigation Options for Phosphorus and Sediment (MOPS) project. Although the MOPS feature and the multi-stage RAF had similar sized contributing areas, the MOPS sediment trap was much larger (area = 200 m^2) that may explain the higher percentage removal. Of course, many other variables can influence the retention capacity of such features but residence time is arguably one of the most important (Braskerud, 2002; Reinhardt et al., 2005).

The impact of all the RAFs on water quality is somewhat difficult to prove, as monitoring can be extremely expensive and time consuming. Also, it may take several years before any change in the sediment and nutrient regime is detected at the catchment scale (Haygarth, 2010). Therefore, management at the field- and farm-scale remains crucial to water quality outcomes and delivering on the WFD requires

Fig. 6. Wood chip filter (left) and a sediment trap (right) placed in ditch upstream of RAF 12.

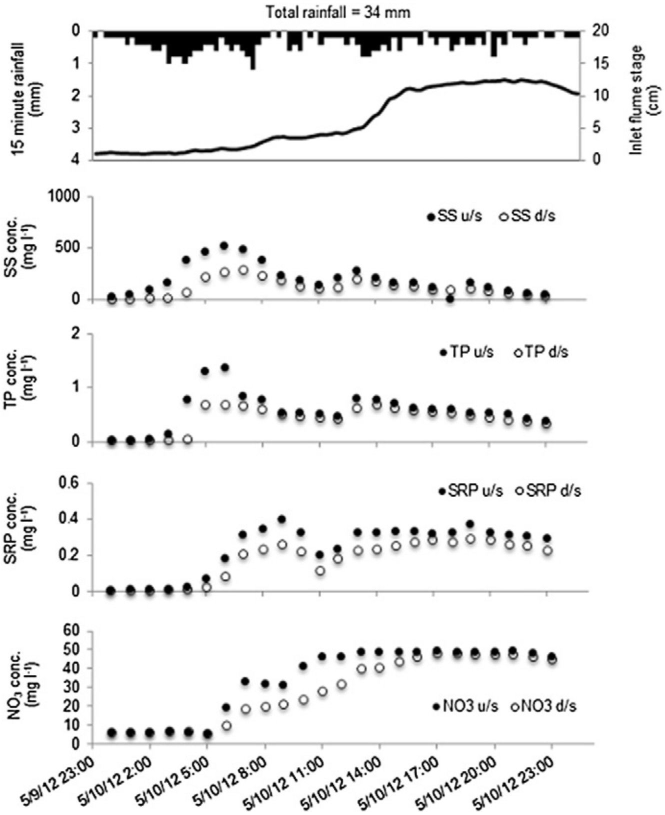

Fig. 7. Storm sample data collected up- and downstream of the multi-stage RAF (Fig. 6) during a May 2012 event.

coordination that transcends a continuum of scales (Winter et al., 2011). However, a number of underlying design criteria are being determined and some solid, local evidence is being accrued.

5. Conclusions

Many environmental issues have been identified in the Belford catchment. The motivation for this project was to reduce the flood risk in Belford whilst delivering multipurpose benefits. Natural, upstream mitigation measures have been identified by the Floods Directive and WFD to reduce flood risk and improve water quality, respectively. However, there was a desire in Belford to create a catchment plan that would have multi-purpose benefits meeting the aims for the two directives. A framework has been developed throughout the project at Belford showing how a catchment management plan can be achieved; to which the CSE approach and stakeholder engagement are the key. RAFs are at the heart of the CSE approach; they are soft-engineered structures that could potentially provide a cost-effective solution to achieving multiple benefits. However, they do not offer a single solution and should be considered alongside traditional flood defences. RAFs also require maintenance; the potential need to recover trapped sediment and whether it is of agronomic value to the farmers is part of the on-going assessment.

The framework continues to show, step-by-step, how evidence can be gathered to underpin new policy and how a catchment management plan can be achieved using the CSE approach (Fig. 1). A provisional assessment of the current data suggests that most RAFs are functioning as intended and many fast flow pathways are being intercepted. The degree to which the local catchment system has been 'engineered' is still being determined. The overall performance of these RAFs in terms of addressing pollution and ecology is also difficult to quantify and requires a further weight of evidence. As the initial findings are positive, with sediment accumulating and the creation of new ecological niches, these measures can be categorised as the 'no-regret measures' being pursued by the European Commission. In the study shown here it is important to stress the simple underlying concepts that flow pathway behaviour can be changed using soft engineering. For flood flow, and nutrient losses, the simple concept of disconnecting fast flow pathways, adding storage and attenuating flow pathways can be applied to a catchment.

Finally, local stakeholders have had a say in creating a local catchment plan. Many other stakeholders who have similar issues in their own catchments are now assessing the Belford project. The framework has been developed in Belford but it may have generic applicability to many other catchments. Belford is not unique in its issues; many other similar scaled catchments have flood risk and diffuse pollution issues. Although initial water quality impacts proved to be complicated, the dedicated sediment traps and filters are exhibiting positive impacts on sediment and nutrient losses. CSE has endeavoured to change the flood flow regime of the catchment whereby an adaptive approach is required and must continue in the future. Intervention is required at many locations but with the help of local stakeholders and regulators the potential framework for holistic environmental management has been trialled at the small catchment scale.

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References

Allenby B. Earth Systems Engineering and management. IEEE Technol Soc Mag 2000;19:10–24.

Allenby B. Earth Systems Engineering and management: a manifesto. Environ Sci Technol 2007;41:7960–5.

Balana BB, Lago M, Baggaley N, Castellazzi M, Sample J, Stutter M, et al. Integrating economic and biophysical data in assessing cost-effectiveness of buffer strip placement. J Environ Qual 2012;41:380–8.

Barber N, Quinn PF. Catchment-scale management of farm runoff and the multiple benefits it can achieve. In: British Hydrological Society, editor. BHS Eleventh National Symposium, hydrology for a changing world. Dundee: British Hydrological Society; 2012a.

Barber N, Quinn PF. Mitigating diffuse water pollution from agriculture using soft-engineered runoff attenuation features; 2012b [Area, Early view].

Barber NJ, Quinn PF, Bathurst JC, Jonczyk J. A catchment engineering approach to nutrient and sediment management: a case study from the UK. In: AGU, editor. AGU fall meeting 2011 — H44A. Agricultural surface and groundwater qualitySan Francisco: AGU; 2011.

Braskerud BC. Design considerations for increased sedimentation in small wetlands treating agricultural runoff. Water Sci Technol 2002;45:77–85.

Collins A, Ohandja DG, Hoare D, Voulvoulis N. Implementing the Water Framework Directive: a transition from established monitoring networks in England and Wales. Environ Sci Policy 2012;17:49–61.

Deasy C, Brazier RE, Heathwaite L, Hodgkinson R. Pathways of runoff and sediment transfer in small agricultural catchments. Hydrol Process 2009;23(9):1349–58.

de Kok JL, Kofalk S, Berlekamp J, Hahn B, Wind H. From design to application of a decision-support system for integrated river-basin management. Water Resour Manage 2009;23:1781–811.

Doody DG, Archbold M, Foy RN, Flynn R. Approaches to the implementation of the Water Framework Directive: targeting mitigation measures at critical source areas of diffuse phosphorus in Irish catchments. J Environ Manage 2012;93:225–34.

Earl JE, Whiteman HH. Effects of pulsed nitrate exposure on amphibian development. Environ Toxicol Chem 2009;28:1331–7.

Environment Agency. Lessons learned: the autumn 2000 floods. In: Agency E, editor. Bristol: Environment Agency; 2001.

Environment Agency. River basin management plan Northumbria River Basin District Environment Agency, Bristol; 2009.

European Commission. A blueprint to safeguard Europe's water resources. In: E C, editor. 2012a. [Brussels].

European Commission. Report from the Commission to the European Parliament and the Council on the Implementation of the Water Framework Directive (2000/60/EC) River Basin Management Plans. In: Commission E, editor. 3rd implementation report; 2012b. [Brussels].

European Environment Agency. European waters—assessment of status and pressures. In: EEA, editor. 2012. [Copenhagen, Denmark].

Greenan CM, Moorman TB, Parkin TB, Kaspar TC, Jaynes DB. Denitrification in wood chip bioreactors at different water flows. J Environ Qual 2009;38:1664–71.

Halcrow. Environment Agency North East region Belford Burn. In: Halcrow group Ltd, editor. Belford: prefeasibility study; 2007. [Edinburgh].

Hall JW, O'Connell PE. Earth Systems Engineering: turning vision into action. Proceedings of ICE, 160. 2007. p. 114–22.

Haygarth PM. Managing soil and water for multiple objectives. In: SAC, editor. SAC and SEPA Biennial Conference — climate, water and soil: science, policy and practice. Edinburgh: SAC and SEPA; 2010.

Haygarth PM, Wood FL, Heathwaite AL, Butler PJ. Phosphorus dynamics observed through increasing scales in a nested headwater-to-river channel study. Sci Total Environ 2005;344:83–106.

Hewett CJM, Quinn PF, Whitehead PG, Heathwaite AL, Flynn NJ. Toward a nutrient export risk matrix approach to managing agricultural pollution at source. Hydrol Earth Syst Sci 2004;8:834–45.

Hewett CJM, Quinn PF, Heathwaite AL, Doyle A, Burke S, Whitehead PG, et al. A multi-scale framework for strategic management of diffuse pollution. Environ Model Software 2009;24:74–85.

Hickey CW, Martin ML. A review of nitrate toxicity to freshwater aquatic species. In: Canterbury E, editor. 2009. [Christchurch, NZ].

Hilton J, O'Hare M, Bowes MJ, Jones JI. How green is my river? A new paradigm of eutrophication in rivers. Sci Total Environ 2006;365:66–83.

Johnes PJ, Foy R, Butterfield D, Haygarth PM. Land use scenarios for England and Wales: evaluation of management options to support 'good ecological status' in surface freshwaters. Soil Use Manage 2007;23:176–94.

Jonczyk J, Quinn PF, Rimmer D, Burke S, Wilkinson ME. Farm Integrated Runoff Management (FIRM) plans: a tool to reduce diffuse pollution. In: British Hydrological Society, editor. Proceedings from the Tenth National British Hydrology Society Symposium, Exeter; 2008.

Jordan P, Arnscheidt A, McGrogan H, McCormick S. Characterising phosphorus transfers in rural catchments using a continuous bank-side analyser. Hydrol Earth Syst Sci 2007;11:372–81.

Klauer B, Rode M, Schiller J, Franko U, Mewes M. Decision support for the selection of measures according to the requirements of the EU Water Framework Directive. Water Resour Manage 2012;26:775–98.

Laurent F, Ruelland D. Assessing impacts of alternative land use and agricultural practices on nitrate pollution at the catchment scale. J Hydrol 2011;409:440–50.

Neal C, Davies H, Neal M. Water quality, nutrients and the Water Framework Directive in an agricultural region: the lower Humber Rivers, northern England. J Hydrol 2008;350:232–45.

Nicholson AR, Wilkinson ME, O'Donnell G, Quinn PF. Runoff attenuation features: a sustainable floodmitigation strategy in the Belford catchment, UK; 2012 [AREA, Early view].

Ockenden MC, Deasy C, Quinton JN, Bailey AP, Surridge B, Stoate C. Evaluation of field wetlands for mitigation of diffuse pollution from agriculture: sediment retention, cost and effectiveness. Environ Sci Policy 2012;24:110–9.

O'Connell PE, Beven KJ, Carney JN, Clements RO, Ewen J, Fowler H, et al. Review of impacts of rural and land use and management on flood generation. Impact Study Report, Defra/Environment Agency R&D Technical Report (FD2114), Defra, London; 2004.

O'Connell PE, Ewen J, O'Donnell G, Quinn PF. Is there a link between agricultural land-use management and flooding? Hydrol Earth Syst Sci 2007;11:96–107.

O'Donnell G, Ewen J, O'Connell PE. Sensitivity maps for impacts of land management on an extreme flood in the Hodder catchment, UK. Phys Chem Earth 2011;36:630–7.

OECD. Environmental indicators for agriculture. Methods and results, vol. 3. Paris: OECD; 2001409.

Palmer MW. Agricultural fine sediment: sources pathways and mitigation. School of Civil Engineering and Geosciences. PhD. Newcastle upon Tyne: Newcastle University; 2012.

Parker DJ. Floods. London and New York: Routledge; 2000.

Parrott A, Brooks W, Harmar O, Pygott K. Role of land use management in flood and coastal risk management. J Flood Risk Manage 2009;2:272–84.

Penning-Rowsell E, Johnson C, Tunstall S. 'Signals' from pre-crisis discourse: lessons from UK flooding for global environmental policy change? Glob Environ Change Hum Policy Dimens 2006;16:323–39.

Posthumus H, Hewett CJM, Morris J, Quinn PF. Agricultural land use and flood risk management: engaging with stakeholders in North Yorkshire. Agric Water Manage 2008;95:787–98.

Quinn PF. Scale appropriate modelling: representing cause-and-effect relationships in nitrate pollution at the catchment scale for the purpose of catchment scale planning. J Hydrol 2004;291:197–217.

Quinn PF, Jonczyk J, Rimmer D, Hewett CJM. The proactive approach to Farm Integrated Runoff Management (FIRM) plans with respect to nutrients. Newcastle University; 2007.

Quinn PF, Burke S, Wilkinson ME, Hewett CJM, Jonczyk J. Catchment science and engineering. In: British Hydrological Society, editor. British Hydrological Society International Symposium; 2010. Newcastle upon Tyne.

Reinhardt M, Gachter R, Wehrli B, Muller B. Phosphorus retention in small constructed wetlands treating agricultural drainage water. J Environ Qual 2005;34:1251–60.

Saliling WJB, Westerman PW, Losordo TM. Wood chips and wheat straw as alternative biofilter media for denitrification reactors treating aquaculture and other wastewaters with high nitrate concentrations. Aquacult Eng 2007;37:222–33.

Scheuer S, Naus J. 10 years of the Water Framework Directive: a toothless tiger?—a snapshot assessment of EU environmental ambitions. In: Bureau EE, editor. 2010. [Brussels].

Schneider SH. Earth Systems Engineering and management. Nature 2001;409:417–21.

Scottish Environment LINK. Towards sustainable flood management in Scotland. Perth: Scottish Environment LINK; 2007.

Seibert J, McDonnell JJ. On the dialog between experimentalist and modeler in catchment hydrology: use of soft data for multicriteria model calibration. Water Resour Res 2002;38.

Shaw EM, Beven K, Chappell N, Lamb R. Hydrology in practice. fourth ed. London and New York: Spon Press; 2011.

Skinner A, Young M, Hastie L. Ecology of freshwater pearl mussel. In: Life, editor. Conserving Natura 2000 Rivers, No. 2. Ecology series; 2003.

UNDP. United Nations Development Programme: Human Development Report 2007/2008. New York: United Nations; 2007.

Wilby RL, Keenan R. Adapting to flood risk under climate change. Prog Phys Geogr 2012;36:348–78.

Wilkinson ME, Quinn PF, Welton P. Belford catchment proactive flood solutions: storing and attenuating runoff on farms. In: British Hydrological Society, editor. Tenth National Hydrology Symposium. Exeter: British Hydrological Society; 2008.

Wilkinson ME, Quinn PF, Benson I, Welton P. Runoff management: mitigation measures for disconnecting flow pathways in the Belford Burn catchment to reduce flood risk. In: British Hydrological Society, editor. British Hydrological Society International Symposium. Newcastle upon Tynee: British Hydrological Society; 2010a.

Wilkinson ME, Quinn PF, Welton P. Runoff management during the September 2008 floods in the Belford catchment, Northumberland. J Flood Risk Manage 2010b;3:285–95.

Wilkinson ME, Quinn PF, Hewett CJM. The Floods and Agriculture Risk Matrix (FARM): a decision support tool for effectively communicating flood risk from farmed landscapes. Int J River Basin Manage 2013. http://dx.doi.org/10.1080/15715124.2013.794145. [accepted: early view].

Winter M, Oliver DM, Fish R, Heathwaite AL, Chadwick D, Hodgson C. Catchments, sub-catchments and private spaces: scale and process in managing pollution from source to sea. Environ Sci Policy 2011;14:315–26.

Woli KP, David MB, Cooke RA, McIsaac GF, Mitchell CA. Nitrogen balance in and export from agricultural fields associated with controlled drainage systems and denitrifying bioreactors. Ecol Eng 2010;36:1558–66.