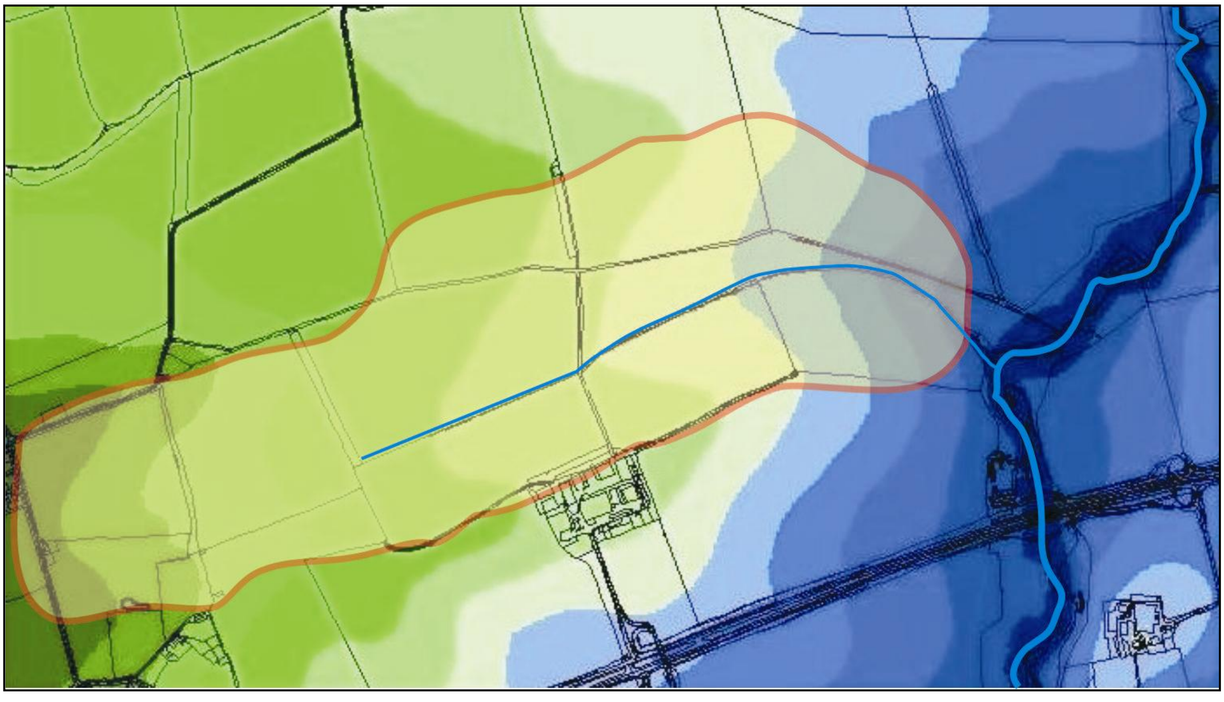
The PROACTIVE approach to Farm Integrated Runoff Management (FIRM) Plans

Flood storage on farms

September 2007

Paul F Quinn, Caspar J M Hewett, Jennine Jonczyk and Vassilis Glenis



Digital elevation model of Nafferton Farm with catchment boundary

The PROACTIVE Approach to Farm Integrated Runoff Management (FIRM) Plans

The ***proactive*** approach is committed to:-

- changing land use management in order to mitigate a range of environmental problems at demonstration farms, at full scale in partnership with stakeholders
- Instrumenting and quantifying processes on small research catchments that are undergoing land use management change.
- Creating multi-functional, economically viable land units through joining, pollution, flooding, waste recycling and renewable energy/ carbon into a common integrated framework.
- To producing decision support tools and modelling frameworks that support catchment management and policy making.

Farm Integrated Runoff Management (FIRM) Plans are at the heart of the PROACTIVE approach. FIRM Plans are committed to the concept of the storage, slowing, filtering and infiltration of runoff on farms at source. We believe this to be practical, achievable and could easily be funded by the strategic investment of agri-environment, flood mitigation, waste recycling and renewable energy/ carbon reduction subsidies. The best place to control runoff is at source and within hours of the runoff generation, these spatial and temporal windows of opportunity are not being fully exploited in environmental management.

Ponds, bunds wetlands, buffer strip have all been designed, constructed and tested at Nafferton farm in Northumberland. All features are multi-functional and will address pollution reduction, lower flood risk, trap and recycle waste, use recycled material and create new ecological zones. FIRM plans can be achieved without damaging the profits of the farm and can funded through an imaginative, strategic integrated funding mechanisms

All the constructed features can be demonstrated to be working to reduce pollution, store and slow runoff and to trap and recycle waste on the farm. The operational performance of the features during large storm events is still to be proven. We will not be recommending all the features listed in this report be adopted on farms, but crucially we have gained the experience to recommend a series of practical, fundable interventions that could work at the larger catchment scale and address urgent WFD needs, for example:-

- All fast and polluting flow paths can be disconnected from the channel network.

- Ponds, barriers, bunds can physically store large amounts of runoff.
- All features help to slow flow, creating ‘transient storage’.
- Wetlands are slowly de-nitrifying the runoff, but large amounts of buffering will capacity will be needed on farms, but this may allow more flow to be slowed.
- Sediment and nutrients can be trapped and recycled. A one-off sediment and phosphorus trap can reduce Total P by 20-60% even during storms.
- Saturated buffer strips are denitrifying the flow and they have the potential to treat large amounts of flow and the act as flood retardation channels.
- Ditches can be widened and can act as sediment traps, wetlands and flood retardation channels.
- FIRM plans will need framers to adopt new sediment management plans and sediment/nutrient recovery plans.

What is needed now?

A fully costed, full scale trial of the FIRM plans on a wide range of farms, working closely with farmers and farm advisors.

To test a new mode of subsidising farmers to become ***proactive*** farm runoff managers and thus solve a wide range of environmental problems.

Continued work at Nafferton to prove the performance of the features during large storm events and improve on design and operation issues.

What will FIRM Plans cost?

Costs are comparable with the budgets available from flood control projects (or possibly cheaper), agri-environment schemes and activities such as upland grip blocking. If other subsidies related to renewable energy, carbon storage, waste recycling and ecological initiatives are joined together then FIRM plans can be funded sustainably, with visible, quantifiable, multiple benefits and will address the needs of the WFD.

In order to address flood control at source we estimate the costs as between **£1000/km^2/mm of extra runoff (rainfall depth equivalent) stored and 10000/km^2/annum/mm of runoff stored and no farmland inundated.**

In terms pollution control mitigation we feel that this would cost between **£1000/km^2/annum and 10000/km^2/annum.** This will give drastic reduction in nutrient pollution and sediment losses in most storms. **N.B. The FIRM plans are identical for both nutrient pollution and flood risk mitigation and should be treated together.**









1. BACKGROUND

The ***proactive*** approach is a dynamic philosophy geared towards intervening in the environment to improve water quality, reduce flood risk and diffuse pollution, recycle waste and introduce renewable energy generation into farming. The ***proactive*** approach includes introducing features such as temporary storage ponds, buffer strips and phosphorus stripping zones in the landscape. Demonstration sites are currently under development to prove the effectiveness of such features on working farms. Decision Support Matrices (DSMs) have been developed to communicate the results of research to farmers and land use managers/planners, in particular the Nutrient Export Risk Matrix (NERM) and the Floods and Agriculture Risk Matrix (FARM). All the mitigation features created at the demonstration farms are either made from recycled material or are designed to trap waste that can be put back to land. Examples of waste include the reuse of ochre, which is used to trap phosphorus that is lost from the land and the use of Aquadyne, a recycled plastic material which can be used for draining land and for constructing flow control barriers. Willow, sedge and reused oak have all been sourced locally and are used to construct wetlands. Examples of trapping waste include sediment traps such as ponds and channel sedimentation zones at Nafferton Farm, phosphorus traps either attached to sediment or locked up by the ochre and wetlands that lower N loss and capture carbon.

The ***proactive*** project aims to take a balanced approach to problem solving involving researchers in a range of disciplines and stakeholders at all scales including farmers, land management planners at all scales and bodies such as the Environment Agency and Defra. We propose to apply a multi-scale toolkit for catchment management using existing tools including stakeholder workshops, research scale and catchment scale models (in particular TOPCAT-NP), GIS, DSMs and visualisation tools such as TopManage. Full details of the tools can be found at http://www.ncl.ac.uk/iq.

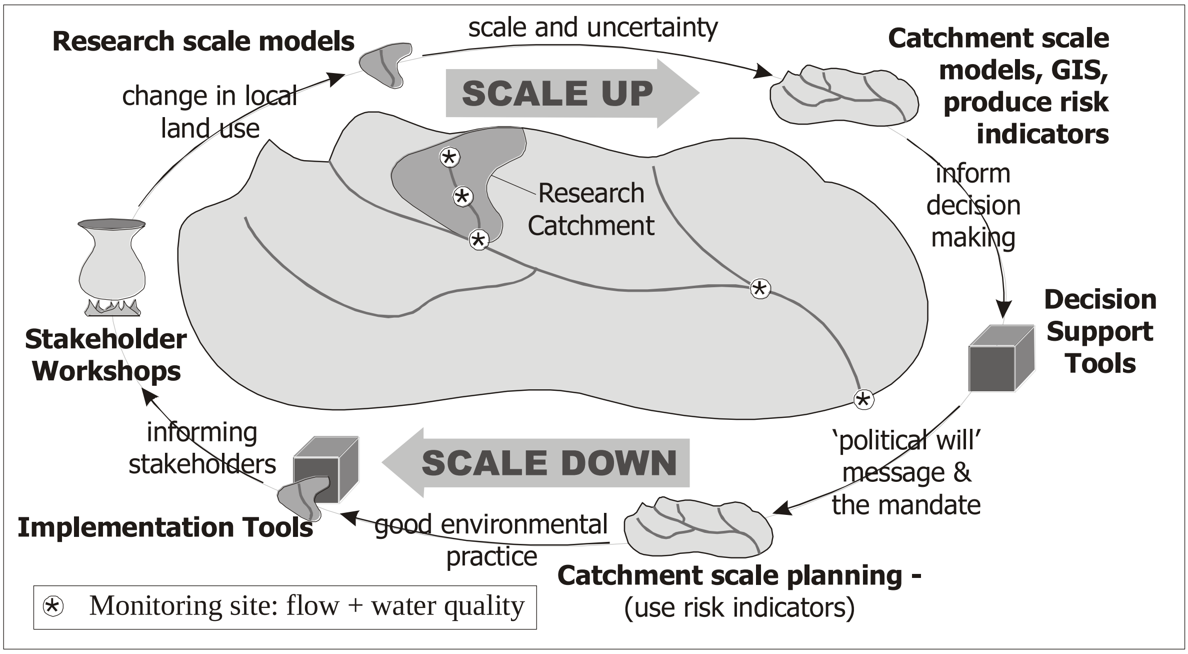


Figure 1.1. Multi-scale Toolkit for Catchment Management

The Decision Support Matrix (DSM) approach is built on a set of tools designed to support policy and decision making. Conceptual models, interactive tools and examples of good and bad land management practice are used to communicate the results of research to end users such as policy makers, farmers and agronomists. The DSM approach has proven effective for communicating novel concepts such as integrated runoff management and proactive interventions for improved land management. DSMs created to date include the Nutrient Export Risk Matrix (NERM), the Phosphorus Export Risk Matrix (PERM) and now the Floods and Agriculture Risk Matrix (FARM). The FARM tool reflecting the possibilities for farmers to use FIRM plans.

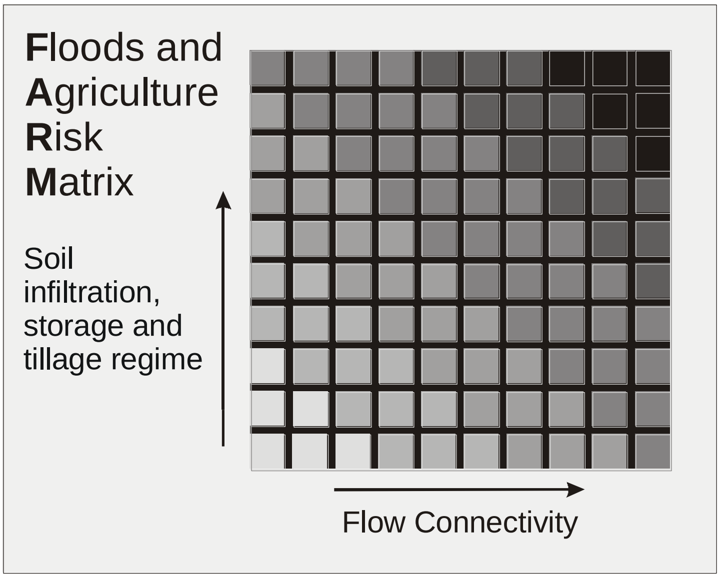


Figure 1.2. The FARM tool decision support matrix. www.ncl.ac.uk/iq.

The FARM is a decision support matrix designed to allow farmers and land use planners to assess the risk of increased runoff from their land, and to explore options to reduce that risk whilst maintaining farmer income. The goal is to allow farmers to compare their current land use practice within the wider context of alternative land management options. The matrix has two axes: a vertical axis for properties related to soil management, and a horizontal axis related to flow connectivity, see Figure 1.2. The lowest risk of runoff corresponds to the lower left hand corner of the matrix while a high risk of increased runoff corresponds to the top right corner. The FARM has been developed as an interactive computer-based tool in the form of a spreadsheet. First a number of examples of good and bad practice are presented to give the user a feel for the features that increase the risk of flooding.

Second the toolkit contains a set of questions for each axis which the user answers, providing a plot of the risk level on the decision support matrix. The final position plotted on the matrix depends on to answers to all of the questions. If the user ends up with a risk plot in the top right area of the matrix then changes in practice that could reduce this risk should be considered. By opting for different management strategies (e.g. use cover crops to improve soil structure or install hedgerows to reduce connectivity) the risk of runoff can be reduced. Thus different scenarios can be tested by answering the questions in different ways, enabling the user to establish ways of improving on current practice. Given normal UK practice the likelihood is high of ending up with a high risk, it is only when good farming practice and runoff management are clearly evident, that a lower risk plot is obtained. The FARM itself gives several management options that can reduce the risk. The FARM can be used during a discussion on land management and flood risk, to explore and discuss soil management options. Free copies are available to test at www.ncl.ac.uk/iq.

2. FLOOD STORAGE ON FARMS

In principal, the idea of storing water on farms is not new. However the key questions still remain:-

- How much water can be stored?
- How much will it cost to build storage on farms?
- What disruption/cost is there to the farm business?
- Where on the farm should water be stored?
- Can water be slowed and temporarily stored enough to impact on downstream flood peaks?
- Where in the landscape (i.e. which farms) will it be useful to physically store/delay water or which areas of farms should be treated as washland?

Following the ***proactive*** approach we would use FIRM plans to propose active intervention and most farms to store and slow down large amounts of runoff. That is, at source, within hours of the flow being generated. The features recommended have multi-purpose, as they can address nutrient pollution problems, help trap and recycle waste (sediments and nutrients) and all features benefits to ecology and carbon storage (see the Proactive approach to FIRM plans for nutrients report, Quinn et al., 2008). We would however target small man made ditches and channels on farms. These locations offer many kilometres of low grade ditches that be engineered without damaging existing conservation and ecological factors (as might exist on a larger river).

It has been concluded in the FD2114 project (O'Connell et al., 2005) that intensive farming does give rise to increased runoff and that the evidence for local 'muddy' floods is strong. Whilst the ***proactive*** initiative would encourage large scale management of flood flow on floodplains as means of lower flood risk, here we would like to focus on farms situated across the landscape that generally contribute flow to channels and are not situated on the larger flood plain areas. Equally, some flood flow could be stored in the uplands of catchments even though the likely impact downstream may be minimal. However, the basis for the creation of ponds, wetlands and attenuation structure in the uplands could be tied to other initiatives such as upland grip blocking, reduction of sediment, nutrients and other water quality problems.

This report and the evidence it provides, is the first step in showing that runoff can be stored and attenuated on farms and that this should be able to reduce food risk down stream by lowering Qp (the peak discharge) and affecting Tp (the time to peak) of an event. Attempts will be made to quantify the storage at Nafferton farm in Northumberland which is our key demonstration farm. This report will try to project the likely impacts of up scaling the **FIRM** approach for the whole farm. Evidence arising from both observed measurements and hydraulic routing will be presented. Finally the cost of interventions will be made, although the numbers determined are quite uncertain, they do give an indication of likely costs.

The conclusion at this time is that it is possible to create a series of ***proactive*** interventions on farms that do not disrupt the business of the farms; where the costs are comparable with other flood schemes; that multiple benefits arise from such interventions and that the imaginative combination farm subsidies can support **FIRM** plans. Practical design, implementation and operational knowledge have been gained and we feel that **FIRM** plans could now be deployed in large scale catchment studies.

The more strategic issues of where it is best to store flood flow within the landscape, related to flood routing is not addressed here. These wider concerns should be addressed by the recommendations of the FD2114 project (O'Connell et al., 2005) and 'The Review of the impacts on land and management on flooding' report (2007). However, the commonality between the interventions required by **FIRM** plans required by nutrient and sediment management means that substantial amount of flow could be stored in the rural environment already. This alone could give enormous cost savings and provide practical, real subsidies to farmers to play a ***proactive*** role in the reducing flood risk.

3. DEMONSTRATION SITE – NAFFERTON FARM

Figure 3.1. Ordinance Survey map showing position of Nafferton Farm

Nafferton Farm is a 294 ha farm situated in the Tyne Valley to the West of Newcastle upon Tyne. The farming system is based on dairying, beef production, arable crops and small scale vegetable production. Run by the School of Agriculture, Food and Rural Development at Newcastle University, the farm is operated as a commercial enterprise as a land-based research facility, especially in the area of Organic production and to provide demonstration facilities for teaching purposes.

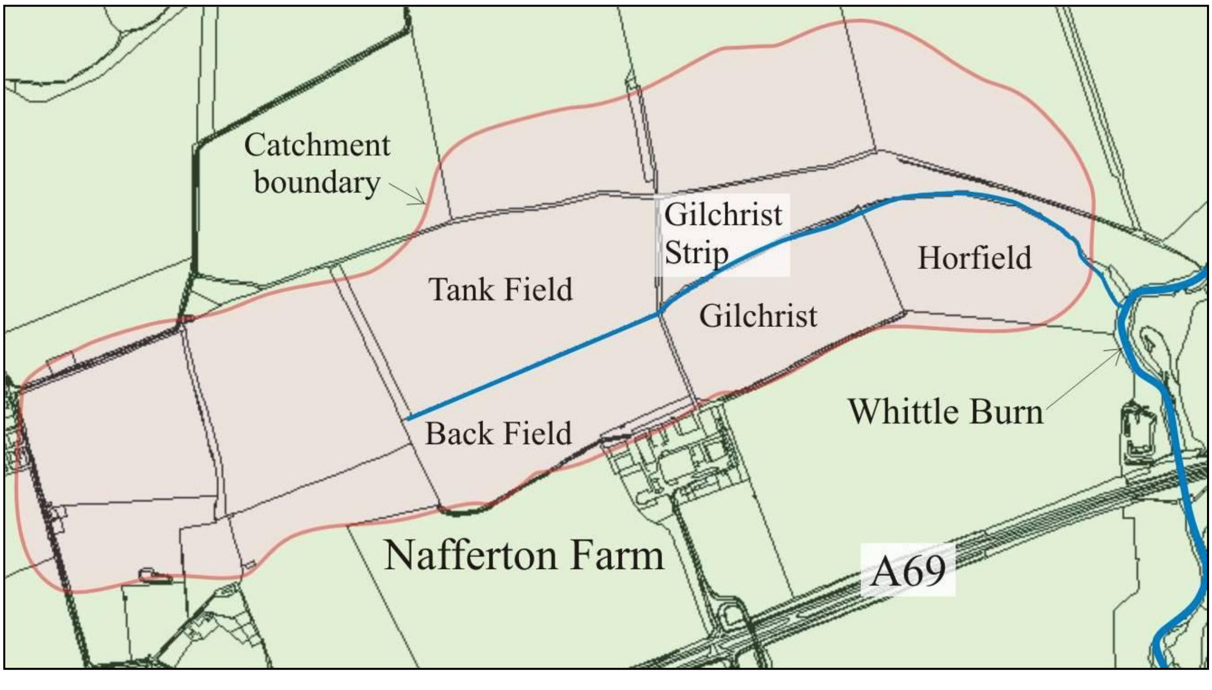


Figure 3.2. Detailed view of Nafferton Farm showing the position of the different fields, the catchment boundary and the entry point of the ditch into Whittle Burn

The original goal at Nafferton Farm was to create a Farm Integrated Runoff Management Plan (**FIRM**) for a demonstration site where a series of ***proactive*** measures would be taken to control runoff flow paths and the physical and chemical properties of the water before the flow enters the Whittle Burn – thus reducing flood peaks and diffuse pollution levels. The catchment that feeds into the ditch shown in Figure 2 has an area of 0.96 km^2 and thus the storage requirement for, say, 10mm of rainfall would be 9600 m^3 of water. In the first instance the features that have been introduced are only of a small scale and thus would not be expected to have a significant effect in the event of a large storm. However, the philosophy behind introducing the features is as a testing ground for larger scale interventions and to assess what contribution small scale mitigation measures might be able to make.

With this is mind a series of ***proactive*** measures and features have now been added and are being evaluated at Nafferton Farm. Additional aspects of the project include the use of renewable energy, addressing the issue of waste recycling and examining the ecological benefits of all the features. The site affords facilities for many scientists from many disciplines and organisations to work together on the common goal of mapping out the future of farming in the UK.

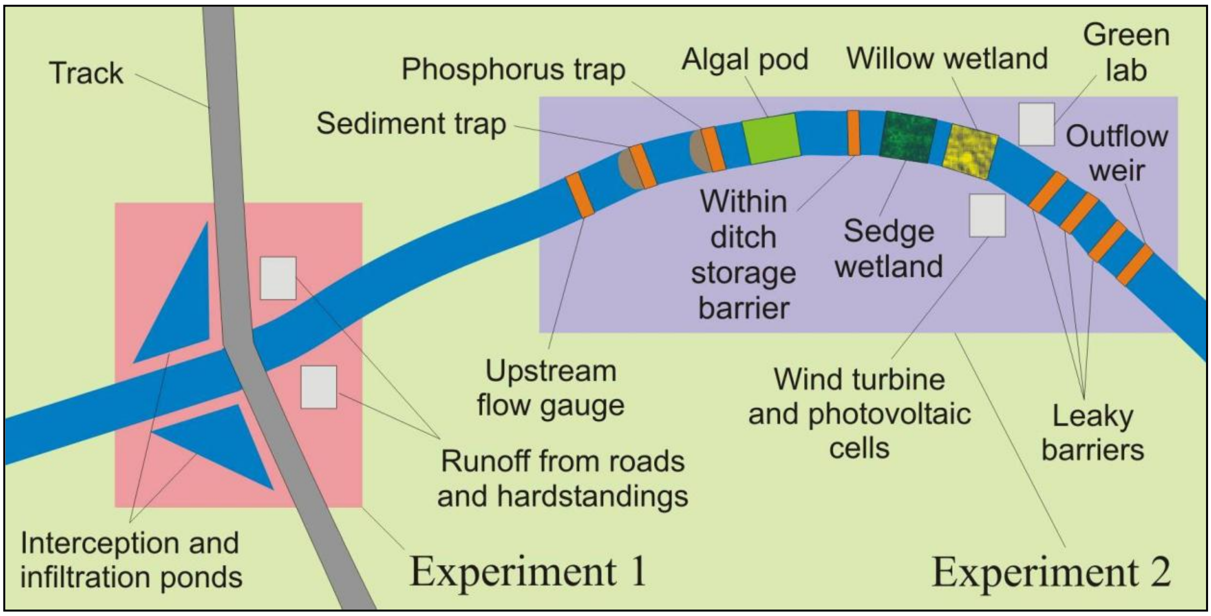


Figure 3.3. Features and kit along the ditch at Nafferton Farm.
Experiment 1: Offline ponding of runoff
Experiment 2: Within ditch remediation and storage

There are currently two experiments being undertaken at Nafferton Farm which are intended to provide multiple benefits, primarily reducing nutrient export and flood risk.

Experiment 1 aims to intercept runoff from roads and within field overland flow, providing temporary storage during storm events. The fastest and most polluting flow path on the farm is fact arising from the roads crossing the farm, delivering flow directly to the ditch.

Experiment 2 consists of a series of features in the ditch to slow down flow, provide further temporary storage and to remove nutrients from the system alongside state of the art monitoring equipment to evaluate the effectiveness of the runoff management measures. Figure 3.3 shows the position of the features, all of which are discussed in detail in the following sections.

3.1 Experiment 1: Offline Interception Ponds

From visual inspection on the farm it was obvious that large amounts of sediment laden flow ere arising from the roads. Some flow came directly from the farm buildings and roads, but even more was lost through a field gate onto the road. This flow entered the ditch directly. Hence a first objective was to remove to disconnect this flow form the ditch. Hence road drains and an interception pond would be needed. The idea was to place a physical storage in a zone within a field that could store fast polluting flow from roads and hard-standings and from overland flow generated in fields.

Two of the fields upstream of the ditch, Tank and Back fields (see Figure 3.2), were analysed to establish where best to intercept flow using the TopManage modelling suite (Heathwaite et al, 2005). TopManage (www.ncl.ac.uk/iq) is a flow terrain analysis model driven by a topographic digital elevation model (DEM) that allows the dominant flow paths to be represented, evaluated and modified for the purposes of runoff management. The flow connectivity model simulates connectivity between land and stream by combining existing surface and subsurface flow assumptions with high resolution digital terrain analysis. This can be used to distinguish between surface, subsurface lateral, drain flow and ditch flow accumulation. The key terrain attribute calculated in is the upslope accumulated area A, calculated in m^2 which is a measure of the volume of water accumulating in a particular location. As flow concentrates the value of A increases. Thus areas receiving large amounts of overland flow can be visualised clearly. If a design storm is used to give the likely flow depth, for example 10mm of overland flow, then A can be converted to a volume, allowing the capacity of a design feature such as a storage pond to be estimated. In ditch networks the design storm runoff multiplied by A provides an estimate of the total flow in the ditch. Used in conjunction with a Geographical Information System (GIS) TopManage enables the user to assess what the effect would be of adding to, or removing from, the land topographic features. Starting from a digital terrain map of a particular field or area of farmed land, usually derived from Geographical Positioning System measurement, maps can be input to the GIS, topographic features added, and augmented terrain maps analysed using TopManage.

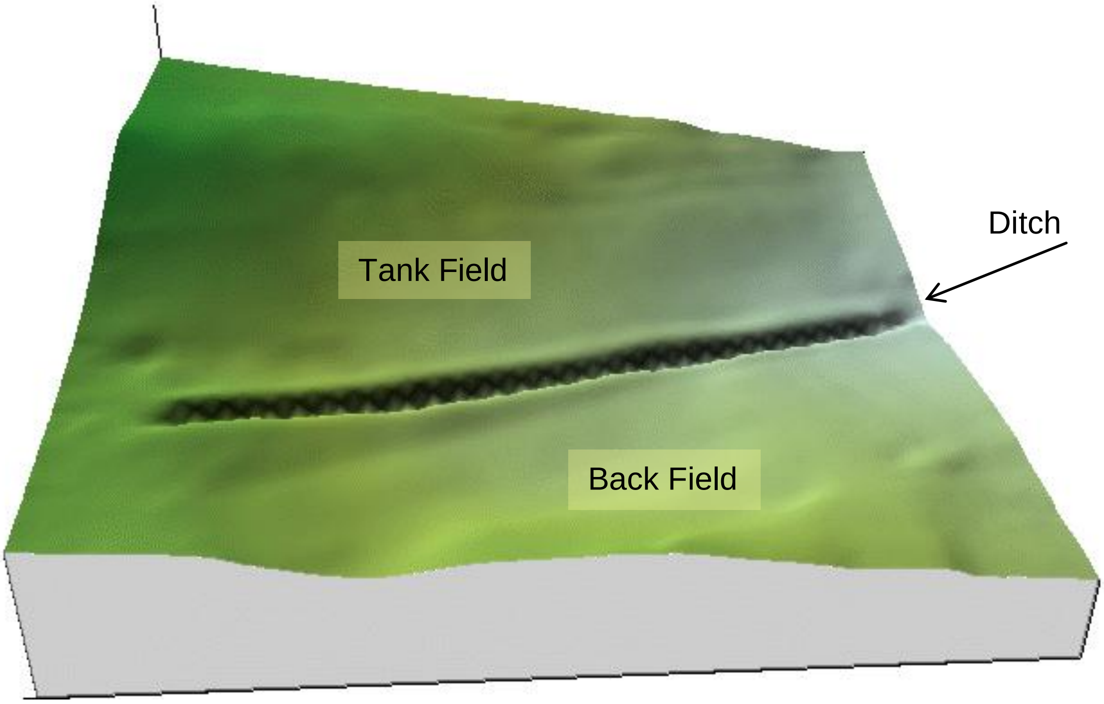


Figure 3.4. Three dimensional rendition of digital elevation model of Tank and Back Fields, mapped with a GPS system.

Figures 3.5 and 3.6 below show the results of the terrain analysis performed before the introduction of the ponds for Tank and Back Fields respectively. The legends show the accumulated flow area in m^2.

For Tank Field it is clear that the ideal position for an interception pond would be in the East corner of the field as this is where the highest flow accumulation is (Figure 3.5). In practice however there was a gate in this corner of the field which the farmer was unwilling to move so a compromise had to be reached and the pond is set back from the gate, meaning that it does not capture all the overland flow. However, as researchers we have to accept that dealing with the real world means rarely being in a position to put a feature *exactly* where we want. The overriding issue here is construct a pond and judge the reaction of the farming community but essentially to capture runoff from the roads adjacent to the fields.

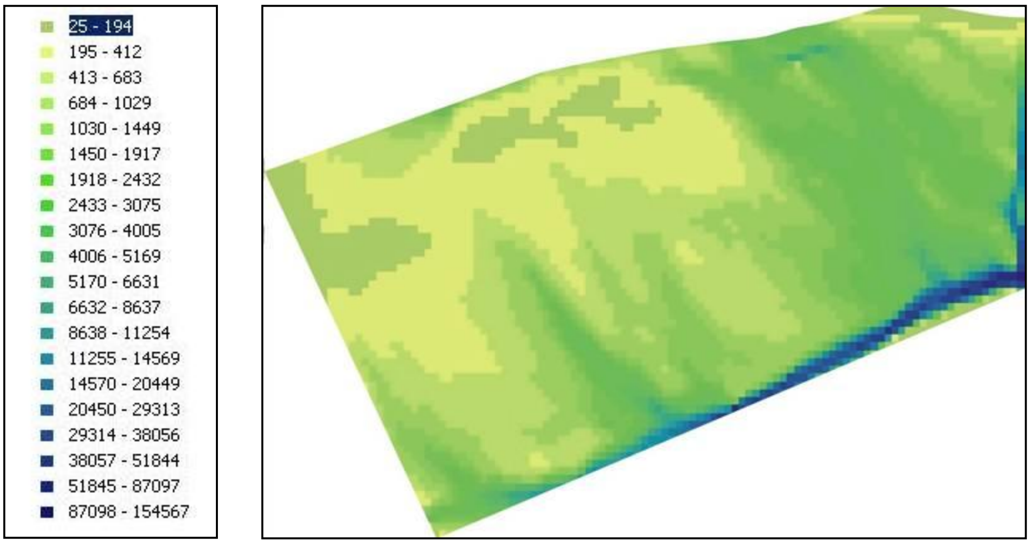


Figure 3.5. Flow accumulation map (m^2) for Tank Field prior to introduction of ponds

In the case of Back Field the model shows that that the majority of the flow goes into the ditch and that the best place to position a flow interception pond would be about a third of the way along the North side of the field (Figure 3.6). Again this was not possible for practical reasons and a compromise was made in which the pond was introduced in the North East corner of the field, which has the second greatest flow accumulation. Thus we knew from the outset that a significant proportion of the overland flow from this field would still go directly into the ditch. However we would argue that this does not negate the usefulness of the pond as it fills up during storm events and thus is clearly contributing to disconnecting the runoff from the roads as intended and could receive approximately a third of the overland flow arising from the field (~60000m^2). Which is only 60m^3 for storing 1mm of runoff? This would be or 154567 m^2 or ~155m^3 (the maximum value in figure 3.5) to store 1mm of runoff for the whole field. This may still seem small if 10mm of runoff were generated, but the flow would not be generated instantly, the pond offer some transient storage effects and it is assumed that other storage would also be available on the farm. Therefore on a field by field basis each pond or a number of ponds could significantly address the runoff issue.

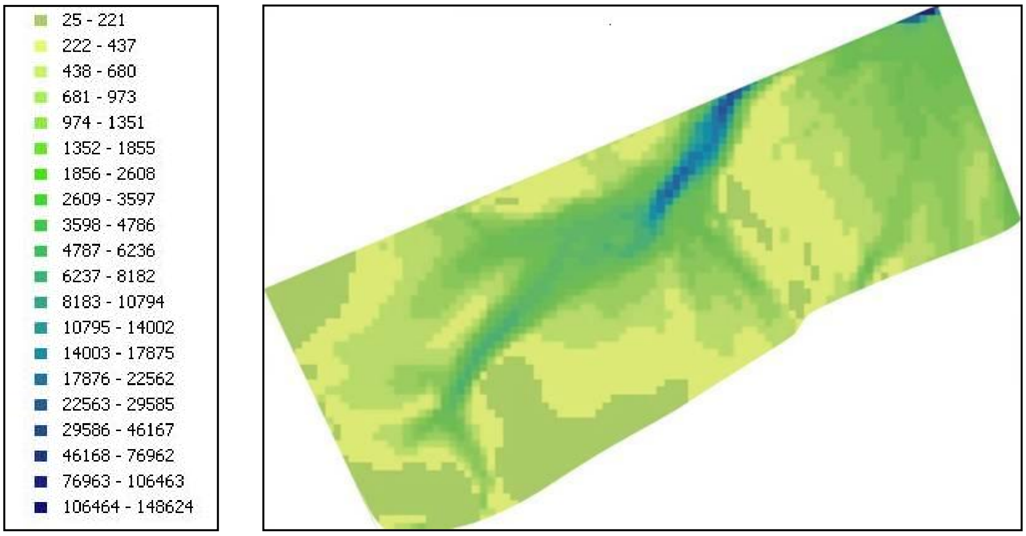


Figure 3.6. Flow accumulation map for Back Field prior to introduction of ponds.

3.1.1 Interception and Infiltration Ponds

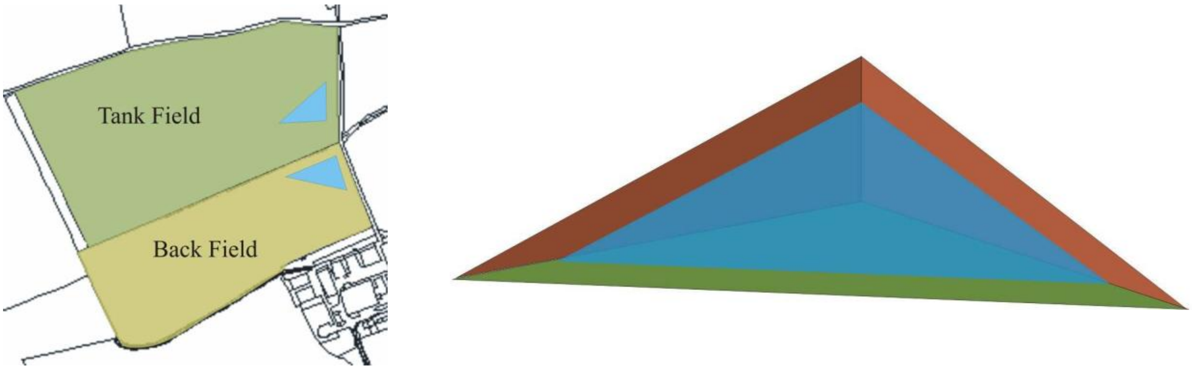


Figure 3.7. The triangular ponds installed in Tank and Back Fields

As part of Experiment 1 triangular ponds have been installed in the lower corners of Tank and Back Fields at Nafferton Farm (see Figure 3.7). The pond in Back Field has maximum depth of 80cm and dimensions 25m × 25m, providing a storage volume of 83.3m^3. The pond in Tank Field has maximum depth of 80cm and dimensions 35m × 35m, providing a storage volume of 163.3m^3. The total storage for these two ponds is **247.7m^3**. Considering that 1mm of rainfall over this catchment (~1km^2) generates **1000m^3** of water this is a relatively small amount of storage and much larger ponds or a larger number of ponds would clearly be required if significant storage in the event of a storm is required. However the ponds do intercept a significant amount of fast flow, with nutrient pollution reduction, sediment trapping and, we assume pathogens and pesticide reduction as well.

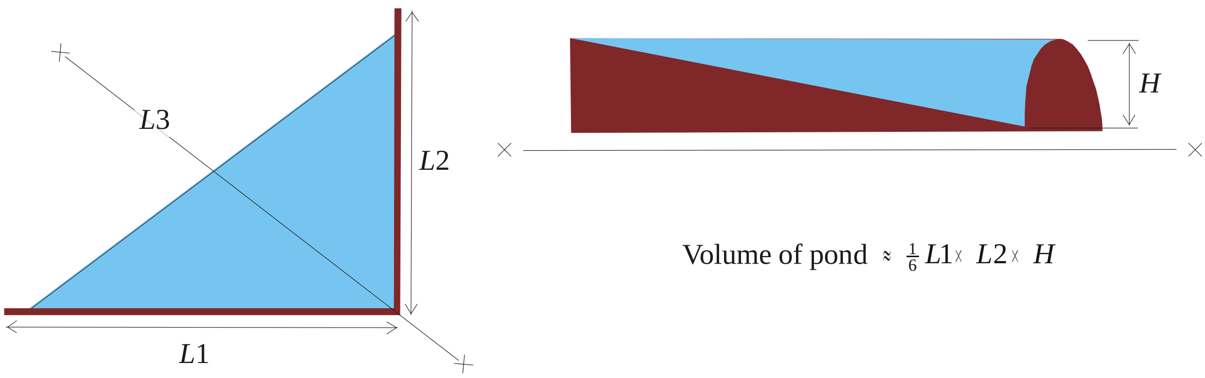


Figure 3.8. Plan and cross-sectional view of right angled triangular pond

Figure 3.9. Photograph of the ponds installed in Back Field (left) and Tank Field (right)

The runoff management features deliberately target runoff from roads and overland flow as these are the fastest and most polluting flow paths. Currently two test ponds (figure 3.9) that have been installed gather most of the flow from the roads and some flow from the fields. As the fields are currently under grass the amount of overland flow is low. However, when arable crops are installed much more overland flow is expected. We believe that any sedimentation and slowing down or infiltration of the flow will always be beneficial in terms of pollution reduction and lowering flood risk. The ponds also act as sediment traps and it is already clear that large amount of sediment is accumulating. At sometime the pond will be dried down and the sediment will be recovered and return to the land. This sediment will be tested for it nutrient/fertiliser potential at a later date. The ponds are set back from the corner of the field at the request of the farmer who does not wish to move the field gate, as currently the gate is used for animal and vehicle access, hence hard core was placed in the entrance to minimise any future poaching and ponding in this area. After construction, it has taken the summer months for vegetation to grow back onto the feature. The edges of the ponds have had to be cut as thistles grow rapidly in the area. At sometime the sediment in the pond will be removed and hopefully return to the land as a beneficial recycled waste.

The ponds have not been instrumented as yet, so the exact operation is not fully quantified. An adjustable overflow drain is used to discharge the pond back into the main ditch, and as such it controls the maximum level in the pond. It would be interesting to quantify exactly how well the ponds are working. To date a visual inspection of the pond is showing that the ponds are filling and emptying, largely with flow from the roads. The roads are laden with fresh sediment and manure each day, this has given rise the large amounts of sedimentation in the pond. The original design life was to be 5 years but the pond may need to be emptied before that. It would be interesting to monitor the ponds after the grass has been removed and a winter crop is sown, as large amounts of overland flow are expected to be generated on this field. Financial constraints have not allowed the optimum operation of the pond to be determined. There is also a clear trade off between allowing the pond to fill quickly (as this helps sedimentation effects) and the lowering the overflow pipe position (so that the pond will empty quickly). The positioning of the overflow pipe controls how quickly the pond will draw down and thus give the flood storage capacity back in between storms. At this time we conclude that any physical storage capacity is beneficial but it could be optimised better.

3.1.2 Runoff from Roads and Hardstandings

Figure 3.10. Photographs of drains that feed runoff from roads and hardstandings to the ponds

The fastest and most polluted flow paths on the farm arise from runoff generated on the hardstandings and from overland flow arising from fields. The runoff picks up any fresh sediment, of which most is deposited from the dairy herd that use the roads twice a day. Hence, two sets of interception drains have been placed on the tracks as they slope down to the main ditch (figure 3.10). The drain entrances are as far down as possible to capture the maximum amount of flow/sediment but they need to be far enough up so that the drains can fall under gravity into the runoff interception ponds. On occasion large amounts of flow have surcharged the drain, so not all the flow is getting into the pond. This will hopefully be solved by better control of the flow on the road and sharing it between the two man holes equally.

3.2 Experiment 2: Within ditch remediation and storage

Experiment 2 consists of a set of features set in series along the ditch to slow down and filter flow, provide further temporary storage and to remove nutrients from the system. There is also a variety of monitoring equipment to measure flow and water quality which have been put in place to help evaluate the effectiveness of the runoff management measures. Starting at the upstream end of the ditch the features are an upstream flow gauge, sediment trap, phosphorus trap, an algal pod, two wetlands, the Green lab, three leaky barriers and an outflow weir. These features have been reviewed in detail in the 'Proactive approach to FIRM plans with respect to nutrients' report (Quinn et al, 2007)

3.2.1 The Upstream Flow Gauge: The Start of Ditch Runoff Attenuation and Remediation Zone

At the flume (figure 3.11) the inflow rate and a series of water quality parameters will be measured as the flow passes into at 400m long attenuation and remediation zone. The Flume, shown in the photograph, contains a logging pressure transducer. This will trigger water quality sampling as the water level rises. 1 water quality sample is also taken each day. The Flume is designed not to sediment up, but the flume still requires maintenance and cleaning.

Figure 3.11 Upstream Flow gauge

3.2.2 Sediment Trap

The site has always shown evidence large turn over in sediment and thus phosphorus loss. Numerous locations along the ditch are prone to sedimentation and hence we believed that any features places in the ditch would be prone to sedimentation that would be difficult to recover. We proposed a zone to remove sediment as it moves down the ditch system. Hence a 5m concrete lined section was installed. A barrier at the lower end of the ditch causes water to pond and induces sedimentation (figure 3.12). After one year the trap was full of sediment and thus the feature requires drying down and the sediment removing. The sediment will again be tested for its nutrient/ fertiliser potential. The concrete lining allows easy access and for the maximum removal of sediment.

Figure 3.12. Photograph of the sediment trap

Flood storage potential: is essentially the backing up of flow as the permeability of the Aquadyne plastic is surcharged. This forms a pond of 1m depth and about 25 m long. Therefore we estimate a physical storage of approximately 25 m^3. However, this storage is not always available as the sediment trap is filing quickly with sediment. Th average depth of the pond (i.e. the maximum depth that sediment can accumulate) is 20cm. the impact of a pond on transient storage effects may also be significant. From observation only one storm has caused a pond to form behind the Aquadyne dam, but we estimate that the pond will form in low return interval events, i.e. the physical storage would be full in a large return interval events. The impact of transient storage may be more significant. Later in the report, hydraulic simulations have been attempted to address the transient storage case.

3.2.3 Phosphorus Trap

Figure 3.13. Ochre pellets and the phosphorus trap

A minewater waste product called ochre has been massed produced into small absorbent pellets which are capable of absorbing phosphorus. The Ochre P trap has two actions firstly, any water coming dissolve P coming into contact with the ochre will be absorbed. The ochre also acts as a direct sediment filter. It seems that very fine sediment is being trapped in the ochre matrix (Figure 3.13). We are still unsure as to how effective the 'filtration option' is, but we have observed large reductions in TP and small reductions is DP. We intend to install up to 3 tonnes of ochre to react with the runoff in high flows. The life of the feature should be several years, after which the P rich ochre can be return to land as a slow release fertiliser. The photograph shows ochre sitting in the P trap. It is worth noting that all the features introduced at Nafferton Farm are constructed from recycled waste materials.

Flood storage potential: there is a small but essentially negligible amount of physical storage on the ochre trap. There is probably more transient storage caused by the feature as significant amounts of the flow go through the ochre pellets and Aquadyne barriers. Observations have shown excessive amounts of flow travelling over the ochre trap in large events.

3.2.4 The Algal Pod

Figure 3.14. Photographs of the Algal pod

Eutrophic conditions that give rise to algal bloom are commonly seen with the local ditch network. There are also many sites in the UK that are prone to eutrophic conditions, which may become worse as the climate changes. The idea here is to mimic a shallow ditch/river system (figure 3.14) and, induce ideal eutrophic conditions to grow algae, absorb nutrients and then harvest the algae and then recycle it back to land. This feature could then protect sensitive downstream sites by preferentially removing nutrients from the environment. We feel this may be needed during the spring time conditions when eutrophication risk may be at its maximum. Incidentally, the algal pod becomes an excellent sediment trap during larger winter runoff events.

Flood storage potential: This feature supplies a small amount of physical storage and a small amount of transient storage. We are unsure how to proceed with the design of the channel to induce algal blooms that could be harvested at large scale. However, should the technique be adopted, then a typical stream would require quite a wide and slow flowing channel which has flow retardation properties. The zone would have to be clear of vegetation so roughness effects would be at a minimum.

3.2.5 Within Ditch Flood Storage Barrier

Figure 3.15. Photographs of within ditch storage barrier and as seen during a storm event.

Until the construction of the numerous features within the ditch, the flow rates during storm could be very high and there was little or no resistance to the flow. Here we wish to maximise any online storage/attenuation capacity within the ditch system. As the ditch is quite incised (figure 3.15), it is perfect for the instalment of within ditch barriers. This may not be true of all ditches however, the capability to store some flow should be possible in or around the riparian area on most small ditches and streams. Again we use Aquadyne material for the construction, which is made from recycled plastic (figure 3.15). The material is freely draining so average storms will pass through the feature, however in the more extreme events will back up and will establish a temporary pond.

We would like to install pressure transducers placed behind the feature to identify under which storm conditions the flow is backing up and being stored. Some evidence of sediment accumulation behind this feature is also occurring. The barrier is deliberately placed in this position as it also has a second function to destroy the energy in high flows and thus protect the wetland that is immediately downstream. During large events the barrier is designed to fill up and create a temporary pond.

Flood storage potential: This feature operates in manner identical to the other Aquadyne barrier in the sediment trap. Therefore we assume a maximum physical storage of around 25m^3 but the pond will form during quite small storms. The impact of transient storage may be more significant. Later, hydraulic simulations have attempted to address the transient storage case.

3.2.6 The Sedge Wetland

Figure 3.16. Sedge wetland after construction. Sedge is 'borrowed' from another local wetland to maximise denitrification in a small linear feature. Also shown are sevarl gaseous emission chambers.

The sedge wetland is constructed by widening the ditch (to about 3m wide) and back filling the earth to create a shallow flat bed (figure 3.16). Aquadyne strips, secured with willow pegs create a series of steps in the flow, thus maximising the contact of the flow with the sedge and roots. The theory is that some denitrification will take place. The efficiency of the feature still has to be assessed. The willow pegs also come to life and add colour and protection to the feature. The sedge and the willow flourish over the summer, absorbing more nutrients, so they are cut back once per year.

Edinburgh University are also working at Nafferton Farm to measure the gaseous emissions arising from the wetland.

Flood storage potential: There is little physical storage on this feature, however the roughness of the vegetation is high and this will attenuate flow. The bulk of the high flow is designed to go across the top of the feature. We argue later (se section 5) that if large amounts of shallow and broad channels exist, with rough vegetation, this could have a significant transient storage effect.

3.2.7 The Willow Wetland

Figure 3.17. The willow wetland, after construction and during a winter storm event

A series of willow hurdles are used to slow and control the flow. Willow cuttings have been planted along the bed and the channel has a new sinuous path (figure 3.17). The willow soon takes root and grows very rapidly. During rainfall events the stalks act as giant obstacles retarding the flow. One cut per year is required to mange the willow growth. Trash does build up at the upper end of the willow hurdles, therefore some maintenance is needed from time to time (or after every large event).

Flood storage potential: There is little more physical storage on this feature than the sedge wetland, however the roughness of the vegetation is very high and this clearly attenuates flow. The bulk of the high flow is designed to go through the willow stems (as in figure 3.17). We argue later that if large amounts of shallow, broad channels exist with very rough vegetation this could have a significant transient storage effect (se section 5).

Fig 3.2.8 Leaky Barriers

One obvious concern about the interventions listed so far is that they do tend to fill quite quickly and in most storms. Therefore the barriers may not operate as physical storage in flood events other than adding some transient storage effects. One main reason for this is that most of the features are addressing nutrient pollution and sediment trapping issues. One experiment has thus proposed the idea of using ‘leaky’ barriers in ditches. In essence barriers that can provide flood storage in larger events as the bulk of the flow will pass through in small events.

Figure 3.18, two leaky barriers, the firs has small gaps between the planks, the second has 1cm gaps between the planks.

The features are made from green oak taken from a sustainable source (figure 3.18 and 3.19). The barriers are designed to let more and more water through during storms. The first therefore does fill up during and average storm (several time in the year), the second has started to fill (based on visible evidence on the wood) the third and most leak barriers has not filled as yet. As to the return interval storm that will overtop the feature is still difficult to assess. Here we have designed the feature to fill the space in the ditch. The feature should only start to fill as the flood waves passes through. Should evidence show that the features are filling too often it is easy to add more gaps to the features. We would like to assess the barriers operation over the next few winters and give recommendations at later date. The features are designed to have small ponds behind them (10cm depth), this gives a small pond of about 1m length. This feature does allow sedimentation to occur. The sediments can be retrieved and recycled back to land.

Figure 3.19, a leaky wooden barrier, with 2cm gaps.

It may seem unlikely that such feature can afford significant flow storage in very large events but they could have a role to play in smaller storm events. We also may require within ditch barriers for other purposes, such as protecting wetland and acting as sediment barriers. There could therefore be some dual design aspects of the feature that can allow nutrient pollution trapping for most of the time but intermittent flood storage at others. As will be seen in the last section of **FIRM** plans for a whole farm, it is proposed that the buffer strip are may be a great place to attenuate flood flow and denitrify flow, the within ditch barriers will be needed to control the flow on and though the buffer strip area. Here we have gained invaluable expertise about the construction costs, implementation and the operation of such barriers.

Flood storage potential: Each feature supplies a 1.5 m maximum depth and so the temporary storage ponds is about 40 m long. So 30-40m^3 of water is stored in the feature when it is surcharged. The purpose of the feature is really designed to let significant amounts of flow through, hence we think extensive simulation and modelling would be needed to determine which flow rates and return interval flood events could be addressed by leaky barriers.

3.2.9 Buffer Strip Experiment

A small experiment run jointly with Edinburgh University has established a small saturated buffer strip and a non saturated 'control' buffer strip. As can be seen in the Proactive approach to **FIRM** plans with respect to nutrient report (Quinn et al., 2007) that the current wetlands are probably too small to denitrify large amounts of flow and they may not work too well in winter (when it is colder). However, the saturated buffer zone is treating a significant amount of water from the ditch and is producing N_2, a safe gaseous emission. In order to achieve saturation a structure or a draw off pipe is need to push water onto the buffer zone. The water infiltrates into the soil and returns to the ditch via a subsurface pathway. As such, later work (section 5 and 6) will stress the important opportunity to use buffer strips to retard faster flow and treat the nitrate rich flow at the same time.

3.2.10 The Green Lab, Renewable Energy and The Outfall Flume


Figure 3.20. The Green Lab, Wind turbine and PV array

The Green lab contains an automatic telemetered water sampling kit (figure 3.20). Samples from four locations are pumped to the lab for analysis and the results are sent to Newcastle directly. Samples are taken at the upstream gauge, below the Ochre P trap below the sedge wetland and at the outfall of the ditch remediation zone. The Green lab is positioned at the end of Experiment two, and thus flow is also measured here, for comparison with the inflow flume see below. The Aqualab contains analysers for TRP, N, pH, conductivity, NH3, temp, turbidity, DO and TP. The reagent back can last for several months (the results are shown Quinn et al., 2007)

When all the pumps are operating and the equipment is fully operating, the green lab can consume energy at the rate of a small house. Hence, we choose to use a wind turbine and a complement this energy source with a photo voltaic cell array (figure 3.20). These two energy sources can run the lab for long period, and only occasionally has the equipment failed due to energy needs. The role of energy/ carbon on farms is relevant and often we have to demonstrate the technologies and cost to farmers in order to persuade them that it might a long term benefit to se such technologies. When the sun is shining (which is not always in Northumberland) we can create 1- 1.5 KW. When the wind is blowing (which is most of the time) we can create about 2KW of energy. We feel there is more of a role to be played by smaller modest micro-wind features rather large scale wind turbines that are seen as problematic in rural areas. Experience has shown that farmer have a great interest in renewable energy and we see it as an opportunity to subsidise farmers as part of the **FIRM** plan.

3.2.11 Outflow Weir and Flume

Figure 3.21. The outflow weir, during the January 2007 event

The outflow weir marks the end of the experiment. Here the final flow rate and final water quality sample is taken. Originally a V- notch weir was installed. This was vital to identifying the low flow regime and it works well in most events. As can be seen a large event in January 2007 did overtop the weir. As flood storage is now a focus of the Nafferton work, an extra flume (60cm wide and 60 cm high) as been constructed, so that high flows can be calculated. The lower flume is now identical in design to the upper flume. This will give the best input and output comparison, and will show the cumulative effects of all the features situated in the ditch in experiment 2.

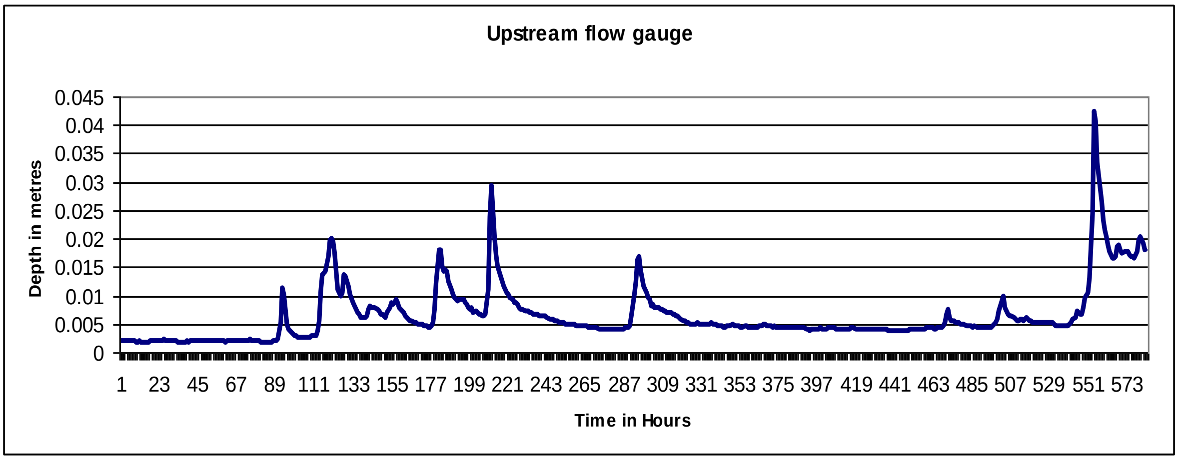
4.0 CUMULATIVE FLOW ATTENUATION EFFECTS IN EXPERIMENT 2.

Over a distance of 400m a large number of features have been installed in experiment 2. One aspect of the work will be to see just how much attenuation can be gained by **FIRM** plans associated with experiment 2. Any conclusions are a little ad-hoc at this time as the ditch is an experiment with many interventions are geared towards nutrient issues, and many of them are quite small and experimental in nature. However, we have argued that all features should supply some flow/flood retardation potential. Hence we will present the flow evidence as it is available now. As stated above, flume has been installed at the start of the experiment upstream but a V-Notch weir was installed downstream. With the weir overtopping and the difficulty we have had getting to the site to create a calibration curve, given the rapid time to peak, we feel that a quantitative and fair comparison can not be given at this time. With the construction of a new flume identical to the upstream flume we hope that full calibration can be achieved this winter. If however, we are still missing the high flow calibration measurements, we will at least have identical flumes to make a fair comparison of input and output hydrographs. What we have presented in figure 4.1, is the comparison of flow depths exhibited between the upstream start of experiment and the exit. Clearly more flow is entering the ditch over the 400m distance and more flow is observed. The measurements are made with pressure transducers, note at the upstream site the lowest flow is 0.002 m whereas at the downstream site this is at 0.027 m, which is because the pressure transducer is sitting in a pool behind the V-Notch weir. Over the summer period April to July there was a prolonged period long large storms (similar to winter conditions). The results of the April to July storm period have been analysed. Despite this weakness in the direct comparisons, we think there is good visible evidence that:-

- The peaks at the downstream site have been visibly reduced. The weir may have been overtopped in the larger events, but this was not observed on field visits.

- The low flow regime at the downstream site seems to be much longer and drawn out that the flashier upstream site. Again effects caused by the V-Notch weir may be partly responsible for this difference.

At this time the reader can conclude for themselves what impact the cumulative effect of the all the features are. The results for the flow comparison for the next winter period should prove very interesting.



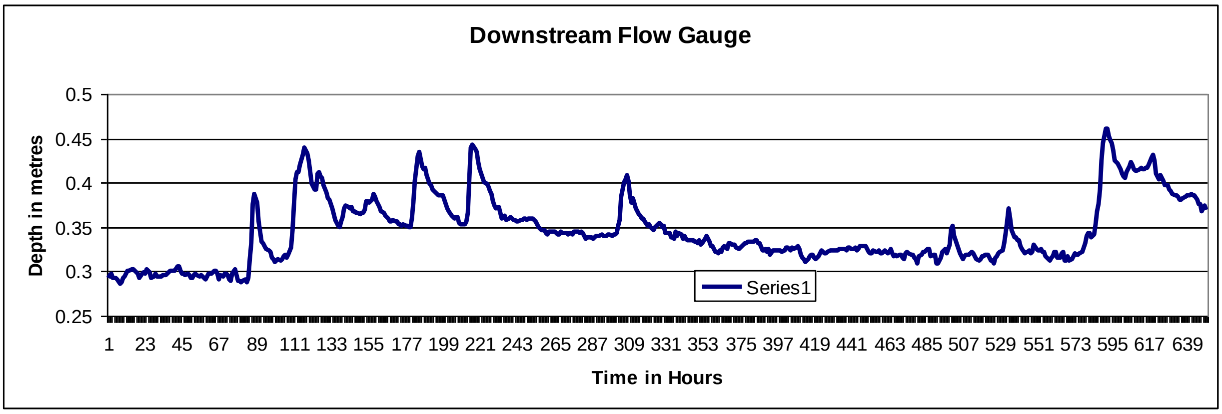


Figure 4.1 Observed upstream and downstream flow depths for the period April – July 2007

5. DYNAMIC HYDRAULIC MODELLING

A series of theoretical calculations were performed in order to better understand the effect of each feature in the ditch using the one dimensional hydrodynamic model NOAH 1D, an advanced modelling system for hydraulic networks under unsteady, free surface flow conditions (http://www.ncl.ac.uk/noah/). The model allows the simulation of ditches and a range of flow structures. Primarily the model uses the de St Venant Equations to approximate to flow effects in rivers and channels. The model captures the effect of roughness and low control features on Qp and Tp for a typical UK farming ditch. The following examples scenarios were modelled:

- a 500m well maintained, smooth ditch,
- a 500m vegetated ditch, within a 500m rough vegetated ditch
- a 30m long sedge wetland, within a 500m vegetated ditch
- a 30m long willow wetland, within a 500m vegetated ditch
- a 1m step barrier (as conceptualised in see Figure 5.1), within a 500m vegetated ditch
- two leaky barriers, one with 50% of its surface as gaps, within a 500m vegetated ditch
- and a leaky barriers the other 25%. within a 500m vegetated ditch

It was assumed that the ditch is vegetated along its whole extent (except where the feature is) using a Manning's number of 0.03 for all examples except the smooth ditch. In all cases the ditch was of length 500m with a change in elevation of 1.5m from along its length. The ditch has a trapezoidal cross section with bottom width of 1m and top width of 2m, see Figure 5.2.

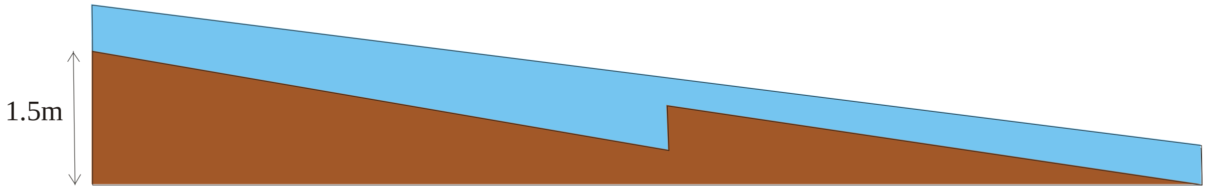


Figure 5.1. The 1m step barrier

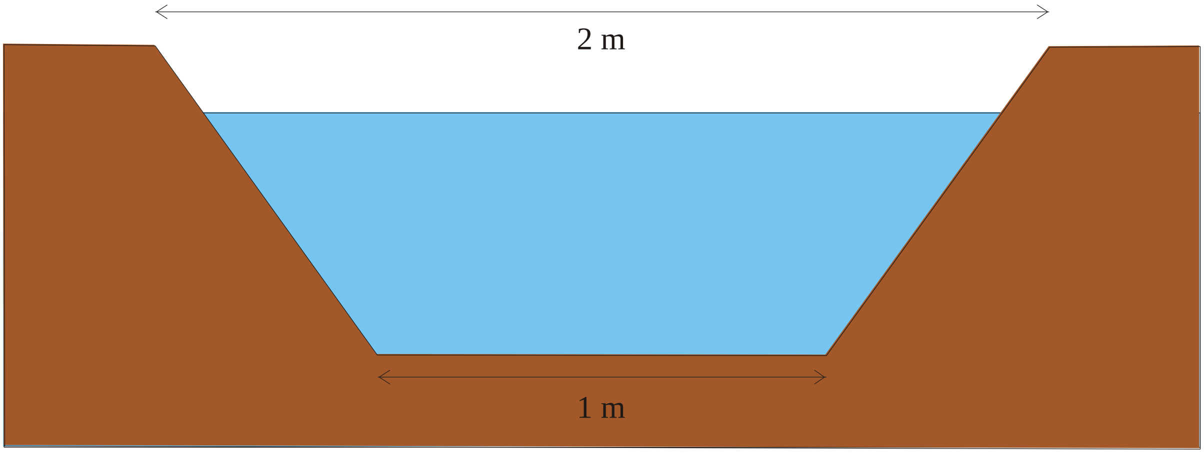


Figure 5.2. Simulated cross section of the ditch

The table below summarises the additional assumptions and key parameter values. In examples 3 to 7 the structure is positioned half way along the ditch, i.e. at 250m.

No	Description	Manning's no.	Structure Dimensions (m)
1	Smooth ditch	0.02	Fig 5.2
2	Vegetated ditch	0.03	Fig 5.2
3	Sedge wetland	0.03 / 0.06	w = 3, l = 30
4	Willow wetland	0.03 / 0.1	w = 3, l = 30
5	Step barrier	0.03	h = 1m
6	Leaky barrier (50% gaps)	0.03	h = 1m
7	Leaky barrier (25% gaps)	0.03	h = 1m

Three different input hydrographs were used for the simulations, labelled A, B and C representing heavy, medium and light rainfall respectively. Table 2 gives the key parameters associated with each hydrograph. Note these are the input hydrographs, it is assumed that a large runoff event would be 10mm/hour of rainfall at the peak of the storm, the typical percentage runoff in the area in 25%, therefore the Qp of 0.51m^3/s (event A), assuming a catchment area of 0.9 km^2, gives a runoff depth at the peak of the hydrograph of approximately 2mm (in terms of rainfall depth equivalent). The highest observed flow in the upstream flume was 60 cm in depth, which was estimated (from current metering) to be 0.3m^3/s.

Two smaller events (B and C) were simulated to see if there was any non-linearity of the features response with magnitude of the simulation.

Input hydrograph Q_{in}	Peak, Q_p (m^3/s)	Time to peak, T_p (s)
A	0.51	1740
B	0.383	1740
C	0.255	1740

The results of the simulations are given in the figures below. Figures 5.3 to 5.9, show the hydrographs for each of the features in turn for all three input hydrographs. In figure 5.3, the effects of routing the simulation over 500m is represented. This simulation is a well maintained smooth ditch and some attenuation is seen as the flow is routed. Also note that there are no assumed lateral inflows over the 500m, thus the overall effect is a drop in Qp, whereas is reality lateral inflows would increase Qp.

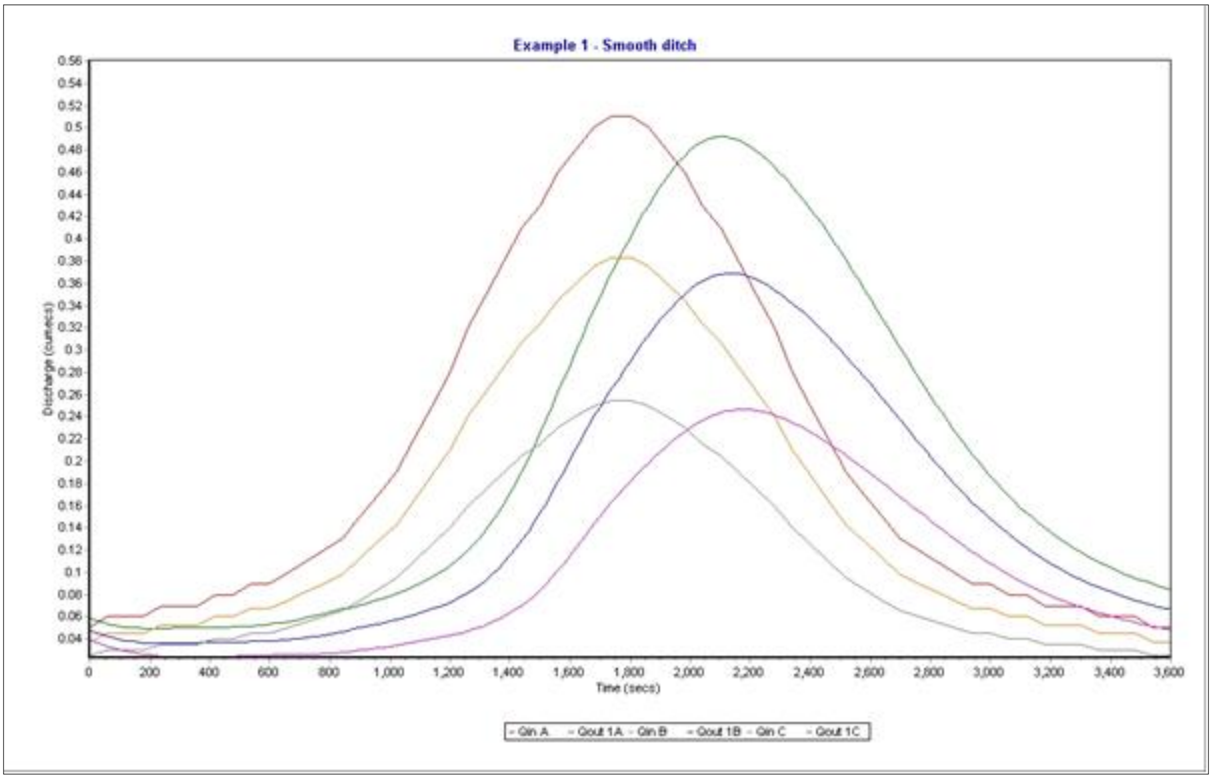


Figure 5.3. Example 1: Smooth ditch. Results obtained for Q_{in} A, B and C

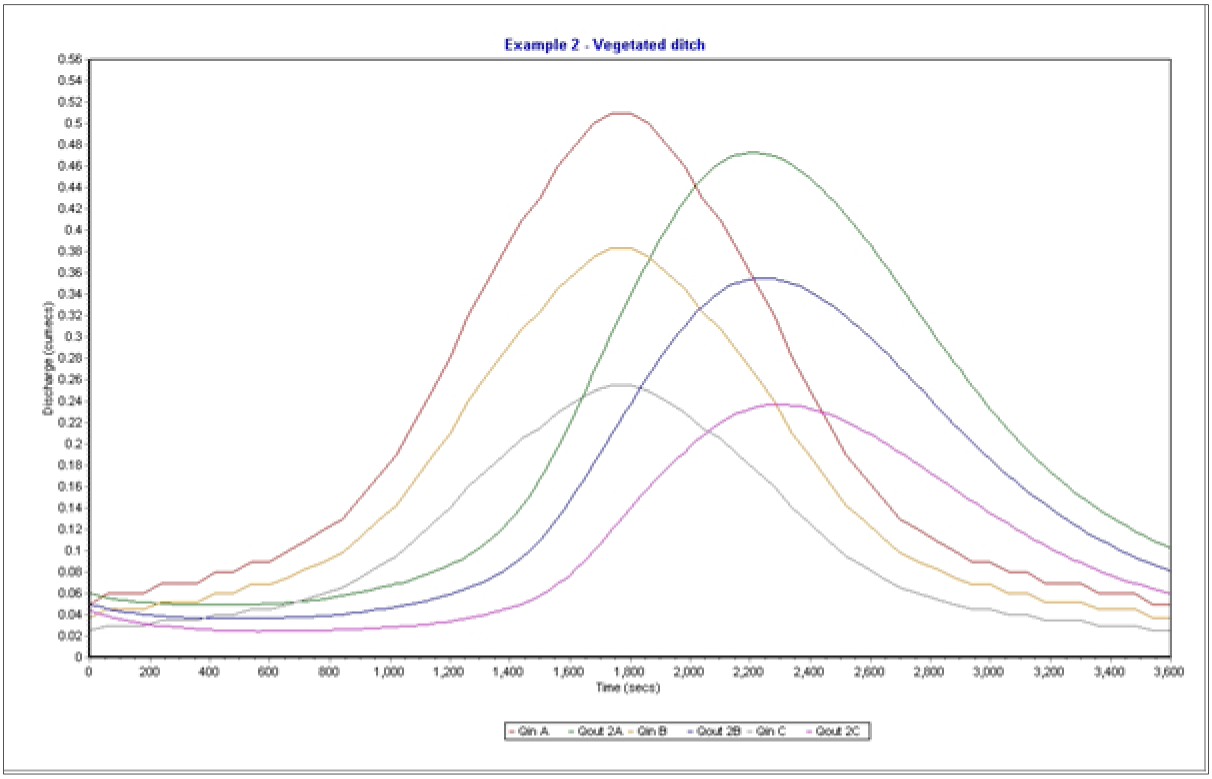


Figure 5.4. Example 2: Vegetated ditch. Results obtained for Q_{in} A, B and C

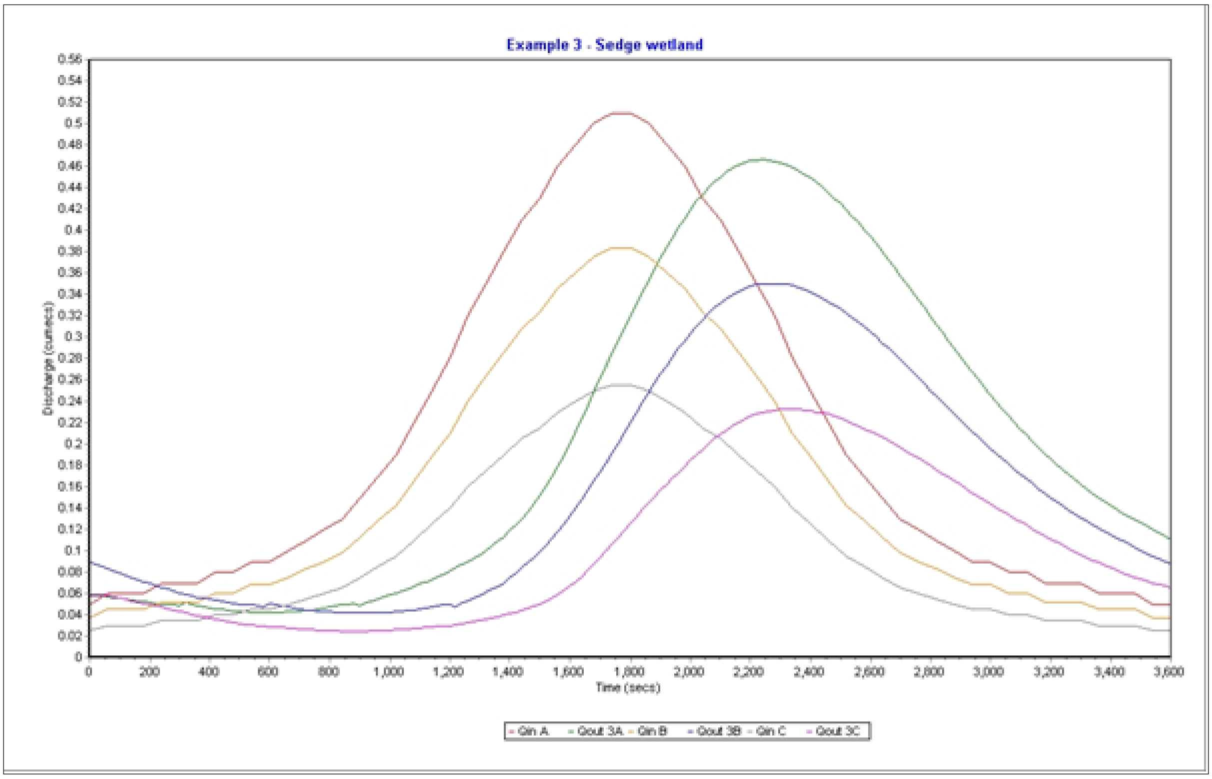


Figure 5.5. Example 3: Sedge wetland. Results obtained for Q_{in} A, B and C

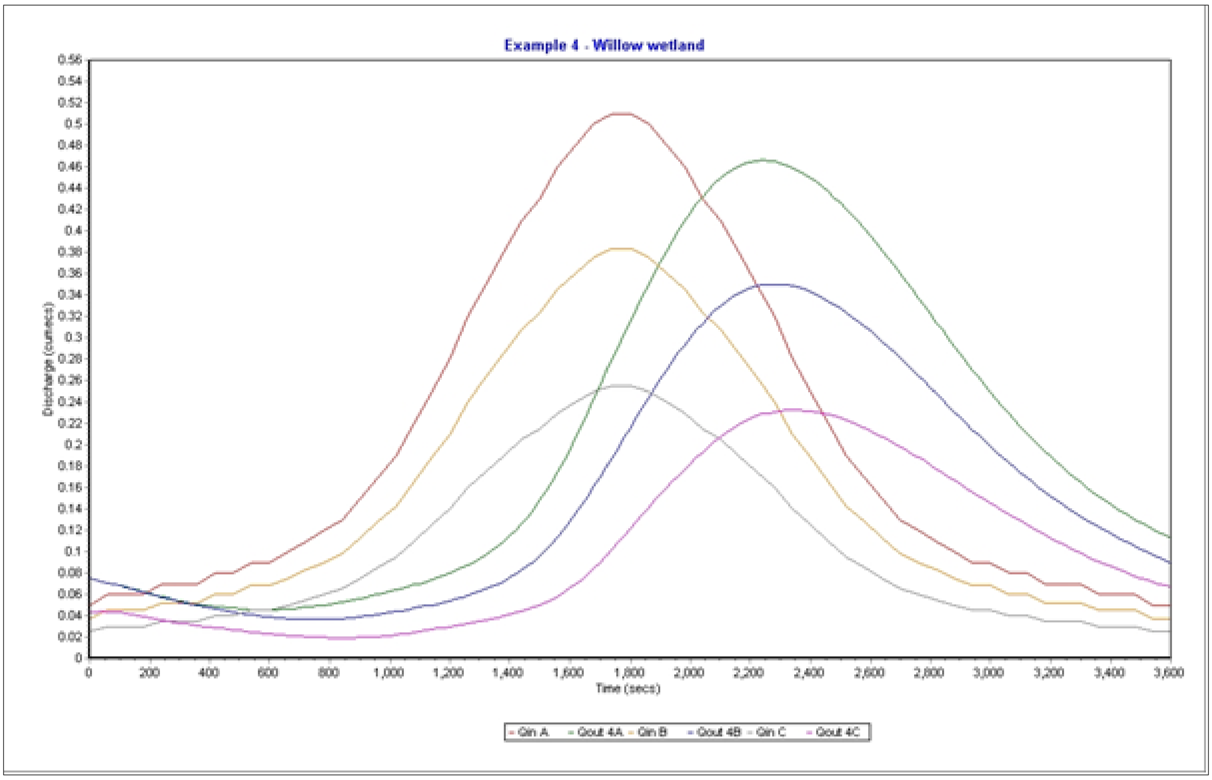


Figure 5.6. Example 4: Willow wetland. Results obtained for Q_{in} A, B and C

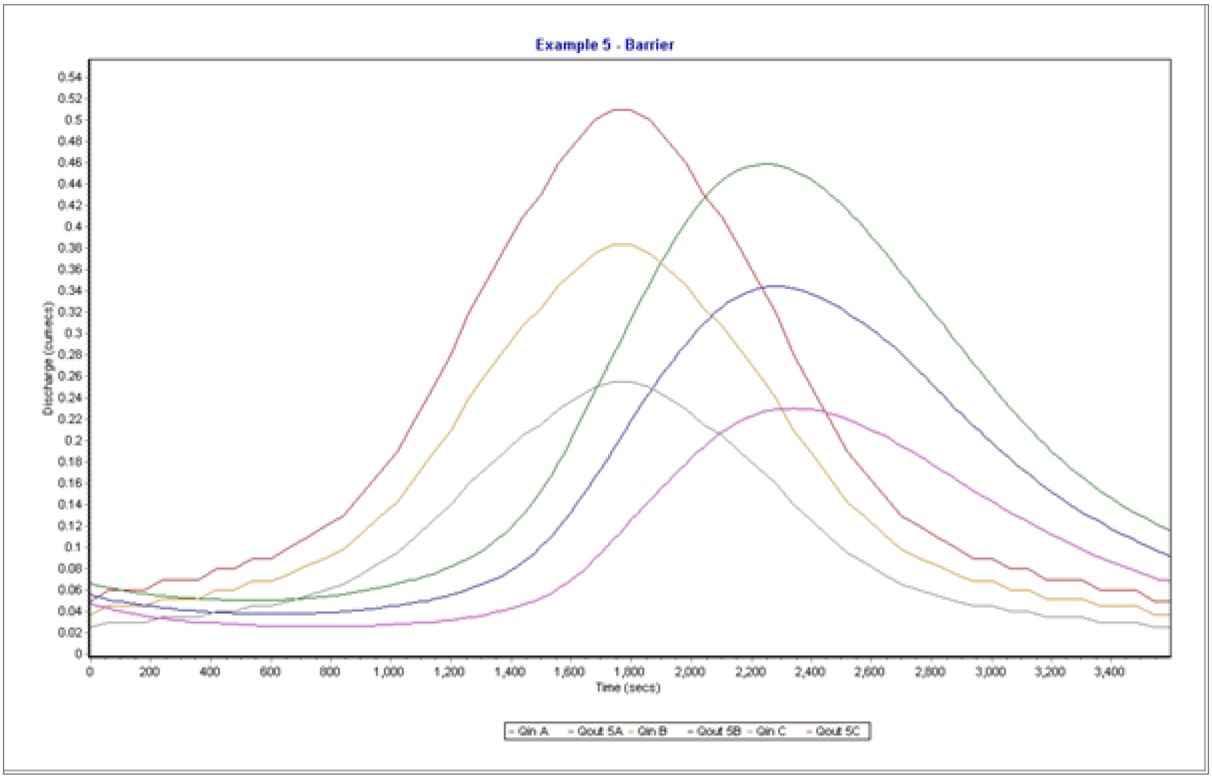


Figure 5.7. Example 5: Step barrier. Results obtained for Q_{in} A, B and C

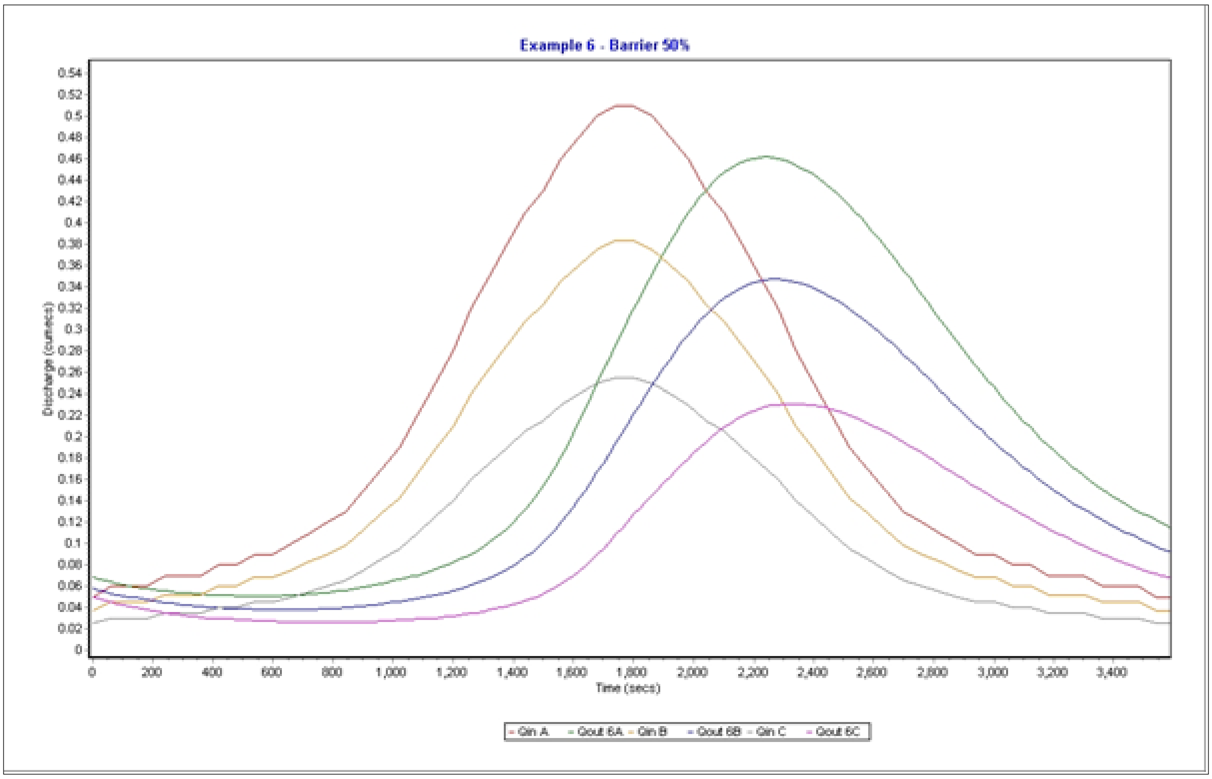


Figure 5.8. Example 6: Leaky barrier (50% gaps). Results obtained for Q_{in} A, B and C

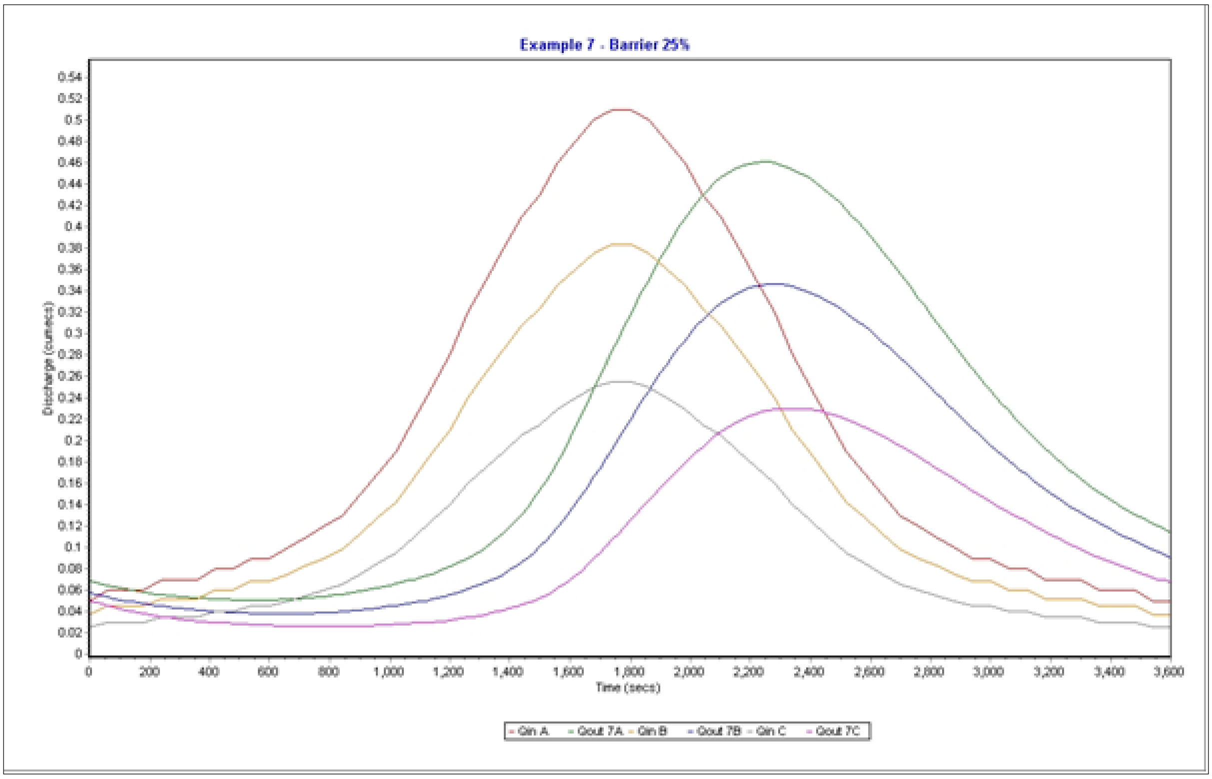


Figure 5.9. Example 7: Leaky barrier (25% gaps). Results obtained for Q_{in} A, B and C

For figures 5.3 to 5.9, show some deviations in Qp and Tp but it is not significant. The small size of the feature, in reality, may mean that when they are simualted separately they do not have any impact on the overall flow conditions.

The main conclusion to be drawn here is that there is little or no effect seen between the small medium and large events. This similarity in shape for all magnitude storms seems to be true for all simulation scenarios. It was expected that the leaky barriers would have caused a more prominent difference between small and large storms, but this is not seen in the simulations.

Figures 5.10 to 5.12, show the output hydrographs for all seven examples for each input hydrograph in turn to enable direct comparison to be made between the results. Here the 'control' output hydrograph is the simulation for the smooth ditch. The impact of the feature simulated is thus the deviation from the control. Hence some estimate of the impacts of the Qp and Tp can be seen.

For event A, all the features have a small effect on Qp and Tp. However, the bulk of the effect on Qp and Tp is caused by the fact that the ditch is vegetated (scenario 2), the subsequent construction of the features only add a small reduction to Qp and longer Tp. This does suggest that leaky barriers are not effective in storing flow. It could be possible that the hydraulic simulation is not representing the actual effects of the barriers. More work will be undertaken in the simulation and in the field to address this question.

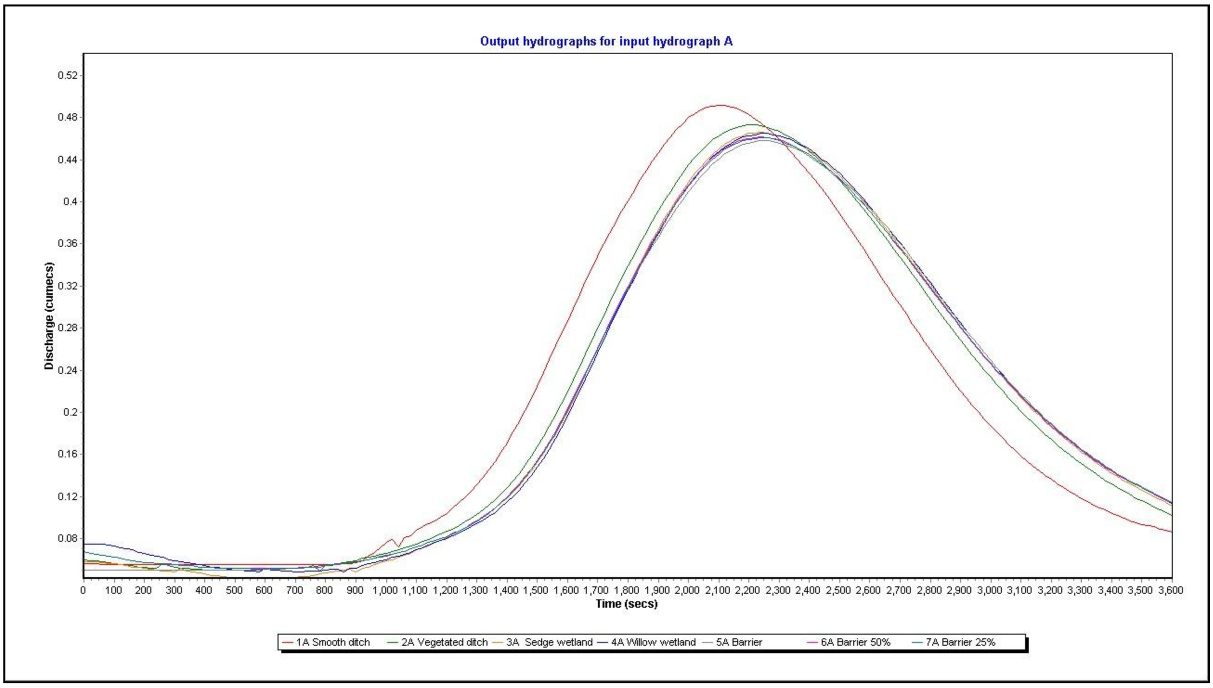


Figure 5.10. Output Hydrographs for input hydrograph A

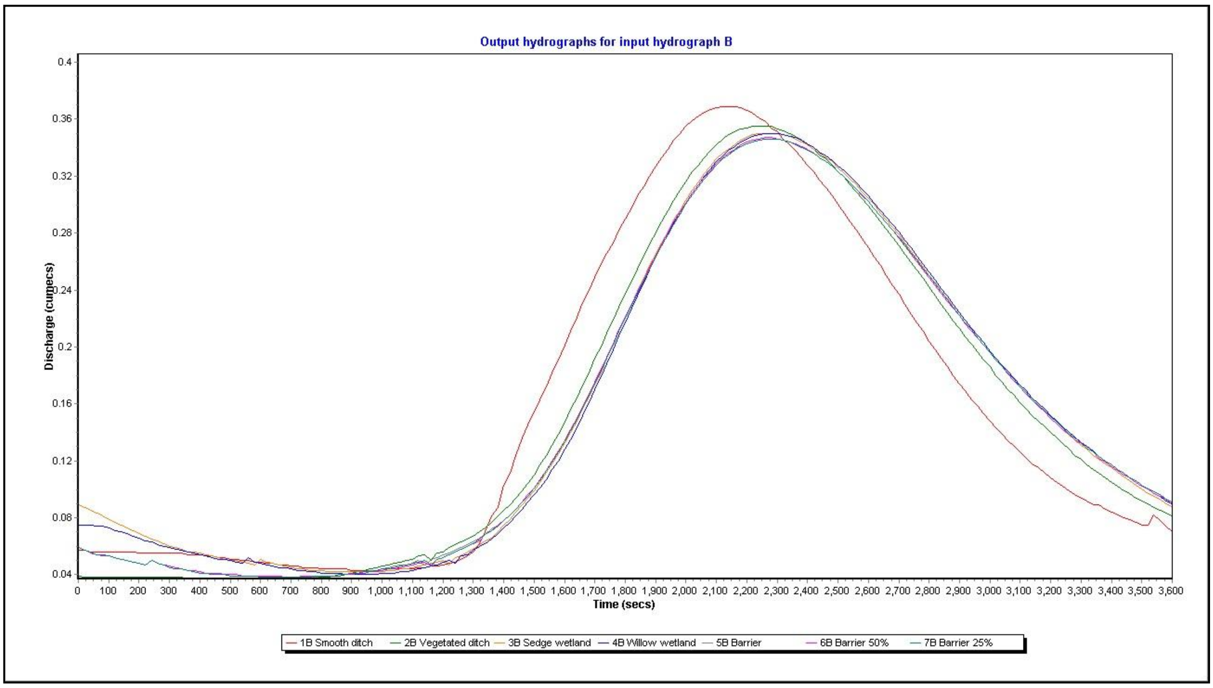


Figure 5.11. Output Hydrographs for input hydrograph B

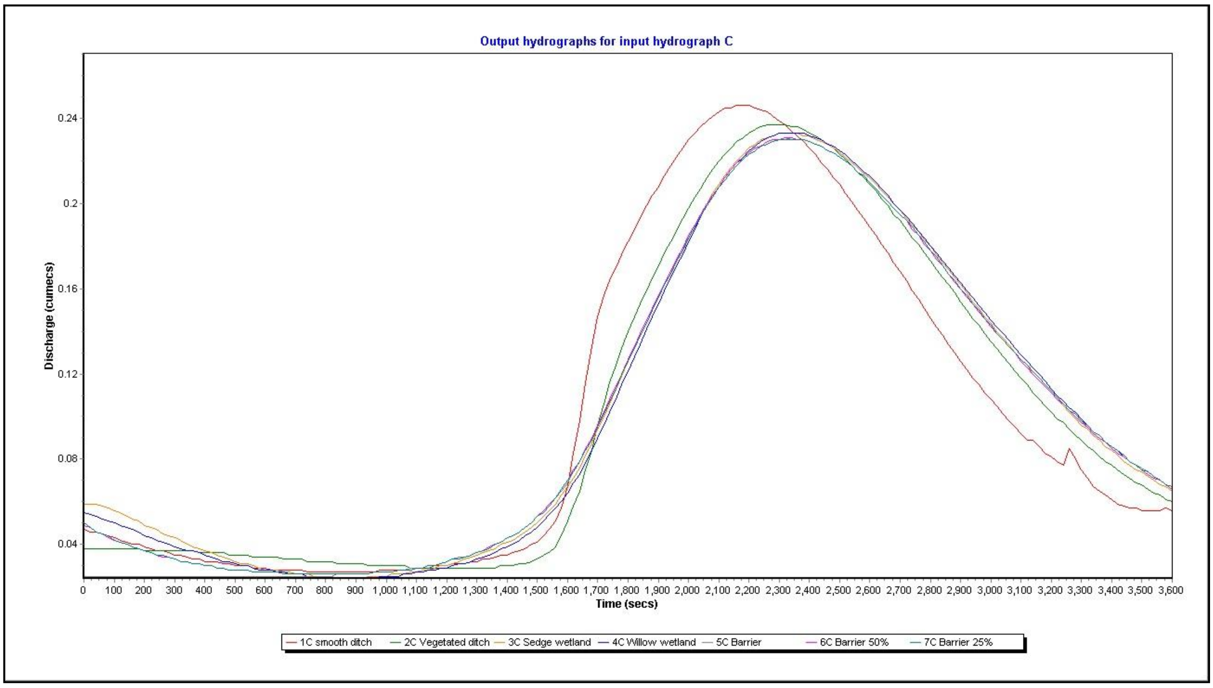


Figure 5.12. Output Hydrographs for input hydrograph C

The results above may just reflect that all the feature are too small to have any effect. Each feature represents about 30m of the overall simulation, or for the case of the barriers will back up a pond of approximately 30m length. The power (and danger) of modelling it that it does allow us to upscale our results to the whole farm for alternative scenarios. If the results are believed they can also help form the basis of further up scaling to large catchments and basins. Her we are only using the model to help think about possible future scenarios and how they may shape the thinking of FIRM plans. SO some caution in over interpretation is needed.

Following these simulations a new series of were encouraged to tackle two factors:-

1. The impact of roughness and vegetation on flow rough vegetation.
2. To upscale the size of the feature to exploit the whole ditch, wetlands and buffer strips to the full.

The scenarios chosen reflect the likely impact of a full scale FIRM plan being implemented. Five more scenarios were:-

- A wetland situated in the middle of the ditch – with a dimension of 30m *15 m. In essence a widening of the ditch, as if a 6m buffer strip were available on each bank. Therefore 6m+6m plus 3m for the widened ditch gives 15m in total. It also assumes that some kind of structure is available to spread the flow across this zone before the flow re-enters the original vegetated ditch. Also the vegetation on the wetland is rough.
- A wetland feature where a dedicated zone of farm land is designed as a wetland with dimensions of 30m*30m.
- A wetland of 30*50m as above. This assumes the cooperation of the farmer in dedication a large are of land to the wetland.

- The final two scenarios reverse the situation above by expanding the ditch to 3 metres in width across the whole of its length (3m*500m). It assumed here that the whole ditch is the equivalent to the sedge wetland over 500m and that structures are available to keep the flow spread across the whole 3m area of ditch (similar to scenario 3 above and as constructed in figure 3.15).
- This scenario is the same as the above but now the wetland is planted with willow which is rougher than the sedge vegetation.

Figure 5.13 to 5.17 show the results of the new full scale **FIRM** scenarios for the three events A, B and C.

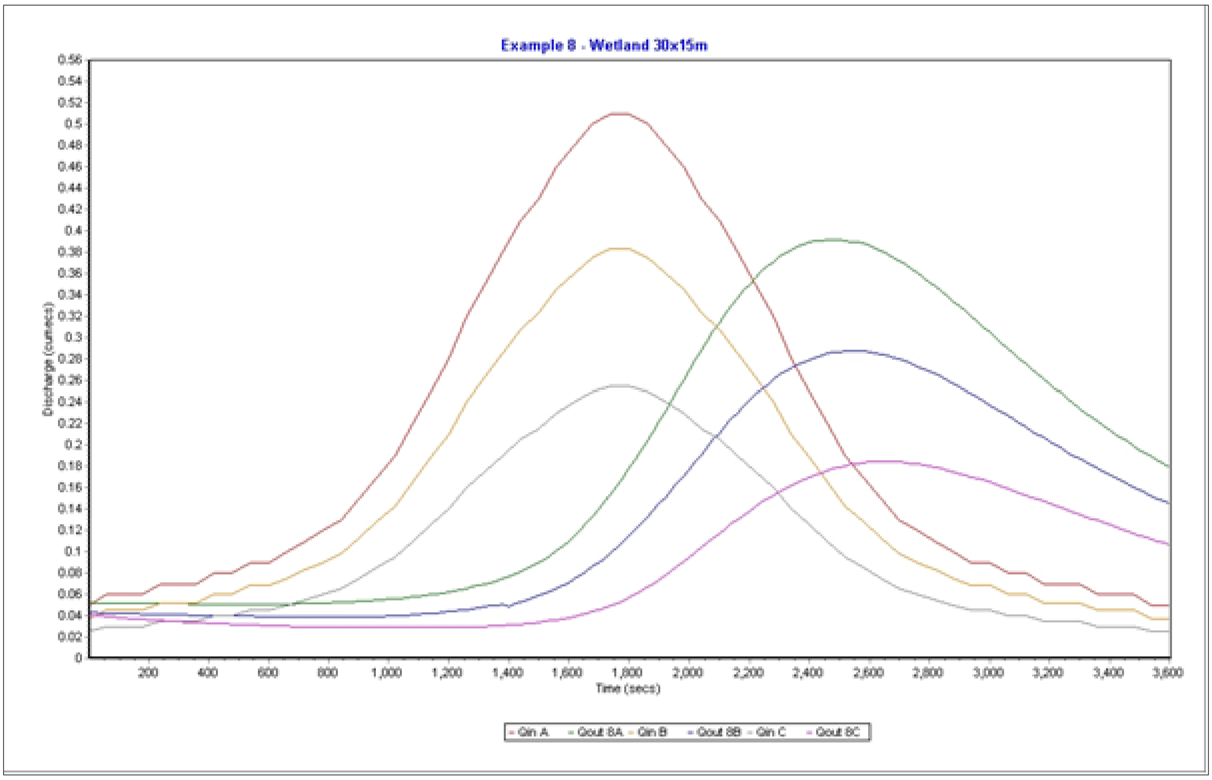


Figure 5.13, A wetland 30*15m in size

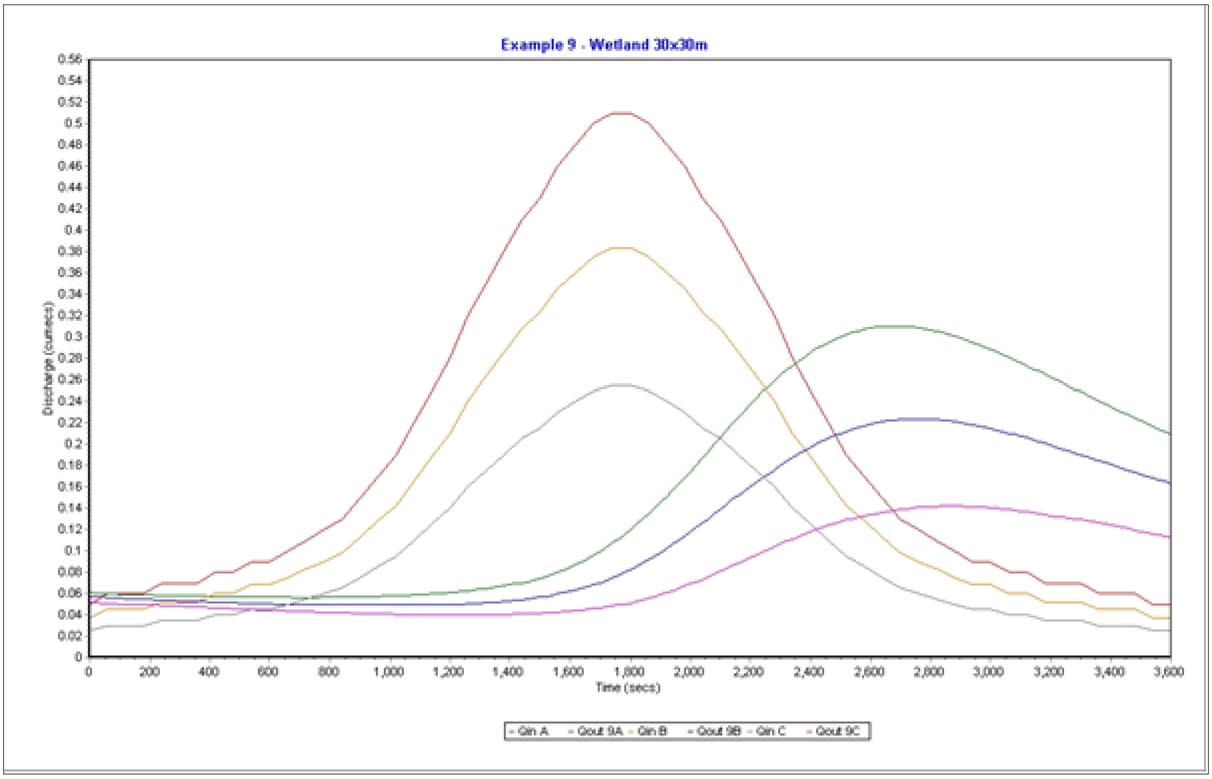


Figure 5.14 A wetland 30*30m in size

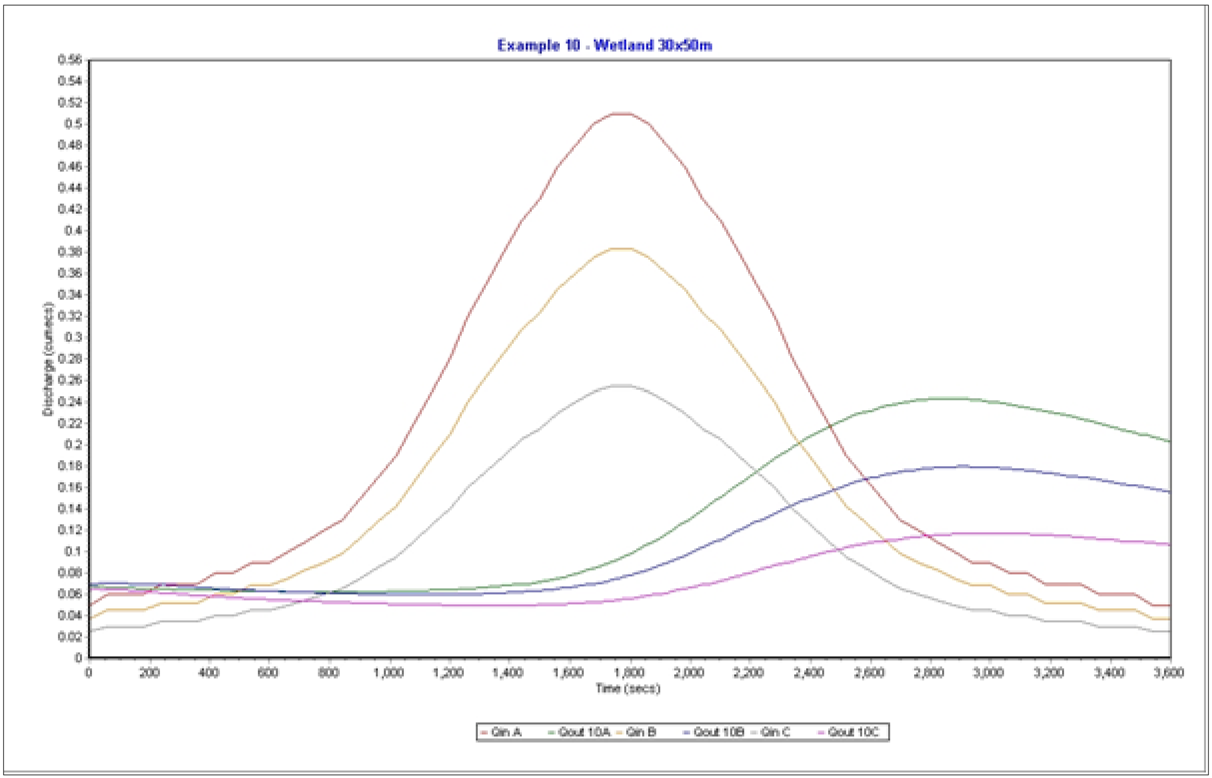


Figure 5.15 a wetland 30*50m dimension

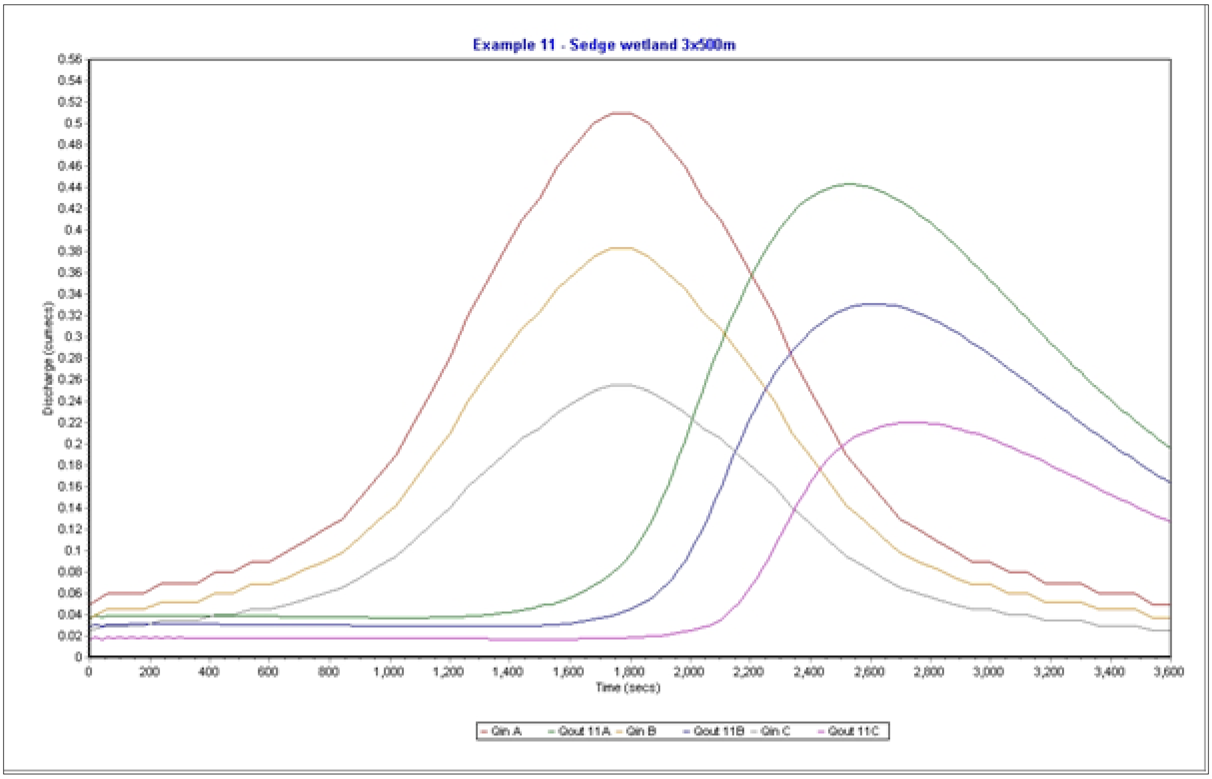


Figure 5.16, a widening of the ditch to 3m and the plating of sedge, where the flow is forced across the whole ditch bottom.

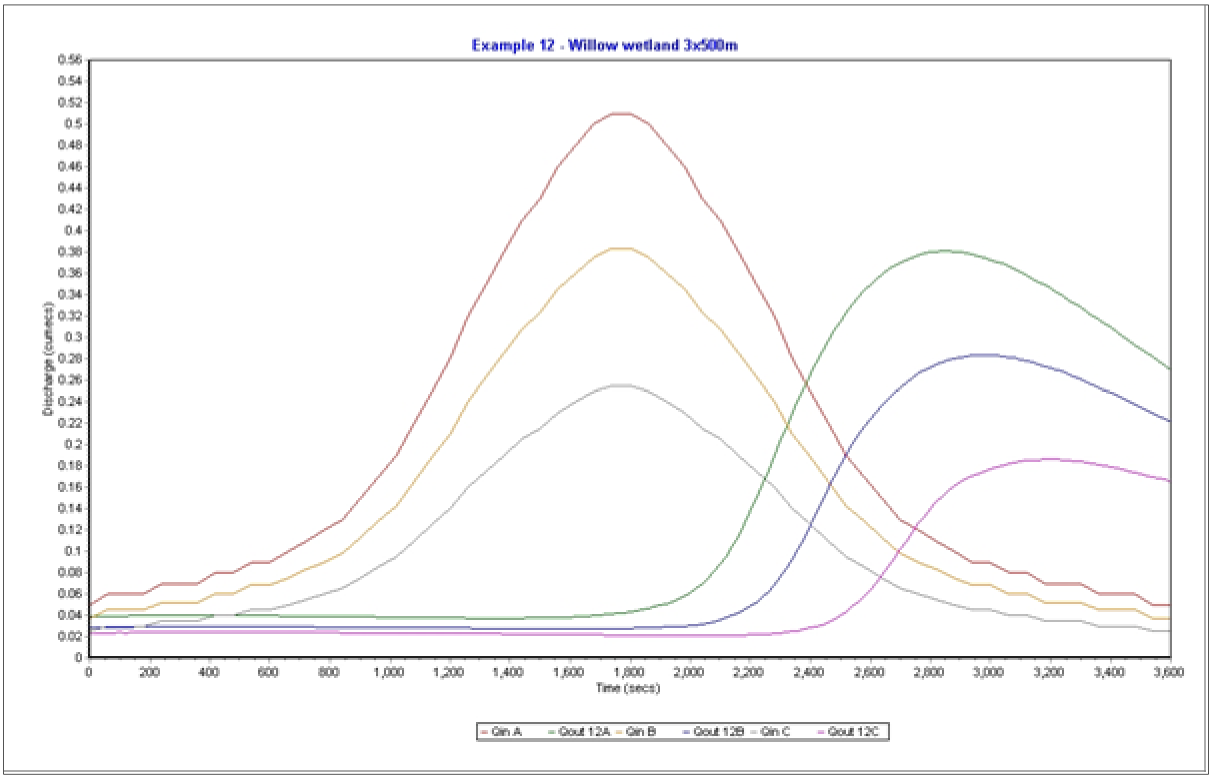


Figure 5.17. A widening of the ditch to 3m and the plating of willow. The flow is forced to cross the bottom of the ditch.

The impact on Qp and Tp for these the simulations are much more striking than the original simulations. Clearly the up scaling of the size of the features and the significance of shallow flow across rough vegetation, together have a large impact on the and Qp and Tp. There are some more effects seen between the small medium and large storms, in figure 5.16 and 5.17, as it clearly takes longer in the smaller events to fill up and overcome the storage effects of the vegetated/wetland ditch. The smoothing effects caused by zones of dedicated wetland (figures 5.13 to 5.15) seem to be greatly increased as the size of the wetlands are increased.

In figure 5.18 to 5.20, we show a comparison of the new FIRM plan scenarios against each other for each of the storms. Also included on these figures are the outputs from the original scenarios, as these most overlay each other and can be taken together. This gives a visual impact of the differences the large features are making in the simulations.

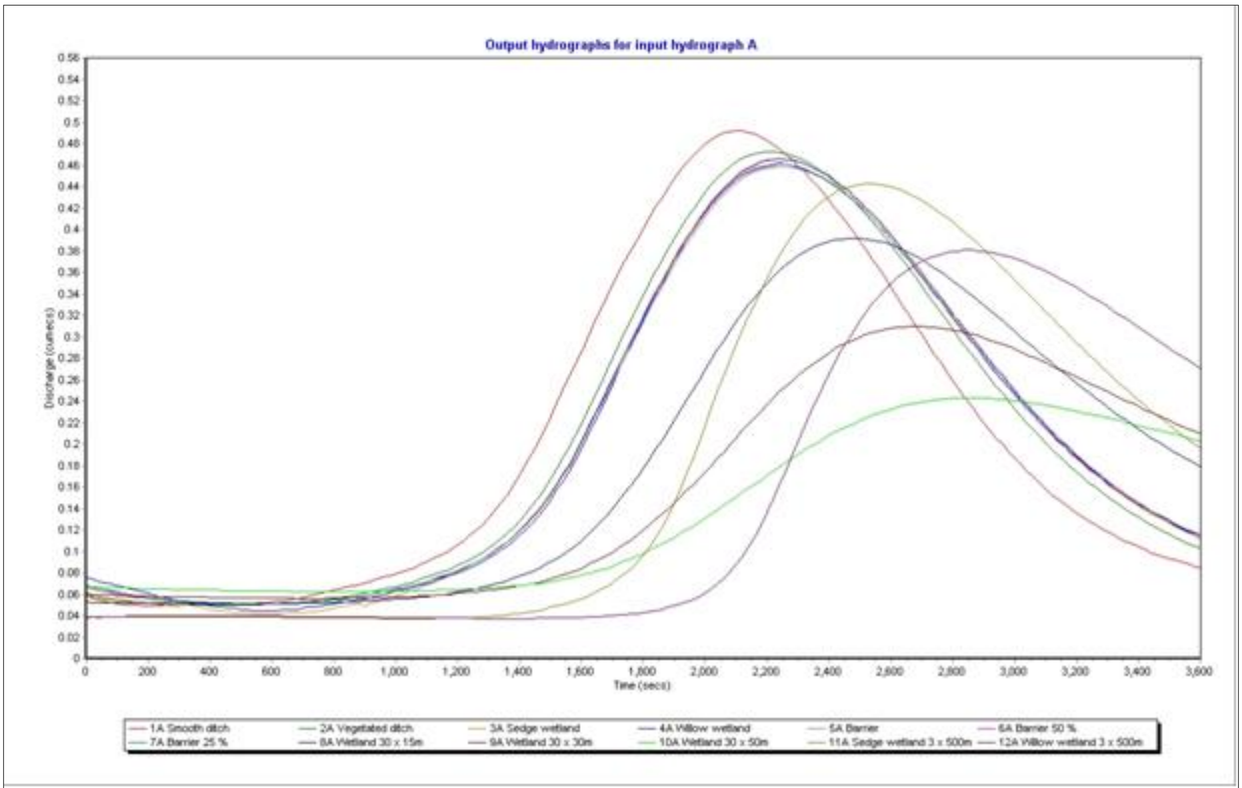


Figure 5.18, Event A, are simulation compared against each other

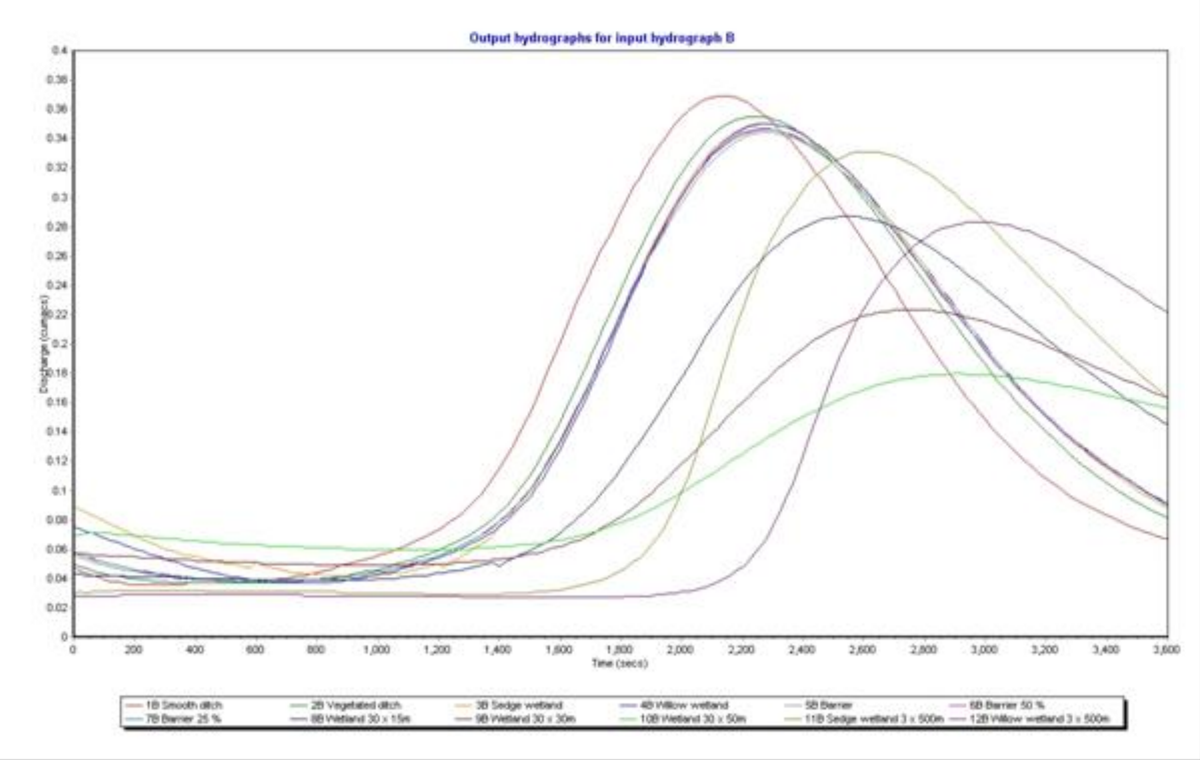


Figure 5.19 Event B simulations

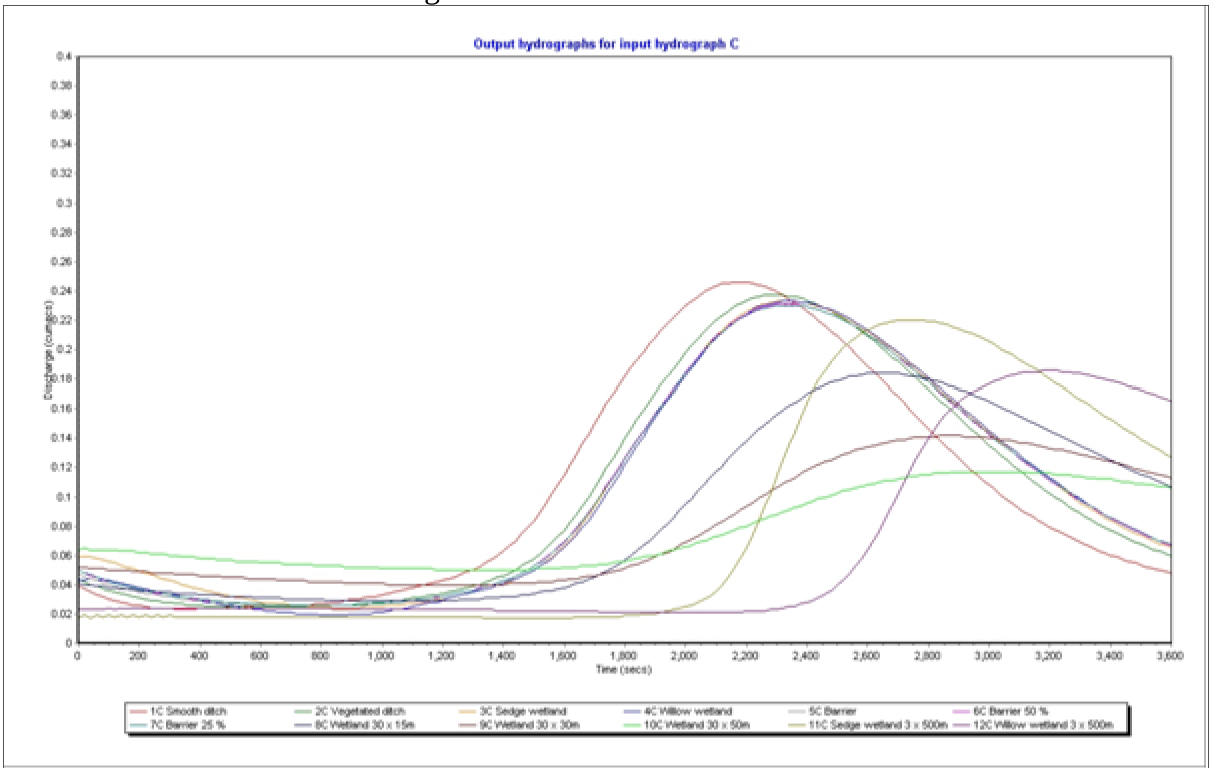


Figure 5.20 Event C simulations

The large impact on Qp and Tp (see table below) for the full scale FIRM features when compared to the original simulations is very clear. Also, the difference between the dedicated wetland and the widened ditch can also be seen. For the long thin widened ditch the delay effects are very high (effecting Tp) but they have less impact on the Qp as the dedicated wetland areas have.

Table of Qp and Tp for all simulations

Case A	Time to peak, Tp (secs)	Peak, Qp (cumecs)	Qp change	Tp change
Input hydrograph A	1740	0.51	%	%
1A Smooth ditch	2120	0.492		
2A Vegetated ditch	2200	0.473	3.86	-3.77
3A Sedge wetland	2240	0.466	5.28	-5.66
4A Willow wetland	2260	0.465	5.49	-6.60
5A Barrier	2240	0.459	6.71	-5.66
6A Barrier 50 %	2240	0.462	6.10	-5.66
7A Barrier 25%	2240	0.461	6.30	-5.66
8A Wetland 30x15m	2460	0.392	20.33	-16.04
9A Wetland 30x30m	2660	0.31	36.99	-25.47
10A Wetland 30x50m	2800	0.243	50.61	-32.08
11A Sedge wetland 3x500m	2520	0.443	9.96	-18.87
12A Willow wetland 3x500m	2840	0.381	22.56	-33.96

The full scale **FIRM** scenarios are giving Qp reductions of above 50% and increases in Tp 32% of (30 *50m dedicated wetland zone). The widened ditch with willow vegetation gave a 22% reduction in Qp but the Tp increase was 34%. If it is possible to combine both the widened ditch and the wetland zone then the maximum impact of flow retardation and nutrient trapping would probably occur.

It may be to bold to accepts the results as presented above, but the basic message of creating large amounts of space with slow flow, over vegetated areas seems to be emerging. This does not mean that the features are just left to become overgrown, in order to get the simulations seen above does mean extensive work within the channels. The commitment to create dedicated wetland zones and features to control the flow onto, within and back into the ditch will require careful thought and planning. Further, all the features would require maintenance. The implications to buffer strip development and wetland design general is high, the flow of water should be controlled so that large areas of farm eland are not inundated. For the case of 6m buffer strips we would suggest that a bund be constructed on the outside edge of the buffers strips must be built to keep flow within the buffer zone. This will afford the 15m width of flow as suggested in figure5.13. The ability to force flow onto the buffer strips in higher flows is also needed. It will be important to show farers that their land will not be flooded as a result of such an intervention. A means of bypassing very large flows may also be needed. The conclusion for the Proactive approach to FIRM plans with respect nutrients (2007), has also suggested that forcing flow on buffer strips and making maximum use of the available ditch area afford the best chance of denitrifying flow during larger events. This is all food for thought and we would urge more testing of these ideas at full scale in the near future.

6.0 A CRITIQUE OF COSTS AND IMPLEMENTATION STRATEGIES

Here a critique of costs is made and the estimate of the likely cost of whole **FIRM** plan being implemented. The cost of each feature built is shown below which reflects the full cost (though estimated) that has been incurred by the project.

Infiltration ponds, constructed by Owen Pugh, civil engineers.	£7000 each
Road drain ponds constructed by Owen Pugh, civil engineers.	£1000 each
5m concrete section in sediment trap constructed by Owen Pugh, civil engineers.	£1000
Ochre manufacture, 5 tonnes of ochre pellets	£25000

Ochre P trap	£2000
Barriers in ditches	£1000 each
Sedge wetland – 30 m long	£5000
Willow wetland – 30 m long	£6000
Algal Pod	£6000
Buffer strip (draw off pipe and 50 m of fence)	£500
Green lab and analyser	£70000
Renewable energy micro wind and PV array	£27000

An estimate of physical storage achieved at Nafferton Farm

FEATURE	COST (£)	STORAGE (m^3)	Rainfall depth-mm	Cost per mm stored
Ponds	14000	250	0.25	5600
Sediment trap	1000	25	0.025	40000
Barriers (when full) * 4	4000	100	0.1	40000
Wetlands 60m*3m	11000	5	0.005	2200000
Total	30000	380	0.38	78947
Total without wetlands	19000	375	0.375	50666

Clearly only the physical storage in ponds seems to be reasonable at this time. The other features were placed into ditch for multiple reasons, therefore the disproportionate cost of some features needs to be a balanced against the other functions they perform (for example the sediment trap is an effective feature (Quinn et al 2007). Note no attempt has been made to include any contribution they can make transient storage effects of the features as yet. A value of £50000/km^2/mm of runoff stored is not reasonable even if other benefits are taken into account. Therefore a number of cost reductions are required or need to be set within a wider context.

So at first viewing the interventions may seem very costly. However, there are many considerations to be taken into account:-

1. The cost are higher that would be expected if installed by local farmers and local agricultural engineers. All the features have been over designed and have extra built in research related components. As such the construction has incurred some extra cost. A number of the features took longer to construct as many practical lessons were being gained during the construction.
2. What is the real cost of flood damage in the UK per mm of rainfall. Can this expressed at damage per km2 per mm of runoff?
3. What benefit is there is stopping other farm land from being inundated, i.e. the price of washland? Here, washland would only be used once all other storage is full.
4. There may be locations on the farm where a large dedicated flow storage pond could be created at low cost but with high storage capacity. Nafferton farm has assumed that 100% of farm is in full production.
5. What is the practical cost of sediment loss, P loss and nitrate loss to the environment? If this is high, then it needs to be quantified and estimated per

square kilometre of farmland so that real cost can be assigned to allow some construction of feature on farms. Sediment traps and fine filters seem to be working efficiently and offer an immediate way forward.

6. How long does a feature last? How many years of subsidy can be saved by lump sum investment, say every 5 years?
7. How much will it cost to maintain the features and execute a sediment, ditch and management plan? Is it higher or lower than other pollution reduction measures in annual costs.
8. Can it be shown that sediment and nutrient capture can have economic benefits to farms if it can be effectively recovered and reused?
9. What are the multiple benefits of features that are designed for nutrient pollution management to flood risk reduction, waste recycling and carbon reduction? What bout pesticide reduction and pathogen removal? All the features should contribute to a reduction in overall emissions.
10. What ecological benefits are gained from runoff management at source? Should these costs be compared with upland grip blocking expenditure?
11. How much is currently paid to farmers per square kilometre in the current agri-environment schemes?
12. Should we pay farmers to actively take part in pollution/waste reduction from farms? Independent visible evidence that features are being constructed and maintained can be done quickly by farming advisors, EA and Defra.
13. Can farmers be given incentives to manage runoff, by joining flood management funding and renewable energy/carbon funds with agri-environment funding? Can vast savings be made if multi functional feature are delivered by 1 over arching funding method of farm payment?

Despite the above questions, there is still a need to bring down the real cost of **FIRM** plans if flood storage is to be justified on farms. The only means to achieve this is to create **FIRM** plans for whole farms where economies of scale can be achieved and the available space to create ample flood storage is maximised. Essentially we are attempting to address two key questions of the Making Space for Water Initiative by:-

1. stating where water can be stored in the landscape
2. having a holistic multi-functional approach

Below we will propose a **FIRM** plan for a farm similar to Nafferton that is built on all the finding proposed here and the findings of Quinn et al., 2007. Note the FIRM plan is to address both the nutrient pollution problem and the flood storage problem.

6.1 A Possible Future Scenario.

Assume there is a 1 km^2 square catchment on a typical farm (with field drains), with 6 fields and 500 m of ditch/channel (see figure 6.1). The **FIRM** plan suggests that all fast polluting flow paths should be disconnected using on the farm using ponds. In order to maximise the pollutant reduction in the ditch it will be widened and saturated zones induced. In order to maximise use of the buffer strips, flow will be forced onto the zone to enhance nutrient stripping and attenuate flood flow. A bund and fencing (or hedgerow) on the edge of the buffer strip will stop flow from propagating onto the productive areas of the farm.

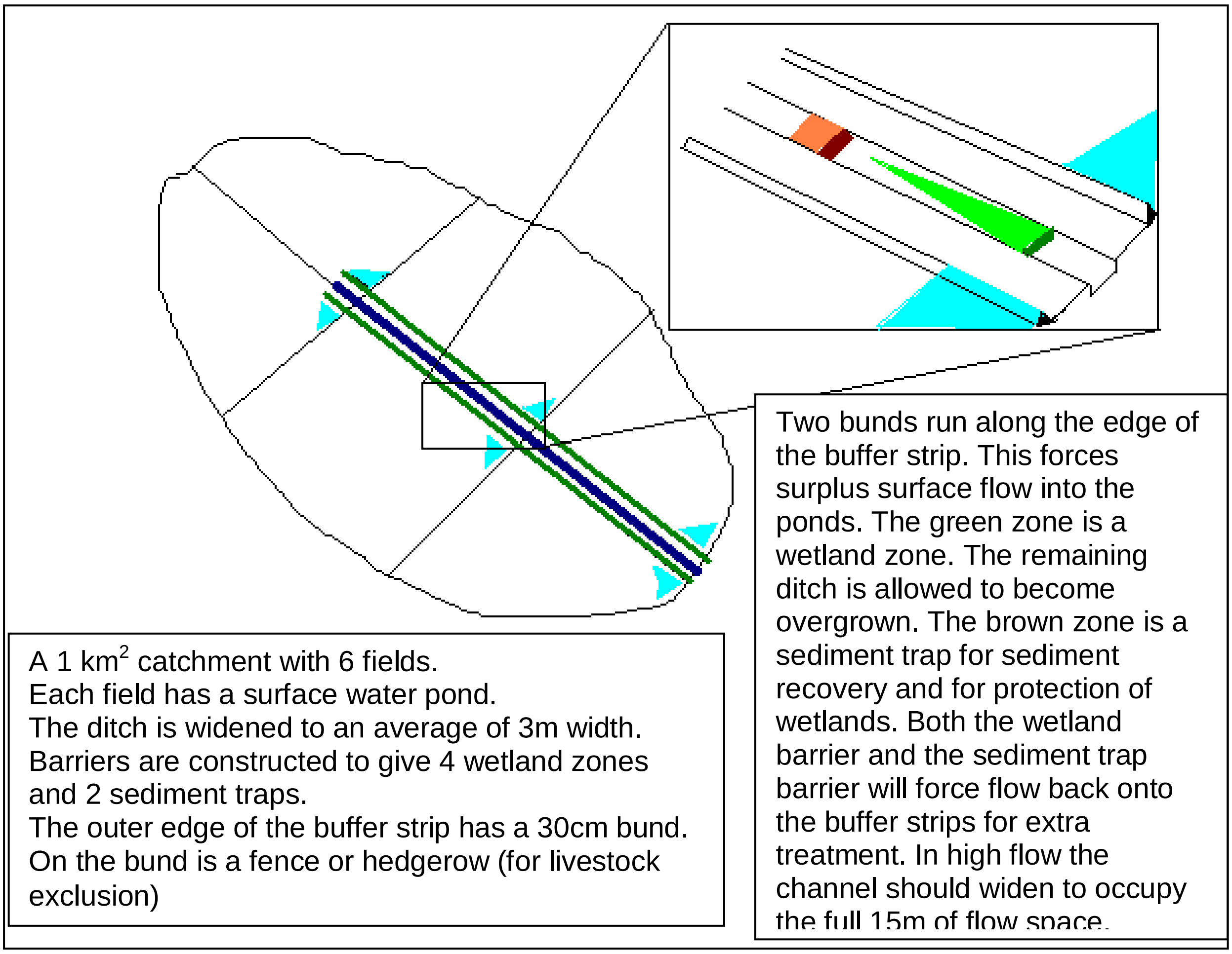


Figure 4.1. A theoretical 1km^2 catchment with a proposed **FIRM** plan.

Please note the proposed FIRM plan is designed to address both the nutrient pollution and flood control objective. Other spin off to ecology, carbon trapping, pathogens and pesticide control are not evaluated but they are expected to be occurring.

Features to be constructed over the life cycle of the **FIRM** plan:-

- 1 pond in each field, that takes all runoff from hardstanding, road and overland flow from bare fields. 6*£2000
- A 30cm high, 1km soil bund at the edge of a 6 meter buffer strip £3000
- The 6 meter buffer strip will use 1km of fencing along the top of bund (or a hedgerow) £5000
- Ditch is widened to 3 m (as at Nafferton) with zone of sedge and willow is planted. £5000
- 4 flow control barrier 1 every 100m, which are using to slow flow and keep sedge and willow zones wet, they also force flow onto the buffer strip in storm events £5000
- 2 Sediment traps in the ditch £2000
- Maintenance payment to recover sediment and the maintenance of all features – £1000/year

Physical storage achieved

FEATURE	COST (£)	STORAGE (m^3)	Rainfall depth-mm	Cost per mm stored
Ponds (100m3)*6	12000	600	0.6	20000
Buffer strip and bund	8000	2250	2.25	3555
Wide ditch 500*3	11000	1500	1.5	7333
Sediment trap *2	2000	50	0.05	40000
Total	32000	4400	4.4	7272
Total without sediment trap	30000	4350	4.35	***6896***

N.B. the calculation for buffer strip storage is assuming length 500m* width 15m * 0.3m maximum depth of flow. The calculation for the ditch assumes a ditch 500m long, 3m wide and maximum depth of 1m (so it does not include the buffer strip depth of flow)

Over a 5 year FIRM plan = £37000 or **£7400/year/km^2**
Over a 10 year FIRM plan =£42000 or **£4200/year/km^2**

Or this could be calculated as ***£6896/km^2/per mm*** of runoff stored, where no other farmland is inundated. Another way of using the number would be to imagine 1mm storage per km^2 being added each year, in a 5 year plan. This would be 0.5 mm per year of storage being added over a 10 year plan.

This analysis as yet has not included the effects of transient storage. The findings of the features are that all features do give a little transient storage (see section 5). The simulated full scale **FIRM** plan scenarios showed that reduction in Qp of up 50%. If we assume that the average was 50%, then a 2mm runoff event would not equate to a 1mm runoff event. In essence the storage rate cost per mm of runoff stored as estimated above, would now be 6896/2 = ***3448 km^2/per mm*** stored, where no other farmland is inundated

Clearly these numbers are very rough and subject to great uncertainty. The idea here is to demonstrate the kind of economic costs/arithmetic needed to produce **FIRM** plans. It is almost impossible to gauge the financial benefits arising from a **FIRM** plan, either to the farm business or to a whole basin. Some estimate is needed of environmental benefits arising from a **FIRM** plan and these results need to presented on per kilometre square basis for comparison purposes.

In the ***proactive*** project at Belford (Northumberland), a £600,000 scheme has been proposed to solve the flood problem for a catchment of 8km^2 using bunds, ponds, washlands and ditch structures. This would equate to £75000/km^2. The blocking of upland grips is also comparable in cost to the **FIRM** plans.

Strategic deployment of **FIRM** plans in areas with high pollution and flood risk or in catchments with sensitive water courses or lakes would also be a chance to test the ***proactive*** hypothesis, to carry out full economic analysis and look a ways to keep construction costs down for a typical farm. Farmers and farm advisors would also be encouraged to deploy renewable energy schemes and use recycled waste materials. We would go further and would heavily subsidize or purchase a renewable energy system for each farm as means of persuading farmers to join in and take a ***proactive*** part in the **FIRM** plan. The benefits to carbon reduction alone may be a reason to do this, but as part of an integrated plan for a farm it may have many benefits. It may be possible to get flood management subsidies to reduce carbon and carbon subsidies to reduce flood risk. The economics of paying farmers to proactively address key environmental problems should be actively pursued if the WFD is to stand any chance of achieving the 2015 targets.

7.0 CONCLUSIONS

The Nafferton farm study is ambitious in its goals to quantify the potential of flow attenuation and total pollution control, at source. By creating a sound evidence base, the potential ***proactive*** interventions and their likely cost and viability of taking the FIRM approach can be determined.

Even though the accumulation of the solid evidence is ongoing, the work so far has shown for a typical intense farm:-

- Large amounts of flow can be stored on farms and
- rough vegetation can potentially attenuate flow.
- Simulation has shown that if space within the ditch and a buffer strip are used there could be sufficient flow storage and pollution buffering capacity on a typical farm. Up to 60% reduction in Qp may be possible and Tp could be increased.
- Large amounts of pollution and sediment is being produced during storms (Acute losses) and between storms (chronic loss). The flood control features will address these losses.
- The runoff generation is varied and fast and even if agri-environment schemes are taken up and if the farm was operating with best practise, then large amounts of runoff would still occur and inevitable contamination of polluted flows would occur
- Hence by targeting and modifying fast flow paths and its physical and chemical content we can address runoff related problems at source as the runoff is generated

Ponds, bunds wetlands, buffer strip have all been designed, constructed and tested at Nafferton farm in Northumberland. All features are multi-functional and will address pollution reduction, lower flood risk, trap and recycle waste, use recycled material and create new ecological zones. FIRM plans can be achieved without damaging the profits of the farm and can funded through an imaginative, strategic mechanism that joins agri-environmental, flood risk management and carbon/renewable budgets together.

All the constructed features can be demonstrated to be working to reduce pollution, store and slow runoff and to trap and recycle waste on the farm. The operational performance of the features during large storm events is still to be proven. We will not be recommending all the features listed in this report be adopted on farms, but crucially we have gained the experience to recommend a series of practical, fundable interventions that could work at the larger catchment scale and address urgent WFD needs, for example:-

- All fast and polluting flow paths can be disconnected from the channel network.
- Ponds, barriers, bunds can physically store large amounts of runoff.
- All features help to slow flow, creating ‘transient storage’.

- Wetlands are slowly de-nitrifying the runoff, but large amounts of extra buffering will capacity will be needed on farms.
- Sediment and nutrients can be trapped and recycled. A one-off sediment and phosphorus trap can reduce Total P by 20-60% even during storms.
- Saturated buffer strips are denitrifying the flow and they have the potential to treat large amounts of flow and the act as flood retardation channels if designed appropriately.
- Ditches can be widened and can act as sediment traps, wetlands and flood retardation channels.
- **FIRM** plans will need farmers to adopt a range of new maintenance activities, including sediment management plans and sediment/nutrient recovery plans. The construction and the maintenance funding will be vital to the delivery of **FIRM** plans.

The potential to store water is obvious, and we feel that each field could justify at least one pond. The pond will stop fast flow paths such as overland flow or could act to receive fast polluting runoff from hard-standings and roads.

All the features listed have some component of physical water storage but they also have a significant component of transient storage. All features should have a high roughness value and all flow should be as tortuous as possible, for example using willow. Willow has proven itself robust and useful as part of the **FIRM** plan.

The impact of any slow flow or ponded water is enormous as there is a very large sediment budget on this farm, though as yet it is not quantified. The abundance of sediment means that it should be removed at strategic points within the farm and then be reused.

Buffer strips could play a pivotal role in flood control and denitrification if they are designed and maintained properly. Buffer strip at this time seem to be quite wasteful, though there impact on lowering pesticide losses and excluding animals is a clear benefit. However it is hoped that these features will buffer flow from the hillslope before reaching the channel. In many cases this may be true but buffering capacity may be quickly exceeded in storm events and there may also be zones with large buffer zones that are not processing much flow. Together this means that fixed width buffer strips are likely to fail in the goal of reducing sediment and pollution levels and will not lower flood risk. We feel that if such a large commitment to taking buffer strips out of production is to occur then buffer strips should be redesigned. The ***proactive*** intervention of barriers and flow control structure should be able to force flow back onto the buffer strips. Equally, a small bund features will be need at the edge of buffer strips to stop larger areas of productive land being flood. Guarantees that the high flows will be conveyed from the farm without causing wider flooding will also be needed.

The final **FIRM** plan for a theoretical full scale application, tries to create numerous opportunities for ponding and filtration. Equally, the buffer strip zone should give extra treatment and flood storage capacity. The potential to capitalise on, ponds, ditch capacity and buffer strips make the cost of the **FIRM** plans viable as part of a subsidised farm subsidy scheme.

The impact of large scale FIRM plans on farms will require a very marked change in ditch management and attitude to recovering the waste. This can be achievable if the farmer values the sediment and nutrients being trapped within the features and should be motivated to recovering their lost waste. However the time and energy required checking and maintaining a wide range of features will have to be tied to the farm subsidy. This will require new advice and education approaches.

What is needed now?

A fully costed, full scale trial of the FIRM plans on a wide range of farms, working closely with farmers and farm advisors.
To test a new mode of subsidising farmers to become ***proactive*** farm runoff managers and thus solve a wide range of environmental problems.

Continued work at Nafferton to prove the performance of the features during large storm events and improve on design and operation issues.

We would propose a means of up scaling the work to the river Eden, where a wide range of rainfall and runoff data is being gathered as apart of the CHASM project. During the life of the CHASM project we have developed close to ties to farmers who have allowed us to instrument their land. Several of the farmers have received renewable energy schemes as part of other projects. These farmers would be willing to trial the FIRM plans as outlined.

The future of the ongoing FD2114 review should be considered, the Making Space for Water should be assessed and the role of Catchment Sensitive farming be considered. Whilst we have made every effort to communicate and work with these groups and more formal series of collaborations and knowledge transfer workshops may be needed.

What will FIRM Plans cost?

Costs are comparable with the budgets available to flood control projects (or possibly cheaper), agri-environment schemes and activities such as upland grip blocking. If other subsidies related to renewable energy, carbon storage, waste recycling and ecological initiatives are joined together then FIRM plans can be funded sustainably, with visible, quantifiable, multiple benefits that will address the needs of the WFD.

In order to address flood control at source we estimate the costs as between **£1000/km^2/mm of runoff (rainfall depth equivalent) stored and 10000/km^2/annum/mm of runoff stored. This is without any other farmland being inundated.** The lower estimate is based predominantly on physical storage in ponds within fields. We would recommend a more complex FIRM plan despite the cost as other benefits will accrue. If **FIRM** plans are rolled out over a 5-10 year period then costs become more acceptable.

The work in this report has not included the possibility to locate areas on farm where there is no crop production, or forested areas where a larger flood storage pond could be created. We have assumed that the farm is in 100% production. Such zone will give the opportunity to storage large amount at source, and the **FIRM** plan could concentrate on the nutrient pollution aspects.

In order to address pollution control we feel that this would cost between **£1000/km^2/annum and 10000/km^2/annum.** This will give drastic reduction in nutrient pollution and sediment losses in most storms and. This cost may fall as more full scale tests are carried out. The option to deploy a **FIRM** plans over a longer period will also reduce cost.

Equally, the dual benefits of the pollution and flooding problem should be treated together.

Other benefits to ecology, carbon budgets, pathogen reduction and pesticide trapping could all be added to make FIRM plan more viable.

Defra and the EA require a means of giving farmers incentives to change their land management whilst regulating land management. Defra and EA must get value for their money. By giving farmers real, physical features to construct and maintain, then regulators will have a solid basis by which they can assess if a farmer is deploying their funds to actively reducing pollution and flood risk. We have stressed that new imaginative integrated funding sources are needed to underpin the FIRM approach. We feel that helping farmers to generate renewable energy and minimise waste on farms will encourage them to construct runoff mitigation features. A new wind turbine or some coppice woodland could help solve flooding and nutrient pollution.

Finally, we would propose that **FIRM** plans on farms are complementary to research into the operation of floodplain/washlands and to the flood protection of towns. A balanced approach to funding all three strategies is probably a wise move. By adding flood risk management money to farm subsidies, it could make all the difference in justifying the **FIRM** approach to farm runoff management. The benefits seen for many aspects of the WFD will also be great.

We conclude that the ***proactive*** approach may be crucial in addressing future farm economics and in the protection of the environment.

8. REFERENCES

O'Connell P.E., Beven K.J., Carney J.N., Clements R.O., Ewen J., Fowler H., Harris G.L., Hollis J., Morris J., O'Donnell G.M., Packman J.C. Parkin A., Quinn P.F., Rose S.C., Shepherd M., Tellier S. Review of impacts of rural land use and management on flood generation: Impact study report. Department of Environment, Food and Rural Affiars, Research and Development Technical Report FD2114/TR. Defra, Flood Management Division, London. 142pp + Appendices (219 pages). 2005.

Heathwaite. A.L., Quinn, P.F. and Hewett ????

Quinn, P.F., Jonczyk, J., Rimmer D. and Hewett. C. 2007. The proactive… approach to Farm Integrated Runoff Management (FIRM) plans with respect to nutrients